Estimating Intra-Day to Long-Term Energy Storage Needs for Grids Dominated by Solar and Wind Generation

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Solar photovoltaics (PV) and wind accounted for approximately 75% of net new global generation capacity additions in 2022 (IRENA, 2023). Installation of solar PV has been growing at an exponential rate (Bond, et al., 2023; International Energy Agency, 2023). Balancing a high penetration of variable renewable energy sources within the grid will require energy storage systems to time-shift electricity. Batteries and pumped hydro energy storage (PHES) are the most prolific electrical energy storage systems, with PHES already providing 97% of the power and energy capacity of storage systems worldwide (Sandia National Laboratories, 2023).

The Australian National University has published a number of studies that model the amount of energy storage required to support 100% renewable grids dominated by solar PV and wind in Australia, Southeast Asia, Japan, East Asia, and Bolivia (Blakers, et al., 2017; Cheng, et al., 2022a; Cheng, et al., 2022b; Lu, et al., 2021a; Lu, et al., 2021b; Cheng, et al., 2019; Nadolny, et al., 2022). These analyses perform hour-by-hour energy balancing to find the least-cost configuration of solar PV, wind, energy storage, and transmission capacity to meet demand over decades of data. Categorising energy storage systems at a grid-level according to their cycle frequency is an important step in grid planning and determining the effectiveness of electricity market rules for incentivising the development of appropriate systems.

Energy Storage System Taxonomy

A taxonomy has been developed that categorises energy storage systems according to the duration of time-shifting services. These categories are summarised in Table 1. Longer-term storage systems require large energy reserves for balancing infrequent calm, cloudy weeks in grids with high penetration of solar PV and wind.

Table 1 Categories of energy storage systems

Category	Minimum Cycle Period	Maximum Cycle Period
Intra-day	2 hours	20 hours
Overnight	20 hours	28 hours
Monthly	28 hours	30 days
Seasonal	30 days	1 year
Long-term	-	-

Frequency Spectrum of an Energy Storage Profile

Hourly demand was balanced through a net-load model using 10-years of solar data, existing hydroelectric capacity, legacy fossil fuel power stations, and new PHES. Solar PV and PHES capacities were optimised through a least-cost differential evolution (Lu, et al., 2021b). Hour-by-hour energy balancing was used to produce a time-series defining the amount of electricity stored in energy storage systems (i.e., a stored electricity profile). The process in Figure 1 was then used to develop stored electricity profiles and estimate the energy capacity required for each category of storage system.

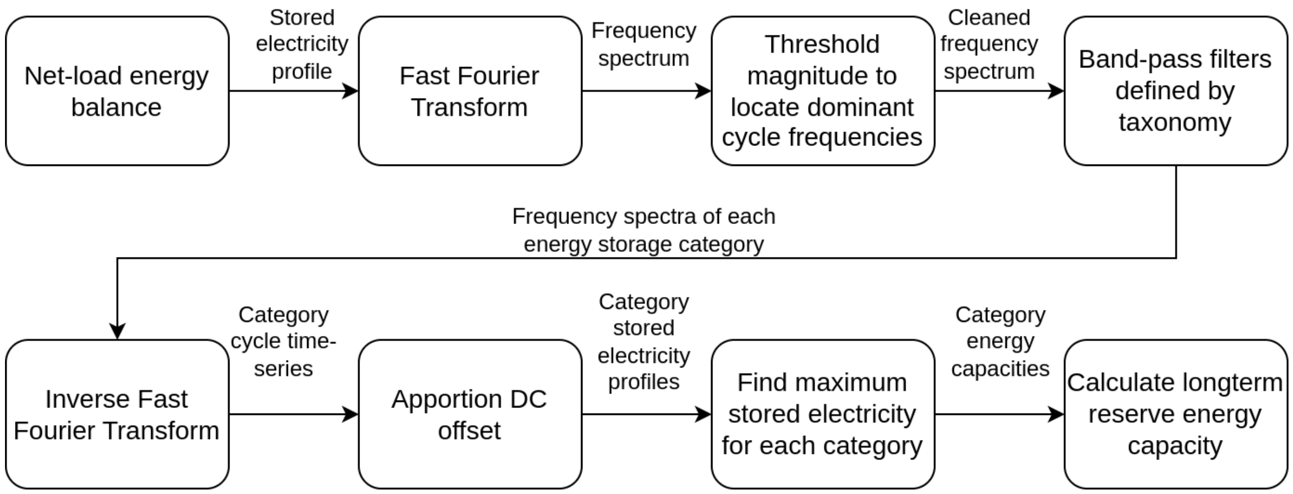

Figure 1. Method for Determining Energy Capacity of Storage System Categories

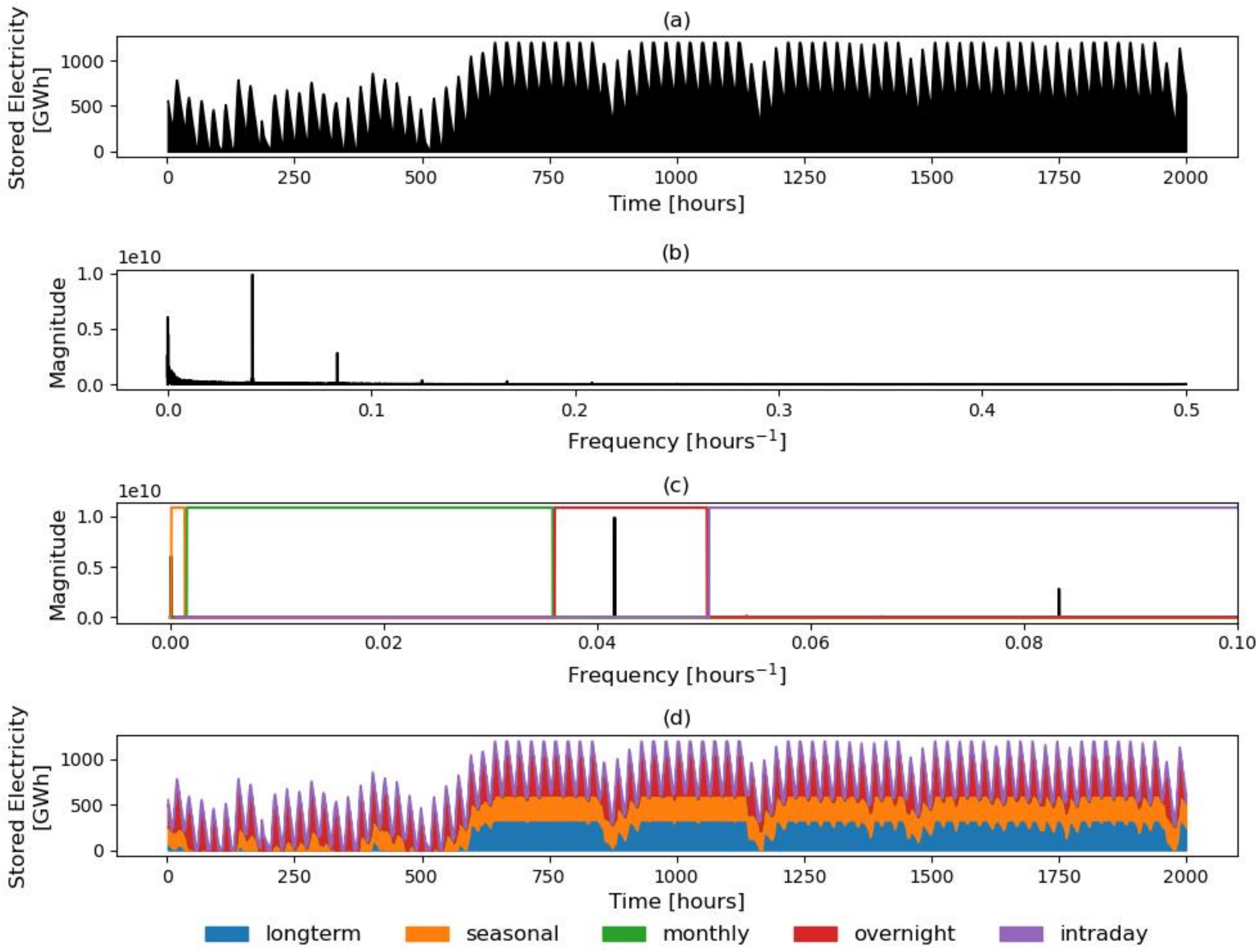

Figure 2. (a) Sample of stored electricity time-series; (b) frequency spectrum of stored electricity for Malaysia copper plate scenario; (c) dominant frequencies and band-pass filters for each category of storage system; and (d) stored electricity time-series for each category of storage system

The first 2000 hours of the stored electricity profile for a scenario with 10 MWh per capita annual demand in Malaysia is provided in Figure 2(a).

A total population of 41 million people by 2050 was assumed for Malaysia (World Bank Group, 2023). The frequency distribution determined by FFT of the hourly stored electricity profile is shown in Figure 2(b) (excluding DC offset). The peak with the largest magnitude corresponds to the daily cycling of the energy storage. Since Malaysia has very little wind resources, solar PV is considered the primary source of new generation capacity within the energy balance model and must be time-shifted on a daily basis to meet demand during the night. Peaks to the right of the daily frequency correspond to intra-day cycling, while the dominant peak to the left is for seasonal storage with a cycle period of 1 year. Stochastic behaviour of the solar and demand data causes noise in the frequency spectrum. A threshold magnitude was used to extract dominant peaks from the surrounding noise and spectral leakage, as shown in Figure 2(c).

An inverse FFT transformed the filtered frequency spectra into the corresponding time-series for each category of storage system. DC offset was apportioned to the stored electricity time-series for each category to remove negative values (refer Figure 2(d)). Long-term storage was used to balance remaining noise.

Effect of Increasing Electricity Demand

The electricity demand was varied from 5–25 MWh/capita/year for the same Malaysia copper plate model. Malaysia currently consumes about 5 MWh/capita/year (Energy Commission, 2023). A developed country with fully electrified transport, heating and cooling, and industry could be estimated to have an annual electricity demand of roughly 20 MWh per capita. Energy capacity was calculated according to the maximum value in each category's stored electricity time-series. The proportion of total energy capacity required for each category of energy storage system is described in Figure 3.

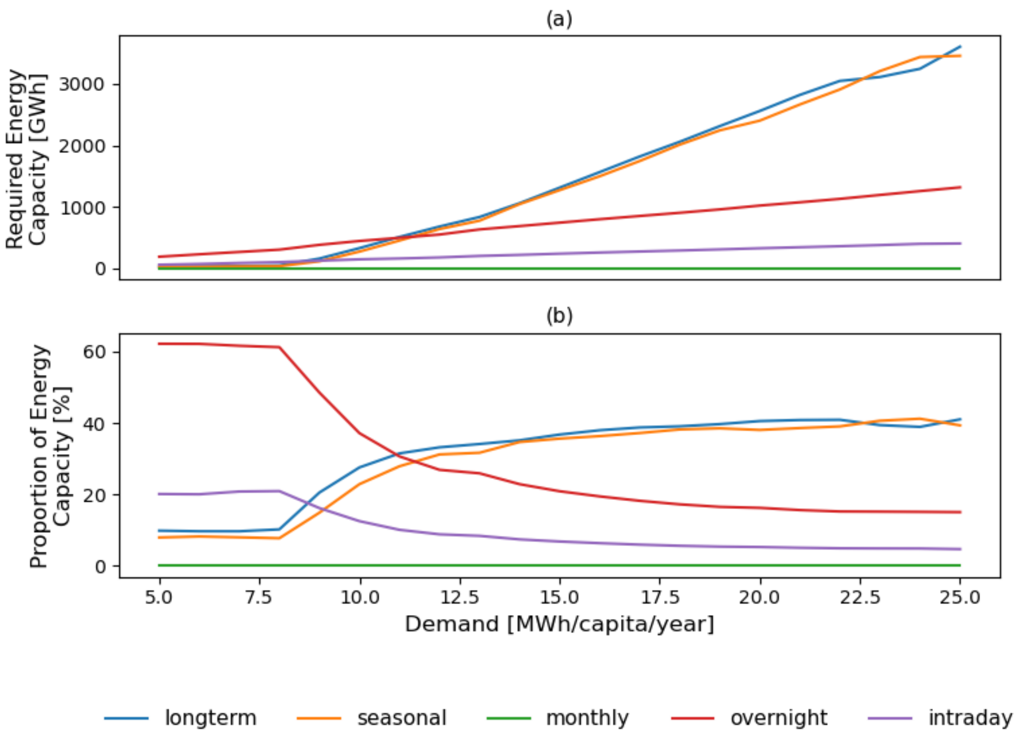

Figure 3. Energy Storage Capacity vs Annual Demand in Decarbonised Malaysia Grid

As electricity demand increases, seasonal energy storage rapidly becomes a much more important component of the energy storage mix. Annual flexible generation from hydro and legacy fossil fuels steadily increased up until the 8 MWh/capita/year demand scenario, before steadily decreasing again for all higher demand scenarios. This represents a tipping point at which the levelised cost of flexible generation with large, low frequency solar spillage exceeds the cost of adding longer-term storage to reduce spillage. As Malaysia's electricity demand reaches parity with Singapore (i.e., double its current demand) and transport, heating, and industry are electrified (i.e., doubling demand again), storage systems with large energy reserves will be essential for balancing a grid with high solar penetration. Other balancing technologies, such as demand management or firming from green synthetic methane/hydrogen generators, may reduce the need for seasonal and long-term storage, which each represent about 40% of total storage capacity for higher electricity demand scenarios.

Off-river Pumped Hydro Energy Storage Potential

In 2021, the Australian National University published the Global Greenfield Atlas of Pumped Hydro Energy Storage sites ("Greenfield Atlas"). Using Geographic Information System (GIS) analysis, the Greenfield Atlas identified 616,000 dry gully sites with 23,000 TWh of energy storage potential around the world. Since then, global atlases that locate PHES sites that use existing lakes and reservoirs ("Bluefield"), repurpose mining sites ("Brownfield"), and treat the ocean as a lower reservoir have been developed (Stocks, et al., 2021; Stocks, et al., 2023; Blakers, et al., 2022). All sites are closed-loop (off-river) systems located outside protected areas and large urban centres. GIS analysis has also been used to locate large-scale PHES connected to large rivers (similar to the 5000 GWh Lake Onslow project under consideration in New Zealand (New Zealand Ministry of Business, Innovation and Employment, 2023)).

A summary of the energy storage potential of each type of PHES in Malaysia is provided in Figure 4. The off-river systems range from 2 GWh, 6h to 1500 GWh, 504h in size. The two possible sites for large-scale PHES systems connected to rivers are each 5000 GWh, 2000h. As per Figure 3(a), the energy balance modelling estimated Malaysia could need 6300 GWh of energy storage to support a 100% renewable electricity grid at 20 MWh/capita/year consumption in 2050 (i.e., affluent, fully electrified country). There is approximately 30X more off-river and large-scale PHES energy storage potential than what would be required to support this decarbonised system.

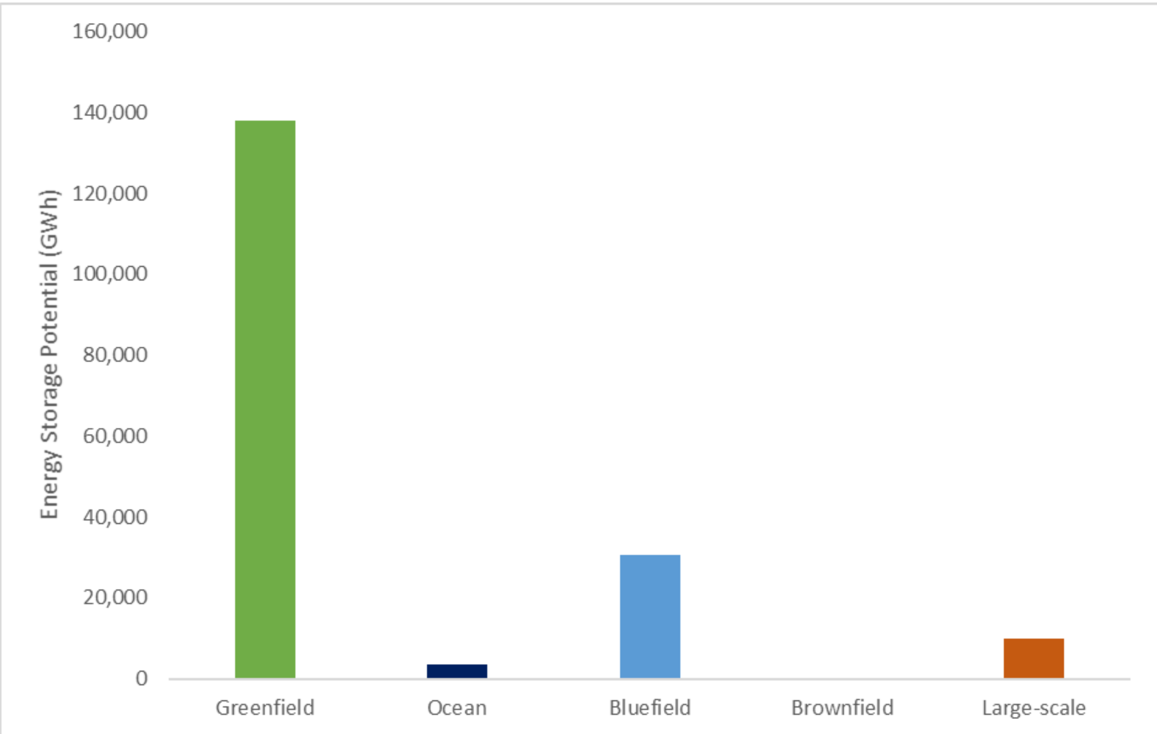

Figure 4. Off-river and Seasonal PHES Energy Storage Potential in Malaysia

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