Supplementary Information for

Beyond Energy Density: Flow Battery Design Driven by Safety and Location

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Methods

The land area occupied by a battery energy storage system (BESS) was determined using the polygon measurement tool in Google Earth Pro. This approach has a mean square error for horizontal distance measurements of 0.57 feet, which is accurate enough to determine the footprint of large facilities.[1] For a given site, the measured area was chosen so that the infrastructure associated with the battery systems is reasonably considered without including excessive land area or service roads. Three meters to the closest battery containers were included on all sides of the polygon used to determine the footprint of the installation. Note that some installations are either fenced-in, so the boundary of the site is well defined, or housed in a building where footprint areas are clearly defined by the walls reaching the ground. The three-meter criterion was not employed in these cases. Naturally, this implies that the areal energy density values reported here, calculated by dividing the rated energy capacity of the site by the measured footprint, may vary depending on selection criteria. We report a best effort in fairly assessing the various installations and battery technologies deployed in several countries. Two examples of how various selection criteria affect the areal energy density of the installation are shown below for the 409 MW/900 MWh site in Parrish, Florida and the 182.5 MW/730 MWh Elkhorn site in Moss Landing, California.

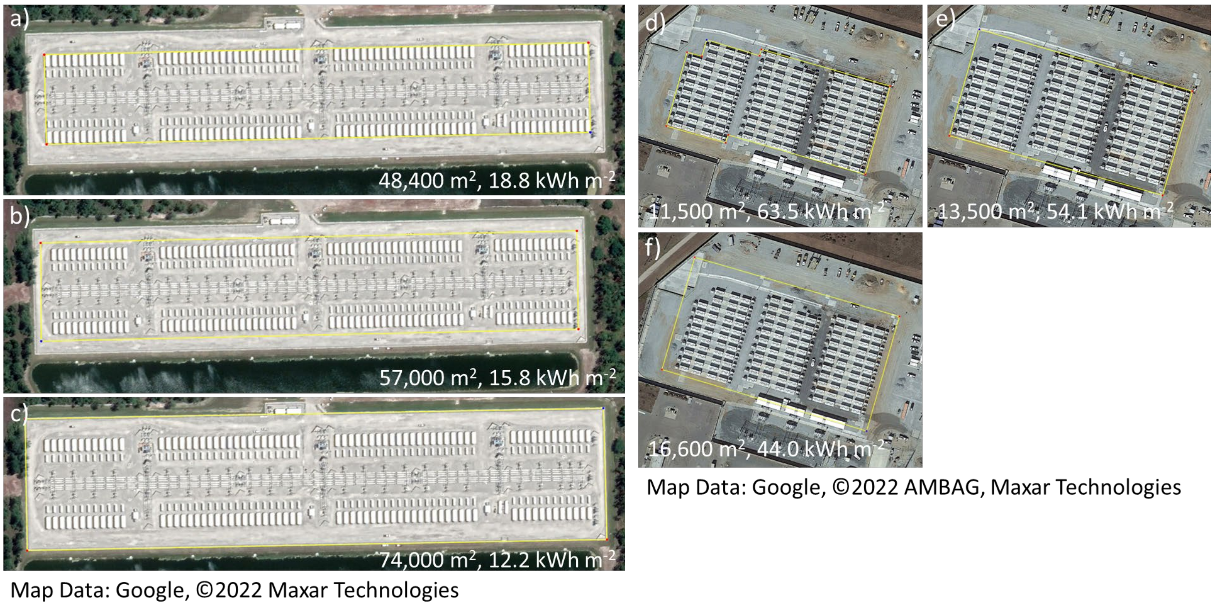


Figure M1: Impact of area selection criteria on areal energy density. **a)** 409 MW/900 MWh site in Parrish, Florida, leaving no space between batteries and boundary, **b)** leaving 3 meters between batteries and boundary, **c)** considering the entire concrete slab the system is built on. **d)** 182.5 MW/730 MWh Elkhorn site in Moss Landing, California, leaving no space between batteries and boundary, **e)** leaving 3 meters between batteries and boundary, **f)** considering excessive land area.

Several BESS for which up-to-date satellite imagery is not available or that are under construction are mentioned in this work and their locations are provided. These systems were, however, excluded from footprint calculations and are, accordingly, not listed in Table S1 (Figures S27-38).

The number of individual cells in a Tesla Megapack was calculated as follows: The pre-September 2022 Megapack had an energy rating of 2.6 MWh, using 2170-type cells.[2] The energy rating of a 2170 cell was calculated from publicly available information about the Tesla Model Y that contains 4416 such cells and is rated at 75-80 kWh, corresponding to roughly 18 Wh per cell. This translates to about 145,000 cells per Megapack. Tesla has deployed 6.3 GWh since the 2021 third quarter, corresponding to at least 2,400 Megapacks or approximately 350,000,000 individual cells.[2] The two Megapack fires discussed in the manuscript (Moss Landing, California, and Geelong, Australia) suggest that a minimum of two cells out of roughly 350 million have failed catastrophically, suggesting a cell failure rate of less than one in 100 million, but unit failure rate of about one per thousand. This highlights the fact that fire hazards significantly scale with BESS size.

The energy density of flow batteries is calculated by multiplying the discharge capacity with the average discharge cell voltage at a given current, divided by the total volume of electrolytes. The theoretical capacity of an electrolyte is calculated as $Q_t = \frac{n*c*v*F}{3600}$, where n is the number of electrons per mole of active species in solution, c is the concentration in mol L^{-1}, v is the volume, and F is the Faraday constant, resulting in 26.8 Ah L^{-1} for a one molar, one electron electrolyte. As an example, a vanadium flow battery with an average discharge voltage of 1.3 V and 1.6 M vanadium concentration in each electrolyte, corresponding to 42.8 Ah L^{-1} for each electrolyte, has an energy density of 27.8 Wh L^{-1} per total volume of electrolytes.

To calculate space utilization for sites with external tanks visible on satellite images, the footprint of the storage tanks (m^2) was divided by the total footprint of the site (m^2) and multiplied by 100 to get a percentage. In Google Earth Pro, each of these was calculated using the polygon or circle measurement tools. To find the footprint of the storage tanks, a circle was drawn over the tank, ensuring that the circumference of the circle was well-aligned with the outer edges of the tank. The area of the circle (m^2) was then multiplied by the number of tanks. The dimensions of all tanks on a given site appeared to be identical, but to account for limited measurement precision, at least three tanks in each site were measured in this manner (three measurements across the two tanks in the case of the Regenesys site, see Figure S75) and the resulting total tank area estimates were averaged. The total site footprint was calculated using the Polygon option, as described above. For all measurements, it was ensured that the satellite view was directly overhead by selecting View → Reset → Tilt. The EnerVault site is shown below as an example (see also Figure S72).

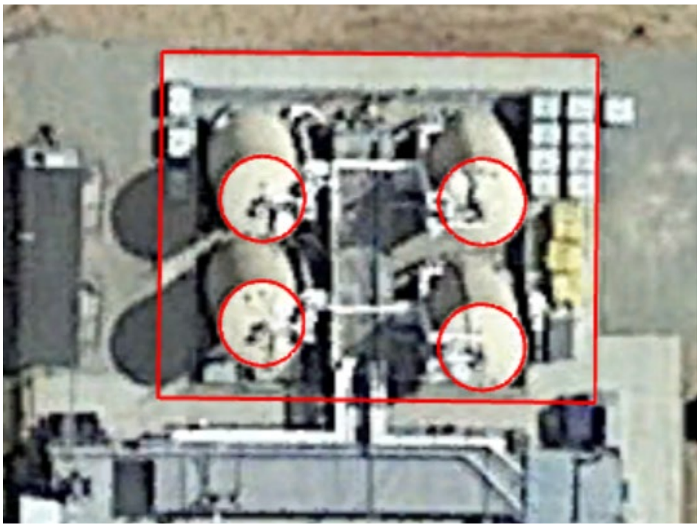


Figure M2: Visualization how space utilization was determined for flow batteries that use large, external tanks. The tank area is divided by the footprint of the installation to get the fraction of the BESS-sites' area that is occupied by tanks.

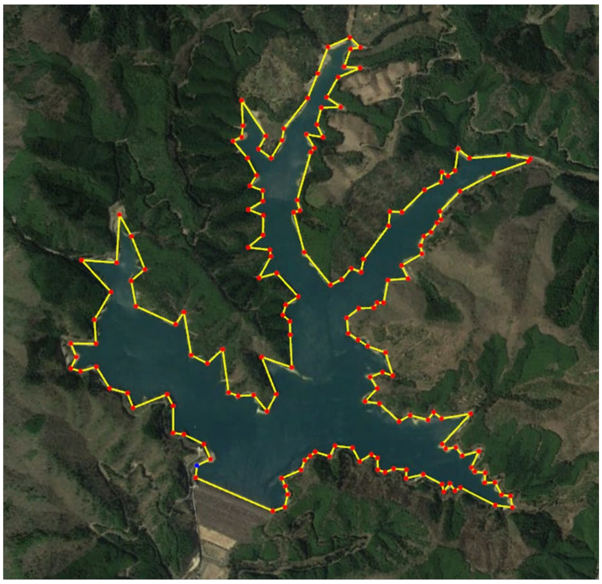
Table M1: Tank areas and resulting space utilization from the above EnerVault site.

EnerVault Fe-Cr battery (CA)	Area (m^2)
Tank 1	10.2
Tank 2	10.3
Tank 3	10.5
Tank 4	10.5
Tank Total	41.5 ± 0.13
Site footprint	275
Space utilization	**15.1%**

The height of the Regenesys sites' tanks (Figure S75) was calculated using the formula $h = \frac{V}{A}$, where h is the tank height (m), V is the volume of the tank (m^3), and A is the area of the tank calculated using Google Earth Pro (m^2). V is 700,000 gallons corresponding to 2,650 m^3, while A is 320 m^2, resulting in a tank height of 8.3 m.[3]

Areal energy densities considering various space utilization and electrolyte energy density values were calculated as $\sigma = u\rho h$, where σ is the areal energy density (kWh m^{-2}), u is space utilization (expressed as a decimal), ρ is the volumetric energy density of the electrolyte (kWh m^{-3} = Wh L^{-1}), and h is the tank height. For Figure 3a in the manuscript, h was set to be 8 m. For Figure 3b, σ was plotted as a function of h, with the slope being equal to $u\rho$.

The surface area of pumped storage hydropower reservoirs was again determined using the polygon tool in Google Earth Pro, as shown in Figure M3. The storage capacity in MWh and cubic meters of water for the upper reservoir of the individual sites was extracted from references listed in Table S4. The volume of the upper reservoir was used to calculate volumetric energy densities as this volume is what defines the maximum amount of water that can effectively be cycled back and forth for storage/generation. For hydropower plants that use two artificially constructed reservoirs, the surface area of both was considered to calculate the areal energy density. For plants that use pre-existing water bodies as a lower reservoir, only the surface area of the upper reservoir was considered to calculate areal energy densities, as this is the only surface occupied by an artificially constructed body. This rationale was also employed for sites where the lower reservoir is a reservoir of a pre-existing hydropower generating (not pumped storage) station, for example the Nant de Drance plant in Switzerland.



Map Data: Google, ©2022 Landsat / Copernicus

Figure M3: Surface area measurement of the upper reservoir at the Okutataragi Pumped Storage Power Station in Japan.

Supplementary Discussion

Power market

The energy prices in Figure 1 and Figures S1-3 are real-time locational marginal prices (LMP) at certain network nodes obtained from CAISO.[4] The LMP is the marginal cost of serving the next increment of demand at a given node and is composed of an energy component that represents the load-weighted average price at a given node (based on bids of buyers and sellers), a congestion component that reflects the cost of congestion (congestion is when the lowest-price energy cannot flow freely to a certain area because the transmission line is operating at its limits due to heavy electricity use), and a loss component that represents electrical losses over large-distance transmission. This cost breakdown is shown in Figures S1-3 for several nodes. Most system operators have day-ahead and real-time LMP markets, whereas the real-time market balances differences between day-ahead commitments by buyers and sellers and real-time supply and demand.[5,6] Note that zonal markets with less granularity than nodal markets also exist. In fact, CAISO has switched from a zonal market to a nodal system in response to the 2000 California energy crisis, as the zonal system with its lower granularity was perceived as one of the factors leading to the crisis.[7] Additional market processes include short-term ancillary services that help to maintain grid stability (a key market for LIB-BESS),[8] congestion revenue rights used to offset congestion costs,[9] or convergence or virtual bidding that helps day-ahead and real-time prices move close thereby reducing incentives for market participants to wait to bid physical schedules only in the real time market.[10]

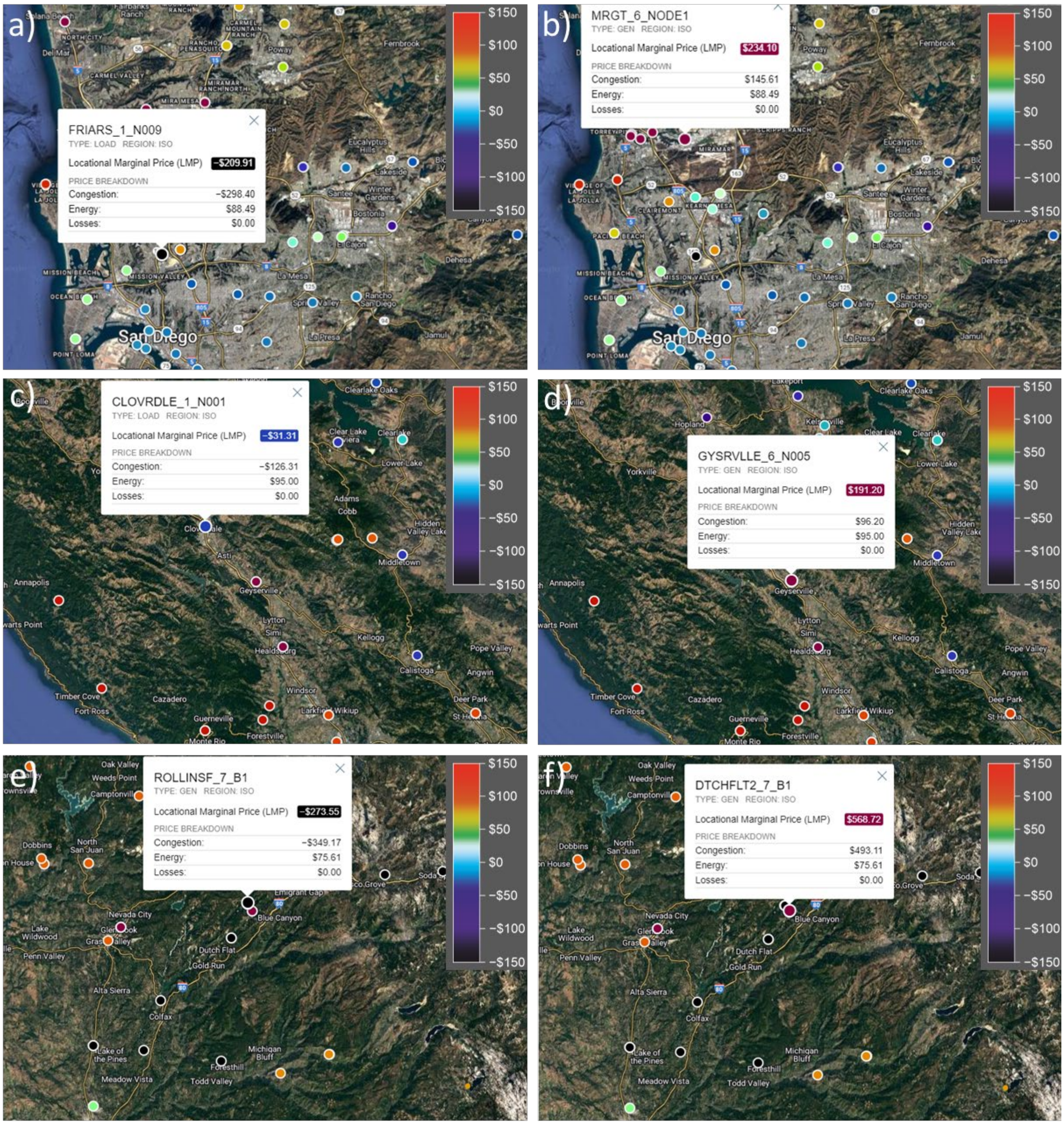
Safety codes

The 2021 International Fire Code (2021 IFC) and National Fire Protection Agency code 855 (Standard for the Installation of Stationary Energy Storage Systems) require BESS systems to be listed in accordance with the international standard UL9540 (Energy Storage Systems and Equipment) and allow BESS units of up to 50 kWh with a maximum number of units totalling 600 kWh.[11–13] Residential units are restricted to not exceed 20 kWh or a total of 80 kWh for an installation. These BESS units must be installed with a three-foot (91.4 cm) separation distance between units and any surrounding exposure. Prior to the July 2022 version of UL9540, code authorities were allowed to approve larger BESS units and systems with smaller separation distances, as evidenced by the large number of BESS discussed in this study that do not follow these restrictions or recommendations. With the latest update of the standard, size restrictions can only be waived based on large scale fire tests following UL9540A (Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems) and BESS larger than 50 KWh or with separations less than three foot cannot be listed to the previous edition of UL9540 without complying to appropriate UL9540A fire test performance requirements.[11,14] UL9540A tests systems on cell level, module level, unit level and installation level, and a BESS needs to go through each one to meet performance criteria for certification. Note, that the world's largest LIB manufacturer CATL has entered a strategic cooperation with UL recently to conduct UL9540A testing in their own labs.[15] Furthermore, BESS modules are increasingly certified by standards such as UL1973 (Batteries for Use in Stationary and Motive Auxiliary Power Applications). This standard includes construction requirements such as prerequisites for metallic parts resisting corrosion, enclosures, wiring, separation of electrical circuits, insulation, protective grounding, cooling and thermal management, electrolyte containment, battery cell construction, and further outline safety performance tests such as overcharge test, short circuit test, over-discharge protection test, temperature and operating limits check test, imbalanced charging test, failure of cooling and thermal stability system test, or working voltage measurements. UL1973 further requires mechanical tests such as impact tests or pressure release tests. External fire tests where a fully charged unit is exposed to a hydrocarbon flame for twenty minutes further make sure the unit does not deflagrate upon exposure to a surrounding fire. Internal tests where thermal runaway of a centrally placed cell is induced via heating of the unit are also required.[16,17] Current fire codes further require compliance with standards that cover electrical safety (NFPA 70/NEC), alarms and detection (NFPA 72), fire suppression (NFPA 13 and NFPA 15) and protection against explosions (NFPA 68 and NFPA 69).[18]

Policy tools

The Inflation Reduction Act in the United States introduces investment tax credit (ITC) subsidies for standalone energy storage systems. This means that BESS do not anymore have to be installed directly onsite at, for example, solar generation sites, decreasing the upfront project costs by up to 30%.[19] To qualify for such ITC's most planned BESS projects now were paired with solar PV and removing this barrier means they can cost-effectively be deployed where they make most sense, rather than arbitrarily needing to be built at solar farms. Such ITC put standalone battery storage on parity with other generation sources and are considered a major boost to the industry. The first project claiming ITC from the Inflation Reduction Act via tax equity investments, a 200 MW Li-ion BESS by Eolian L.P. and Wärtsilä, was already completed in late March 2023 in Mission, Texas (Figure S30).[20] Note that such tax equity investments are often complex with high transaction costs, a disadvantage for smaller developers.[21] A corresponding Clean Technology tax incentive was introduced in Canada's Budget 2023,[22,23] and the European Union has released the Green Deal Industrial Plan as part of REPowerEU, an energy strategy in response to Russia's Invasion of Ukraine, that outlines plans to rapidly reduce dependence on fossil fuels by e.g., mandating maximum permit-granting times of one month for solar and storage projects, acknowledging the need for grid-scale storage.[24]

Supplementary Figures and Tables



Map Data: Google, © 2022 INEGI Imagery / TerraMetrics

Figure S1: Real-time price fluctuations in the renewable-rich power grid operated by the California Independent System Operator CAISO. Locational Marginal Prices (LMP) in dollar per MWh at 8 a.m. on November 2, 2022, in **a-b)** the San Diego, California region, **c-d)** the Cloverdale, California region, and **e-f)** the Emigrant Gap, California region, for various network nodes. The two nodes with the largest price difference in each region are highlighted, showing the breakdown between energy and congestion costs. Nodes in a-b), FRIARS_1_N009 and MRGT_6_NODE1, are separated by 10 km. Nodes in c-d), CLOVRDLE_1_N001 and GYSRVLLE_6_N005, are separated by 13.5 km. Nodes in e-f), ROLLINSF_7_B1 and DTCHFLT2_7_B1, are separated by only 1.5 km. All data obtained from references [4,25].

Map Data: Google, © 2022 INEGI Imagery / TerraMetrics

Figure S2: Real-time price fluctuations in the renewable-rich power grid operated by the California Independent System Operator CAISO. Locational Marginal Prices (LMP) in dollar per MWh at 1:30 p.m. on November 2, 2022, in **a-b)** the San Diego, California region, **c-d)** the Cloverdale, California region, and **e-f)** the Emigrant Gap, California region, for various convergence bidding network nodes, the bottom of the duck curve, on November 2, 2022. The nodes highlighted in Figure S1 are again marked, showing the breakdown between energy and congestion costs. Nodes in a-b), FRIARS_1_N009 and MRGT_6_NODE1, are separated by 10 km. Nodes in c-d), CLOVRDLE_1_N001 and GYSRVLLE_6_N005, are separated by 13.5 km. Nodes in e-f), ROLLINSF_7_B1 and DTCHFLT2_7_B1, are separated by only 1.5 km. All data obtained from references [4,25].

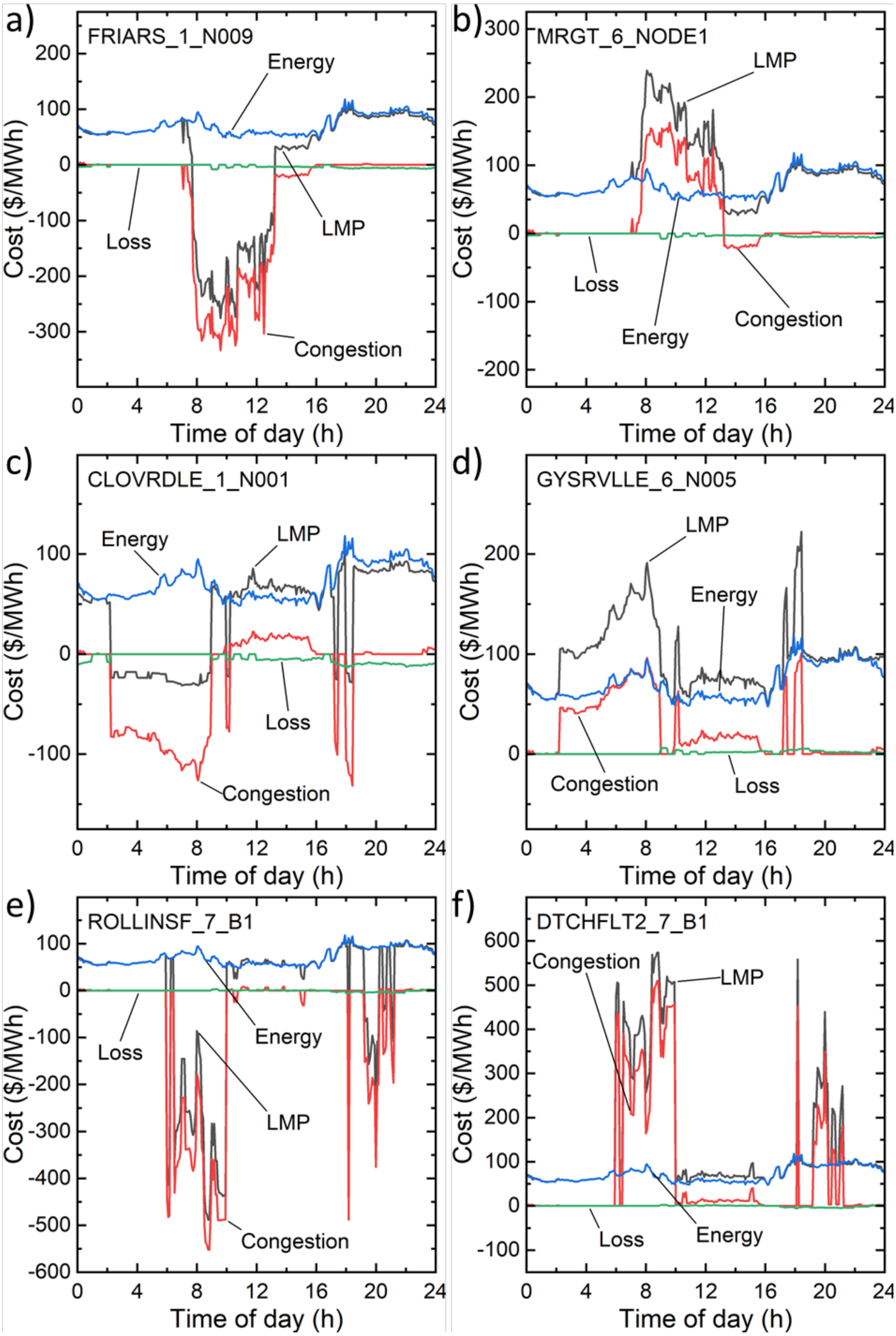


Figure S3: Real-time Locational Marginal Price (LMP) fluctuations and price breakdown in five-minute increments for nodes **a)** FRIARS_1_N009, **b)** MRGT_6_NODE1, **c)** CLOVRDLE_1_N001, **d)** GYSRVLLE_6_N005, **e)** ROLLINSF_7_B1, and **f)** DTCHFLT2_7_B1 on November 2, 2022. In e-f) note the maximum difference of 1063 $/MWh at 8:50 a.m. All data obtained from references [4,25].

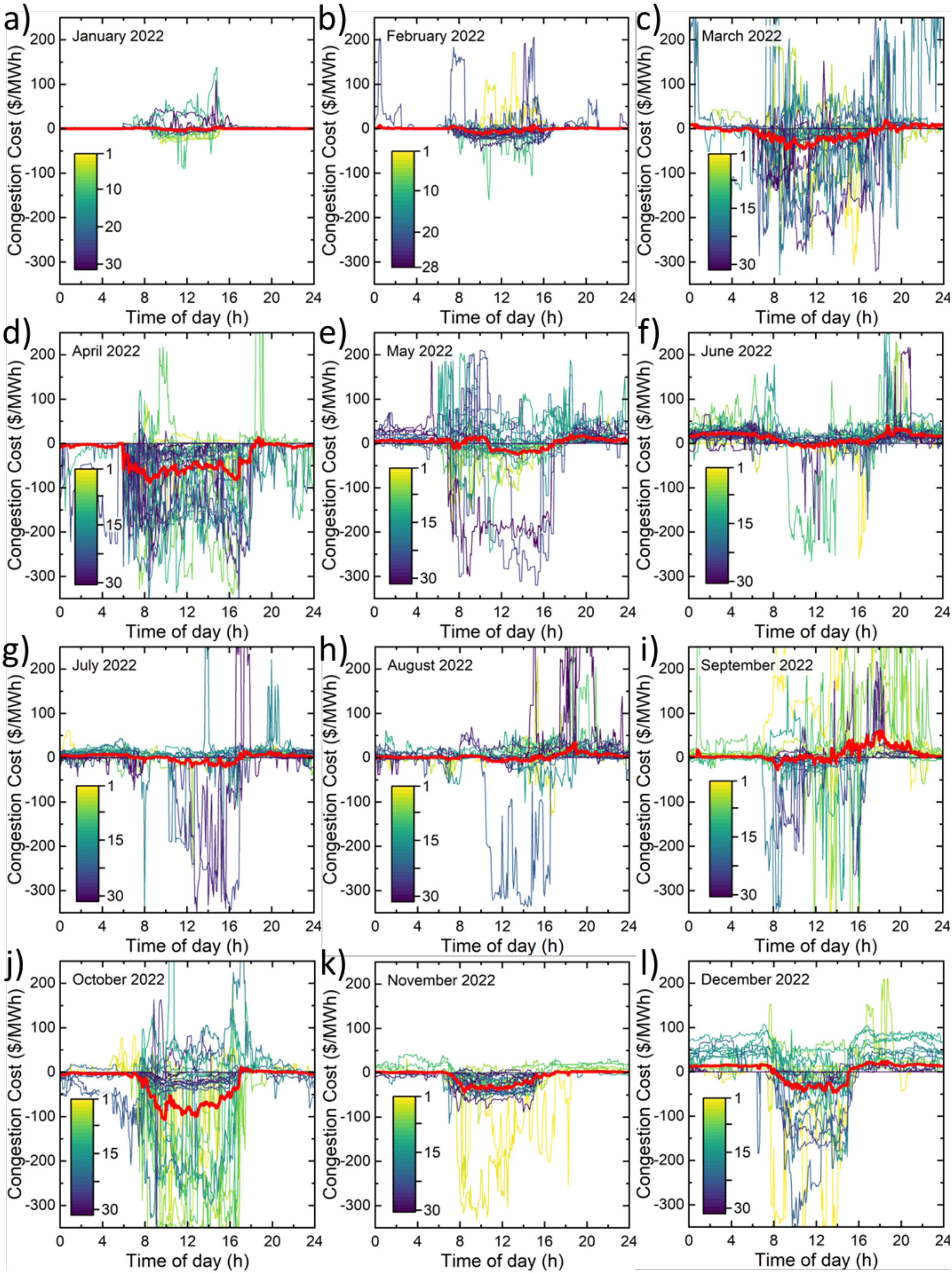


Figure S4: Real-time contribution of congestion to Locational Marginal Prices (LMP) at node FRIARS_1_N009 throughout 2022 in five-minute increments. The color bar indicates the day of the month, and the red curve represents the average throughout each month. Spikes of up to 1400 $/MWh at the beginning of September coincide with a near-collapse of the California power grid. All data obtained from references [4,25].

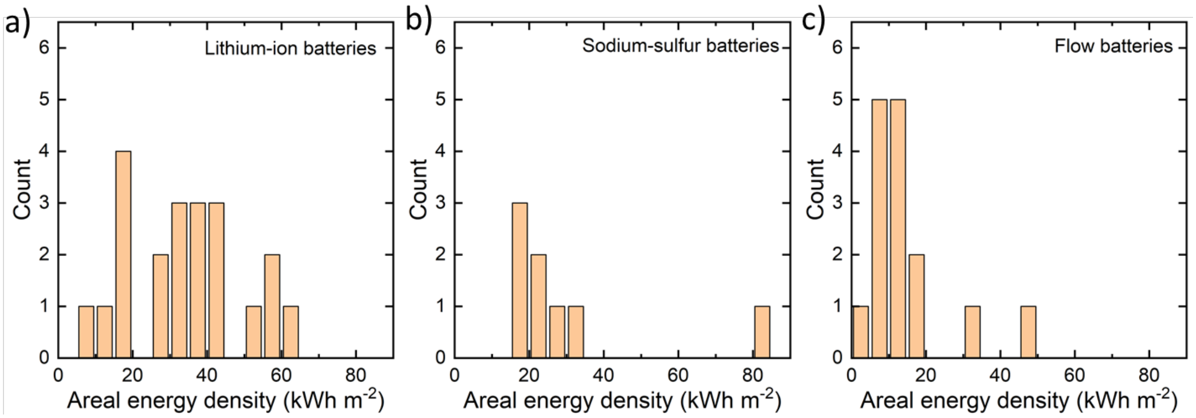


Figure S5: Binned areal energy densities of the studied **a)** lithium-ion, **b)** sodium-sulfur, and **c)** flow batteries.

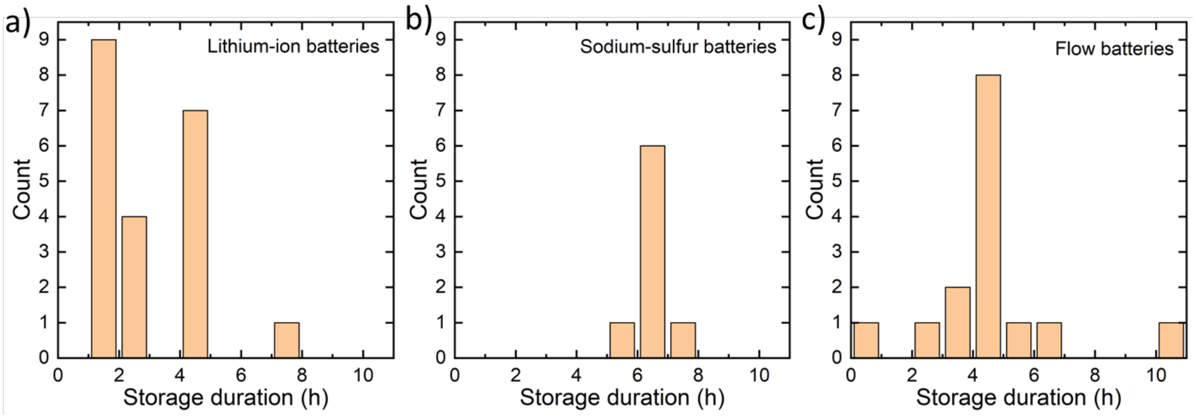


Figure S6: Binned storage durations of deployed a) lithium-ion, b) sodium-sulfur, and c) flow batteries.

Table S1: Overview of lithium-ion BESS compared in this study.

Site	Power Capacity (MW)	Energy Capacity (MWh)	Area (m^2)	Areal energy density (kWh/m^2)	Storage duration (h)
Moss Landing, California, Vistra Phase I	300	1,200	21,500	56	4.0
Moss Landing, California, Vistra Phase II	100	400	6,500	62	4.0
Moss Landing, California, PG&E site	182.5	768	13,500	54	4.2
Parrish, Florida	409	900	57,000	16	2.2
Geelong, Australia	300	450	11,500	39	1.5
Granbury, Texas	260	260	16,500	16	1.0
Otay Mesa, California	250	250	10,000	25	1.0
Angleton, Texas	100	200	3,700	54	2.0
Mililani, Hawaii	39	156	3,600	43	4.0
Escondido, California	37.5	150	4,800	31	4.0
Jamestown, Australia	100	129	6,600	20	1.3
Minety, England	100	100	7,900	13	1.0
Golmud, China	50	100	12,000	8	2.0
Peoria, Arizona	25	100	2,500	40	4.0
Sydney, Australia	50	75	1,700	44	1.5
Burgess Hill, England	34	68	1,800	38	2.0
Oxford, England	50	50	1,500	33	1.0
Stocking Pelham, England	50	50	3,100	16	1.0
Upton County, Texas	10	42	1,300	32	4.2
Hallen, England	32	32	1,250	26	1.0
Dubai, United Arab Emirates	1.2	8.6	220	39	7.2
Average	**118**	**261**	**8,975**	**34**	**2.6**
Std. Dev.	**114**	**312**	**12,103**	**15**	**1.6**

Table S2: Overview of sodium-sulfur BESS compared in this study.

Site	Power Capacity (MW)	Energy Capacity (MWh)	Area (m^2)	Areal energy density (kWh/m^2)	Storage duration (h)
Buzen, Japan	50	300	14,000	21	6.0
Rokkasho, Japan	34	245	3,000	82	7.2
Ginestra, Italy	12	80	4,900	16	6.7
Flumeri, Italy	12	80	4,200	19	6.7
Scampitella, Italy	10.8	72	4,100	18	6.7
Varel, Germany	4	20	820	24	5.0
Kinmen Island, Taiwan	1.8	10.8	320	34	6.0
Dubai, United Arab Emirates	1.2	7.2	280	26	6.0
Average	**16**	**102**	**3,953**	**30**	**6.3**
Std. Dev.	**16**	**103**	**4,173**	**20**	**0.6**

Table S3: Overview of flow BESS compared in this study.

Site	Power Capacity (MW)	Energy Capacity (MWh)	Area (m^2)	Areal energy density (kWh/m^2)	Storage duration (h)
Yokohama, Japan	1	5	920	5	5.0
Abira, Japan	17	51	5,700	9	3.0
Abira, Japan	15	60	5,500	11	4.0
Bonita, California	2	8	1,200	7	4.0
Dalian, China	100	400	17,500	50	4.0
Fraunhofer ICT, Germany	2	20	600	33	10.0
Everett, Washington	2.2	8	540	15	3.6
Oxford, England	2	5	450	11	2.5
Perth, Scotland	1	0.8	135	6	0.8
Shirley, Massachusetts	0.5	3	220	14	6.0
Bolingbrook, Illinois	2	8.5	450	19	4.3
Hot Springs, Arkansas	0.25	1	60	17	4.0
Cameron Corners, California	0.5	2.4	400	6	4.8
Stanislaus County, California	0.25	1	275	4	4.0
Rialto, California	0.5	2	140	14	4.0
Average	**10**	**38**	**2,273**	**15**	**4.3**
Std. Dev.	**25**	**98**	**4,436**	**11**	**1.9**

Table S4: Overview of pumped storage hydropower sites compared in this study.

Site	Storage capacity (MWh)	Volume of upper reservoir (m^3)	Energy density (Wh/L)	Surface area of upper reservoir (m^2)	Surface area of lower reservoir (m^2)	Surface of artificial reservoir (m^2)	Areal energy density (kWh/m^2)	Location
Raccoon Mountain, Tennessee[26,27]	36,344	405,039,000	0.1	1,940,000	Nickajack Lake	1,940,000	19	35°02′55″N 85°23′48″W
Grand'Maison, France[28,29]	34,800	132,000,000	0.3	2,050,000	Lac Du Verney	2,050,000	17	45°12′21″N 06°07′01″E
Bad Creek, South Carolina[30,31]	25,560	41,815,000	0.6	1,450,000	Lake Jocassee	1,450,000	18	35°0′40.02″N 83°0′52.23″W
Bath County, Virginia[32,33]	30,931	43,911,000	0.7	1,020,000	1,920,000	2,940,000	11	38°12′32″N 79°48′00″W
Ingula, South Africa[34]	21,000	19,200,000	1.1	2,260,000	1,980,000	4,240,000	5	28°16′54″S 29°35′08″E
Nant de Drance, Switzerland[35,36]	20,000	25,000,000	0.8	380,000	Lac d'Emosson	380,000	53	46°03′49″N 06°54′36″E
Ludington, Michigan[37,38]	14,976	102,205,000	0.1	3,550,000	Lake Michigan	3,550,000	4	43°53′37″N 86°26′43″W
Roncovalgrande, Italy[39,40]	17,680	11,200,000	1.6	305,000	Lago Maggiore	305,000	58	46°04′10″N 8°43′55″E
Blenheim–Gilboa, New York[41,42]	17,400	19,000,000	0.9	1,600,000	1,100,000	2,700,000	6	42°27′18″N 74°27′29″W
Entracque, Italy[43,44]	17,040	28,500,000	0.6	595,000	Lago della Piastra	595,000	29	44°13′29″N 07°23′10″E
Okutataragi, Japan[45,46]	15,546	33,387,000	0.5	990,000	690,000	1,680,000	9	35°14′12″N 134°51′23″E
Okuyoshino, Japan[47,48]	14,689	16,850,000	0.9	526,090	350,000	876,090	17	34°7′4″N 135°49′16″E
Qingyuan, China[49,50]	11,520	10,550,000	1.1	537,000	495,000	1,032,000	11	23°44′29″N 112°51′43″E

MWh-scale lithium-ion batteries

Moss Landing, California, Vistra site 400 MW/1600 MWh

Map Data: Google, © 2022 AMBAG / Maxar Technologies

Figure S7: The site is operated by Vistra Corp.: Phase I 300 MW/1200 MWh in and around old turbine hall using LG TR1300 battery racks, occupying 21,500 m^2 with approximately 56 kWh m^{-2}. Phase II rated 100 MW/400 MWh occupying 6,500 m^2 with roughly 62 kWh m^{-2}. Both phases experienced overheating events (not fires) that resulted in shutdowns in September 2021 and February 2022, respectively. Both phases were restarted in July 2022. An additional 350 MW/1400 MWh phase is in development.[51] Location: 36°48'18.33"N 121°46'52.10"W

Photo credits: https://insideevs.com/news/489894/vistra-moss-landing-energy-storage-world-largest/ and https://www.energy-storage.news/worlds-biggest-battery-storage-system-comes-back-online-after-months-of-shutdown/

Moss Landing, California, PG&E site 182.5 MW/730 MWh

Map Data: Google, © 2022 AMBAG, Maxar Technologies

Figure S8: The Elkhorn site is operated by PG&E: 182.5 MW/730 MWh on 13,500 m^2 with approximately 54 kWh m^{-2}, utilizing 256 Tesla Megapacks. Location: 36°48'28.07"N 121°46'54.94"W.

Photo credit: https://www.bloomberg.com/news/articles/2022-09-20/tesla-battery-fire-at-pg-e-facility-closes-california-road

Parrish, Florida, 409 MW/900 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S9: Named Manatee Energy Storage Center, the 409 MW/900 MWh site is operated by Florida Power & Light Company, utilizing 132 battery units, occupying 57,000 m^2 with around 16 kWh m^{-2}. Location: 27°35'51.81"N 82°20'56.88"W

Photo credit: http://www.southdadenewsleader.com/news/fpl-unveils-worlds-largest-solar-powered-battery/article_9c7e0418-5ed1-11ec-ae40-aba82677d170.html

Geelong, Australia, 300 MW/450 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S10: Named Victoria Big Battery and operated by Neoen SA the site utilizes 212 Tesla Megapacks rated 300 MW/450 MWh, occupying 11,500 m^2 with approximately 39 kWh m^{-2}. A fire at this facility received significant media attention. The fire jumped from one container to the next. Location: 38° 2'17.65"S 144°17'24.33"E

Photo credit: https://www.theage.com.au/politics/victoria/in-a-field-near-geelong-switch-flicked-on-australia-s-biggest-battery-20211208-p59fq8.html and https://electrek.co/2021/12/08/giant-tesla-megapack-project-turned-on-after-fire-setback/

Granbury, Texas, 260 MW/260 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S11: Named DeCordova Energy Storage Facility rated 260 MW/260 MWh, operated by Vistra Corp., utilizing LFP batteries in 86 enclosures on 16,500 m^2 with roughly 16 kWh m^{-2}.[52] Location: 32°24'16.05"N 97°41'46.64"W

Photo credit: https://www.3blmedia.com/news/vistra-brings-texas-largest-battery-energy-storage-system-online

Otay Mesa, California, 250 MW/250 MWh

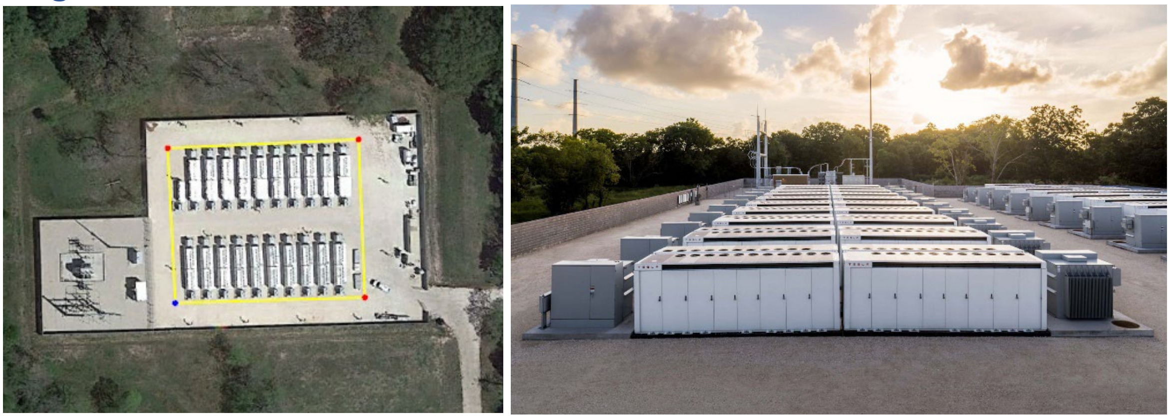
 

Map Data: Google, © 2022 Maxar Technologies

Figure S12: Named Gateway Energy Storage Project rated 250 MW/250 MWh, operated by LS Power, using cells from LG Chem, occupying 10,000 m^2 with around 25 kWh m^{-2}.[53] Location: 32°34'14.21"N 116°54'39.61"W

Photo credit: https://www.bloomberg.com/news/articles/2020-08-19/world-s-biggest-battery-project-comes-to-power-hungry-california

Angleton, Texas, 100 MW/200 MWh

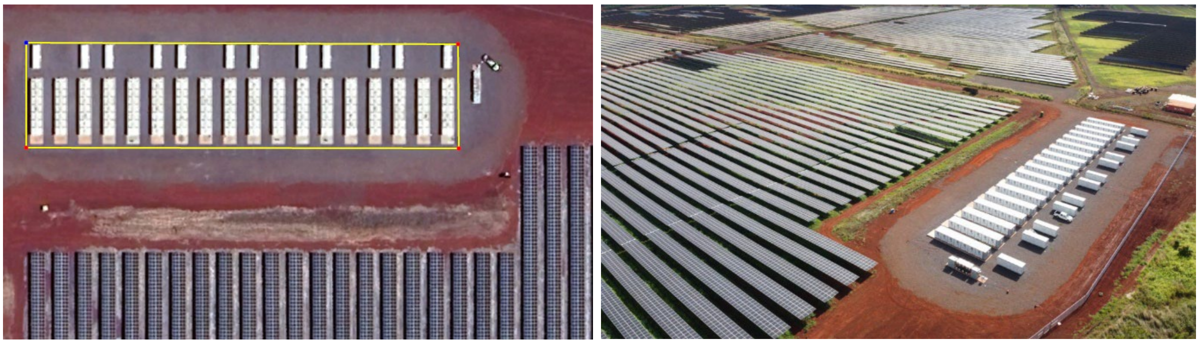


Map Data: Google, © 2022 Maxar Technologies

Figure S13: Named Gambit Energy Storage Project rated 100 MW/200 MWh, using 82 Tesla Megapacks on 3,700 m^2 with approximately 54 kWh m^{-2}. Location: 29°10'5.60"N 95°26'44.94"W

Photo credit: https://www.tesla.com/megapack

Mililani, Hawaii, 39 MW/156 MWh

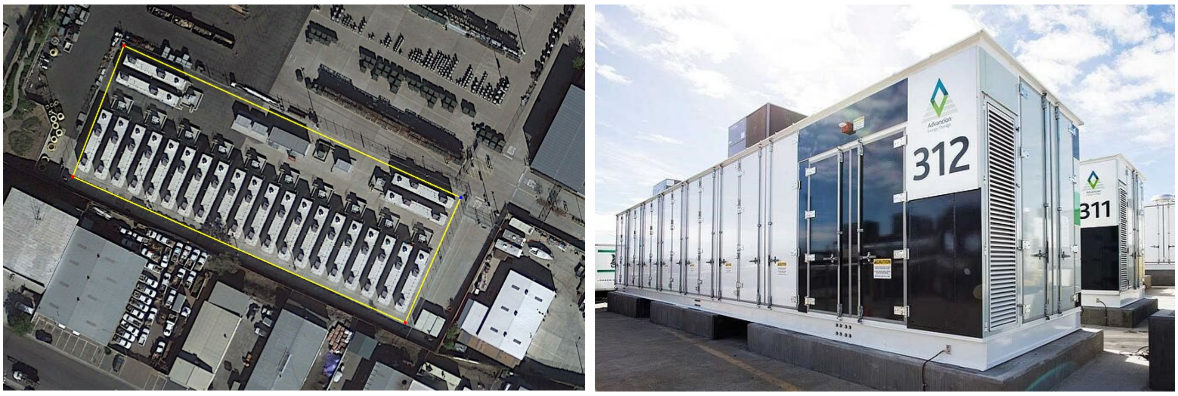


Map Data: Google, © 2022 Airbus

Figure S14: Using LFP batteries in Wärtsilä GridSolv Quantum units, the 39 MW/156 MWh site occupies 3,600 m^2 with around 43 kWh m^{-2}.[54] Location: 21°25'31.23"N 158° 1'2.37"W

Photo credit: https://www.solarpowerworldonline.com/2022/08/clearway-completes-39-mw-solar-156-mwh-storage-project-on-oahu/

Escondido, California, 37.5 MW/150 MWh



Map Data: Google, © 2022 Landsat / Copernicus

Figure S15: AES Corp. battery units rated 37.5 MW/150 MWh, operated by SDG&E on 4,800 m^2 with around 31 kWh m^{-2}. Location: 33° 7'29.02"N 117° 6'55.53"W

Photo credit: https://ie-corp.com/bess/

Jamestown, Australia, 100 MW/129 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S16: Named Hornsdale Power Reserve, operated by Neoen SA at the Hornsdale Wind Farm, utilizing Tesla Powerpacks rated 100 MW/129 MWh on 6,600 m^2 with roughly 20 kWh m^{-2}. A 50 MW/64.5 MWh expansion was added in September 2020 (in front in the photo). Location: 33° 5'9.29"S 138°31'6.70"E

Photo credit: https://hornsdalepowerreserve.com.au/

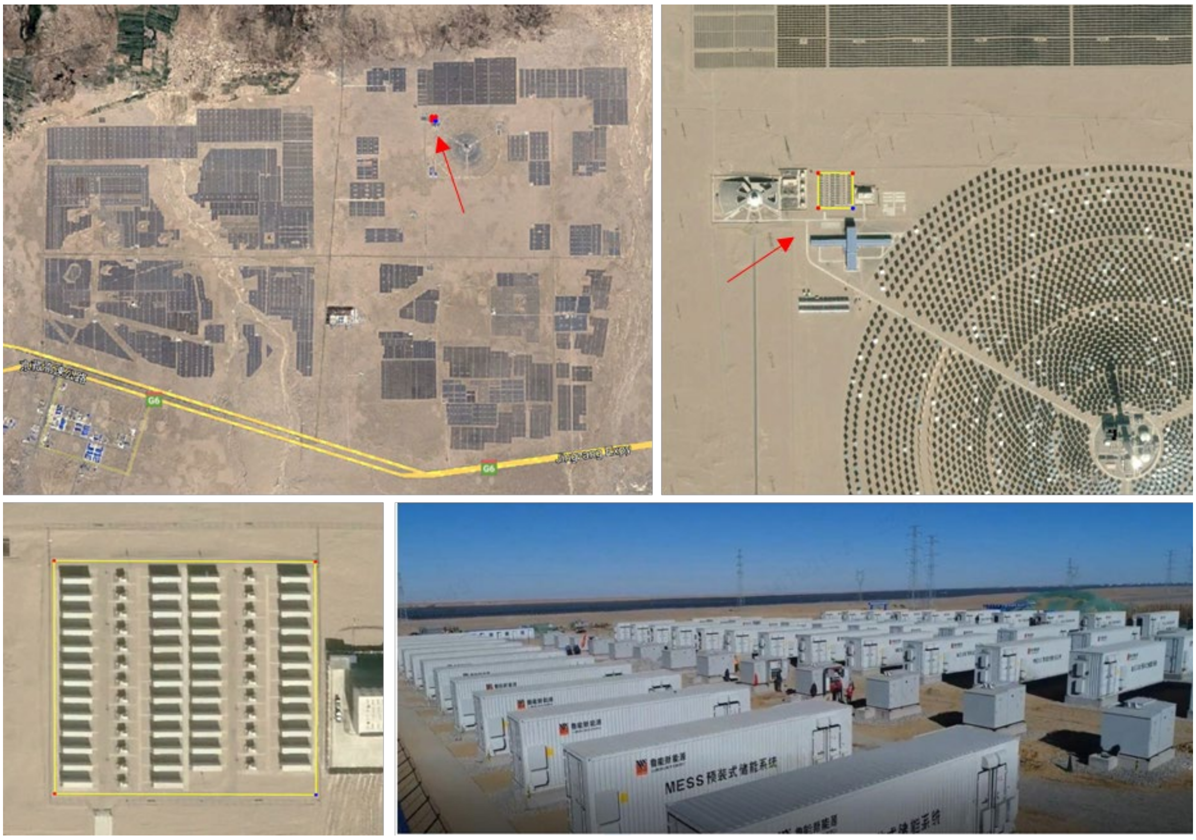
Minety, England, 100 MW/100 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S17: The 100 MW/100 MWh Minety Battery system uses both NMC and LFP batteries by Samsung and CATL and was developed by China Huaneng Group Co. The first 100 MWh phase is seen on satellite images, occupying 7,900 m^2 with approximately 13 kWh m^{-2}. An expansion to 150 MW/266 MWh is under construction.[55] Location: 51°36'20.09"N 2°0'11.81"W

Photo credit: https://www.renewableenergymagazine.com/storage/europea-s-largest-energy-storage-project-celebrates-20220325

Golmud, China, 50 MW/100 MWh



Map Data: Google, © 2022 Landsat / Copernicus / Maxar Technologies / CNES / Airbus

Figure S18: Located at the Luneng National Energy Storage Power Station Demonstration Project with 200 MW photovoltaics, 400 MW wind, and 50 MW concentrated solar power. The 50 MW/100 MWh battery system uses 50 containerized LFP batteries provided by CATL[56] and occupies 12,000 m^2 with around 8 kWh m^{-2}. This example highlights the small footprint of BESS compared to renewable generation sites. The entire solar farm occupies roughly 142,800,000 m^2. Location: 36°24'22.19"N 95°12'49.06"E

Photo credit: https://www.catl.com/en/othercase/484.html

Peoria, Arizona, 25 MW/100 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S19: Named Salt River Project Battery, adjacent to the Agua Fria Generating Station, the 25 MW/100 MWh site occupies 2,500 m^2 with about 40 kWh m^{-2}. Location: 33°33'12.11"N 112°12'46.74"W

Phot credit: https://www.energytech.com/energy-storage/article/21176796/tesla-commercial-energy-tesla-energy-storage-facility-starts-up-in-arizona

Sydney, Australia, 50 MW/75 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S20: The 50 MW/75 MWh Wallgrove Grid Battery is operated by Lumea and uses 36 Tesla Megapacks on 1,700 m^2 with about 44 kWh m^{-2}. Location: 33°48'50.10"S 150°49'50.92"E

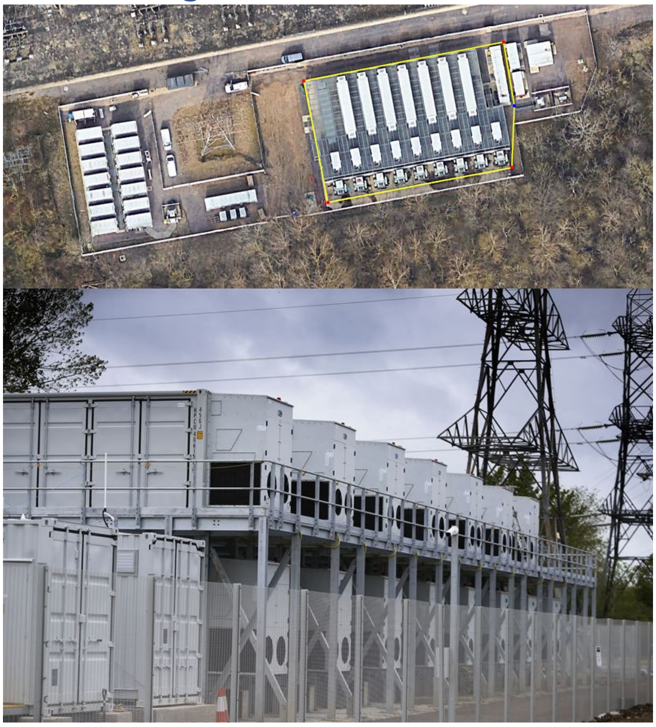
Photo credit: https://www.pv-magazine-australia.com/2021/10/28/synthetic-inertia-put-to-test-with-wallgrove-big-battery-registered/

Burgess Hill, England, 34 MW/68 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S21: The 34 MW/ 68 MWh Contego Battery uses 28 Tesla Megapacks on 1,800 m^2 with about 38 kWh m^{-2}. Location: 50°57'18.81"N 0° 9'46.60"W Photo credit: https://frv.com/en/projects/contego/

Oxford, England, 50 MW/50 MWh



Map Data: Google, © 2022 Landsat / Copernicus

Figure S22: The Energy Superhub in Oxford uses flow batteries (Figure S50) combined with 50 MW/50 MWh stacked lithium-ion battery units from Wärtsilä, occupying 1,500 m^2 with around 33 kWh m^{-2}. Location: 51°42'35.48"N 1°11'21.72"W

Photo credit: https://www.wartsila.com/media/news/23-06-2021-pivot-power-wartsila-and-habitat-energy-activate-50-mw-transmission-connected-battery-in-oxford-uk-2937111

Stocking Pelham, England, 50 MW/50 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S23: The 50 MW/50 MWh Pelham Battery uses 7 customized SMA E-house battery units on 3,100 m^2 with roughly 16 kWh m^{-2}. Location: 51°56'17.11"N 0° 7'12.09"E

Photo credit: https://britishrenewables.com/portfolio/stocking-pelham-battery

Upton County, Texas, 10 MW/42 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S24: Located at the 180 MW Upton 2 solar facility, operated by Luminant, a subsidiary of Vistra Corp., the 10 MW/42 MWh battery occupies 1,300 m^2 with about 32 kWh m^{-2}. The entire solar farm occupies approximately 17,500,000 m^2. Location: 31°15'13.43"N 102°17'45.82"W

Photo credit: https://www.luminant.com/luminant-brings-large-scale-energy-storage-to-texas/

Hallen, England, 32 MW/32 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S25: Operated by Voltalia the 32 MW/32 MWh battery uses 16 modules with stacked containers, resulting in a footprint of 1,250 m^2 with around 26 kWh m^{-2}. Location: 51°31'39.40"N 2°39'34.63"W

Photo credit: https://www.current-news.co.uk/news/limejump-begins-optimising-voltalias-32mw-hallen-battery

Dubai, United Arab Emirates, 1.2 MW/8.6 MWh

Map Data: Google, © 2022 Landsat / Copernicus / Maxar Technologies

Figure S26: Located at the Mohammed bin Rashid Al Maktoum Solar Park, the 1.2 MW/8.6 MWh battery uses Tesla Powerpacks and occupies 220 m^2 with around 39 kWh m^{-2}. Location: 24°45'58.94"N 55°22'5.98"E The entire solar farm occupies about 80,000,000 m^2. Photo credit: Dubai Electricity and Water Authority

Lancaster, California, 227 MW/908 MWh

Figure S27: The AES Luna Battery (100 MW/400 MWh) and Lancaster Area Battery (127 MW/508 MWh) with a combined rating of 227 MW/908 MWh are not visible on satellite images yet but locations are included here for future comparisons. Construction can be seen on wego.here.com satellite images. Location: 34°41'5.04"N 118°18'17.91"W

Photo credit: https://www.aes.com/luna-and-lab-energy-storage and https://trimarkassoc.com/trimark-commissions-controls-for-luna-bess-2/

Riverside County, California, 350 MW/1400 MWh

Figure S28: The Crimson Energy Storage Project is the largest BESS to reach operation in a single phase so far, rated at 350 MW/1400 MWh. It is not visible on Google Earth yet but is included here for future comparisons. Location: 33°34'13.27"N 114°49'47.15"W

Photo credit: https://recurrentenergy.com/project/crimson/

Valley Center, California, 140 MW/560 MWh

Map Data: Google, © 2023 Maxar Technologies

Figure S29: The Valley Center Project was brought online in March 2022. Construction is not complete on satellite images. The site covers ca. 14,000 m^2. Just after one year in operation, a faulty sprinkler system led to decommissioning of several battery packs at this site and some of those packs were subsequently stolen.[57] Location: 33°13'37.48"N 117° 1'8.76"W

Photo credit: https://www.energy-storage.news/terra-gen-battery-storage-560mwh-bess-valley-center-san-diego-california-online/

Mission, Texas, 200 MW/429 MWh

Map Data: Google, © 2023 Maxar Technologies

Figure S30: The Madero and Ignacio battery storage project was completed in March 2023 and the first BESS to claim investment tax credits from the Inflation Reduction Act.[20] Construction is not complete on satellite images. The site covers ca. 20,000 m^2. Location: 26° 9'52.03"N 98°19'24.11"W

Photo credit: https://www.wartsila.com/aze/media/news/27-03-2023-wartsila-and-eolian-complete-200-mw-standalone-energy-storage-facility-in-texas-the-largest-merchant-battery-system-in-the-world-3246410

Edwards Sanborn, California, 439 MW/1505 MWh

Map Data: Here WeGo, © 2023 HERE, Maxar Technologies

Figure S31: The Edwards Sanborn solar-plus-storage project by Terra-gen, LLC started construction in Q1 2021 and will be expanded to more than 900 MW/3300 MWh making it one of the largest BESS in the world.[58] The footprint of the first phase could not be determined from satellite imagery. Location: 35° 1'39.12"N 118° 8'22.08"W

Photo credit: https://www.terra-gen.com/energy-storage

Western Downs, Australia, 200 MW/400 MWh

Map Data: Google, © 2023 Maxar Technologies

Figure S32: The Western Downs Battery by Neoen SA started construction in January 2023 and will be powered by Tesla Megapacks.[59] Construction is not complete on satellite images. The site covers ca. 70,000 m^2. Location: 26°57'8.04"S 150°41'22.55"E

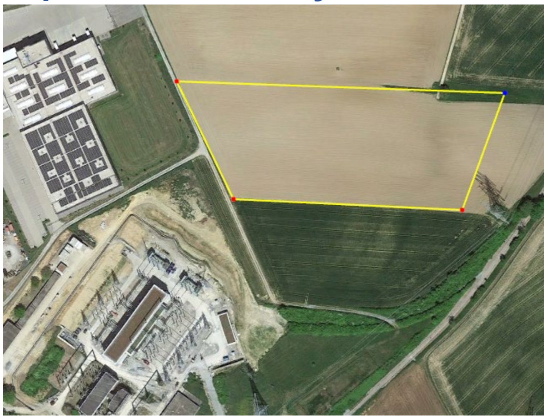
Jurong Island, Singapore, 200 MW/285 MWh

Map Data: Google, © 2023 Maxar Technologies

Figure S33: Constructed in just six months, the Sembcorp Banyan and Sakra BESS is currently the largest in Southeast Asia.[60] Construction is not complete on satellite images. According to Sembcorp the installation covers ca. 20,000 m^2 spread over two sites. Location: 1°15'34.20"N 103°42'0.81"E and 1°15'28.83"N 103°40'13.45"E

Photo credit: https://www.sembcorpenergy.com.sg/business/energy-solutions/energy-storage-systems/

Kupferzell, Germany, 250 MW/250 MWh



Map Data: Google, © 2023 Landsat / Copernicus

Figure S34: The world's largest Netzbooster ("Grid Booster") for battery storage-as-transmission is being deployed by Fluence Energy and TransnetBW GmbH and is planned for completion in 2025.[61] Based on the artist's rendering the site covers ca. 24,000 m^2. Location: 49°14'6.15"N 9°41'48.64"E

Image credit: https://fluenceenergy.com/ultrastack-transmission-energy-storage/

Vilnius, Šiauliai, Alytus and Utena, Lithuania, 200 MW/200 MWh

Map Data: Google, © 2023 Maxar Technologies

Figure S35: The world's first "Grid Booster" for battery storage-as-transmission is being deployed by Fluence Energy and Energy Cell on four locations in the Vilnius, Šiauliai, Alytus and Utena districts in Lithuania, each comprising 50 MW/50 MWh with 78 battery packs.[62] Construction at the Vilnius and Šiauliai substations can be seen on satellite images. The screenshot in the lower right shows the Utena site. Locations: 54°36'46.74"N 25° 7'4.03"E and 55°54'55.44"N 23°17'46.03"E and 55°32'28.10"N 25°37'54.12"E and 54°26'35.38"N 23°58'34.49"E

Image credit: https://www.energy-storage.news/testing-starts-on-fluence-200mwh-battery-storage-projects-in-lithuania-for-spring-2023-activation/ and screenshot from https://www.linkedin.com/posts/ministry-of-energy-of-the-republic-of-lithuania_trumpa-vaizdo-med%C5%BEiaga-apie-energetikos-sistemos-ugcPost-6976133686345789441-m881?utm_source=share&utm_medium=member_desktop

Queanbeyan, Australia, 100 MW/200 MWh

Map Data: Google, © 2023 Airbus

Figure S36: The Capital Battery by Neoen SA started construction in December 2021.[63] Construction is not complete on satellite images. The site covers ca. 20,000 m^2. Location: 35°20'18.07"S 149°12'55.72"E

Photo credit: https://neoen.com/en/news/2022/neoen-completes-financing-for-its-100-mw-200-mwh-capital-battery-in-the-australian-capital-territory/

Clay Tye, England, 99 MW/198 MWh – under construction

Map Data: Google, © 2022 Landsat / Copernicus

Figure S37: Construction on the 99 MW/198 MWh battery started, the site will use 52 Tesla Megapacks.[64] The construction site covers ca. 19,000 m^2. Location: 51°33'8.47"N 0°17'53.71"E

Photo credit: https://frv.com/en/projects/clay-tye-battery-energy-storage-system/

Kwinana, Australia, 100 MW/200 MWh – under construction

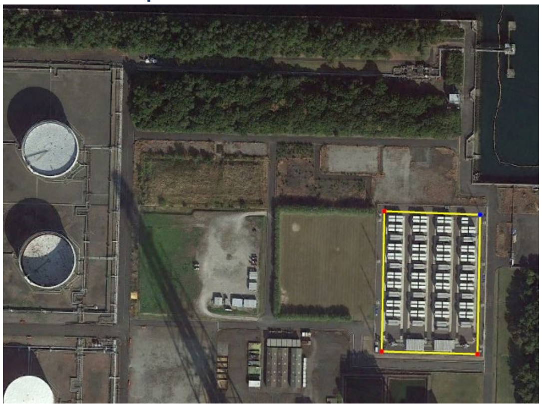
Map Data: Google, © 2022 Maxar Technologies

Figure S38: The 100 MW/200 MWh site will use LFP batteries in 600 CATL units.[65] The construction site covers ca. 10,000 m^2. Location: 32°11'54.84"S 115°46'42.47"E

MWh-scale sodium-sulfur batteries

NGK Insulators Ltd.

Buzen, Japan, 50 MW/300 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S39: At 50 MW/300 MWh currently the world's largest Na-S battery, in operation since March 2016, occupying 14,000 m^2 with around 21 kWh m^{-2}. Location: 33°37'41.83"N 131° 7'12.80"E

Photo credit: https://www.mitsubishielectric.com/news/2016/0303-b.html

Rokkasho, Japan, 34 MW/244.8 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S40: The 34 MW/244.8 MWh site occupies 3,000 m^2 with about 82 kWh m^{-2}. This is the highest areal energy density among all the systems compared in this study. Location: 40°57'46.85"N 141°18'42.88"E

Photo credit: https://www.ngk-insulators.com/en/product/nas-solutions01.html

Ginestra, Italy, 12 MW/80 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S41: Operated by Terna S.p.A, the 12 MW/80 MWh site occupies 4,900 m^2 with roughly 16 kWh m^{-2}. Location: 41°17'6.86"N 15° 4'21.25"E

Photo credit: https://www.ngk-insulators.com/en/product/nas-solutions02.html

Flumeri, Italy, 12 MW/80 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S42: Operated by Terna S.p.A, the 12 MW/80 MWh site occupies 4,200 m^2 with about 19 kWh m^{-2}. Location: 41° 4'4.53"N 15° 7'24.23"E

Scampitella, Italy, 10.8 MW/72 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S43: Operated by Terna S.p.A, the 10.8 MW/72 MWh site occupies 4,100 m^2 with about 18 kWh m^{-2}. Location: 41° 4'57.51"N 15°20'34.62"E

Varel, Germany, 4 MW/20 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S44: The 4 MW/20 MWh site occupies 820 m^2 with about 24 kWh m^{-2} in combination with 7.5 MW/2.5 MWh lithium-ion batteries. Location: 53°22'32.34"N 8° 7'31.34"E

Photo credit: https://www.mc.showadenko.com/english/information/2018/n_181031zk8.html

Kinmen Island, Taiwan, 1.8 MW/10.8 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S45: The 1.8 MW/10.8 MWh site occupies 320 m^2 with roughly 34 kWh m^{-2}. Location: 24°26'25.40"N 118°23'58.68"E

Photo credit: https://www.ngk-insulators.com/en/news/20211118_1.html

Dubai, United Arab Emirates, 1.2 MW/7.2 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S46: Located at Mohammed bin Rashid Al Maktoum Solar Park, the 1.2 MW/7.2 MWh site occupies 280 m^2 with approximately 26 kWh m^{-2}. Location: 24°45'56.88"N 55°22'6.70"E

Photo credit: https://www.dewa.gov.ae/en/about-us/media-publications/latest-news/2018/08/dewa-tests-energy-storage-systems-at-mohammed-bin-rashid-al-maktoum-solar-park-with-amplex-emirates

Dubai, United Arab Emirates, 108 MW/648 MWh

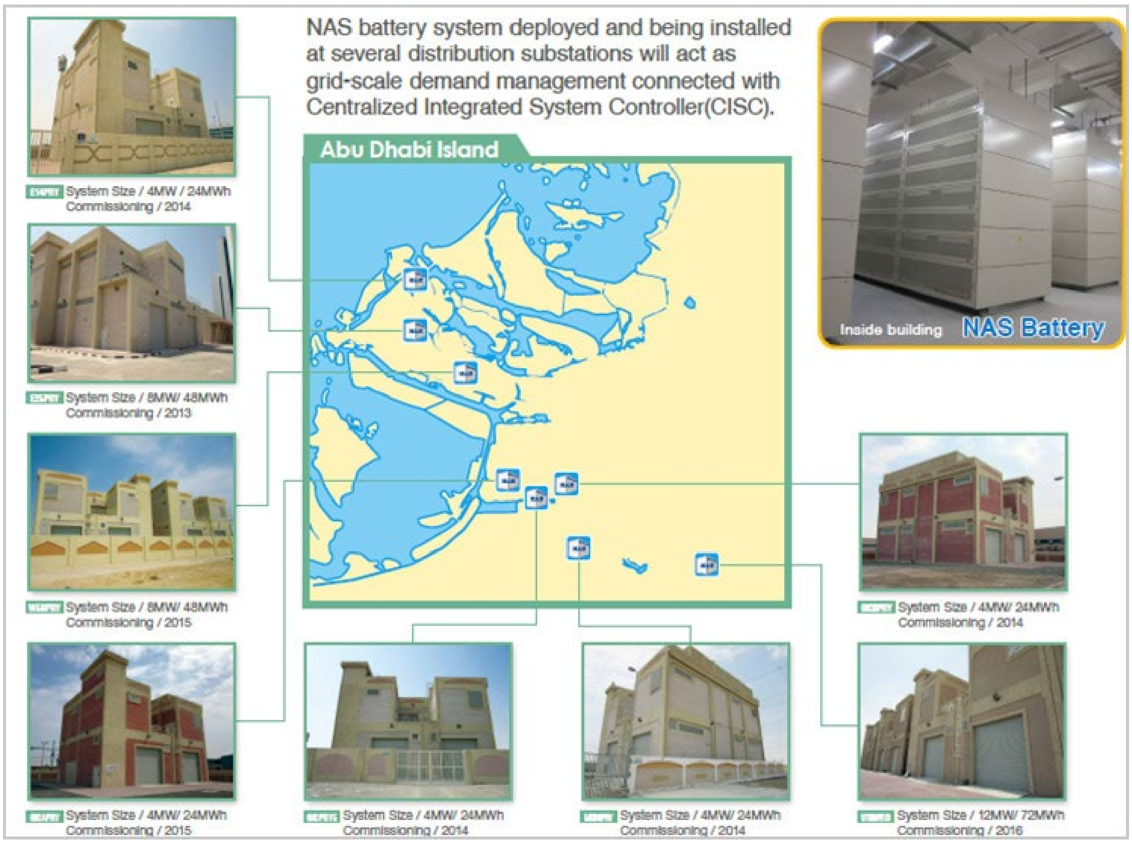


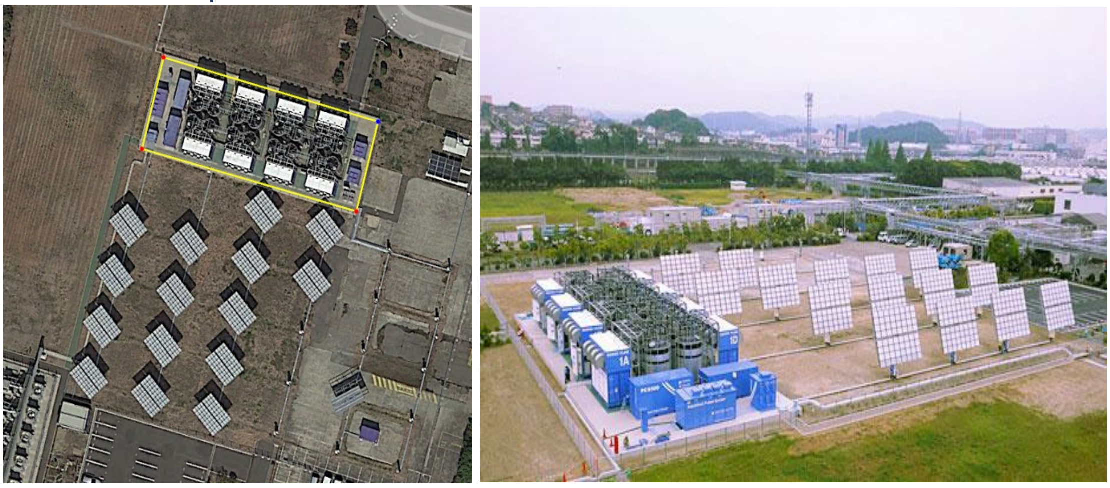
Figure S47: Started operation in 2019 with 10 different sites, all interconnected as virtual power plant. No corresponding satellite images could be found.

Source:
https://resources.mynewsdesk.com/image/upload/t_limit_1000/kuuk0dgj6dleqfdof1fb.jpg

MWh-scale flow batteries

Sumitomo Electric Industries, Vanadium

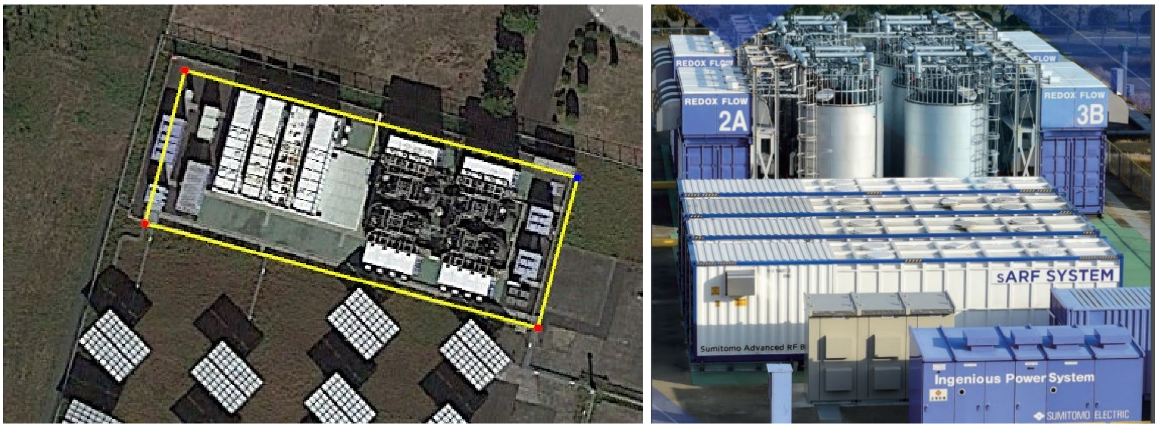
Yokohama, Japan, 1 MW/5 MWh



Map Data: Google, © 2022 Landsat / Copernicus

Figure S48: At 1 MW/5 MWh this was the world's largest vanadium flow battery in 2012, occupying 920 m^2 with about 5 kWh m^{-2}. Location: 35°22'22.46"N 139°31'34.50"E

Photo credit: https://energystoragereport.info/wp/wp-content/uploads/2013/07/Sumitomo-redox-flow-battery-Yokohama.jpg



Map Data: Google, © 2022 Landsat / Copernicus

Figure S49: The site was updated between 11/2015 and 2/2017 to accommodate containerized systems.

Photo credit: https://sumitomoelectric.com/sites/default/files/styles/crop_sei_cp_656x410/public/2020-12/products/overview_card/1610.jpg?itok=3NExZ02T

Abira, Japan, 17 MW/51 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S50: Located at Abira Town Minami-Hayakita substation, the 17 MW/51 MWh site started operation in April 2022 and occupies 5,700m^2 with approx. 9 kWh m^{-2}. Location: 42°42'44.77"N 141°46'52.98"E

Photo credit: https://sumitomoelectric.com/sites/default/files/2022-08/download_documents/2022_%E3%83%AC%E3%83%89%E3%83%83%E3%82%AF%E3%82%B9%E3%83%95%E3%83%AD%E3%83%BC%E9%9B%BB%E6%B1%A0%EF%BC%88A4%EF%BC%89.pdf

Abira, Japan, 15 MW/60 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S51: Located next to Abira Town Minami-Hayakita substation, the 15 MW/60 MWh site started operation in 2015. The tanks are located on the 1st and stacks on 2nd floor. Occupies 7,000 m^2 for the entire building with roughly 11 kWh m^{-2}. Location: 42°42'47.31"N 141°46'41.33"E

Photo credits: https://global-sei.com/smartgrid/ and https://www.cenelest.org/2020/02/29/industry-visit-of-15-mw-60-mwh-vrfb/

Bonita, California, 2 MW/8 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S52: Operated by SDP&G, the 2 MW/ 8 MWh site started operation in March 2017, occupying 600 m^2 with 7 kWh m^{-2} each. First flow battery to obtain the safety standard UL1973.[66] First flow battery participating in the US electricity wholesale market.[67] Location: 32°40'42.71"N 116°58'52.02"W

Photo credit: https://energy-storage.news/wp-content/uploads/2021/08/VRF_Aerial_Photo.png

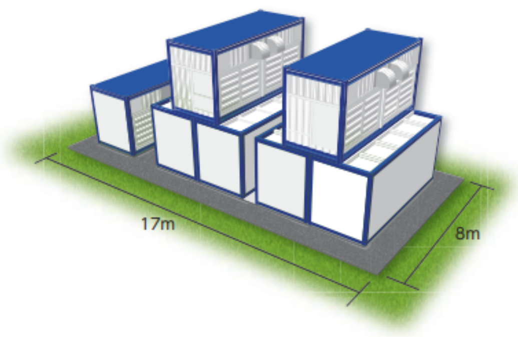
Proposed design for future installations

Product Lineup

Basic Specification per Module	Output	Capacity	Dimensions
3 hours model	AC250kW	AC750kWh	6.1m×4.9m×6m
4.5 hours model	AC250kW	AC1,125kWh	9.1m×4.9m×6m
6 hours model	AC250kW	AC1,500kWh	12.2m×4.9m×6m

Example of System Layout

Example: 500 kW × 3h (1,500 kWh) Model



System Size & Installation Area

Output	Capacity	Installation Area
1MW	3MWh	15m×17m
1MW	4.5MWh	21m×17m
1MW	6MWh	27m×17m
10MW	30MWk	85m×27m
10MW	45MWh	103m×27m
10MW	60MWh	131m×27m

Figure S53: The product brochure advertises areal energy densities of up to 17 kWh m^{-2}.

Image credit: https://sumitomoelectric.com/sites/default/files/2022-08/download_documents/2022_%E3%83%AC%E3%83%89%E3%83%83%E3%82%AF%E3%82%B9%E3%83%95%E3%83%AD%E3%83%BC%E9%9B%BB%E6%B1%A0%EF%BC%88A4%EF%BC%89.pdf

Dalian Rongke Power and UniEnergy Technologies, Vanadium

Dalian, China, 100 MW/400 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S54: Currently the largest flow battery in the world with the first 100 MW/400 MWh phase connected to the grid in July 2022. The stacks are arranged on the floor above the tanks. A second phase of equal size will be installed on the same site occupying 16,000 m^2 with currently 25 kWh m^{-2} and 50 kWh m^{-2} upon completion.[68] The latter value is used for calculations in this study. Location: 38°56'27.69"N 121°34'55.80"E

Photo credit:
https://english.cas.cn/newsroom/research_news/chem/202205/t20220531_306054.shtml

Fraunhofer ICT, Germany, 2 MW/20 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S55: The 2 MW/20 MWh battery is housed in a multi-use building with stacks arranged on the floor above the electrolyte tanks. The battery hall is 600 m^2 leading to 33 kWh m^{-2}. Location: 49° 1'4.82"N 8°31'5.28"E

Photo credit: https://kogerec.org/wp-content/uploads/2019/04/3_Fischer_Redox-Flow-Battieries.pdf

Everett, Washington, 2.2 MW/8 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S56: The 2.2 MW/8 MWh site occupies 540 m^2 with roughly 15 kWh m^{-2}. Location: 47°58'18.46"N 122°11'55.06"W

Photo credit: https://2qibqm39xjt6q46gf1rwo2g1-wpengine.netdna-ssl.com/wp-content/uploads/2016/11/web1_M1PUD-EDH-161028-1024x390.jpg

Proposed designs for future installations

Figure S57: The ReFlex Storage Plant is rated 10 MW/40 MWh, occupying 1,350 m^2 with roughly 30 kWh m^{-2}.

Image credit: https://nelha.hawaii.gov/wp-content/uploads/2018/12/05.-Rick-Winter_UET.pdf

Figure S58: The TPower series is rated 500 kW/2 MWh on 70 m^2 with around 29 kWh m^{-2}. The module is employed at the 10 MW/40 MWh Guoshun Leija Wind Farm that is under construction and at the Wafangdian Liaoning Wind Farm since 2021.[69] No corresponding satellite images could be found. Image credit: http://en.rongkepower.com/?about/13.html

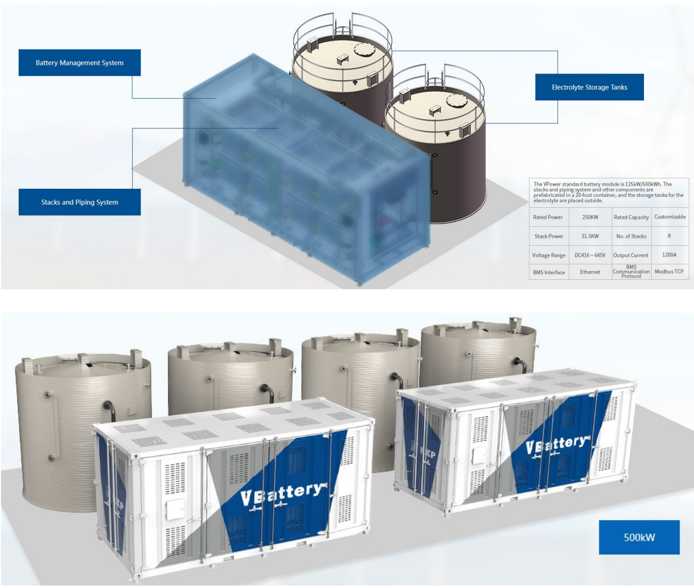


Figure S59: The VPower series is rated 500 kW/2 MWh on 125 m^2 with around 16 kWh m^{-2}. It is used at the 5 MW/10 MWh Guodian Longyuan Woniushi Wind farm since 2013.[70] No satellite images could be found. Image credit: http://en.rongkepower.com/?about/12.html

Invinity Energy Systems, Vanadium

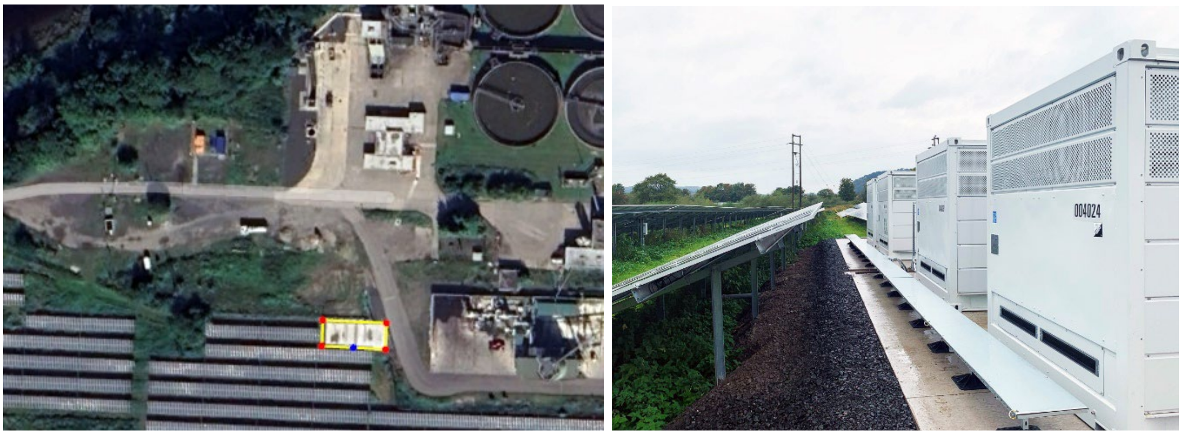
Oxford, England, 2 MW/5 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S60: The 2 MW/5 MWh flow batteries at the Oxford Energy Superhub occupy 450 m^2 with around 11 kWh m^{-2}. The site is coupled with a 50 MW/50 MWh lithium-ion battery (Figure S20). Location: 51°42'34.90"N 1°11'25.52"W

Photo credits: https://www.energy-storage.news/project-with-worlds-largest-lithium-vanadium-hybrid-bess-officially-launched-in-oxford-uk/ and https://www.wartsila.com/media/news/23-06-2021-pivot-power-wartsila-and-habitat-energy-activate-50-mw-transmission-connected-battery-in-oxford-uk-2937111

Perth, Scotland, 1 MW/0.8 MWh



Map Data: Google, © 2022 CNES / Airbus

Figure S61: Operated by Scottish Water near Perth wastewater plant, the 1 MW/0.8 MWh site occupies 135 m^2 with around 6 kWh m^{-2}. Location: 56°22'57.15"N 3°23'8.05"W Photo credit: https://invinity.com/scottish-water-treatment-solar-storage-lowcarbon/

Largo Clean Energy, Vanadium

Shirley, Massachusetts, 0.5 MW/3 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S62: The 0.5 MW/3 MWh site occupies 220 m^2 with roughly 14 kWh m^{-2}. Location: 42°35'45.62"N 71°38'35.25"W

Photo credit:
https://mms.businesswire.com/media/20221017005340/en/1603332/4/PXL_20210410_142503468.jpg?download=1

Palma, Balearic Islands, Spain, 1.2 MW/6.1 MWh – under construction

Map Data: Google, © 2022 Maxar Technologies

Figure S63: To be operated by Enel Green Power Spain, the containers will not be stacked according to correspondence with Largo Clean Energy. Location: 39°35'57.38"N 2°44'33.15"E

Proposed designs for future installations

Figure S64: The product brochure advertises 6 MWh on 132 m^2, 8 MWh on 166 m^2, 10MWh on 200 m^2 which would afford 45-50 kWh m^{-2} in a stacked configuration.

Image credit: https://www.largoinc.com/Our-business/clean-energy-storage/default.aspx

CellCube, Vanadium

Bolingbrook, Illinois, 2 MW/ 8.5 MWh

Figure S65: Satellite images of the 2 MW/8.5 MWh site are not up to date, according to the company, the site uses four FB500-2000 units with a footprint of 450 m^2, corresponding to around 19 kWh m^{-2}. Location: 41°40'24.86"N 88° 4'13.68"W

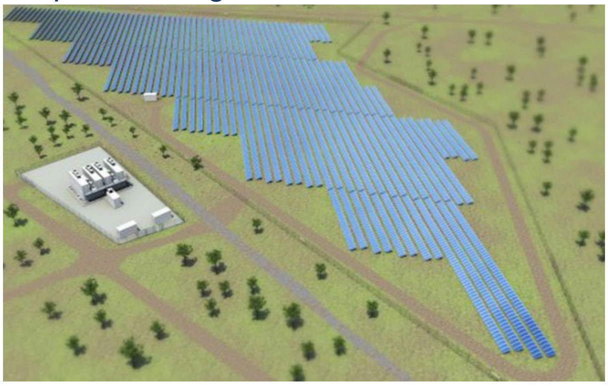
Image credit: https://www.gwelectric.com/blog/2022/08/02/completion-of-battery-energy-storage-system-bess/ and https://media-exp1.licdn.com/dms/image/C5622AQHI5V3PE1Bu6Q/feedshare-shrink_1280/0/1657220631232?e=1669248000&v=beta&t=zNarjHHF6UojrGDnHRXAFb7hNsPwvkv-5y1wEfR5Zr0

Hot Springs, Arkansas, 0.25 MW/1 MWh

Figure S66: Satellite images of the 0.25 MW/1 MWh site are not up to date, according to the company, the site uses a FB250-1000 unit with a footprint of 60 m^2, corresponding to roughly 17 kWh m^{-2}. Location: 34°28'1.45"N 92°56'52.39"W

Photo credit: https://www.cellcube.com/wp-content/uploads/2022/02/USV_Beitragsbild_m_Text-1.jpg

Proposed designs for future installations



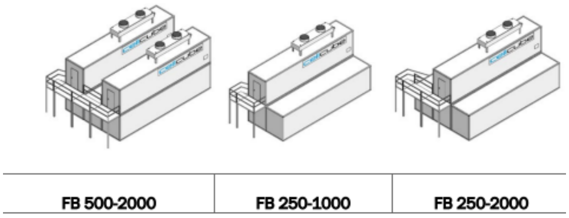


Figure S67: The company is currently constructing a 1 MW/4 MWh installation at Vametco Mine in South Africa that will have an overall footprint of 242 m^2, corresponding to roughly 17 kWh m^{-2}. The FB500-2000 series battery alone is advertised to occupy 90 m^2 for a 0.8 MW/2.8 MWh battery with around 31 kWh m^{-2}.

Source: https://www.cellcube.com/wp-content/uploads/2021/08/CellCube-Projetcs-Bushveld-666.66666666667x0-c-default.jpg and https://www.cellcube.com/wp-content/uploads/2022/09/Datasheet-CellCube-Rel.4.0-Family_V2.0.pdf

VRB Energy, Vanadium

Figure S68: The company, formerly known as Pu Neng and before that as Prudent Energy, has deployed several MW-scale flow batteries, but no information on exact locations could be retrieved. A 100 MW/500 MWh battery in the Automobile Industrial Park of the Xiangyang High-tech Development Zone in Hubei Province, China, is reportedly under construction and is planned to occupy 20,000 m^2.[71] This promises an areal energy density of 25 kWh m^{-2}. A representative of the company put in promising 125 MWh per acre, or ca. 25 kWh m^{-2}, in private correspondence and the official brochure also proposes 80 m^2 for a 0.5 MW/2 MWh system, or 25 kWh m^{-2}.

Photo credit: https://vrbenergy.com/vrb-energy-commissions-3mw-12mwh-vanadium-redox-battery-energy-storage-system-vrb-ess-2/

ESS Inc., Iron

Cameron Crossing, California, 0.5 MW/2.4 MWh

Map Data: Google, © 2022 CNES / Airbus

Figure S69: The 0.5 MW/2.4 MWh site occupies 400 m^2 with roughly 6 kWh m^{-2}. Location: 32°37'52.48"N 116°28'20.55"W

Photo credit: https://www.sandiegouniontribune.com/business/story/2022-06-07/new-microgrid-promises-some-relief-from-power-outages-for-folks-in-campo

Westgrove, Pennsylvania, 75 kW / 0.4 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S70: Installed at Sycamore International Inc. in September 2022, occupying 30 m^2 with around 13 kWh m^{-2}. Location: 39°49'6.41"N 75°50'35.61"W

Photo credit: https://www.inquirer.com/business/pennsylvania-solar-renewable-iron-flow-battery-ess-sycamore-20220904.html

Proposed design for future installations

Figure S71: The proposed design for the ESS Energy Center supports 6 MW/90 MWh per acre, corresponding to around 22 kWh m^{-2}. The company is planning a 3 MWh battery next to its corporate headquarters in Wilsonville, Oregon, but no construction can be seen on satellite images as of June 2021. The company is also planning to deliver 17 Energy Warehouse containers to Enel Green Power Spain with a total energy capacity of 8.5 MWh and 75 containers with 5.6 MW/37.5 MWh to ESI in Australia.

Source: https://essinc.com/ess-and-portland-general-electric-reach-agreement-to-demonstrate-ess-energy-center-long-duration-storage-system/ and https://essinc.com/energy-center/ and https://essinc.com/ess-inc-contracts-with-enel-green-power-espana-to-deliver-17-energy-warehouse-long-duration-iron-flow-battery-systems/

https://essinc.com/ess-celebrates-australia-partnership-following-major-announcements-in-the-united-states/

EnerVault, Iron-Chromium

Stanislaus County, California, 250 kW/1 MWh

Map Data: Google, © 2022 Landsat / Copernicus

Figure S72: The demonstrator was operated from May 2014 until 2015/2016, occupying 275 m^2 with roughly 4 kWh m^{-2}. Location: 37°33'10.16"N 120°33'34.63"W

Photo credit: https://www.greentechmedia.com/articles/read/Flow-Battery-Startup-EnerVault-Files-For-Assignment-Before-Creditors

Redflow, Zinc-Bromine

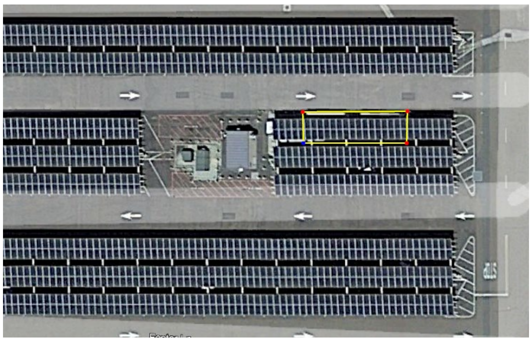
Rialto, California, 0.5 MW/2 MWh

Map Data: Google, © 2022 Maxar Technologies

Figure S73: The system incorporates 192 Zn-Br batteries in 12 160 kWh pods, arranged in four strings. Located at Anaergia's Rialto Bioenergy Facility it occupies 140 m^2 with about 14 kWh m^{-2}. Otherwise, the company primarily focuses on smaller installations for residential use. Location: 34° 3'8.81"N 117°21'31.12"W

Photo credit: https://www.anaergia.com/reference-facilities/rialto-bioenergy-facility/

Primus Power, Zinc-Bromine

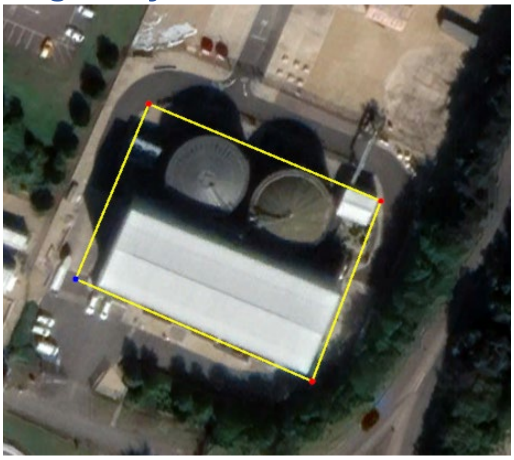


Map Data: Google, © 2022 Landsat / Copernicus

Figure S74: The company deployed one 1 MWh container at the Marine Corps Air Station in Miramar, California, occupying 30 m^2 with around 33 kWh m^{-2}. Originally the company planned a “Wind Firming Energy Farm” with 25 MW/75 MWh capacity, but the project did not move forward.[72] Location: 32°53'13.32"N 117° 7'44.88"W

Photo credit: https://twitter.com/primus_power/status/926250818407485441

Regenesys, Bromide-Sulfide



Map Data: Google, © 2022 Landsat / Copernicus

Figure S75: Developed by Regenesys Technologies Ltd. and owned by Innogy, then RWE, the company constructed a 12 MW/120 MWh battery in 2002 that never entered operation due to engineering challenges and pulled funding.[3] The site would have occupied 2,800 m^2 with roughly 43 kWh m^{-2}. This is the only example we could find employing the classical “very large tanks” approach. Location: 52°12'15.32"N 0°16'12.10"W

Photo credit: https://docplayer.net/90065885-Handbook-of-energy-storage-for-transmission-or-distribution-applications.html

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