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# Coupling Maritime Electrification with Renewable Power Systems: The Potential of Battery Vessels

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## Abstract

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### JEL Classification

Q41, Q42, Q47, R40, Q54

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# Coupling maritime electrification with renewable power systems: The potential of battery vessels

Anthony Wiskich*

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Battery vessels (BVs) have been proposed to partially electrify long-distance shipping by connecting to ocean-going vessels at sea and recharging at port, ensuring frequent cycling of the battery. While previous work has examined their maritime economics, we quantify their system-wide effects in a detailed multi-regional capacity expansion model of the Australian east coast in 2050, under multi-year weather variability. BVs have two revenue streams of comparable value - powering ships at sea and temporal grid arbitrage - and can relocate between ports. Thus, they are deployed even at costs per MWh well above stationary batteries, lowering electricity system costs (-1.3%) and reducing renewable curtailment (-31%). As peaker gas generation and electricity-sector emissions are reduced (-12%), decarbonisation through partial ship electrification is reinforced by a cleaner electricity supply.

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# 1 Introduction

Global efforts to decarbonise both transport and electricity systems are accelerating. In maritime transport, the International Maritime Organization has adopted targets to reduce greenhouse gas emissions per transport work and to reach net zero emissions around mid-century (IMO, 2023). At the same time, many electricity systems are projected to become dominated by wind and solar generation by 2050, creating new challenges related to variability, transmission congestion and the need for large-scale energy storage (IEA, 2024). These transitions are typically analysed in isolation, with limited attention to technologies that physically couple maritime energy demand with electricity system flexibility. However, emerging technologies may couple them in ways that reshape both sectors.

One such technology is the dedicated battery vessel (BV). This vessel carries large-scale battery capacity and can connect to ocean-going vessels at sea to provide propulsion and auxiliary power, then disconnect and recharge at port. Such a vessel has recently been developed for "e-bunker" power at port ("SeaFjord Energy", 2025), and the concept is comparable to swappable containerised batteries used on the Yangtze river (Yang et al., 2024). A single onboard battery charge is not economical over large distances due to excessive costs and low energy density (Kersey et al., 2022; Kistner et al., 2024; Moon et al., 2024; Seidl-Zelenka & Normann de Boer, 2024; Wu & Bucknall, 2016).

In previous work, BVs were proposed as a novel approach to partially electrifying long-distance container routes (Wiskich, 2025). By separating battery capital from the container ship itself, BVs enable frequent battery cycling across multiple ships and reduce the risk of underutilisation when routes change. That analysis focused on maritime economics, evaluating whether such vessels could compete with fuels under different future battery costs and energy densities.

Yet BVs possess an additional and unexplored characteristic: they are mobile, high-capacity electricity storage assets embedded within coastal power systems. When not supplying ships at sea, BVs can charge and discharge at port, interacting with wholesale electricity markets, including relocating to take advantage of interregional price variation. In wind- and solar-dominated systems, where price volatility is expected to increase due to variable renewable generation, this dual role transforms BVs from a maritime decarbonisation device into a cross-sector flexibility resource.

This paper examines how BVs interact with, and potentially reshape, a future electricity system. We model the east coast Australian electricity market in 2050, a useful case study due to its high renewable resource potential, long coastline and geographically dispersed ports (AEMO, 2025). We use a multi-regional capacity expansion model with endogenous investment in generation, storage, transmission and BVs under multi-year weather variability.

We make two main contributions. First, we identify the sources of value for mobile BVs in a wind- and solar-dominated electricity system by progressively relaxing behavioural constraints. These include charging timing, maritime departure decisions, grid temporal arbitrage, and inter-port relocation. The flexibility of choosing whether to power ships at sea reflects the necessary hybrid capability of ocean-going ships.

Our second contribution is the effect of BV adoption on the electricity system as a whole. We quantify the equilibrium effects on system costs, generation mix, emissions and transmission. The flexibility of BVs can improve the efficiency of power supply including reducing curtailment, as found for EVs (Štogl et al., 2024) and electric ferries (Frković et al., 2025; Mimica et al., 2022). Our analysis explicitly considers port power constraints, recognising that large-scale maritime electrification will require substantial upgrades to port grid connections with associated grid implications (Ramasan et al., 2025).

More broadly, the paper contributes to the literature on the impact of forthcoming technologies on and firming of power systems (Blakers et al., 2017; Gilmore et al., 2023; Simshauser & Gilmore, 2026) and the advantages of mobile versus stationary energy storage (Moraski et al., 2023; Yan et al., 2024). By coupling the inherent flexibility of powering hybrid maritime ships to the electricity market, BVs can lead to emissions and cost reductions in both sectors.

# 2 Model

In this section, we first outline our approach to modelling BVs. Then we present our full model. Third, we discuss how we use the results from the Base case of our model to decompose the value of a marginal BV using exogenous electricity prices. Monetary values are in Australian dollars unless otherwise indicated.

## 2.1 Battery vessels

For clarity and ease of modelling, we simplify the cost of BVs to be $100/MWh/day, or an annualised cost of $36,500/MWh/yr, excluding connection costs at port. This implicitly includes the various and uncertain (due to the novelty of approach) costs involved (Wiskich, 2025). For comparison, the equivalent daily cost for stationary 8-hour batteries in the model we use (discussed below) is between $61 and $64 per MWh, depending on the region. Coupled with this daily figure, we assume that BVs always depart port with a full battery at the start of a day and arrive empty at the end of the day to a neighbouring port. Thus, the BV is at sea at most half of the time (alternate days). Given that ports are selected to be approximately one day's sailing apart, the model abstracts from explicit distance and speed modelling and instead constrains BVs to operate at sea for a full day.

We also assume a constant price for revenue at sea of $250/MWh. Losses to propulsion and auxiliary systems, as well as the energy needs of powering the BV itself, implicitly form a part of this price. Ignoring the propulsion energy needs of the BV itself, this assumption implies a cost-equivalent price of fuel oil of around $1400/t or US$930/t, or a carbon price of around US$140 with a fuel oil price of US$500 (Wiskich, 2025). This assumption does not leave much room for economic adoption of BVs. It implies a breakeven electricity price of $30/MWh when operating at sea on alternate days, even less when taking into account port power connection costs. This is well below the values of US$40 and US$60 assumed by Wiskich, 2025. Further, we constrain the daily capacity of BVs that can discharge at sea on each route, as well as the maximum collective power transfer at port.

There are over 20,000 freight port calls each year to Australia's eastern seaboard (BITRE, 2025). Consider 10,000 as an illustrative figure as BVs would only apply to larger ships. On average, each port call could have several days of battery-powered travel. For example, routes between Melbourne and east asia might use 8 in total (4 BVs each way, see Figure 1A). Assuming 4 BV uses per port call makes 40,000 BV-powered days per year or about 100 per day. This estimate does not consider growth in vessel numbers and non-cargo ships such as cruise ships. Assuming 20MW transfer over 24 hours implies ≈ 500MWh per vessel and a daily aggregate capacity limit of 50GWh.

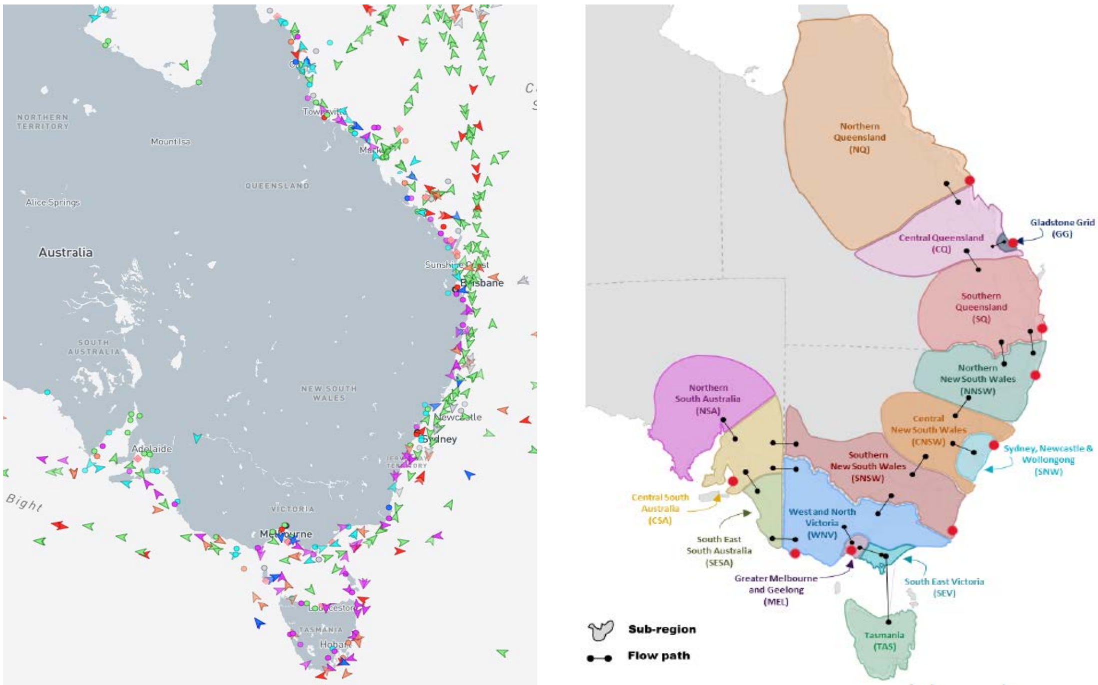
The regional disaggregation of our model is shown in Figure 1B (AEMO, 2025). There are 9 regions where we consider ports available to BVs, shown by the red dots. The following ports have been used for illustration: Mackay (NQ), Gladstone (GG), Brisbane (SQ), Coffs Harbour (NNSW), Sydney (SNW), Eden (SNSW), Melbourne (MEL), Portland (WNV), and Adelaide (CSA). We assume up to 8 BVs/day can run in each direction on legs between Brisbane and Melbourne, 6 for the two legs either side of Gladstone, 4 between Melbourne and Portland and only 2 to Adelaide as ships travelling from Victoria to Western Australia do not pass near Adelaide. We implement the constraint by limiting the daily capacity between region pairs, shown in Table 1.

We also operationally constrain BVs by limiting the maximum combined port power of electricity transfer to and from BVs (Table 1). Our default value is 1000MW for a main port, including Portland which already has high transmission. For SNW we use 2000MW as it includes Sydney, Newcastle and Wollongong, while we use 500MW for the smaller ports of Mackay, Coffs Harbour and Eden.

**Table 1:** BV regions, example ports and operational constraints

| **Parameter** | NQ | | GG | | SQ | | NNSW | | SNW | | SNSW | | MEL | | WNV | | CSA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max port power (MW) | 500 | | 1000 | | 1000 | | 500 | | 2000 | | 500 | | 1000 | | 1000 | | 1000 |
| Max capacity at sea (MWh/day each way) | | 3000 | | 3000 | | 4000 | | 4000 | | 4000 | | 4000 | | 2000 | | 1000 | |
| Nautical miles between ports | | 247 | | 319 | | 208 | | 257 | | 267 | | 378 | | 206 | | 321 | |

Capacities at sea and distances relate to legs between the ports in the column header regions.




**A:** Snapshot of marine traffic

**B:** AEMO regions and modelled BV ports

**Figure 1:** Marine traffic, AEMO regions and modelled ports (red dots)

## 2.2 Complete model

The model is based on the Simple Electricity Model (SEM) from CSIRO (Graham et al., 2025), which allows for stationary batteries with durations of 2, 4 and 8 hours. We assume that at port, the BV can charge and discharge in the same way as an 8-hour battery. We restrict the set of storage technologies available to be 8-hour batteries and pumped hydro where it already exists. Including 2- and 4-hour batteries and allowing 10-, 24- and 48-hour pumped hydro options in all regions limits the number of weather years we can consider, due to computational constraints. However, running the model with all storage technologies available across 1 and 2 weather years leads to only 8-hour batteries being deployed as storage in all of our scenarios, so we expect that our approach does not affect results. Table 2 contains model sets and mappings and Table 3 shows variables and parameters, some of which are in an excel file.

**Table 2:** Model sets and mappings

| Set name | Symbol | Elements |
|---|---|---|
| Generation | $g$ | OCGTgas, RecipGas, SolLargePV, Wind |
| Gas (methane) generation | $m$ | OCGTgas, RecipGas |
| VRE generation | $v$ | SolLargePV, Wind |
| Storage | $s$ | BattStor08, HydPump10, HydPump48, HydPump159 |
| Battery Vessel | $b$ | BattVess08 |
| Storage + Battery Vessel | $sb$ | |
| Regions | $r, \rho$ | NQ, CQ, SQ, GG, NNSW, CNSW, SNSW, SNW, NSA, CSA, SESA, WNV, MEL, SEV, TAS |
| BV regions | | NQ, GG, SQ, NNSW, SNW, SNSW, MEL, WNV, CSA |
| States | $\tilde{r}$ | TAS, NSW, VIC, QLD, SA |
| Weather year | $y$ | 2011..2015 |
| Time period | $h$ | 1..4380 (2-hour periods) |
| Day | $d$ | 1..365 |
| Mapping time period to day | $\Theta_d(h)$ | $h \rightarrow d$ |
| Mapping to first period of day | $\Theta_h(h)$ | $h \rightarrow h$ |
| Mapping first period to day | $\Phi_{h,d}$ | 1 if $\Theta_h(h) = h$ & $\Theta_d(h) = d$, else 0 |

**Table 3:** Model variables and parameters

| Variable | Symbol | Parameters in excel file | Symbol |
|---|---|---|---|
| Cost of electricity supply ($) | **Cost** | Generation capital cost ($/MW) | $\hat{k}_g$ |
| Storage, BV cap (MWh) | $\mathbf{K}_{s,r}, \mathbf{K}_b$ | Grid connection cost ($/MW) | $\hat{c}_{g,r}, \hat{c}_{sb,r}$ |
| BV cap at port, sea (MWh) | $\mathbf{K}_{b,r,y,d}$, $\mathbf{K}_{b,r,\rho,y,d}$ | Operating reserve requirement at peak demand (MW) | $O_{\tilde{r}}$ |
| Generation cap (MW) | $\mathbf{K}_{g,r}$ | Storage capital cost ($/MWh) | $\hat{k}_s$ |
| Tx cap interregion (MW) | $\mathbf{T}_{r,\rho}$ | Tx capital cost ($/MW) | $\hat{t}_{r,\rho}$ |
| Port power cap (MW) | $\mathbf{T}_r$ | Maximum VRE cap (MW) | $V_{v,r}$ |
| Electricity production (MWh) | $\mathbf{E}_{g,r,h}$ | Renewable energy zone Tx cost ($/MW) | $\hat{t}_r$ |
| Exports interregion (MW) | $\mathbf{X}_{r,\rho,h}$ | Contribution of solar and wind at peak demand | $P_{v,r}$ |
| Storage, BV charging (MW) | $\mathbf{C}_{sb,r,h}$ | Existing Tx (MW) | $T_{r,\rho}$ |
| Storage, BV discharging (MW) | $\mathbf{D}_{sb,r,h}$ | Fixed operating and maintenance cost ($/MW) | $\hat{f}_g, \hat{f}_s$ |
| Hydro state of charge (MWh) | $\bar{\mathbf{S}}_{r,h}$ | Fuel emissions ($tCO_2$/GJ) | $\nu_{g,r}$ |
| Hydro discharge (MW) | $\bar{\mathbf{D}}_{r,h}$ | Existing storage (MWh) | $K_{s,r}$ |
| State of charge (MWh) | $\mathbf{S}_{sb,r,h}$ | Existing hydro (MW) | $\bar{K}_r$ |
| | | Regional Storage cost factor | $R_{s,r}$ |
| **Parameter** | | **Values** | **Symbol** |
| Time period (hours) | | 2 | $\delta$ |
| Variable O&M cost ($/MWh) | | 8.1 OCGTgas, 8.51 RecipGas | $\hat{v}_g$ |
| Remediation cost for non-synchronous inverter-based resources ($/MW) | | 60677.2 | $\hat{i}_g$ |
| Efficiency of batteries, HydPump | | 0.8649, 0.775 | $\eta_{sb}$ |
| Tx loss factor | | 0.055 | $\omega$ |
| Price of gas (methane, $/GJ) | | 12.6611 | $\hat{m}$ |
| Carbon tax ($/tCO_2$) | | 420 | $\hat{\tau}$ |
| BV cost ($/MWh) | | 36500 | $\hat{k}_b$ |
| BV revenue at sea ($/MWh) | | 250 | $\hat{p}$ |
| Electricity demand (MWh) | | From AEMO | $Q_{r,y,h}$ |
| VRE generation profile | | From AEMO | $V_{v,r,y,h}$ |
| Hydro charge (inflows, MW) | | From AEMO | $\bar{C}_{r,y,h}$ |
| Maximum port power cap (MW) | | See Table 1 | $\bar{T}_r$ |
| Maximum cap at sea (MWh) | | See Table 1 | $\bar{K}_{b,r,\rho}$ |
| Storage duration (hours) | | See number in element name | $H_{sb}$ |
| Fuel factor OCGT, Recip (GJ/MWh) | | 10.8108, 8.8020 | $\epsilon_g$ |

Tx=Transmission. Cap=Capacity. Decision variables are in bold; non-bold denote parameters or existing capacity.

The choice of variables minimises total system costs. Capital and fixed costs are annualised. Generation capital costs include the price per MW subject to a regional cost factor, a connection cost and a remediation cost for non-synchronous inverter-based resources. Storage costs include capital costs per MWh and connection costs per MW. BV capital is not region-specific and connection costs at port apply. BV revenue is based on a constant price per MWh delivered to the ocean-going ship. Apart from gas, the model does not consider variable costs for technologies, consistent with SEM.

$$
\begin{aligned}
\min\ \text{Cost} = & \sum_{g,r} \mathbf{K}_{g,r} \left( \hat{k}_g R_{g,r} + \hat{c}_{g,r} + \hat{i}_g \right) && \text{generation capital} \\
& + \sum_{s,r} \mathbf{K}_{s,r} \left( \hat{k}_s R_{s,r} + \frac{\hat{c}_{s,r}}{H_s} \right) && \text{storage capital} \\
& + \mathbf{K}_b \hat{k}_b + \sum_{r} \mathbf{T}_r \hat{c}_{b,r} && \text{BV} \\
& + \sum_{g,r,y,h} \mathbf{E}_{g,r,y,h} \epsilon_g \left( \hat{m} + \hat{\tau} \nu_{g,r} \right) && \text{fuel (methane)} \\
& + \sum_{g,r,h} \mathbf{E}_{g,r,y,h} \hat{v}_g \delta + \sum_{g,r} \mathbf{K}_{g,r} \hat{f}_g && \text{generation variable/fixed} \\
& + \sum_{s,r} \frac{\mathbf{K}_{s,r} \hat{f}_s}{H_s} && \text{storage fixed} \\
& + \sum_{v,r} \mathbf{K}_{v,r} \hat{t}_r + \sum_{r,\rho} \frac{\mathbf{T}_{r,\rho} \hat{t}_{r,\rho}}{2} && \text{transmission} \\
& - \sum_{r,\rho,y,d} \sqrt{\eta_b} \mathbf{K}_{b,r,\rho,y,d} \hat{p} && \text{BV revenue at sea} \qquad (1)
\end{aligned}
$$

Electricity supply in each region must equal or exceed (implying curtailment) demand in all time periods. Demand can be negative so we account for network bidirectional losses to and from households.

$$\forall r, y, h \text{ and for } Q^*_{r,y,h} = \begin{cases} \frac{Q_{r,y,h}}{1-\omega} \text{ if } Q_{r,y,h} \geq 0 \\ Q_{r,y,h}(1-\omega) \text{ if } Q_{r,y,h} < 0 \end{cases}$$

$$\sum_{\rho} \mathbf{X}_{r,\rho,y,h} + \frac{Q^*_{r,y,h}}{1-\omega} \leq \sum_{g} \mathbf{E}_{g,r,y,h} + \sum_{\rho} \mathbf{X}_{\rho,r,y,h}(1-\omega) + \sum_{sb} \mathbf{D}_{sb,r,y,h} - \sum_{sb} \mathbf{C}_{sb,r,y,h} \tag{2}$$

VRE generation from utility solar and wind is determined by the weather and generation capital, while generation from gas is limited by capacity.

$$\mathbf{E}_{v,r,y,h} = V_{v,r,y,h}\mathbf{K}_{v,r} \tag{3}$$

$$\mathbf{E}_{m,r,y,h} \leq \mathbf{K}_{m,r} \tag{4}$$

The sum of BVs at port and sea equals total capacity (5.The states of charge of storage and BVs at port are limited by capacity (6). The BV capacity at port evolves with the departure and arrival of these vessels at the start of each day (7). The evolution of the state of charge depends on charging and discharging. The state of charge of BVs at port also considers the departure of capacity to sea, implemented using the mapping function $\Phi$ (8,9). The model assumes equal efficiency losses in charging and discharging, noting that losses differ between batteries and pumped hydro. BVs fully deplete at sea, so the arrival of vessels to port does not appear in the state of charge equation. Final states of charge must be equal or exceed initial states (10). Storage charge and discharge is limited by the state of charge (11), and by the maximum power of the battery capacity (12). For BVs, charging is limited by the capacity minus the state of charge at the start of the day (13). This conservatively limits the charge rate applied for arrived empty capacity to a port with an existing state of charge. We keep the same form of equation for discharge as for storage, noting that aggregate BV discharge to grid is less than half the aggregate charge. Finally, charging and discharging BVs are limited to the port power capacity (14).

$$\sum_{r} \mathbf{K}_{b,r,y,d} + \sum_{r,\rho} \mathbf{K}_{b,r,\rho,y,d} = \mathbf{K}_{b} \tag{5}$$

$$\mathbf{S}_{s,r,y,h} \leq \mathbf{K}_{s,r} + K_{s,r},\ \mathbf{S}_{b,r,y,h} \leq \mathbf{K}_{b,r,y,d} \tag{6}$$

$$\mathbf{K}_{b,r,y,d+1} = \mathbf{K}_{b,r,y,d} - \sum_{\rho} \mathbf{K}_{b,r,\rho,y,d+1} + \sum_{\rho} \mathbf{K}_{b,\rho,r,y,d} \tag{7}$$

$$\mathbf{S}_{s,r,y,h+1} = \mathbf{S}_{s,r,y,h} + \sqrt{\eta_s}\mathbf{C}_{s,r,y,h}\delta - \frac{1}{\sqrt{\eta_s}}\mathbf{D}_{s,r,y,h}\delta \tag{8}$$

$$\mathbf{S}_{b,r,y,h+1} = \mathbf{S}_{b,r,y,h} + \sqrt{\eta_b}\mathbf{C}_{b,r,y,h}\delta - \frac{1}{\sqrt{\eta_b}}\mathbf{D}_{b,r,y,h}\delta - \sum_{d,\rho} \Phi_{h+1,d}\mathbf{K}_{b,r,\rho,y,d} \tag{9}$$

$$\mathbf{S}_{sb,r,y,1} \leq \mathbf{S}_{sb,r,y,end} \tag{10}$$

$$\mathbf{D}_{sb,r,y,h} \leq \frac{\mathbf{S}_{sb,r,y,h}}{\delta} \tag{11}$$

$$\mathbf{C}_{s,r,y,h} \leq \frac{\mathbf{K}_{s,r} + K_{s,r}}{H_s},\ \mathbf{D}_{s,r,y,h} \leq \frac{\mathbf{K}_{s,r} + K_{s,r}}{H_s} \tag{12}$$

$$\mathbf{C}_{b,r,y,h} \leq \frac{\mathbf{K}_{b,r,\Theta_d(h)} - \mathbf{S}_{b,r,y,\Theta_h(h)}}{H_b},\ \mathbf{D}_{b,r,y,h} \leq \frac{\mathbf{K}_{b,r,y,d}}{H_b} \tag{13}$$

$$\mathbf{D}_{b,r,y,h} \leq \mathbf{T}_{r},\ \mathbf{C}_{b,r,y,h} \leq \mathbf{T}_{r} \tag{14}$$

Standard hydro differs as capacity is in units of MW (rather than MWh for other storage) and charging is a parameter determined by inflows dictated by the weather.

$$\bar{\mathbf{S}}_{r,y,h+1} = \bar{\mathbf{S}}_{r,y,h} + \bar{C}_{r,y,h}\delta - \bar{\mathbf{D}}_{r,y,h}\delta \tag{15}$$

$$\bar{\mathbf{D}}_{r,y,h} \leq \frac{\bar{\mathbf{S}}_{r,y,h}}{\delta},\ \bar{\mathbf{D}}_{r,y,h} \leq \bar{K}_{r} \tag{16}$$

Electricity exports are limited by new and existing transmission. Transmission is symmetric and restricted to neighbouring regions, as depicted in Figure 1B.

$$\mathbf{X}_{r,\rho,y,h} \leq \mathbf{T}_{r,\rho} + T_{r,\rho},\ \mathbf{T}_{r,\rho} = \mathbf{T}_{\rho,r} \tag{17}$$

VRE capacities in each region are subject to a maximum level, consistent with

SEM. BV capacities at sea and port power are also limited.

$$\mathbf{K}_{v,r} \leq V_{v,r},\ \mathbf{K}_{b,r,\rho,y,d} \leq \bar{K}_{b,r,\rho},\ \mathbf{T}_r \leq \bar{T}_r \tag{18}$$

Minimum reserve margins apply for each Australian state, calculated from generation, storage and port capacities minus peak demand in each region. Including port capacity assumes that BVs can discharge to the grid during peak periods, but excluding port capacity from reserve calculations does not materially affect results.

$$\mathbf{O}_{\tilde{r}} \leq \sum_{r \in \tilde{r}} \left( \sum_g \mathbf{K}_{g,r} + \bar{K}_r + \sum_v P_{v,r} \mathbf{K}_{v,r} + \sum_s \frac{\mathbf{K}_{s,r} + K_{s,r}}{H_s} + \mathbf{T}_r - \max_{y,h} Q_{r,y,h} \right) \tag{19}$$

## 2.3 A simple model for a marginal BV addition

To decompose the sources of value, we analyse a marginal BV facing exogenous shadow prices from the equilibrium solution of (2). As shown in Table 4, we progressively relax behavioural constraints. First, we assume that the BV charges at the average shadow price and discharges at sea on alternate days. Second, we allow the BV to charge at the average of the four time periods (8 hours in total, consistent with the assumed duration of the BV battery) with the lowest price. Revenues and costs for these scenarios are derived from a mechanical calculation.

The third scenario introduces optimisation by allowing the BV to do nothing at port, so that the BV has a choice of either waiting or discharging at sea when starting the day full, and a choice of waiting or charging when starting empty. Fourth, we allow the BV to discharge to the grid, introducing a third option when the BV is full. We assume the discharge price is the average of the four time periods with highest price in the day. Note that, unlike in our full model, we do not allow both charging and discharging on the same day, or any other combinations - our simple marginal analysis model only allows one activity per day. Fifth, we allow the BV to move between different ports, meaning the BV has two options for discharging at sea (heading clockwise or counterclockwise) when at an intermediate port.

**Table 4:** Marginal model scenarios and behavioural options

| **Scenario** | Charging price | Options when initially (start of day) Full | Empty |
|---|---|---|---|
| 1 | Average | Sea | Charge |
| 2 | 4 lowest-price periods | Sea | Charge |
| 3 | 4 lowest-price periods | Wait, Sea | Wait, Charge |
| 4 | 4 lowest-price periods | Wait, Discharge to Grid, Sea | Wait, Charge |
| 5 | 4 lowest-price periods | Wait, Discharge to Grid, Sea clockwise, Sea counterclockwise* | Wait, Charge |

* Only one direction applies to terminal ports in *CSA* and *NQ*.

# 3 Results

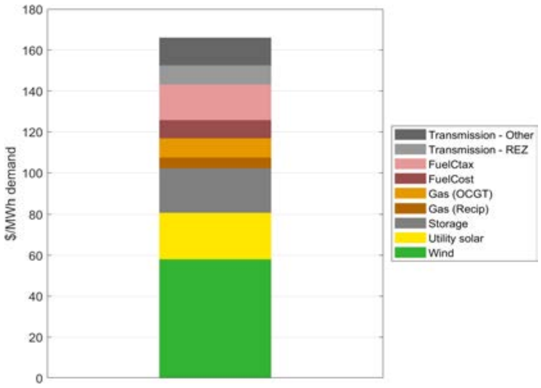
In this section, we first discuss our Base model results. Then we decompose the value of a marginal BV facing exogenous electricity prices from our Base model. Third, we discuss system-wide results in the full model, and fourth we consider the case where a carbon price does not apply to electricity generation.

## 3.1 Base model

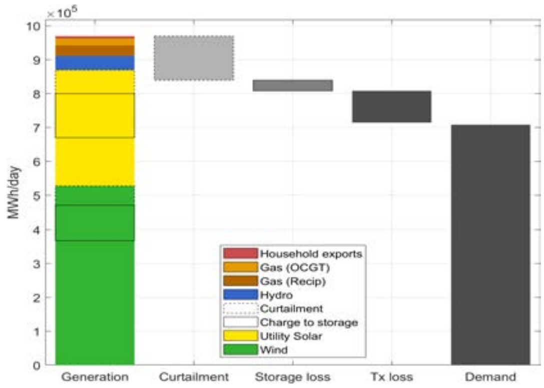
The 2050 system is dominated by capital-intensive wind and utility solar generation (Figure 1A), which together account for roughly half of total system costs. Storage, gas generation (including fuel), carbon tax transfers, and transmission comprise the remainder in similar proportions.

Although carbon tax transfers are material in total cost accounting, gas contributes only a small share of generation (Figure 1B), reflecting its role primarily as peaking and balancing capacity in a wind–solar dominated system. For these two dominant technologies, we show the amount of generation that is either curtailed or used to charge storage, with solar having a higher percentage for both. A small amount of negative demand exists which we have labelled as "Household exports". Curtailment, storage round-trip losses and transmission losses create a substantial wedge between gross generation and final demand.

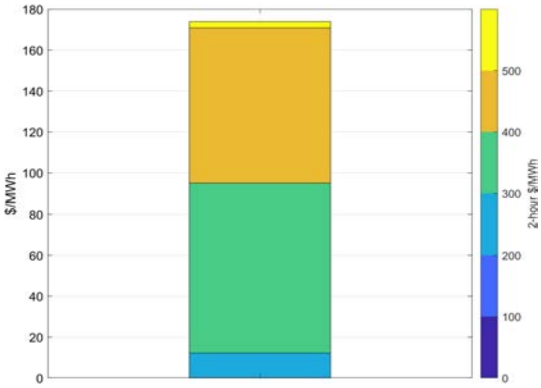
We use the shadow prices on the electricity demand/supply balance equation (2) as a proxy for electricity prices. The average demand-weighted shadow price (Panel C) slightly exceeds the average system cost (Panel A), reflecting sunk costs in the model such as Hydro. Most of the demand-weights average shadow price arises during scarcity periods where shadow prices are between \$300 and \$500 per MWh. However, shadow prices fall below \$100/MWh (in fact are near zero) most of the time (Panel D). Average shadow prices are lowest during daylight hours, reflecting solar generation. Shadow prices are highest in weather year 2011, but variability between years is small (Panel E). Price variation is greater between regions, with Melbourne having the highest average price (Panel F).



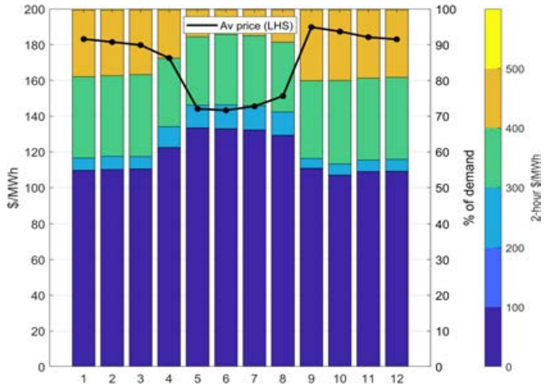

**A:** System cost



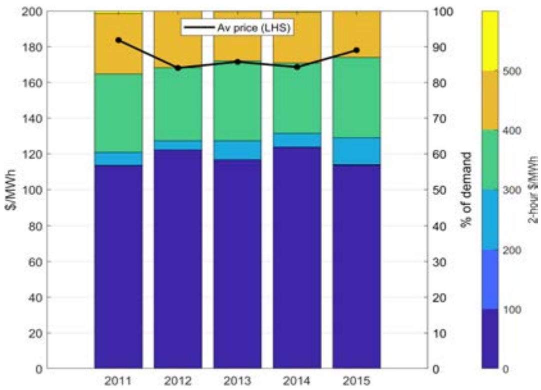

**B:** Electricity supply and demand



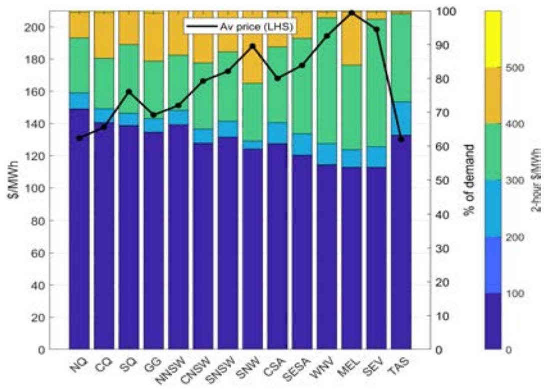

**C:** Average shadow price decomposition




**D:** Shadow prices by 2-hour time of day




**E:** Shadow prices by weather year




**F:** Shadow prices by regions

**Figure 2:** Base model results. A: Average system costs. B: Average daily electricity generation, including curtailment and storage charging, losses and demand. C: Average shadow price for electricity slightly exceeds average system costs. D: Shadow prices are lower during the day when prices are less than \$100/MWh more than 60% of the time. E: Shadow prices are highest in weather year 2011, but variability is small. F: There is greater variability between regions.

## 3.2 A simple model for a marginal BV addition

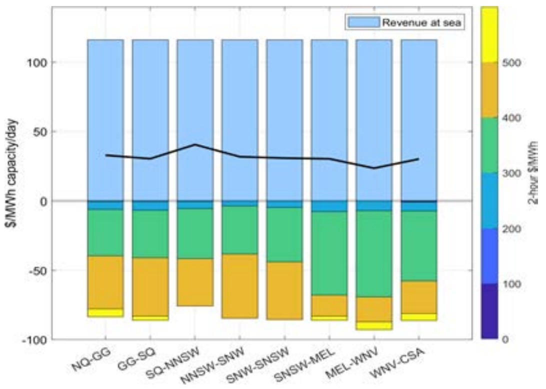
Consider a simple model that examines the effect of the operational behaviour of a marginal BV facing fixed electricity prices from the Base model equilibrium. For the moment, we abstract from capital and fixed operating costs and focus solely on electricity purchase costs and revenue streams.

Consider the case where a BV operates between two regions, alternately charging at port and discharging at sea each day. If the BV charges at the time-weighted average price in each region, daily charging costs range between \$75–\$100 per MWh (Figure 2A), reflecting alternating-day operation. High-price periods dominate costs which nearly offsets the daily revenue from discharging at sea of \$116 (\$250$\sqrt{\eta}/2$) per MWh after accounting for battery efficiency loss.

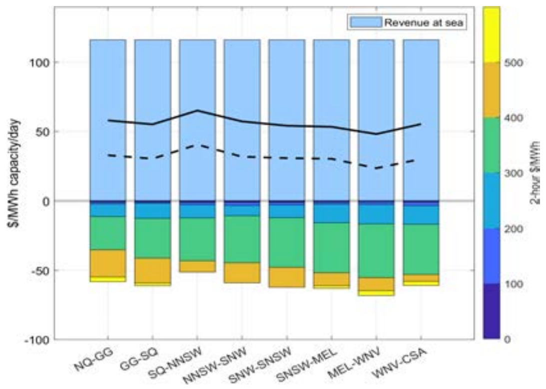
Allowing the BV to charge at the best times of the day removes much of the charging costs, while the revenue at sea remains unchanged (Panel B, compare solid line with dashed line). However, it may be optimal for the BV to do nothing in a day: for example, it does not make sense to pay more to charge than the revenue derived from discharging at sea. Adding this option to do nothing further boosts the value of BVs (Panel C). Time and revenue at sea are reduced by about 20%, but this loss is outweighed by the fall in the average price paid for electricity to nearly zero.

Permitting discharge to the grid enables the BV to arbitrage like a stationary battery, increasing daily value (Panel D). Time at sea is now reduced to around 50-60% of the maximum. Finally, allowing the BV to move between region pairs further boosts value, albeit only slightly from simply operating in the region pair with highest value, NQ-GG (Panel E). This regional mobility allows the BV to take advantage of variation in prices between regions (see Figure A.1 in Appendix A).

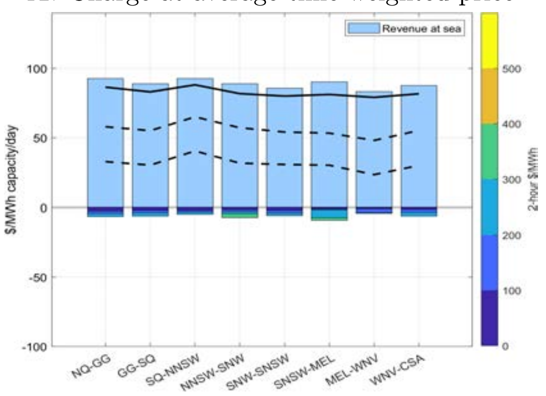
For comparison, the value of operating purely as a grid-connected battery, rather than a BV, is shown in Panel F. The parameter settings of our model imply an eight-hour battery costs around \$65 per MWh per day, consisting of about \$50 in capital costs, \$12 in fixed costs and \$3 in connection costs. Our simple model used in this section, which excludes factors such as intra-day charging and discharging, finds a value just above \$50 per MWh for most regions. As 8-hour batteries are deployed in all regions except SNSW, this suggests that our model underestimates the marginal value of 8-hour batteries and, by extension, the value of BVs. Further, comparison with the value in Panel E highlights the considerable added value from the option to discharge at sea.



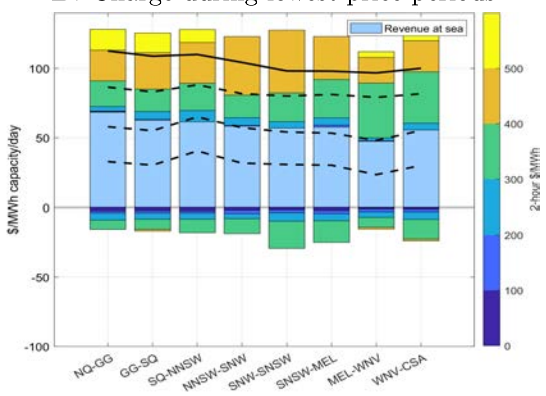

**A:** Charge at average time-weighted price



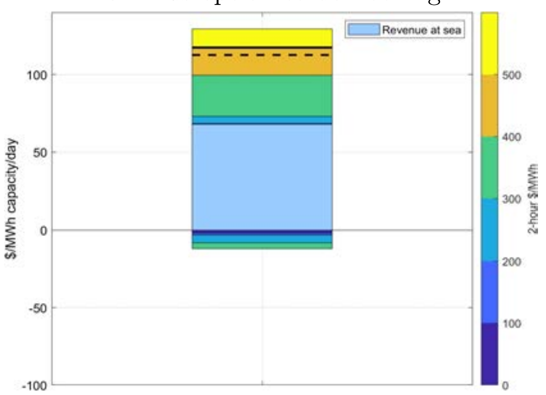

**B:** Charge during lowest-price periods



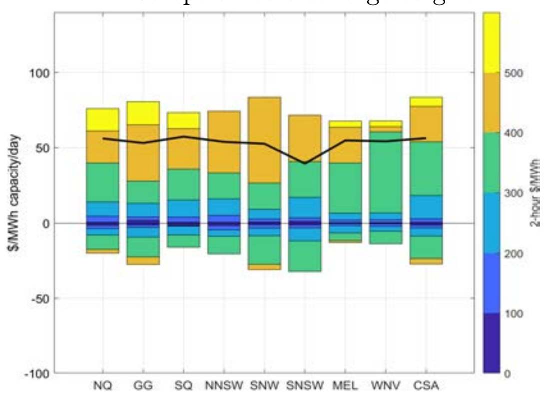

**C:** Plus option to do nothing




**D:** Plus option to discharge to grid




**E:** Plus option to move between regions




**F:** Stationary battery

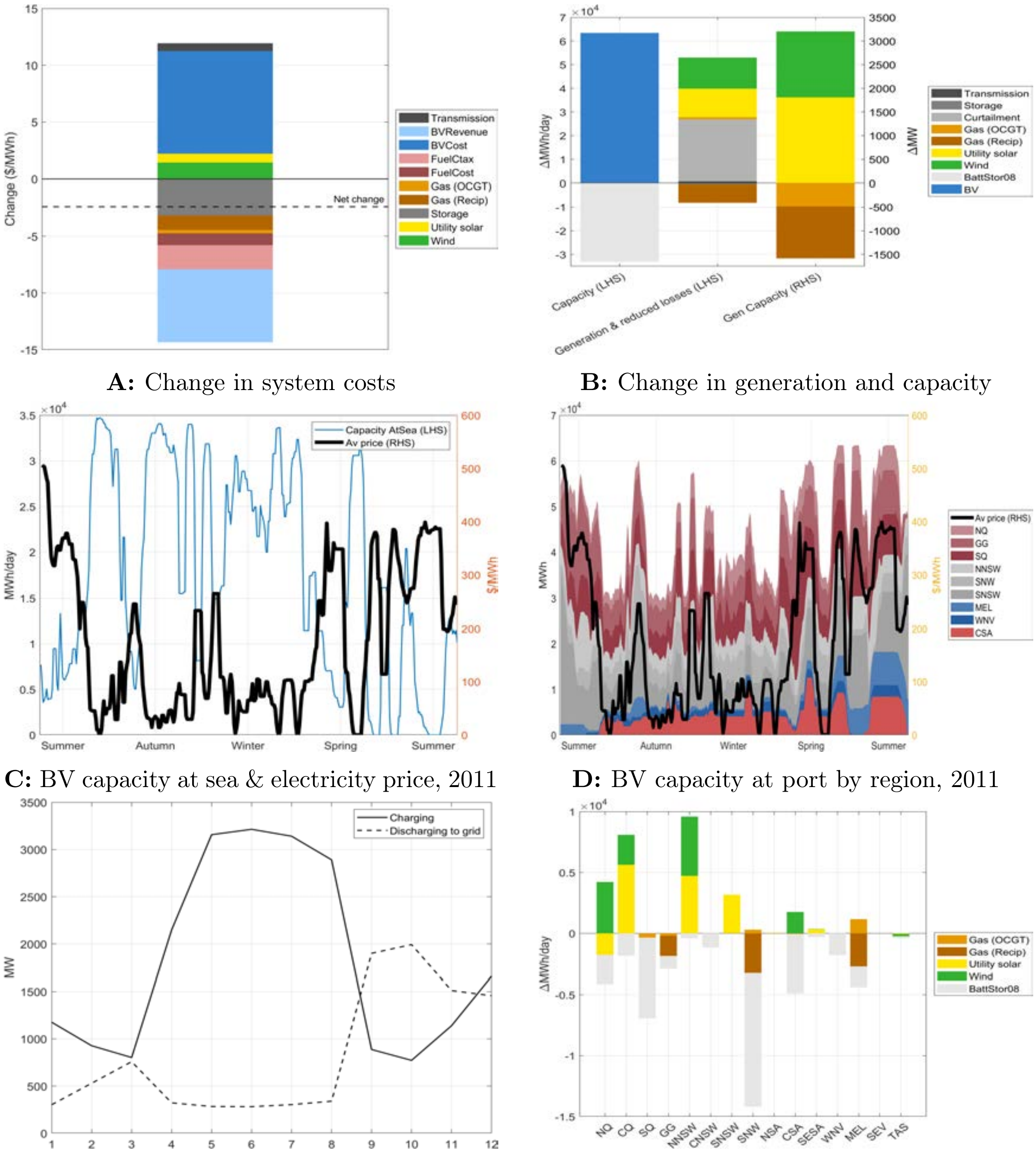
**Figure 3:** Net daily BV revenues, hereby referred to as "value", excluding costs other than charging. Base model results with prices from weather year 2011. A: Taking the average time-weighted price and charging then discharging at sea on alternate days leads to very low values of BVs. B: Charging at minimum prices over the day materially improves value (compare solid with dashed line). C: Sometimes staying at port and doing nothing is best. D: Discharging to grid further improves value. E: Moving around between regions boosts value further, exceeding the highest-value pair NQ-GG. F: For comparison, stationary batteries have about half the value per MWh.

### 3.3 Full model

The optimal BV capacity deployed is 63.4GWh, reducing curtailment by 31%, electricity emissions by 12%, and average system cost by 1.3% (Appendix B). Figure 3A shows the decomposition of the change in the average system cost of electricity. The denominator of the system cost is total demand excluding BVs, which is unchanged from the Base model. As outlined in the Model section, system costs include the (daily) costs associated with BVs minus their revenue from discharging at sea.

By increasing demand during low-price periods and supplying energy during scarcity periods, BVs improve the economics of variable renewables, reducing curtailment. In fact, the additional electricity needed to power ships derives from reduced curtailment and additional renewable supply in roughly equal measure (Panel B). While wind and solar generation rise, the use of gas in generation falls. However, generation from OCGT increases along with the capacity factor, so OCGT capacity falls, indicating more intensive use of a smaller peaking fleet. Total battery capacity (stationary batteries plus BVs) increases by 15%.

BVs are more frequently at sea during prolonged low-price periods, when opportunity costs of charging are lowest (Panel C). Naturally, BVs therefore spend more time at port during periods of high prices (Panel D). Overall, BVs spend about 30% of their time at sea (or 60% of their maximum potential given alternate day travel, see Appendix B), similar to that found in the previous section. The allocation of BVs between ports varies over time with the opportunity for each BV revenue stream. Revenues at sea are maximised when minimum prices are low (see Appendix A), allowing BVs to generate revenue during periods without electricity price variability, unlike stationary batteries. Grid temporal arbitrage opportunities occur with large differences between minimum and maximum prices, such as in the early autumn of 2011 in NSW (See Figure A.1C), leading to a high level of BVs at port to discharge to grid. Overall, most such discharge occurs in the evening, while BV charging occurs mainly during daylight hours when solar depresses prices (Panel E). Additional wind and solar generation are concentrated in Queensland while reductions in stationary batteries are more evenly spread (Panel F).




**A:** Change in system costs

**B:** Change in generation and capacity

**C:** BV capacity at sea & electricity price, 2011

**D:** BV capacity at port by region, 2011

**E:** BV (dis)charging by 2-hour periods of day

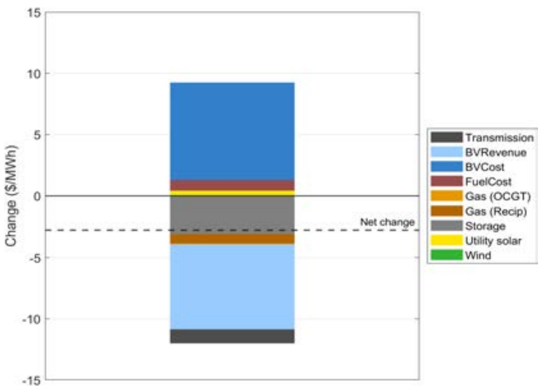
**F:** Δ generation/day and battery capacity

**Figure 4:** Full model results. A: Change in average system costs relative to the Base, for all years. B: BVs reduce curtailment and gas generation and increase wind and solar generation. C: BVs tend to be at sea more during periods with low electricity prices. D: BVs choose different ports according to price variation across regions. E: Most BV charging occurs during daylight hours, while most discharging to grid occurs in the evening. F: Most additional wind and solar occurs in Queensland.

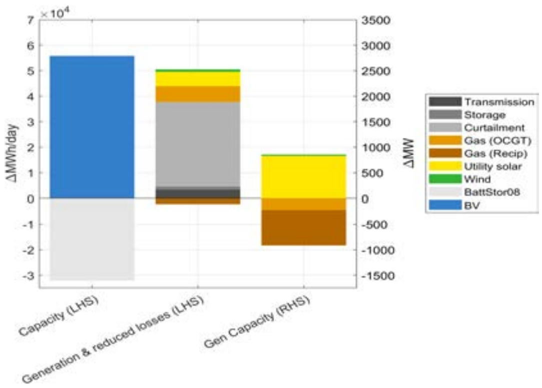
## 3.4 Without a carbon price

As a sensitivity, here we discuss results when no carbon price is applied to a new Base case and Full model. As the electricity price reduction induced by BVs in the previous section roughly equals the reduction in carbon transfers, the reader may believe that BVs would have a lower price effect in the absence of a carbon price. However, system costs actually fall further and the reduction in curtailment is stronger (Figures 5A and 5B). Thus, BVs improve the efficiency of the power system whether or not a carbon price applies to the power sector.

Less BV capacity is adopted without a carbon price (compare Figure 5B with 4B). Whereas BVs induce an increase in wind generation with a carbon price, there is almost no impact on wind without one. Instead, electricity from gas generation increases, contrary to what occurs with a carbon price. The capacity factor of OCGT increases, as generation rises while capacity drops, similar to the Base case. Without a carbon price, the marginal price of electricity from gas is about $140 per MWh for OCGT and $110 for reciprocating. These prices increase to about $410 and $330 with a carbon price. As the opportunity cost for the BV discharging to grid is about $230, the carbon price switches the "merit order" of gas and BVs (i.e. gas marginal costs surpass BV grid discharge opportunity costs), helping explain the different outcomes.




**A:** Change in system costs




**B:** Change in generation and capacity

**Figure 5:** Effect of BVs when no carbon price applies. A: A similar fall in average system costs occurs. B: Electricity generation from gas rises in this case, due to improved OCGT capacity factors.

# 4 Discussion

This study demonstrates that battery vessels (BVs) derive substantial value from two distinct but complementary activities: powering maritime ships and electricity market arbitrage. This dual revenue stream materially alters the economics of maritime electrification. Unlike conventional stationary storage, BVs can allocate energy across sectors, allowing them to respond dynamically to price volatility. Spatial mobility further enhances this value. By redeploying between ports, BVs exploit inter-regional price differences. In equilibrium, this revenue flexibility enables BVs to be deployed at capital costs per MWh that exceed those of stationary grid batteries, because maritime revenue provides a floor that partially insulates BVs from wholesale price risk.

Future technoeconomic analysis of BVs that abstracts from a detailed electricity model would consider the time spent at sea, BV revenues and the cost of electricity. Our results, combined with a maximum alternate day schedule given an optimal duration at sea of a day (Wiskich, 2025), point towards something like the following assumption framework.

- BV operates at sea considerably less (eg 40%) than the maximum
- Total BV revenue (maritime and grid) roughly equals the maximum potential at sea revenue
- Electricity charge costs are close to zero.

While it may seem natural to assume an average (industry) electricity price for charge costs, we find a much lower value more appropriate, at least in a future high wind/solar renewable grid like Australia. BVs can charge during periods of renewable surplus and near-zero prices. In this context, price variability, rather than the average, determines the economics of BVs (similar to stationary batteries). This general insight is also relevant for other ship and port electrification studies where there is some flexibility in charging schedules.

Rather than viewing maritime electrification as an additional burden on electricity systems, BVs reduce total electricity system costs. They shift energy from low-price, renewable-rich periods to high-price scarcity periods, thereby improving renewable utilisation and reducing curtailment. Under a carbon price, this displacement reduces emissions-intensive gas generation. Decarbonisation therefore occurs through two mutually reinforcing channels: direct displacement of fossil maritime fuels, and indirect displacement of peaking gas generation via enhanced electricity system flexibility.

## 4.1 Limitations

First, the concept of BV operations is speculative and needs further engineering research to understand feasibility and operational constraints. Second, BV operations are stylised. Sailing times and schedules are abstracted through an alternating-day structure, and revenue at sea is represented as an exogenous delivered-energy price. In practice, contract structures, route variability, and operational constraints would introduce additional complexity. Further, for computational ease in our full model we consider a continuum of potential capacity flows rather than model discrete vessels (we find a BV capacity of 63.4GWh, which would be 127 discrete 500MWh vessels). Third, port infrastructure costs and constraints are simplified. While port connection capacity is endogenised, broader logistical and regulatory constraints — including berth availability and integration with port operations — are not modelled. Our assumption that connection costs are the same as for stationary batteries abstracts from the greater choice in positioning stationary batteries near major transmission infrastructure. However, port electrification is progressing for other reasons, including shore power. Fourth, uncertainty is represented through multi-year historical weather variation, but investment decisions are deterministic and perfectly foresighted. Real-world risk and financing considerations may affect adoption incentives. Fifth, battery degradation and cycle-dependent lifetime effects are not explicitly modelled; these may alter operational behaviour. Sixth, we abstract from wholesale market design details such as capacity markets, ancillary service markets, and network tariffs. These limitations suggest that the results should be interpreted as demonstrating economic plausibility and system interaction mechanisms rather than providing precise forecasts of deployment levels.

# 5 Conclusion

This paper evaluates the role of mobile battery vessels within a highly renewable electricity system. By embedding maritime energy technology into a multi-regional electricity capacity expansion model, we show that BVs can simultaneously support shipping and power system decarbonisation while reducing renewable power curtailment (-31%).

We find that the value of electricity temporal arbitrage is comparable to revenue at sea; mobility across ports enhances economic viability; and BVs reduce electricity system costs (-1.3%) and emissions (-12%) under a carbon price. BVs can economically operate at vastly higher capital costs than stationary batteries due to the flexibility in accessing dual revenue streams: grid plus sea. They enjoy an exogenous maritime price floor for their power due to the consistent flow of hybrid ships that can operate on fuel or electricity.

BVs therefore represent a novel form of sector coupling, transforming shipping assets into flexible electricity system resources. We hope these economic insights motivate engineering research into the feasibility, optimal configuration and limitations of BV operations.

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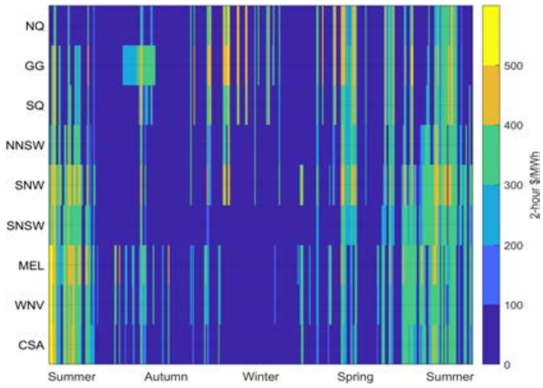
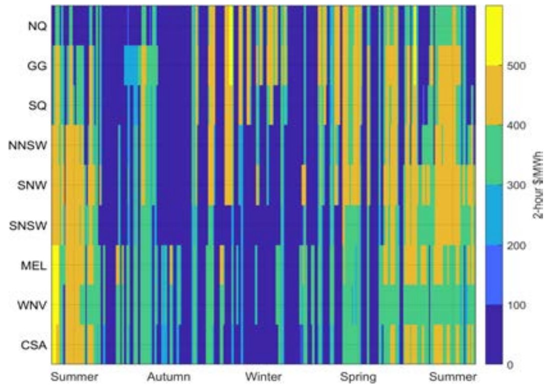
# A Additional figures

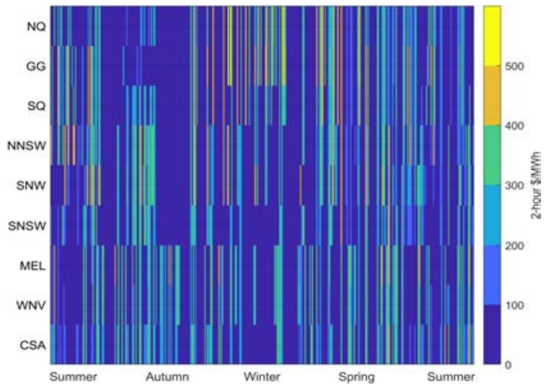
Figure A.1 shows the variation in minimum and maximum prices within and between regions in weather year 2011. BVs can take advantage of this by moving between regions at different times of the year. For example, NSW exhibits large price variability in the early Autumn of 2011, attracting BV arbitrage.




**A:** Minimum prices




**B:** Maximum prices




**C:** Difference between minimum and maximum

**Figure A.1:** Average of four lowest (A) and highest (B) 2-hour price periods per day, and their difference (C), for 2011 and BV regions.

# B Additional results

**Table B.1:** BV results by region

| | AUS | NQ | GG | SQ | NNSW | SNW | SNSW | MEL | WNV | CSA |
|---|---|---|---|---|---|---|---|---|---|---|
| Total BV Capacity (GWh) | 63.4 | | | | | | | | | |
| Av BV Capacity at sea (GWh) | 19.4 | | | | | | | | | |
| Av capacity at port (GWh) | 44.0 | 3.9 | 8.3 | 6.5 | 4.4 | 4.2 | 9.0 | 2.4 | 1.3 | 4.0 |
| Max capacity at port (GWh) | 63.4 | 19.6 | 30.7 | 16.9 | 18.6 | 16.1 | 55.7 | 7.7 | 3.5 | 15.3 |
| Min capacity at port (GWh) | 16.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Av charge price ($/MWh) | 54 | 31 | 55 | 43 | 42 | 85 | 37 | 29 | 31 | 128 |
| Av discharge price ($/MWh) | 243 | 204 | 250 | 241 | 225 | 282 | 214 | 206 | 189 | 284 |
| Av charge at port (MW) | 1827 | 161 | 255 | 328 | 189 | 370 | 209 | 175 | 58 | 82 |
| Av discharge at port (MW) | 832 | 73 | 100 | 143 | 78 | 200 | 65 | 81 | 28 | 63 |
| Max charge at port (MW) | 7281 | 500 | 701 | 1000 | 500 | 2000 | 500 | 1000 | 314 | 912 |
| Max discharge at port (MW) | 7115 | 500 | 701 | 1000 | 500 | 2000 | 500 | 1000 | 317 | 676 |

**Table B.2:** System effects of BVs

| **Generation changes** | Demand incl BVs* | Supply | Tx loss | Storage loss | Curtail | Total loss | |
|---|---|---|---|---|---|---|---|
| % change from Base model | 6.4 | 2.0 | -0.4 | 14.2 | -30.9 | -11.9 | |
| Absolute change (MWh/day) | 22299 | 9119 | -195 | 2116 | -15101 | -13180 | |
| **Technology changes** | Gas (OCGT) | Gas (Recip) | Solar | Wind | Tx | Batt | Batt+BV |
| Capacity % change | -3.5 | -23.8 | 4.0 | 1.9 | 4.0 | -13.5 | 15.2 |
| Capacity change (MW) | -520 | -1083 | 2168 | 930 | 2222 | | |
| Capacity change (MWh) | | | | | | -29570 | 33390 |
| Generation % change | 4.3 | -24.1 | 3.7 | 2.3 | | | |
| Generation change (MWh/day) | 438 | -3775 | 6333 | 6122 | | | |
| **System changes** | System cost ($/MWh) | Emissions ($kgCO_2$/MWh) | | | | | |
| % change from Base model | -1.3 | -12.0 | | | | | |
| Absolute change | -2.4 | -5.0 | | | | | |

*We add the energy delivered at sea by BVs, including the loss from charging and discharging the BV batteries. Batt = stationary batteries. Batt+BV = stationary batteries plus BV capacity.