Australia's National
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Dispatchability and energy storage costs for complementary wave, wind, and solar PV systems

For Wave Swell Energy Ltd

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Executive Summary

Wave Swell Energy Ltd (WSE) has commissioned CSIRO to provide an independent analysis of the cost-benefit of using its wave energy technology as a reliable supply of renewable energy. Previous studies have suggested that the consistency and reliability of wave power along Australia's southern coastline can contribute to a significant proportion of Australia's renewable electricity supply. This report assesses three sites in Victoria and South Australia, focussing on the ability of wave energy to complement the intermittency of wind and the seasonal variability of solar photovoltaic (PV) energy thereby improving grid stability and reducing the cost of guaranteeing electricity supply.

The report uses a dispatchability analysis to determine if wave energy, based on the WSE technology, confers a net economic advantage when combined with battery storage in conjunction with wind and/or solar energy. Dispatchability in this report is defined as the ratio of guaranteed power to average power. The dispatchability analysis uses this definition to compare the costs of supplying dispatchable power for a range of renewable electricity generation modes including solar PV, onshore wind, offshore wind, and wave energy. These generators are assessed as either single mode 'standalone' systems, or as 'hybrid' combinations of modes.

In this study wave energy utilising the WSE technology required the lowest energy storage for all standalone configurations to meet dispatchability requirements between 0 and 1. Wave energy was also an essential component where the lowest energy storage was required for hybrid systems that had dispatchabilities greater than 0.35. It is worth noting that the Australian Energy Market Operator's Integrated System Plan report of 2022 implies an approximate dispatchability value of 0.8 for the period 2024 to 2050.

Hybrid configurations that included wave energy required the lowest CAPEX for dispatchabilities above 0.36 and as the CAPEX of the WSE technology reduces further with additional installed capacity, the 0.36 dispatchability threshold that excludes wave energy could be further reduced. This study used redox flow batteries, alternative energy storage modes may increase or decrease the dispatchability threshold.

Energy storage combined with hybrid power generation has the potential to provide much higher levels of cost-effective energy security than any single renewable energy generation mode can provide, particularly those hybrid combinations that include wave energy. For example, if 70 percent of average power generation is to be guaranteed using battery storage, then a hybrid generator of solar, offshore wind and wave energy in the ratio of 1:1:1, could require less than half the CAPEX compared with a hybrid solar and offshore wind farm, and one third the cost of a hybrid solar and onshore wind farm.

1 Introduction

This report is for the exploratory phase of a study for Wave Swell Energy Ltd (WSE), to determine if the lower variability and intermittency of wave power, compared to solar and wind generation, can provide a technical and commercial advantage when used with energy storage and solar or wind power. It covers the use of WSE's wave power technology alone or in hybrid configurations with solar PV and/or wind power, using redox flow battery storage. The issue of monetising the reliability of renewable energy generators is quite new, so our analysis quantifies the concepts being discussed in the power industry [2,3]. The analysis has previously been applied to tidal energy [4] and has been adapted for application to wave energy. The algorithms have been integrated and optimised to allow for the rapid assessment of multiple generator configurations and costings.

The report is based on the concept of dispatchability, defining the dispatchability of a power supply as a threshold of power that can be guaranteed for a given time-period divided by the average power for that time-period. Dispatchable capacity is the total dispatchable power from a system of generators and traditionally, includes some fossil fuel or nuclear power generators, as well as the power that can be supplied from aggregated energy storage but, excludes contributions to dispatchability from renewable energy [5]. However, dispatchable power as defined in this report includes all generators, including the power that can be guaranteed from renewable energy generators with a specific level of energy storage. To achieve this the aggregated energy storage component of dispatchable capacity is reduced by the amounts used to provide dispatchable power and the costs of this storage reduction is assigned to each associated renewable energy mode.

The advantage of thinking in terms of dispatchability is that it allows the energy storage costs of providing dispatchable capacity from a particular renewable energy mode to be compared against other dispatchable power generators. For example, the dispatchability required to meet the AEMO Integrated System Plan [5] is approximately constant at 80 percent from the years 2024 to 2050. This implies that the renewable power components should each include sufficient energy storage capacity to guarantee supply for about 80 percent of the average power generated. Different renewable energy components will require different energy storage modes and capacities to achieve 80 percent dispatchability with appropriate time responses. When estimating the cost-effectiveness of renewable energy modes, the combined energy storage and renewable energy generator costs can be readily compared by assigning a dispatchability factor to each renewable energy mode.

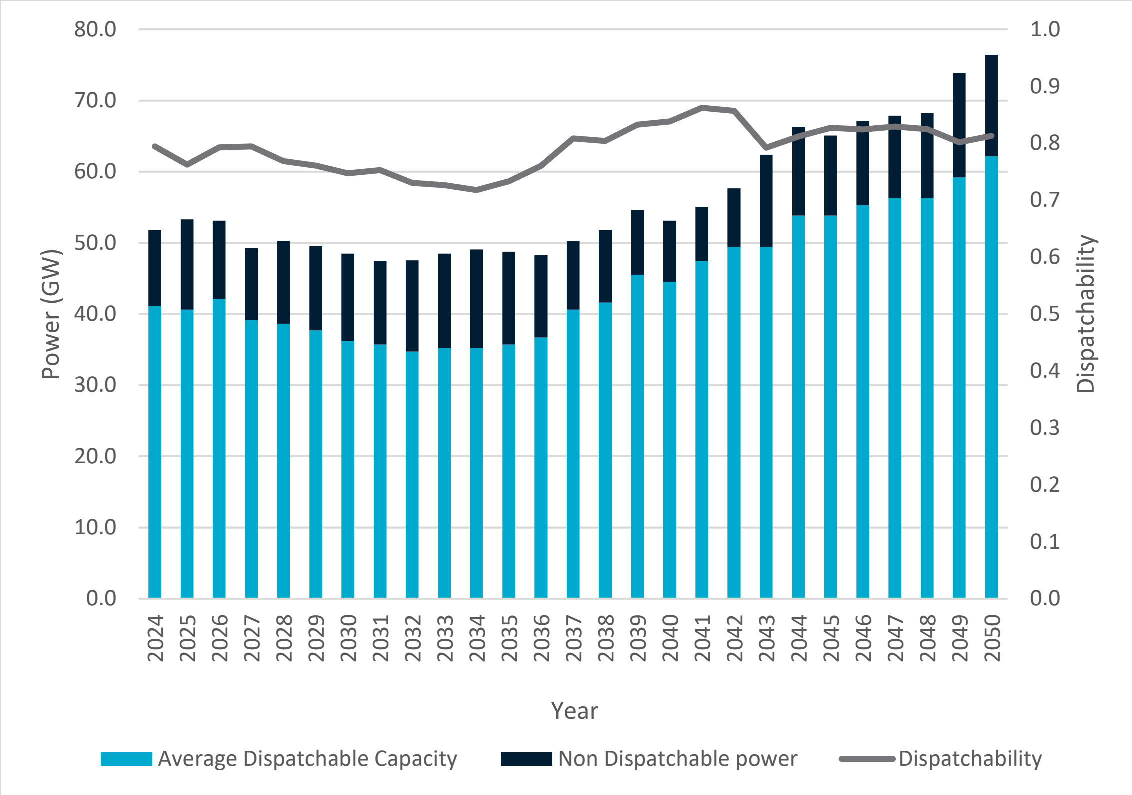


Figure 1. The annual dispatchability requirement from 2024 to 2050 estimated from figure 1 of AEMO's ISP report.

(Calculated as the AEMO figure 1 dispatchable capacity divided by the average total power. Average total power was obtained by applying generic capacity factors to each of the AEMO figure 1 renewable energy components, dispatchable power was evaluated by assigning a proportion of aggregated energy storage to each RE mode to generate a dispatchability of 0.8 associated with each mode.)

As the electricity generated from wind and solar photovoltaic power increases in Australian electricity networks, so does the need to cope with multi-day power loss in these renewable resources [3,4]. Proposed mechanisms for managing multi-day power loss typically include the stock piling of combustible fossil fuels and biofuels, or the use of hydrogen or pumped hydro energy storage. These approaches may be compromised by the high cost of standby generation infrastructure required to manage power loss in a near zero carbon electricity grid.

The comparative analysis of solar wind and wave energy in this analysis examined locations along the South Australian and Victorian coastlines and produced a catalogue of performance characteristics and costings across three sites. The assessment was based on local solar, wind and wave energy resource data, local windfarm data and a hypothetical offshore wind farm model. A site was then selected based on an optimal set of energy generation performance characteristics, proximity to grid connections and separation from marine parks. The catalogue entries for this site were then used in a comparative assessment of dispatchability and CAPEX for a range of standalone and hybrid solar PV, wave and wind power generation configurations.

The report begins with a theoretical background that includes descriptions of the terms used in this study such as 'dispatchability' and the basis for determining the amount of energy storage required to meet dispatchability requirements. The methodology behind site selection and data treatment is described in Section 3, followed by results and discussion in Section 4. Conclusions and areas for additional work based on the results of this study can be found in Sections 5 and 6 respectively.

2 Theoretical background

2.1 Dispatchability, renewable energy and the marketplace

Dispatchability is a loosely defined term that encompasses firmness of supply or the ability of an electrical power generator to guarantee the delivery of a specified power after a specified time delay. It is related but not identical to the idea of baseload which is defined by AEMO [6] as "Generating units that typically run at all times throughout the year except during maintenance outages". Baseload was traditionally associated with coal-fired power and requires demand management strategies such as off-peak tariffs, smart meters or consumer demand response devices. Dispatchability incorporates the idea of baseload, however, it also emphasises the potential for generators such as hydropower or gas turbines to provide power 'on demand'.

The valuation of dispatchability is of growing concern to governments and the National Electricity Market (NEM), [3,5] as increasing levels of variable and intermittent renewable energy are incorporated into the NEM electricity grid network [7]. Rai and Nunn suggest that a dispatchability premium can be evaluated as "the difference between dispatch-weighted prices received by non-dispatchable and dispatchable generators". Using this definition, they calculate an average dispatchability premium of 70% in South Australia since 2016 [8].

Renewable energy resources such as solar PV and wind power are variable and intermittent [5, 9] and therefore often regarded as non-dispatchable. The question addressed here is the extent to which a commercial value can be ascribed to the predictability of renewable energy resources, particularly wave energy, and the degree to which this value can be increased by the complementarity of hybrid or distributed renewable energy generators [10, 11]. Such an evaluation could highlight the potential for renewable energy to enter the market for a dispatchability premium. The first step in this process is to provide a quantitative definition of dispatchability that is compatible with the power industry understanding and which can nevertheless cope with the intermittency and variability of renewable energy resources.

In this paper dispatchable power is quantified as a power threshold (*Pth*) that is guaranteed and that can be tailored to any load vs. time profile that is required. The corresponding dispatchable energy threshold is (*Eth*), and the daily dispatched energy (*Ed*) includes system inefficiencies, following the convention used in the AEMO ISP 2022 [5]. Dispatchability (*D*) is defined here as the ratio of dispatchable power to average power for a given renewable energy resource. Complementarity is defined here as the ratio of dispatchability between hybrid and standalone renewable energy resources. Variability refers to changes in power that are based on regular physical events, for example diurnal and seasonal solar variability. Intermittency refers to changes in generated power that can only be predicted by statistical analysis, for example gusts of wind [4, 9].

2.2 Minimum energy storage and the complementarity of renewable energy resources

The relationship between commercial value and the predictability and complementarity of renewable energy resources is a new area of study and Jurasz et al have identified a need for indices of predictability and complementarity that link model and measured data and that are focused on wave and tidal energy resources [10]. The analysis [4] used in this report addresses both requirements by applying a dispatchable energy threshold (*Eth*) to a renewable energy generation time series (*Ere*). It then identifies a set of the shortest independent time windows in which the power level repeatedly rises and falls across the threshold and where for each window the net energy deficit is zero. The maximum energy deficit in this set (*Ec*) is used to assess the required battery capacity for the system and the complementarity of the renewable energy hybrid components. The theoretical model is then checked against a power management algorithm to ensure that essential energy storage management constraints such as overcharging, energy conservation and the management of diurnal variability are controlled.

Both the maximum energy deficit and battery storage algorithms are only as accurate as their data sample frequencies allow. They do not account for intermittency or variability that is uncorrelated with the sampled intermittent or variable measurements and that occurs during the time required to take a measurement. The battery energy capacity (*Ebattery*) is therefore calculated as the sum of *Ec* and *Es.* The *Es* component is an estimate of uncorrelated variability or intermittency occurring within the time it takes to measure the sample.

The impact of under sampling should be most evident at zero dispatchability and become less evident as the required dispatchability increases. A prime example is the solar diurnal cycle, which cannot be observed using the 24-hour sampling periods available to this study; but which can be estimated separately and then linked to dispatchability so that an associated battery capacity can be added to the study estimate. Solar diurnal intermittent events are more difficult to estimate, the degree of correlation between intermittent events within and outside the sampling period is uncertain and requires a reference sample of data with a higher temporal resolution.

The solar seasonal variability is accounted for in the calculation of *Ec* because the sampling period is much shorter than the seasonal cycle. However, seasonal drops in power below the average power can sometimes be far too expensive to manage with energy storage. This seasonal variability can be included or excluded by using a seasonally variable dispatchable power threshold or by operating with a dispatchable power threshold substantially less than the seasonal minimum. In this report we have limited dispatchability to 0.8 for CAPEX estimates because of the extreme cost of managing solar seasonal variability in the locations of interest and because 0.8 is the estimated value of grid dispatchability required between the years 2024 and 2050 as derived from the AEMO ISP projections [5].

2.3 Calculating the energy storage required to manage intermittent low power periods

The two components of battery energy capacity, *Ec* and *Es* (MWh), are calculated and combined in four steps. Steps 1 to 4 calculate these components using:

1. Equation (1) to evaluate the *Ec* component
2. Equation (2) to evaluate *Es*
3. Equation (3) to confirm that *Ec* and *Es* can meet the basic requirements of a battery management system
4. The battery energy capacity is then calculated as *Ec+Es.*

Equation (1) evaluates *Ec* from the *Ere* time series by checking the intermittent periods containing events in which *Ere* falls below *Eth* one or more times in each period. An energy deficit (*Edeficit*) accumulates during each period while *Ere* varies above and below *Eth*. Each intermittency period commences when *Edeficit* falls below zero and finishes when *Edeficit* returns to zero. The maximum absolute value of *Edeficit* in the *Edeficit* set is the minimum required energy storage capacity *Ec*.

$$Ec = max\ \{|Edeficit_i|\}, \qquad (1)$$

where:

For i = (0..N),

$$Edeficit_i = (Edeficit_{i-1} + Ere_i - Eth)\ for\ Edeficit_i < 0,$$

$$Edeficit_i = 0 \text{ for } (Edeficit_{i-1} + Ere_i - Eth) \geq 0.$$

Equation (2) evaluates *Es* by applying the dispatchability coefficient *D* to the rated average powers (P_{solar}) and the low power diurnal periods (τ_{solar}).

$$Es = D \times (\tau_{solar} \times P_{solar}) \qquad (2)$$

Equation (3) confirms that the values *Ec* and *Es* can be implemented in a battery management system by evaluating the minimum value of *Ebattery* required to ensure that the daily dispatched energy component *Ed* equals or exceeds *Eth.* The algorithm divides the generated renewable energy (*Ere*) into *Ed* and a daily stored energy component (*Estore*). The evaluation then applies a set of battery management constraints to a set of incremented evaluations of *Ed* for a renewable energy time series of typically five to six years.

For i = (1..N) (3)

$$Ebattery = \ min\{Estore_i\}$$

$$Edmin = \ min\{Ed_i\}$$

Where

$Ere_i = Esolar_i \ and/or \ Ewind_i + Ewave_i$	generated renewable energy,
$Ed_i = Ere_i + Estore_{i-1} - Estore_i,$	ensuring conservation of energy
$Ed_i \geq Eth,$	ensuring dispatchability.
$Estore_i \leq Ebattery,$	avoiding battery overcharge,
$Estore_i \geq Es,$	managing solar diurnal variability.

The battery energy capacity, *Ebattery,* can be evaluated rapidly from Equations (1) and (2) when assessing dispatchability for a range of *Ebattery* values. It can also shorten the time to evaluate Equation (3), which is used to show the cumulative frequency for low energy days in the *Ed* time series. Equation (3) is essential for determining if the *Ec* and *Es* values can be implemented in a battery management system.

2.4 Evaluating the CAPEX reduction for hybrid farms

Equation (4) evaluates the difference in CAPEX for dispatchable power generated with or without wave power. The CAPEX for wave power is based on that of the WSE technology, which has been analysed in detail by CSIRO in a previous study [12]. The results and conclusions of this report, therefore, relate to the WSE wave energy technology, and cannot necessarily be applied to other wave energy technologies.

The CAPEX difference included power generation costs (*$P*) in units of ($/MW) and energy storage costs (*$E*) in units of ($/MWh). The power component depended on the dispatchable power threshold *Pth* that governed the battery power costs and the rated average wave power (*Pwave*) that governed the wave and wind or solar PV generator costs. The energy component (*E*) included the battery energy storage costs. The *CF* variables are capacity factors.

$$CapexSaved = P_{th} \times \left(\begin{matrix} (\$P_{BatterySolarWind} - \$P_{BatteryWave}) + \\ (\tau_{SolarWind} \times \$E_{BatterySolarWind} - \tau_{WaveHybrid} \times \$E_{BatteryWaveHybrid}) \end{matrix} \right) + P_{Wave} \times \left(\frac{\$P_{SolarWind}}{CF_{SolarWind}} - \frac{\$P_{Wave}}{CF_{Wave}} \right), \quad (4)$$

where:

The "SolarWind" subscript identifies solar PV or wind farms.

The "Wave" subscript identifies wave energy converter (WEC) farms.

The "WaveHybrid" subscript identifies wave-solar or wave-wind hybrid farms.

The low power periods ($\boldsymbol{\tau}$) are evaluated from their respective battery energy capacities using Equation (5):

$$\tau = \frac{E_{Battery}}{P_{th}}. \quad (5)$$

2.4.1 CAPEX assumptions

The projected year 2025 CAPEX used in this study is shown in Table 1. This work has focused on 2025 to provide relatively accurate values for utility scale battery CAPEX. The projection for large scale batteries to 2030 is uncertain as the most cost-effective batteries currently available for storage periods longer than three hours are vanadium redox flow batteries. For units with capacities significantly greater than eight hours the cost may be dependent on the market price for vanadium pentoxide and the status of global steel production rather than technology development.

The projected 2030 values are also shown to highlight the relative potential for cost reductions between mature technologies (solar PV and onshore-wind) and emerging technologies such as the wave energy technology of WSE. Wave energy is projected to reduce in cost by 45% during the period 2025 to 2030, whereas wind and solar PV are projected to reduce by 1% and 16% respectively.

Table 1. CAPEX reductions from 2025 to 2030.

	Wind ($/kW)	Solar PV ($/kW)	Wave energy ($/kW)	Vanadium battery ($/kW)	Vanadium battery ($/kWh)
2025	1923	1113	6753	2,810	347
2030	1910	933	3694	2,198	271

3 Methodology

This study evaluates and compares the relationship between CAPEX, energy storage and generated power dispatchability for hypothetical WECs, wind and solar PV arrays based on measurements and modelling between the years 2016 and 2021 for each resource along the South Australian and Victorian coastlines. The five to six year period was selected as a compromise between the need for statistical significance and the need to represent contemporary data.

The wind, wave and solar PV projected electricity generation were analysed separately and in combinations of two and three technologies. In this report the separately analysed configurations are referred to as 'standalone' and the combinations are referred to as hybrids. The case study evaluations comprised:

- an assessment of Australian sites suitable for developing wave energy [13]
- an assessment of the variability and intermittency of each resource at each site
- an evaluation of the energy storage required for dispatchabilities ranging from 0 to 1 at each site
- an evaluation of the dependence of CAPEX for renewable energy generation on wave, wind and solar dispatchability.

3.1 Site selection

Three localities were chosen for evaluation - Cape Nelson, Carpenter Rocks, and Warrnambool. Sites were then assessed within these localities. The assessment criteria included a required depth of approximately 10 m to accommodate the WSE converter, as well as optimal dispatchability, annual electricity production (AEP) and average power generation.

3.2 Resource type selection

Solar and wind energy were selected for study as the predominant variable-intermittent renewable energy resources in the Australian market. Wave energy was selected based on observations from Dr Mark Hemer of CSIRO's Oceans and Atmosphere that suggested wave energy was likely to have a relatively high dispatchability [13].

A comparison of the wind farm and wind data analyses contributed to removing power system artifacts from the wind farm data and allowed an assessment of potential averaging effects at scales of about 10 km^2 that might improve wind farm dispatchability. Spatial averaging improvements at the square kilometre scale may not be available to WECs in a single farm configuration, as the wave energy flux is likely to be more homogenously distributed than for a wind farm. Whether spatial averaging over regional areas that are connected by a common grid can contribute to dispatchability improvement in either wave or wind farms was not addressed in this report.

3.3 Data variables

The dependent variables included:

- Minimum required battery capacity
- Generator CAPEX, where the solar PV and wind costs were taken from GenCost 2020-21 [14] and the WEC cost was taken as the average cost for the achievable and conservative scenarios previously calculated by CSIRO for WSE [12]
- Capacity factors were measured as the ratio of the generated peak power measured over a 5.8 year period to the average power measured in that period, for a time series of 2160 daily average power measurements. For hybrid generators each measurement in the time series was the sum of the powers generated by each generator in the hybrid configuration.

Independent variables were set as:

- Dispatchability ranging from 0 to 1 for battery capacity measurements and 0 to 0.8 for CAPEX estimates to avoid the unrealistic costs of battery storage for dispatchabilities greater than 0.8.
- Capacity factor, as calculated above, for the renewable energy resource without energy storage.
- An average value of 1 MW was set for the total average power produced by either standalone or hybrid configurations of solar PV, wind or wave renewable energy.

Because the renewable energy time series were based on daily measurements it was necessary to take account of the solar diurnal variability. For the solar resource, a solar PV farm with tracking panels was assumed so that the low power duration for the diurnal variability component of dispatchability could be set at 16 hours. In the absence of a diurnal peak value for the solar resource, a commonly used capacity factor approximation of 0.22 was applied to determine the solar PV CAPEX.

3.4 Data normalisation

The dispatchability, battery capacity and rated power were all calculated using a normalised value of 1 MW average power. This provided a level playing field for comparative assessments of dispatchability and AEP, which are both based on average power.

In all but one case the hybrid renewable energy generators were configured with equal values of renewable power for each mode in the configuration and with the total average power equal to one. For example, a hybrid of solar PV and wind would have both the solar PV and wind power time series normalised to an average power of 0.5 MW. Likewise, a hybrid of three modes would have each of the solar PV, wind and wave power time series normalised to an average of 1/3 MW.

3.5 Data cleaning and error management

Data cleaning was required for all the energy resource files. False zeroes were of particular importance as they could compromise the dispatchability assessments. The wave energy file addressing was uncertain beyond November 2021, so time series data were taken from 1st January 2016 to 31st October 2021 for all energy resources. The error types in the other energy resource data comprised: blank entries for the wind and solar measurements; and false zeroes and negative values for the wind farm measurements. The false zeroes were distinguished from genuine dips in power by examining: the data power trend; by checking for coincidences with the AEMO annual power system operating incident reports; checking for coincidences with extreme weather events; and crosschecking wind and wind farm values. The blank entries and false zeroes were filled with linearly interpolated values between the start and finish of the faulty data sequences. The negative values were accepted as legitimate data representing standby electricity usage following power dips that were observed adjacent to the negative values.

Sampling periods of 24 hours were the shortest available for the solar exposure time series. A potential sampling period error was corrected by assessing the battery capacity required to manage a 16-hour low period in the diurnal solar cycle. This correction was incorporated into the analysis. A lesser potential error may also be evident for the wind and wave velocity data if their variability in the 24-hour time window is not fully correlated with the sample measurements outside this period. The impact of sampling rate was examined using half-hourly wind data and hourly wave data for a dispatchability of 0.5. The error was estimated as a battery capacity underestimate of 2% for standalone wind or wave generators and 4% for a 1:1 hybrid wind wave system. These values represent a maximum battery capacity error of 0.4 MWh for dispatchabilities between 0 and 0.4 and this is a tenth of the error ascribed to solar diurnal variability in a 1:1 solar PV and wind farm hybrid. If the same level of error was ascribed to solar intermittency within the 24-hour sampling period, then the impact of the wind and wave intermittency errors would be reduced. This scenario is very likely considering the impact that clouds have on solar intermittency.

4 Results and discussion

Regional evaluations (Table 2) were used to select a preferred location for WECs (Figure 2). The selection criteria required that the location should not intrude into a marine park, should be 10 metres deep and with the best possible AEP together with the highest minimum daily energy production assessed between 2016 and 2021. Cape Nelson was the best of three that also included Warrnambool and Carpenter Rocks. Several locations in the region of Cape Nelson lighthouse (Figure 3) met these criteria with the following averages over 5.8 years including an AEP for the WSE technology of 3163 MWh/yr, an annual dispatchability of 0.18 and an annual minimum power of 70 kW.

Table 2. Potential wave power generation for Portland, Warrnambool and Carpenter Rocks.

Portland D (10 m)						
Latitude	38.433	°S				
Longitude	141.545	°E				
	Power (MW)					**Energy/yr**
	Average power	**Maximum power**	**Minimum power**	**Capacity factor**	**Dispatchability**	**MWh/yr**
2016	0.38	0.71	0.09	0.53	0.23	3286
2017	0.35	0.70	0.03	0.50	0.08	3059
2018	0.36	0.72	0.08	0.50	0.22	3178
2019	0.37	0.70	0.07	0.53	0.20	3249
2020	0.35	0.74	0.06	0.47	0.18	3045
Average	**0.36**	**0.03**	**0.07**	**0.49**	**0.18**	**3163**

Carpenter Rocks (10 m)						
Latitude	37.925	°S				
Longitude	140.387	°E				
	Power (MW)					**Energy/yr**
	Average Power	**Maximum power**	**Minimum power**	**Capacity factor**	**Dispatchability**	**MWh/yr**
2016	0.35	0.70	0.07	0.50	0.20	3065
2017	0.32	0.68	0.02	0.48	0.08	2823
2018	0.34	0.67	0.04	0.50	0.11	2944
2019	0.34	0.70	0.05	0.49	0.15	3025
2020	0.32	0.72	0.05	0.44	0.15	2773
Average	**0.33**	**0.03**	**0.05**	**0.48**	**0.14**	**2926**

Warrnambool (10 m)						
Latitude	38.377	ºS				
Longitude	142.416	ºE				
	Power (MW)					**Energy/yr**
	Average power	**Maximum power**	**Minimum power**	**Capacity factor**	**Dispatchability**	**MWh/yr**
2016	0.26	0.66	0.03	0.40	0.13	2286
2017	0.24	0.67	0.00	0.36	0.01	2118
2018	0.25	0.67	0.02	0.38	0.07	2239
2019	0.26	0.68	0.02	0.39	0.08	2319
2020	0.23	0.67	0.01	0.35	0.04	2041
Average	**0.25**	**0.03**	**0.02**	**0.38**	**0.06**	**2201**

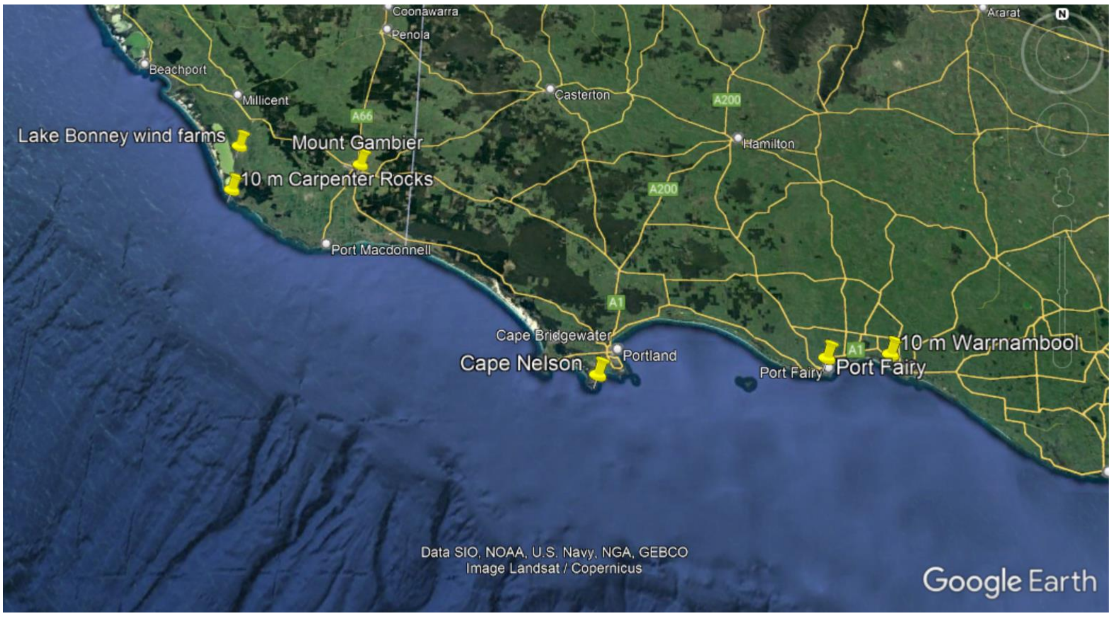


Figure 2. The southern Australia coast assessed for the WSE wave energy converter dispatchability study.

Figure 3. Sites adjacent to Cape Nelson used for detailed study of WSE WEC dispatchability.

4.1 Power generation characteristics for the renewable energy resource configurations

Table 3 shows the capacity factor, rated power, average power and AEP for the range of hybrid configurations based in or near Portland.

Table 3. Rated power, average power and annual electricity production for renewable energy configurations.

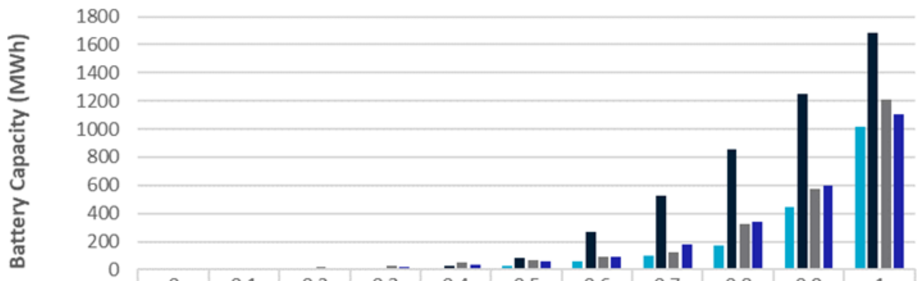
	Capacity factor	Rated power (1 MW average power)	AEP MWh/yr (1 MW rated power)
Standalone wave	0.49	2.04	4292
Standalone wind farm	0.37	2.70	3241
Standalone offshore wind farm	0.31	3.23	2716
Standalone solar PV	0.22	4.55	1927
Wave and solar PV	0.53	1.89	4643
Wave and wind farm	0.44	2.27	3854
Wave and offshore wind farm	0.38	2.63	3329
Solar PV and wind farm	0.43	2.33	3767
Solar PV and offshore wind farm	0.42	2.38	3679
Wave, solar PV and offshore wind farm	0.45	2.22	3942

4.2 A comparative assessment of battery capacity and CAPEX cost vs. dispatchability for renewable energy resource configurations

4.2.1 Standalone energy resources

Figure 4 shows the battery capacities required to achieve dispatchabilities ranging from zero to one for single generation mode 'standalone' configurations. Wave power requires the lowest battery capacity across all renewable energy generation configurations. The high battery capacity required for solar PV to reach high levels of dispatchability is caused by seasonal variation in solar output during the winter period. Between 0.8 and 1 dispatchability it is evident that the battery capacity required by all modalities is likely too extreme for battery storage to be cost effective or practical.

The special case of zero dispatchability shows that wind farms and solar arrays both require battery storage with consequent costs. The solar resource requires about 8 MWh energy storage to manage diurnal variability. The wind farm requires about 1.8 MWh energy storage to manage a negative power phase, i.e. a period of zero production when the farm draws electricity from the grid, possibly to manage standby power needs. The issue of generator standby electricity requires further investigation, and consideration should be given to standby power needs for all the energy resources in the study. However, this standby battery storage becomes increasingly irrelevant as the required dispatchability increases beyond 0.3.



Dispatchability	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Standalone wave	0.0	0.6	3.0	7.4	12.9	29.0	59.2	101.1	172.9	447.7	1017.5
Standalone solar	8.0	9.4	11.8	14.2	26.0	87.7	270.2	530.0	855.9	1252.5	1682.4
Standalone windfarm	0.4	4.0	16.8	31.2	48.1	67.4	92.5	127.6	325.1	571.6	1207.6
Standalone offshore windfarm	0.0	6.4	13.7	23.5	37.3	58.9	94.5	180.9	340.7	595.1	1104.8

Dispatchability

Figure 4. Battery capacities for a range of standalone renewable energy resources to achieve from 0.1 to 1 dispatchability.

4.2.2 Hybrid energy resources

Figure 5 shows the battery capacities required for hybrid configurations for values of dispatchability between 0 and 0.5 and Figure 6 displays the battery capacities required between 0.5 and 0.8. The different patterns reflect the different distributions of drops in power for each energy mode. Solar seasonal variability makes a particularly strong impact on these power drops, which starts to become evident above a dispatchability of 0.5.

For dispatchabilities from 0 to 0.275 the lowest battery capacities required are for hybrids of wave and wind farm, or wave and offshore windfarm. This is despite the wind farm requirement for standby electricity at zero dispatchability. The hybrids that included solar PV required at least 4 MWh battery capacity at zero dispatchability because of the need to compensate for solar diurnal variability. Above 0.275 all but one of the hybrids that included wave energy required less battery capacity than those without wave energy.

4.2.3 The impact of reduced energy storage on system CAPEX

Standalone generation

Figure 7 shows that in standalone systems with a dispatchability of less than 0.5 the CAPEX for renewable electricity generation was lowest for solar PV, while above 0.5 it was lowest for wave energy. A significant contributor to this effect was the increasing influence of seasonal variability in solar PV generation as the dispatchability requirement approached the average power available.

Hybrid generation

Introducing wave energy into hybrid renewable energy configurations reduced the battery capacity required for all levels of dispatchability. However, this did not always translate to a lowest system CAPEX. At low dispatchabilities, the WEC and solar PV costs dominate the CAPEX. Above a dispatchability of 0.36 the battery storage CAPEX became increasingly relevant and wave energy became essential to achieve the lowest CAPEX in hybrids. For example, to guarantee power delivery at 70 percent of average power generation, a hybrid generator of solar, offshore wind and wave energy in the ratio 1:1:1, would require less than half the CAPEX compared with a hybrid solar and offshore wind farm, and one third the cost of a hybrid solar and onshore wind farm (Figure 8, Figure 9).

The learning curve for the WSE WEC CAPEX is another important factor at low dispatchabilities. The analysis in this report is based on the projected CAPEX for the WSE technology in 2025. This was relatively high compared to either solar PV or onshore wind. These costs are expected to reduce further as more WECs are installed globally. The minimum dispatchability threshold will also further reduce as the WSE WEC CAPEX approaches parity with wind and solar. For example, in a separate analysis the CAPEX reduction between the years 2025 to 2030 produced a lowest CAPEX for the wave-solar hybrid and wave-solar PV-wind farm hybrids at a dispatchability of 0.3. Below 0.3 the CAPEX results are increasingly uncertain as further study is required to determine the impacts of solar intermittency for sampling periods less than or equal to one hour.

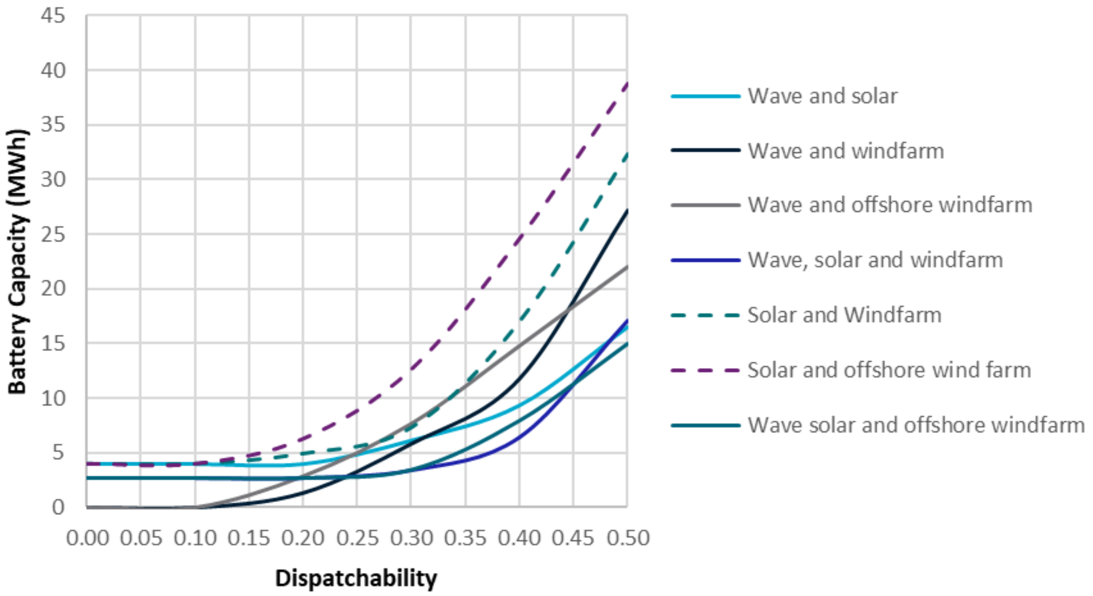


Figure 5. Battery capacities for a range of hybrid renewable energy resources to achieve from 0 to 0.5 dispatchability.

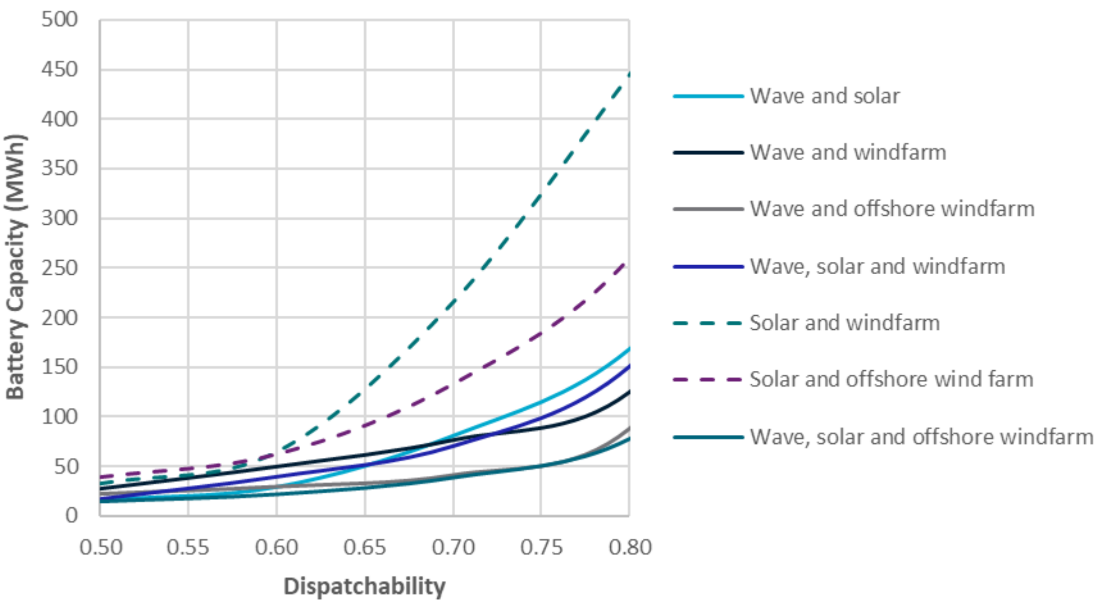
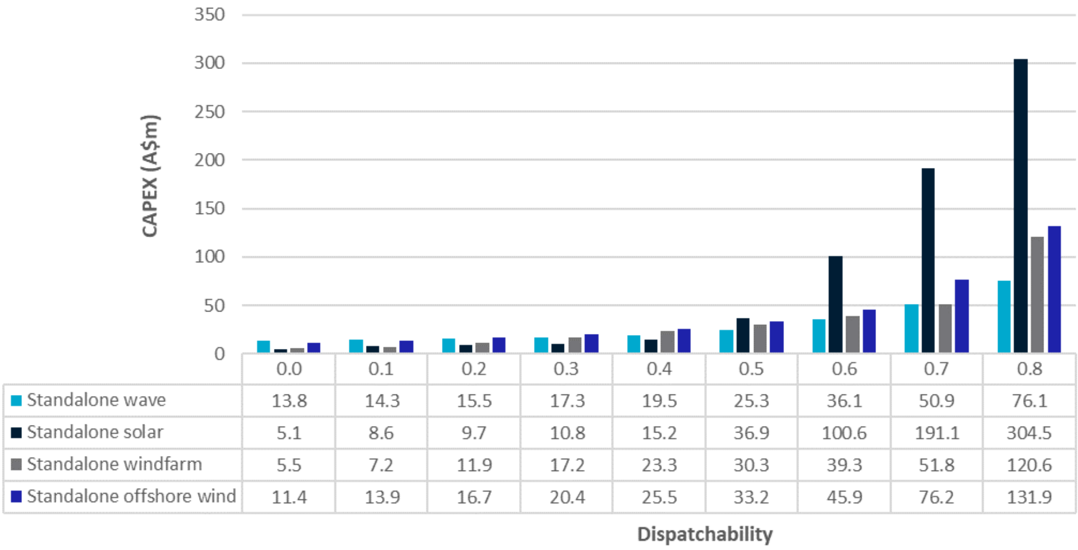


Figure 6. Battery capacities for a range of hybrid renewable energy resources to achieve from 0.5 to 0.8 dispatchability.



	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Standalone wave	13.8	14.3	15.5	17.3	19.5	25.3	36.1	50.9	76.1
Standalone solar	5.1	8.6	9.7	10.8	15.2	36.9	100.6	191.1	304.5
Standalone windfarm	5.5	7.2	11.9	17.2	23.3	30.3	39.3	51.8	120.6
Standalone offshore wind	11.4	13.9	16.7	20.4	25.5	33.2	45.9	76.2	131.9

Figure 7. CAPEX estimates for a range of standalone renewable energy resources to achieve from 0 to 0.8 dispatchability.

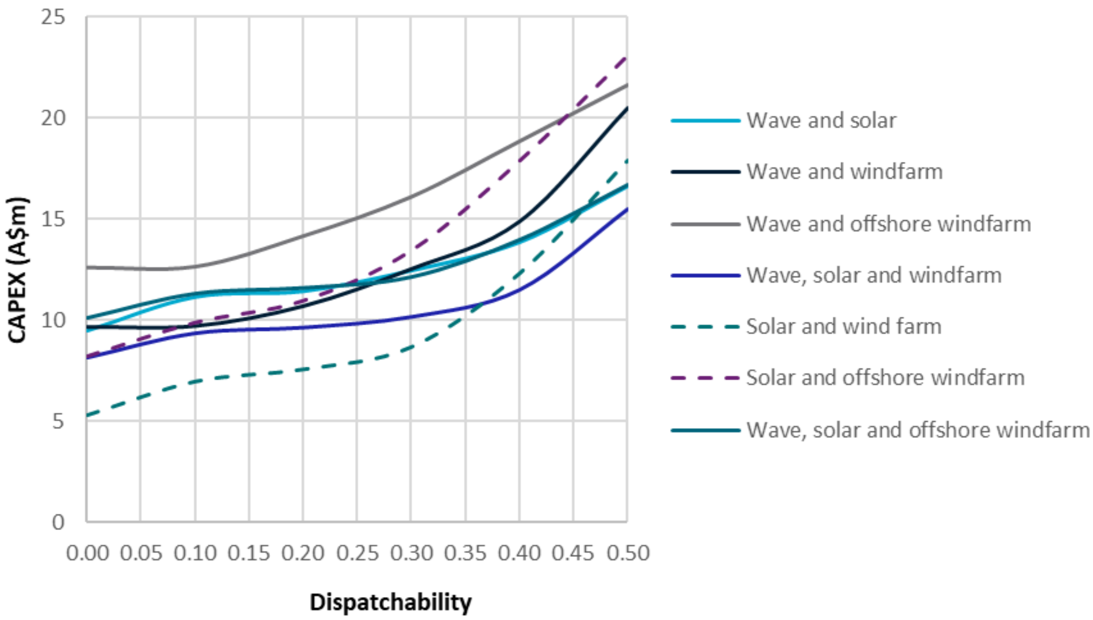


Figure 8. CAPEX estimates for a range of hybrid renewable energy resources to achieve from 0 to 0.5 dispatchability.

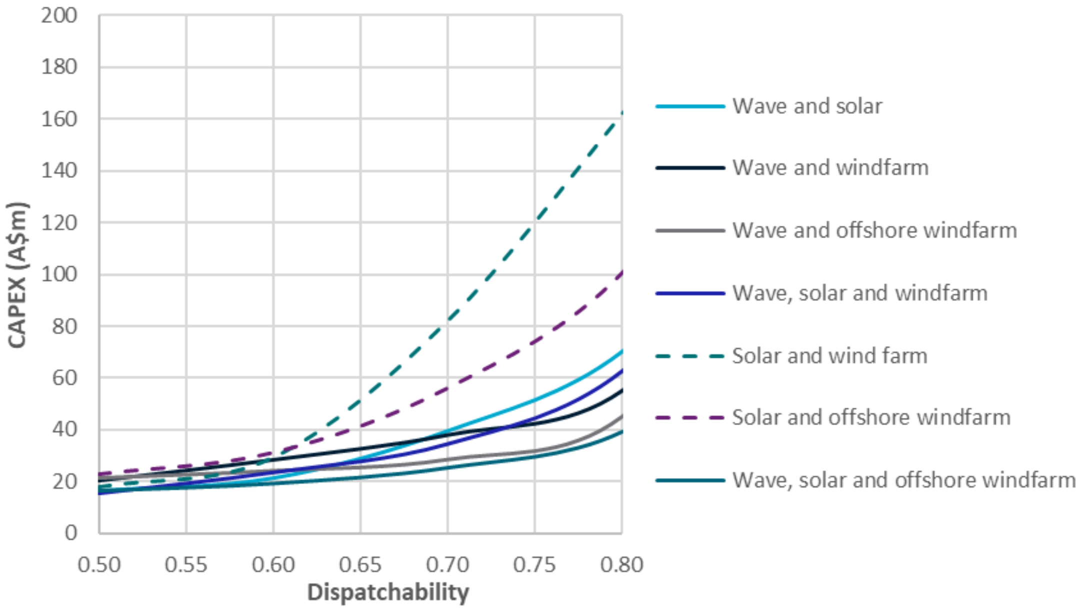


Figure 9. CAPEX estimates for a range of hybrid renewable energy resources to achieve from 0.5 to 0.8 dispatchability.

The benefits of hybrid farm and wave energy may extend beyond providing cost effective energy security. Figure 10 demonstrates the impact on predictability of adding wave power and solar power to an offshore wind farm. It is a histogram that shows how frequently a range of power levels are available from each configuration. The standalone offshore wind farm displays an unpredictable broad power spectrum ranging from 0 to 100 MWh/d while the hybrid farm demonstrates its primary role of guaranteeing a lower limit of 12 MWh/d (i.e. a dispatchability of 0.5) as well as a more predictable power spectrum that can facilitate load control, better utilise the available energy and contribute a greater degree of stability to the grid. Further work is required to determine how the additional improvements can be monetised.

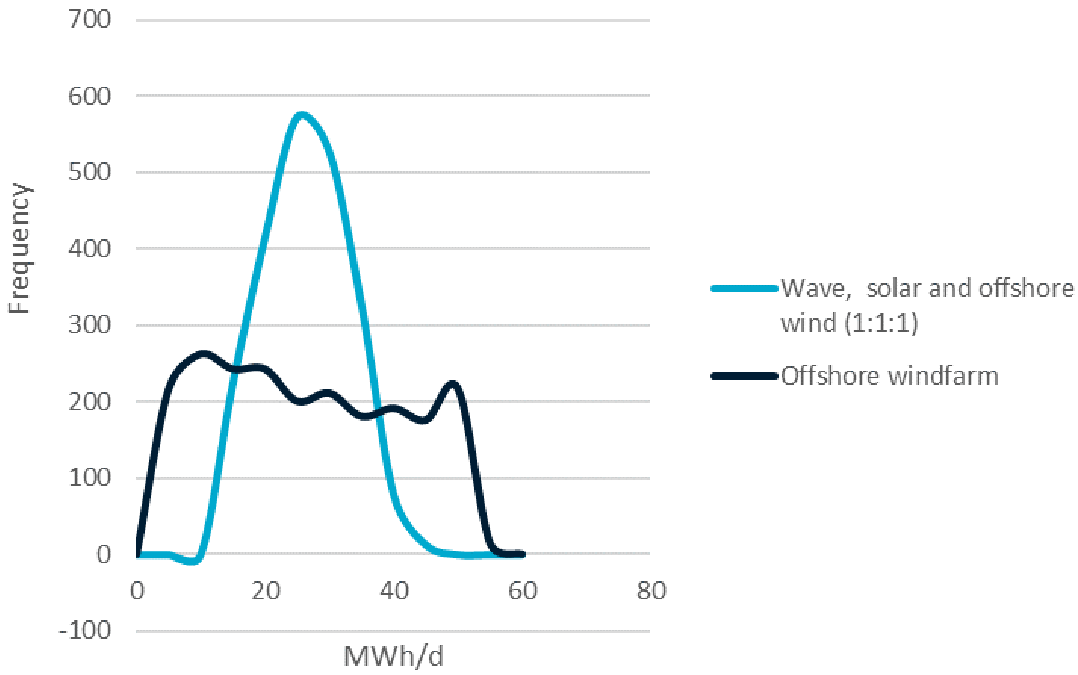


Figure 10. Frequency distribution of daily available energy for hybrid configurations.

Figure 11 demonstrates the impact of the hybrid system on the renewable energy resource and delivery time series, displaying drops in power for the standalone generator. There are no power drops below the critical power threshold in the hybrid component time series. However, the CAPEX is relatively high, and the available power varies over a large range. When solar power is added the cost reduces due to the relative low cost of solar. Likewise, the variability and intermittency reduce very significantly, despite the high variability of solar energy in standalone configuration. This illustrates a significant degree of complementarity between solar, wind and wave power and the commercial value of this complementarity. The histogram power profiles and time series for each standalone and hybrid combination in each of the three locations studied are included in a supplementary data catalogue together with their corresponding cost savings.

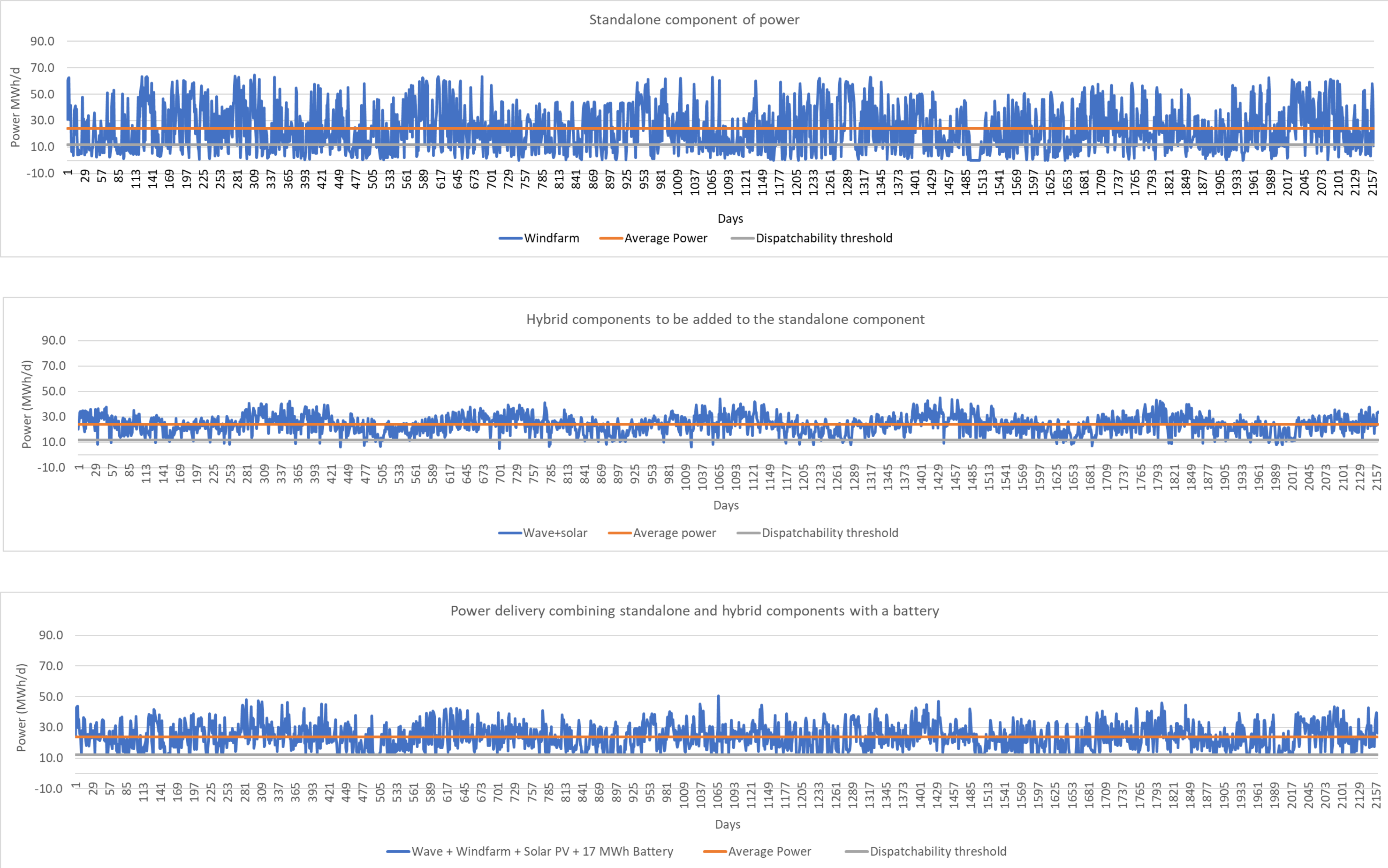


Figure 11. Power time series for a windfarm with wave power, solar power and energy storage added, for a power profile with 0.5 dispatchability.

5 Conclusions

Wave energy utilising the WSE technology required the lowest energy storage for all standalone configurations to meet a specified dispatchability requirement (Figure 4). It is also an essential component where the lowest energy storage is required for hybrid systems with dispatchabilities greater than 0.35 (Figure 5 and Figure 6), noting that AEMO's ISP report implies an approximate dispatchability value of 0.8 will be required in Australia for the period 2024 to 2050.

There is an innate dispatchability of about 0.1 for hybrids of wave and windfarm generators that requires no energy storage. This innate dispatchability is increased to 0.2 if solar power is included but this is compromised by the need to manage solar diurnal variability and to correct for solar intermittency within the 24-hour sample period.

For standalone configurations that use battery storage, solar PV requires the least CAPEX to achieve dispatchabilities between 0.1 and 0.5. For dispatchabilities of 0.5 and above, wave energy requires the least CAPEX (Figure 7).

Hybrid configurations with battery storage that included wave energy required the lowest CAPEX for dispatchabilities above 0.36 (Figure 8 and Figure 9), noting that alternative energy storage modes may increase or decrease this dispatchability threshold. As the CAPEX of the WSE technology reduces further with additional installed capacity, the 0.36 dispatchability threshold that excludes wave energy could be further reduced.

Energy storage combined with hybrid power generation has the potential to provide much higher levels of cost-effective energy security than any single renewable energy generation mode can provide, particularly those hybrid combinations that include wave energy. The advantage that wave energy confers becomes most evident in hybrid systems using battery storage with power guarantees greater than 36 percent, where wave energy was essential to achieve the lowest CAPEX. For example, if 70 percent of average power generation is to be guaranteed using battery storage then a hybrid generator of solar, offshore wind and wave energy in the ratio 1:1:1, would require less than half the CAPEX compared with a hybrid solar and offshore wind farm, and one third the cost of a hybrid solar and onshore wind farm.

The report assessments were made using 2025 WSE WECs values for CAPEX. These values are projected to reduce as the CAPEX of WSE WECs approaches parity with wind and solar PV. Projections suggest a reduction in cost by 45% during the period 2025 to 2030, whereas wind and solar PV are projected to reduce by 1% and 16% respectively.

In summary, for the locations modelled, introducing wave power into hybrids of solar PV, offshore wind, or onshore wind farms has the potential to greatly reduce the energy storage cost required to guarantee power delivery at levels greater than 36 percent of average power generation. WSE WECs are also projected to become increasingly cost effective for dispatchability levels less than 36 percent as the cost of WSE WECs decreases further.

6 Key areas for additional work

This preliminary feasibility investigation is the precursor to a more complete study that will include a range of energy storage modes and a more complete analysis aimed at determining the levelised cost of energy for a range of energy storage modalities and energy generation configurations. The more complete analysis will also address questions raised by WSE after reading this feasibility report. Suggestions raised to date are listed below.

6.1 Current list of areas for future study

- Calculate and compare LCOE values for the standalone and hybrid configurations
- Assess the comparative cost impacts of alternative energy storage modalities, particularly pumped hydro, hydrogen, molten salt and biofuel
- Test the optimisation of the shared proportions of wave, solar and windfarm power in hybrid power generation configurations
- Obtain solar, wind, wind farm and wave data that is resolved to 5-minute intervals or less. Use this data to include spot checks on short period intermittency in the assessment
- Check if appropriate wave farm design across multiple common grid connections at a regional or local level could be used to further improve the wave dispatchability.
- In cases where systems with wave energy do not have the lowest CAPEX, determine what the CAPEX of wave energy needs to be for these systems to be least-cost.
- Look for some examples of industries and future industries where dispatchable power is needed off the main grid. Do we want to consider a case study for the next phase?

Glossary

Capacity factor (CF)	The ratio of average power over a period to the peak power for that period
Complementarity	Complementarity, in this report, is the ratio between hybrid or spatially diverse generators and standalone generators of the minimum energy storage that guarantees delivery per unit of energy
Dispatchable power	Power that can be guaranteed from resources. (This does not preclude hybrid combinations of renewable energy modes with energy storage [4]).
Dispatchable capacity	Power that can be guaranteed from resources that include dispatchable power generators and energy storage as separate components. Traditionally this does not include renewable energy that is intermittent or variable [2].
Dispatchability (D)	The ratio of minimum power that can be guaranteed for a given period to the average power for that period [4]. This is particularly applicable to hybrid renewable energy modes combined with energy storage.
Dispatchable power threshold (*Pth*)	The minimum deliverable power that can be guaranteed from a hybrid renewable energy generator and storage system.
Dispatchable energy threshold (*Eth*)	The minimum deliverable energy that can be guaranteed in a hybrid renewable energy generator and storage system.
Daily energy delivered (*Ed*)	The energy delivered in a 24-hour period.
Intermittent power	Drops in power that are stochastic (predictions require statistical analysis, e.g. gusts of wind or system failures) [9]
Renewable energy	Energy resources that do not rely on fossil fuel and which are replenished by solar flux or gravitational interactions. (e.g.: biomass, solar PV, tidal, wave, wind)
Variable power	Drops in power that are deterministic (based on regular physical events, e.g. diurnal and seasonal solar variability) [9]

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