energies

MDPI

Article

Dispatchability, Energy Security, and Reduced Capital Cost in Tidal-Wind and Tidal-Solar Energy Farms

Peter Osman [1,*], Jennifer A. Hayward [2], Irene Penesis [3], Philip Marsh [3], Mark A. Hemer [4], David Griffin [4], Saad Sayeef [2], Jean-Roch Nader [3], Remo Cossu [5], Alistair Grinham [5], Uwe Rosebrock [4] and Mike Herzfeld [4]

[1] CSIRO Energy, Bradfield Rd., West Lindfield, NSW 2070, Australia
[2] CSIRO Energy, CSIRO Energy Centre, Newcastle, NSW 2304, Australia; jenny.hayward@csiro.au (J.A.H.); saad.sayeef@ausnetservices.com.au (S.S.)
[3] Australian Maritime College, University of Tasmania, Launceston, TAS 7250, Australia; irene.penesis@blueeconomycrc.com.au (I.P.); philip.marsh@utas.edu.au (P.M.); JeanRoch.Nader@utas.edu.au (J.-R.N.)
[4] CSIRO Oceans and Atmosphere, Battery Point, TAS 7004, Australia; mark.hemer@csiro.au (M.A.H.); david.griffin@csiro.au (D.G.); uwe.rosebrock@csiro.au (U.R.); mike.herzfeld@csiro.au (M.H.)
[5] School of Civil Engineering, University of Queensland, St. Lucia, QLD 4072, Australia; r.cossu@uq.edu.au (R.C.); a.grinham@uq.edu.au (A.G.)
* Correspondence: peter.osman@csiro.au

Abstract: The global tidal energy resource for electricity generation is small, and converting tidal kinetic energy to electricity is expensive compared to solar-photovoltaic or land-based wind turbine generators. However, as the renewable energy content in electricity supplies grows, the need to stabilise these supplies increases. This paper describes tidal energy's potential to reduce intermittency and variability in electricity supplied from solar and wind power farms while lowering the capital expenditure needed to improve dispatchability. The paper provides a model and hypothetical case studies to demonstrate how sharing energy storage between tidal stream power generators and wind or solar power generators can mitigate the level, frequency, and duration of power loss from wind or solar PV farms. The improvements in dispatchability use tidal energy's innate regularity and take account of tidal asymmetry and extended duration low-velocity neap tides. The case studies are based on a national assessment of Australian tidal energy resources carried out from 2018 to 2021.

Keywords: capital expenditure; dispatchability; energy storage; intermittent renewable energy; marine energy; solar energy; tidal energy; variable renewable energy; wind energy; complementarity

Citation: Osman, P.; Hayward, J.A.; Penesis, I.; Marsh, P.; Hemer, M.A.; Griffin, D.; Sayeef, S.; Nader, J.-R.; Cossu, R.; Grinham, A.; et al. Dispatchability, Energy Security, and Reduced Capital Cost in Tidal-Wind and Tidal-Solar Energy Farms. *Energies* **2021**, *14*, 8504. https://doi.org/10.3390/en14248504

Academic Editor: Eugen Rusu

Received: 26 October 2021
Accepted: 9 December 2021
Published: 16 December 2021

1. Introduction

The need for electricity grid stability drives the cost of dispatchable power as electricity supplies increasingly rely on renewable energy (RE). For example, in Australia, the Retailer Reliability Obligation now requires National Electricity Market retailers to cover a share of peak demand and the Australian Energy Market Commission is changing energy market regulations to ensure electricity grid security and facilitate RE generation [1,2].

At present, fossil-fuel-powered generators that run continuously, coupled with rapid control of pumped hydro and natural gas power generation, can manage intermittent or variable renewable energy [3], or rapid changes in demand [4]. However, as RE displaces fossil fuel, it will be necessary to increase demand management and energy storage to help stabilise electricity grids. Batteries, pumped hydro, hydrogen, biomass, and thermal energy storage are likely candidates to help provide dispatchability, particularly in remote area power supplies. Tidal stream power is rarely considered in this context, but its regularity should make it a competitive alternative [5]. However, its capital cost is higher than many other commercially available RE technologies. Moreover, the tidal resource may be insufficient to meet the capacity needs of a remote power station that is not connected to a national grid. It may also be necessary to compensate for tidal asymmetry and extended duration low-velocity neap tides.

This paper demonstrates the benefits of combining tidal energy converters (TECs) and wind turbine or solar PV arrays. Such hybrids can supply a predetermined level of dispatchable energy to an electricity grid and compensate for tidal stream energy generation's high capital cost and low capacity. The TEC array does not need to be collocated with either the wind turbine or the solar PV arrays so long as they feed into the same local power network. The capital expenditure (CAPEX) savings will depend on the level of dispatchable power required, the intermittency of the wind or solar resources, the variability of the tidal resource, and how critical the need is for dispatchable power. The design principles are further developed and illustrated in a set of case studies based on data from the Australian Tidal Energy (AUSTEn) project [6].

1.1. Status and Projections for Tidal Power

The potential of tides to generate power worldwide is about 3 TW, of which 1 TW is dissipated in shallow waters suitable for the installation of TECs [7]. However, the most productive and accessible sites limit the extractable power to about 120 GW, distributed across the Americas, Europe, Russia, West Africa, Southeast Asia, East China, and Western Australia [8]. The International Energy Agency has estimated that in 2019 the world used 27,764 TWh of electricity. Extractable tidal energy represents about 5% of this global electricity consumption [9].

Tidal stream energy converters ranging from tens of kilowatts to megawatts are installed worldwide. China, France, Japan, the Netherlands, Korea, and the United Kingdom have megawatt-scale TECs in operation [10]. The last fifteen years have seen increased research and development into tidal stream power systems. The European Marine Energy Centre and the Fundy Ocean Research Center for Energy have provided facilities for collaborative testing in many of these projects. Notable examples for commercialising and upscaling tidal stream power include the Simec-Atlantis Meygen and Orbital Marine Power-Scotrenewables-SR2000 projects [11].

Between 2018 and 2021, the AUSTEn project [6] measured and analysed Australia's tidal stream energy resources. It estimated Australia's economically extractable tidal stream resource as 1.5 TWh/yr. While small, this is not insignificant if one considers tidal power's regularity and modest energy storage requirements. This project determined that a critical role for tidal energy in remote coastal locations could be to provide cost-efficient, secure electricity for defence, emergency services, and industries such as mining or chemical processing.

1.2. Tidal, Wind and Solar PV Generator CAPEX

Table 1 provides CAPEX values for RE generators in Australia. These valuations were based on projections for 2025 and included: concept and definition costs, design and development costs, manufacturing costs and installation costs [6,12,13]. Table 1 indicates that TECs and offshore wind electricity generators have similar costs, and that solar PV and land-based wind turbines require significantly lower capital and operational expenditure.

Table 1. Renewable energy generator CAPEX values (Australia).

Generator Type	2019 (A$/kW)	2025 (A$/kW)
Solar PV	1463	874
Offshore based, seabed attached, wind turbine	6070	5424
Land-based wind turbine	1908	1908
Tidal (modified)	4697	4076

The Offshore Renewable Energy (ORE) Catapult initiative [11] estimates that CAPEX and the cost of capital account for about 77% of the levelised cost of electricity (LCOE) for early-stage tidal stream power projects. Ongoing research aims to reduce the CAPEX and LCOE by improving the efficiency of TECs, for example, by optimising subsea hub connection layouts, incorporating energy storage, developing direct drive power take-off generators, and improving rotor blade pitch control [11]. With further development and economies of scale, ORE Catapult anticipates an LCOE in the United Kingdom of £150/MWh for 100 MW cumulative deployment of tidal stream generation, reducing to £80/MWh for 1 GW cumulative deployment [14]. Such projections evolve continuously and are reassessed annually in Australia [12].

The CAPEX required for dispatchable power is a significant issue for remote area power systems. The Australian national electricity grid spans 850,000 km, and consequently, power averaging from uncorrelated RE resources increases grid electricity dispatchability. Off-grid solar PV and wind farms do not have this capability, so the intermittency of the local RE resource can range from hours to days of reduced power [5,15]. Table 1 does not include the cost of energy storage needed to ensure dispatchability in a remote area power station supplying 100 per cent RE. This cost could double the CAPEX required. Combining tidal stream energy with solar PV or wind farm energy may be a more economical method for providing dispatchable electricity.

1.3. Tidal Arrays and Farms

Countries are starting to move from assessing single tidal turbine test sites to assessing arrays that may be integrated into a single structure or mounted on the seabed and interconnected. High power single structure examples include the Orbital Marine Power O2 with two 1 MW turbines supported by a floating vessel or the Tocardo semi-submersible FloMo, which integrates five T2 turbines for a 1.5 MW array. Simec-Atlantis has developed a 6 MW, seabed-fixed, grid-connected array of four turbines for their Meygen project in the Pentland Firth, and Nova Innovation has developed a seabed fixed, grid-connected, array of four 100 kW turbines for their Bluemull project.

The MeyGen array produced 37.5 GWh of renewable electricity in 2020. It [16] interconnects a Simec Atlantis Energy AR1500 TEC with three Andritz Hydro Hammerfest HS1500 TECs. Each TEC can operate to depths of 100 m and uses an 18 m diameter rotor, producing a rated 1.5 MW for a 3 m/s tidal flow rate. The Simec Atlantis Energy plans to upgrade the MeyGen project to 86 MW rated power. It will be one of three proposals that are eligible to participate in the UK £20 m/year contracts for difference (CfD) subsidy dedicated to tidal stream energy.

Th CfD scheme ensures wholesale price stability by offering a 15 year fixed rate for electricity produced by projects that have secured a leased plot, grid connection and consents. The eligible tidal stream projects for the next CfD round (AR4) include MeyGen, the Perpetuus Tidal Energy Centre and Morlais. These three tidal stream farms could potentially contribute 124 MW towards a projected 2031 cumulative installed capacity of 160 MW that has the potential to reduce the levelised cost of energy (LCoE) from about 240 £/MWh to less than 150 £/MWh [17].

Coles et al. [18] have modelled a tidal stream array in the Alderney Race consisting of 78 sub-arrays. Each has eight TEC's with a lateral spacing of five rotor diameters and a longitudinal spacing of 18 rotor diameters. Three observations from the Alderney Race study are particularly relevant to the AUSTEn study reported here. These include: (a) The impact of array spacing and tidal velocity on the diversion of flow (blockage) from the array. The study found that such blockages reduced flow speeds by up to 2.5 m s^{-1}, reducing the annual energy production by 61%. (b) The need to increase the capacity factor of one subarray from 11% to 18%; and (c) the caution that while increased rotor size might improve TEC efficiency, it would also increase gearbox and bearing load and therefore capital cost. These issues have in common the role of tidal flow rate, which is substantially lower for TEC farms in Clarence Strait and Banks Strait (Australia) than in the Alderney Race. The low tidal flow rates in the Australian sites would make it necessary to reduce the rated power to increase the capacity factor and lower the capital cost of the TECs [6,19].

However, these lower tidal flow rates could make tidal power farms less susceptible to blockage and able to use TECs with larger rotor diameters [20,21] that could facilitate the capacity factor increase and CAPEX reductions.

Tidal energy farms are at an early stage of commercial development. Significant reductions in capital cost may be expected as their size and power output grow and cumulative deployment increases. Goss et al. [22] review the indices and processes of cost reduction, grouping them as: learning rate, in which the industry develops more efficient production and operational procedures; economies of scale, as devices become larger; and economies of volume where the cost of distributing and maintaining devices reduces as their number increases. Learning rates and economies of scale for tidal energy converters are reasonably well understood, and we have used them in our 2025 projections for hypothetical tidal energy farm costs [6,12]. Economies of volume are relatively new as evidence accumulates from installed TEC arrays being developed and planned in the UK and Channel Islands [22]. Incorporating an economy of scale factor into the CAPEX assessment during wind farm design may create opportunities to choose between a few large scale tidal turbines and many smaller turbines for a similar capital cost per unit power coupled with access to increased opportunities for generating tidal power.

1.4. Intermittency and Variability in Tidal Farms

Novo et al. [23] have assessed a range of standalone TEC farm options at 17 sites in Japan to determine the optimal combination of TEC and spatial location needed to produce dispatchable power. They have determined that a "firm capacity of 2.61% of total installed capacity can be reached", with "capacity factors greater than 0.34". This would be equivalent to a 7.8% dispatchability evaluated as the percentage of rated average power whose supply can be guaranteed.

Lewis et al. [24] have also studied the use of phase diversity to provide dispatchability. They comment that three tidal power stations with phase differences of 120 degrees could provide constant power throughout a tidal cycle, given a suitable coastline. However, the availability of such sites is quite uncertain. The study included an analysis of fine timescale effects such as turbulent loading on TEC power curves. It suggested that energy generation estimates would have a less than 1% error and that standardised power curves could be used with low-resolution, typically half-hourly, hydrodynamic data for resource assessment.

Jurasz et al. [25] described the use of spatial and temporal complementarity in hybrid renewable power configurations to manage the impact of their intermittency and variability on dispatchability. The paper reviewed research on the design of solar, wind, hydroelectric, and diesel hybrids to improve RE availability and summarised the associated widespread use of statistical correlation techniques and failure statistics as well as two performance indices based on: (a) partial time complementarity and (b) load tracking that measured the ability of a simulated renewable power supply to manage load. The paper further suggests that new work is needed to include such resources as wind and tidal energy and to determine the differences between measured and model data. The AUSTEn study reported here partially addresses these needs by describing and applying a novel algorithm that measures complementarity as the minimum energy storage required to ensure a predetermined level of dispatchability from a hybrid RE supply (Equations (1)–(3)). The technique is used in a set of hypothetical case studies that demonstrate the impact of including tidal energy in wind or solar farms on RE farm dispatchability and CAPEX.

2. Materials and Methods

This study evaluated the relationship between CAPEX, energy storage and generated power dispatchability for hypothetical tidal farms at locations identified by the AUSTEn project [6,12,20,21]. Three farms included a wind turbine or solar PV component to provide generator capacity and a tidal stream component to provide dispatchable power. The paper will refer to these combinations as tidal-solar PV farms, or tidal-wind farms, or in general tidal hybrid farms. Wind or solar PV farms without tidal power will be referred to as standalone wind or solar PV farms when directly compared against tidal hybrid farms. The case study evaluations comprised:

- an assessment of Australian sites suitable for developing tidal stream energy while taking account of environmental limits on extraction;
- a TEC model matched to the available range of tidal stream velocities;
- an assessment of the variability, intermittency, and meteorological constraints at each site;
- an evaluation of the energy storage required for dispatchable power at each site;
- a model for determining the dependence of CAPEX for RE generation on tidal, wind and solar variability and intermittency.

2.1. Assessing Australian Sites Suitable for Developing Tidal Energy

Sites were selected (Figure 1), and their potential for extractable power was assessed using power curves derived from commercially available TECs. The assessments were repeated after the power curves were modified to match the tidal velocities available in Australia (Table 2).

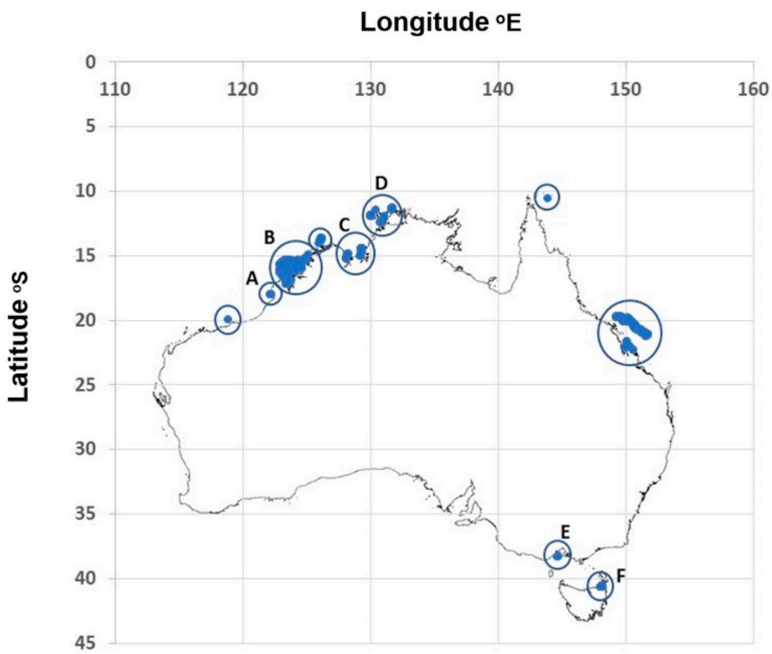


Figure 1. Distribution, in Australia, of tidal flow rates greater than 1.5 m/s. Adapted from Tidal Energy in Australia, by Penesis et al. 2020. Copyright UTAS 2020. Adapted with permission.

Three tidal model velocity datasets, all assessed against observations, were used for the studies. The first was a low-resolution dataset taken from the AUSTEn National Tidal Energy Model to assess national tidal energy resources [19]. The second and third were high-resolution AUSTEn datasets from local-area models of two regions, Banks Strait in Tasmania [20] and Clarence Strait in the Northern Territory [21].

The assessment for tidal stream energy extraction was moderated to protect the marine environment and the tidal resource from the impacts of over-extraction. These impacts are complex and site-dependent, and a detailed assessment was beyond the scope of the AUSTEn project. A significant impact factor (SIF) of 20% was used for the hypothetical case studies described here as an approximate tidal stream energy extraction limit to prevent environmental and resource degradation [26]. The SIF did not include the TEC Betz limit, which further reduced the model extraction.

Table 2. Australian sites with significant extractable tidal stream energy.

Site	Capacity Factor (%)	Annual Energy Generation (GWh)	Rated Peak Power (MW)
Low-resolution site assessments			
Broome [A]	10 to 30	5 to 16	6
Ardyaloon [B]	38	662	199
Derby (south beach) [B]	17	40	27
Wadeye and Tharramurr [C]	18	68	43
Port Phillip Bay [E]	17	3	2
High-resolution site assessments			
Dundas Strait [D]	20	329	188
Clarence Strait [D]	28	76	31
Banks Strait [F]	17	165	111

Note. Adapted from Tidal Energy in Australia, by Penesis et al. 2020. Copyright UTAS 2020. Adapted with permission.

2.2. The Tidal Energy Converter Model

The parameters required for TEC selection included: power curves, rated power, rotor diameter, generator dimensions and operational draught. Specifications were obtained from a confidential survey of tidal energy companies, and these were used to develop generic power curves for rotor diameters ranging from 4 m to 26 m to match operating depths. The model assumed that all TECs would have yaw control to maintain their orientation towards the tidal current flow.

Commercially available TECs with rotors large enough to take advantage of Australia's relatively low-speed tidal currents have power ratings that are too high for them to operate near total capacity. They are built to withstand and exploit current speeds that do not occur in Australian waters, which makes them unnecessarily expensive for this continent. To address this issue the generic power curves (Figure 2a,b) were modified by limiting their rated operating speed to 2 m/s instead of the more typical value of 3.6 m/s for commercially available units. These power curves are for hypothetical reduced power rating TECS designed for the weaker available tidal stream energy resource [6]. The down-rated TECs were applied to regions including Banks Strait, The Tiwi Islands, Ardyaloon, Derby and Wadeye. The generic power curves (Figure 2a,b) reflect the TEC design adjustments needed to operate cost-effectively in Australian waters.

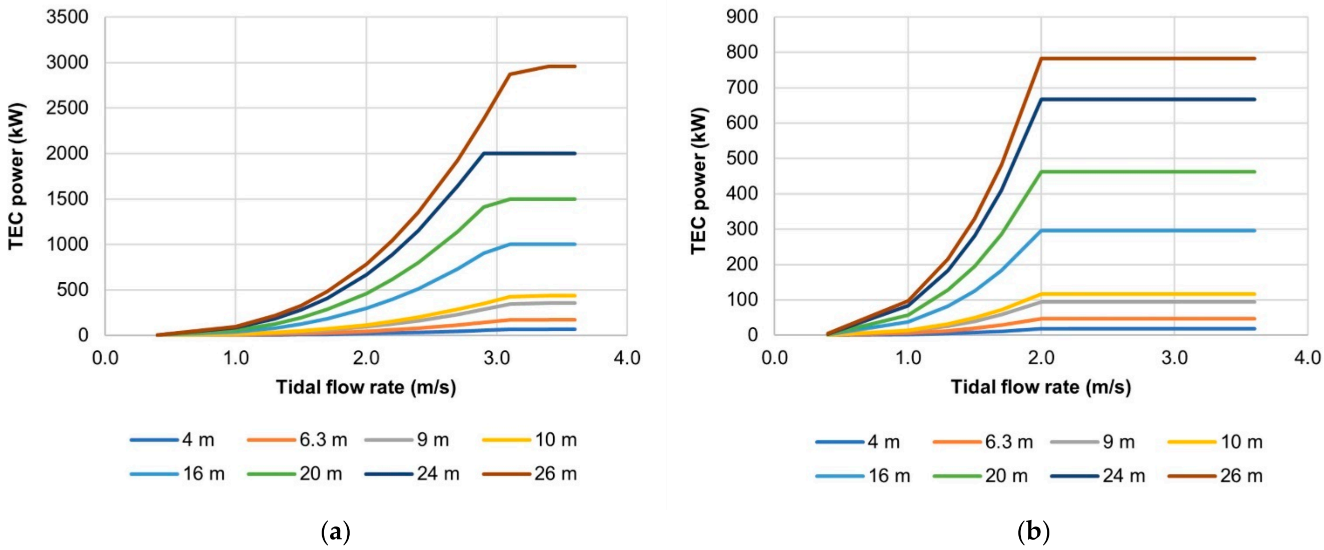


Figure 2. Generic power curves for TEC rotor diameters ranging from 4 m to 26 m: (**a**) based on commercially available TECs; (**b**) matched with the Australian tidal energy resource [6]. Copyright UTAS 2020. Adapted with permission.

The largest possible TEC was selected for any given depth because the CAPEX model indicated that their cost per unit power improved with rotor size up to about 26 m in diameter. A 5 m clearance was allowed below the sea surface for depths greater than 10 m to allow vessels of less than 2 m draught to pass and to protect the rotor from wave action. The TEC specifications were used to determine the clearance for the rotor above the seabed.

TECs to produce the power curves in Figure 2b are not in commercial production. Such turbines would need to have a power rating of about a third of the rated power shown in the generic power curves derived from commercially available TECs (Figure 2a). Savings for the modified TECs were based on limiting their rated operating speed to 2 m/s instead of the more typical value of 3.6 m/s for commercially available units. The gear ratios, rotor blade size, and power rating of distribution and power conversion equipment were then adjusted to match the modified TECs lower rated power and thus reduce the unit CAPEX.

The tidal flow rate (*U*) data comprised 1020 hourly data points representing 42.5 days, including two spring-neap tide cycles. The hourly energy delivered (*E*) was estimated from tidal velocity data using a linear interpolation between each velocity step in the power curves. The resulting time series was cropped to represent a lunar month and replicated to approximate a year of data.

2.3. Managing Variability and Intermittency Using Shared Battery Storage

In this paper, dispatchable power and energy are quantified as a power threshold (*Pth*) that is guaranteed, and a corresponding daily dispatched energy threshold (*Eth*). The daily dispatched energy is (*Ed*). Dispatchability (*D*) can be calculated as the ratio of the dispatchable power threshold (*Pth*) to the rated average power. Variability refers to predictable changes in generated power [3], and intermittency refers to unpredictable changes in generated power [3].

Variability and intermittency were managed using a combination of batteries and tidal stream power. The battery energy capacity required to manage the variation in power during diurnal and semidiurnal tidal and solar cycles was evaluated using spectral and temporal analyses. An energy storage sharing algorithm was used to determine the additional capacity required for managing intermittent drops in solar or wind power.

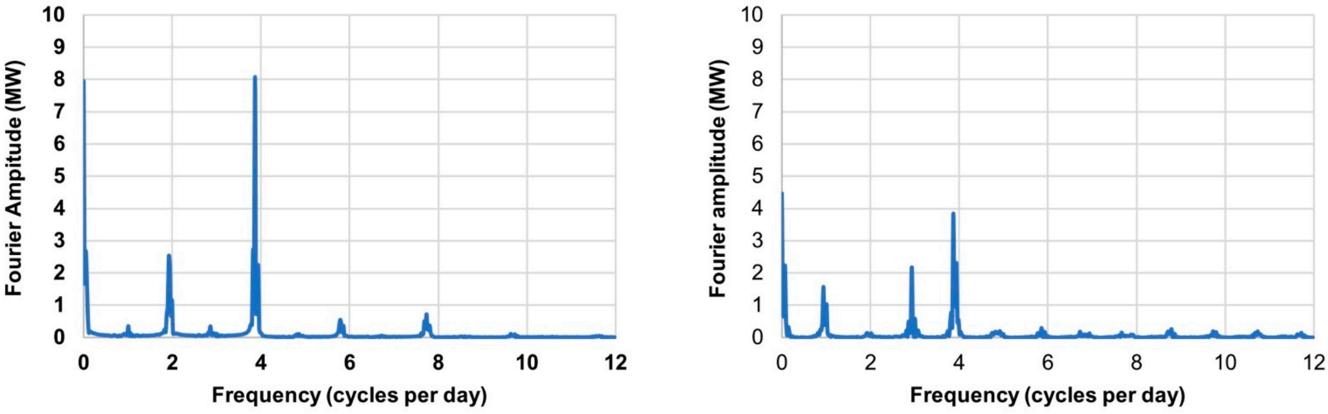
In Case Study 1, the RE intermittency was assessed using wind energy data from Swan Island in Banks Strait on the north coast of Tasmania [15]. In Case Study 2, RE intermittency was assessed using solar exposure data for Murrumujuk south of Clarence Strait and northeast of Darwin [27]. If a daily solar exposure data point was missing from a weather station record, it was replaced by the average of data points for that day from neighbouring weather stations within a 20 km radius. Tidal energy data were from the AUSTEn surveys of Banks Strait [20] and Clarence Strait [21].

Figure 3 shows examples of the spectra for electrical power generated from TEC farms in Banks Strait and Clarence Strait, while Figure 4 shows examples of intermittent and variable wind and solar power in Banks Strait [15,27].

2.3.1. The Tidal Energy Farm Diurnal and Semidiurnal Low Power Periods

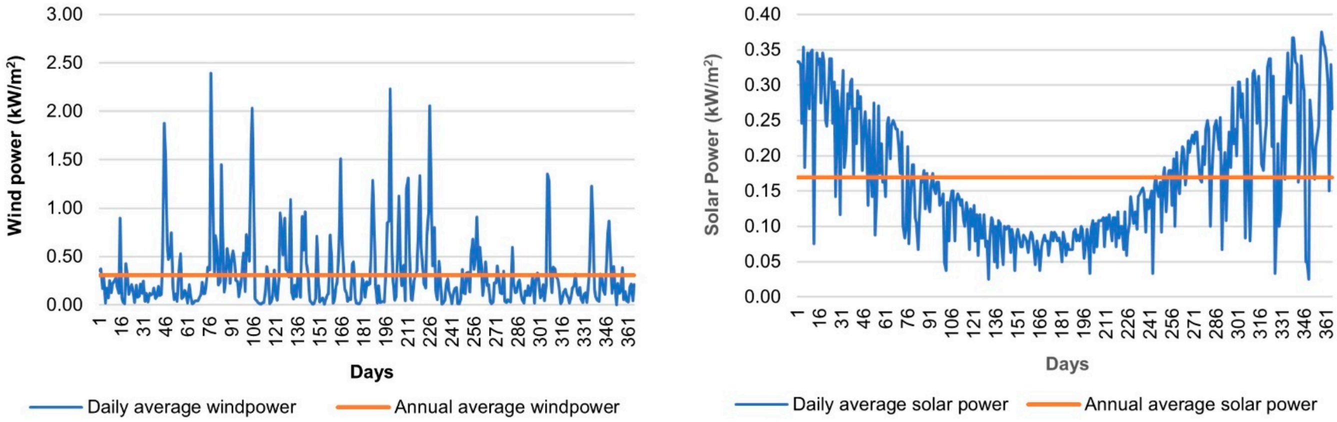
A Fast Fourier Transform was applied to time series data for the average electrical power generated each hour by the TEC farms. The moduli of the Fourier coefficients provided a spectrum for the electrical power from which the low power TEC periods corresponding to diurnal and semidiurnal tidal cycles could be determined. Figure 3 shows the Fourier amplitudes vs frequency representing the TEC power spectra.

The spectra for Case Study 1 (Banks Strait) and Case Study 2 (Clarence Strait) show peaks at 1.95 and 3.87 cycles per day (cpd) corresponding to 12.3 h and 6.2 h periods for the rectified diurnal and semidiurnal tide cycles. The Clarence Strait spectrum also shows a 0.9 cpd line and its harmonic at 2.9 cpd produced by power rectification and the cubic transformation of velocity to power. The 3.1 h half-cycle period for the 3.87 cpd line in the Banks Strait and Clarence Strait spectra characterised the low power phase of the tide cycles and was used with *Eth* to calculate the energy storage capacity required to manage it.



(**a**) (**b**)

Figure 3. FFT spectra for tidal farm hourly average electrical power samples from: (**a**) Banks Strait; (**b**) Clarence Strait. The half cycle of the period corresponding to the line at 3.9 cpd determines the low tidal power period (3.1 h) requiring battery support. The folding frequency was 12 cycles per day and the sample size was 1024 including three zero pads.



(**a**) (**b**)

Figure 4. Swan Island Banks Strait: (**a**) Wind power intermittency; (**b**) Solar power intermittency and variability.

2.3.2. Calculating the Energy Storage Required to Manage Intermittent Low Power Periods

A novel algorithm (Equations (1)–(3)) has been developed that applies phase shifting, linear superposition and a dispatchable power threshold to hybrid tidal-wind or tidal-solar power time-course data. This procedure develops critical energy deficit time windows [25] for each of which the net energy deficit is zero. The maximum energy deficit in this set is the required battery capacity for the system to provide dispatchable power.

The battery energy capacity (*Ebattery*) was calculated as the sum of *Ev* and *Eint*. The *Ev* component managed renewable energy resource variability, and the *Eint* component managed its intermittency. Steps 1 to 4 calculate these components using:

1. Equation (1) to evaluate *Ev* for the solar PV and tidal arrays;
2. Equation (2) to determine the year and day when *Ed* was at its minimum for the standalone wind or solar PV farm and the tidal hybrid farm;
3. Equation (3) to evaluate the *Eint* component for *Ed* to equal or exceed *Eth*;
4. The battery energy capacity was calculated either during step 2 or as *Ev* + *Eint*.

Equation (1) evaluated *Ev* by applying the dispatchability factor (*D*) to the rated average powers (P_{solar}) and (P_{tidal}) and the low power diurnal or semidiurnal periods (τ_{solar}) and (τ_{tidal}).

$$E_V = D \times (\tau_{solar} \times P_{solar} + 2 \times \tau_{tidal} \times P_{tidal}) \tag{1}$$

Equation (2) evaluated the minimum value of *Ebattery* required to ensure that *Ed* equalled or exceeded *Eth* by dividing the generated renewable energy (*Ere*) into a daily stored energy component (*Estore*) and a daily dispatched energy component *Ed*. The evaluation used increments of one day over a period of one year.

$$For\ i = (1 \ldots N) \tag{2}$$

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

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

where:

$Ere_i = Esolar_i\ or\ Ewind_i + Etidal_i$	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,
$Estore_i \geq\ Ev,$	managing tidal and solar variability.

Equation (3) evaluated *Eint* from the *Ere* time series by checking the intermittent periods containing events in which *Ere* fell below *Eth* one or more times in each period. An energy deficit (*Edeficit*) accumulated during each period while *Ere* varied above and below *Eth*. Each intermittency period commenced when *Edeficit* fell below zero and finished when *Edeficit* returned to zero. The maximum absolute value of *Edeficit* in the *Edeficit* set was the battery energy capacity component *Eint*.

$$Eint = max\ \{|Edeficit_i|\}, \tag{3}$$

where:

$$i = (0 \ldots N),$$

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

$$Edeficit_i = 0\ for\ Edeficit_i \geq 0.$$

For the tidal hybrid farm, Equations (2) and (3) included coincident tidal and solar or wind minima. This was ensured using Equation (2) to calculate a set of 30 time series for *Ere* in each of which the tidal energy was phase-shifted relative to the solar or wind energy in increments of one day. The required battery energy capacity was the maximum *Ebattery* value in the set. The year-long time series containing *Edmin* was used to evaluate *Eint*.

The battery energy capacity, *Ebattery*, can be evaluated rapidly from Equation (3) when assessing dispatchability for a range of *Ebattery* values. Using Equation (2) to determine *Ebattery* is slower; however, it can also be used to show the cumulative frequency for low energy days in the *Ed* time series.

2.3.3. The Impact of Energy Storage and Tidal Power on Intermittent Low Power Periods

Figures 5–8 demonstrate the effect of introducing tidal power on the dispatchability of *Ed* generated by a hypothetical tidal-solar PV farm in Clarence Strait. In Figures 6–8, *Eth* is set to 216 MWh except for winter (days 98 to 288) when it is 400 MWh. Figure 5 shows that the minimum value for *Ed* is 21 MWh with no energy storage or tidal power. Figure 6 shows that the minimum *Ed* increases from 21 MWh to the *Eth* target value of 216 MWh when tidal power replaces 25% of the solar power generation and a 624 MWh energy storage battery is added. Figure 6 also shows the cyclic impacts of neap tides; Figure 7 is an average of the 30 tidal-solar power scenarios. It hides the neap tide cycles but accounts for the simultaneous occurrence of solar and tidal power minima. Figure 8 shows that the minimum value of *Ed* falls to 21 MWh if the tidal power component is replaced with solar power.

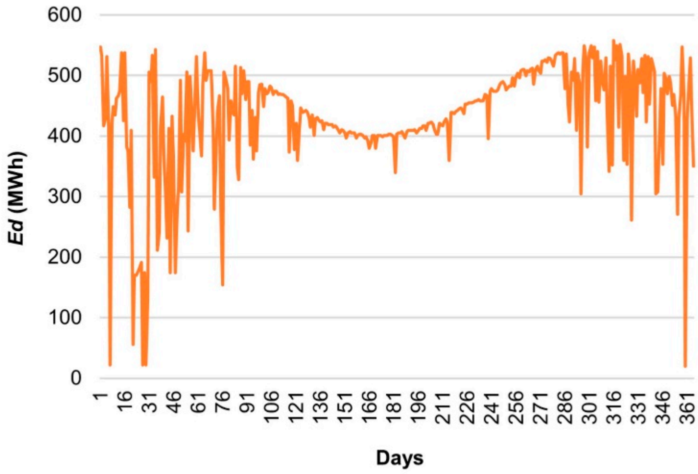


Figure 5. Daily dispatched energy, *Ed*, from a solar PV farm with no energy storage and no tidal energy component. The minimum value of *Ed* is 21 MWh.

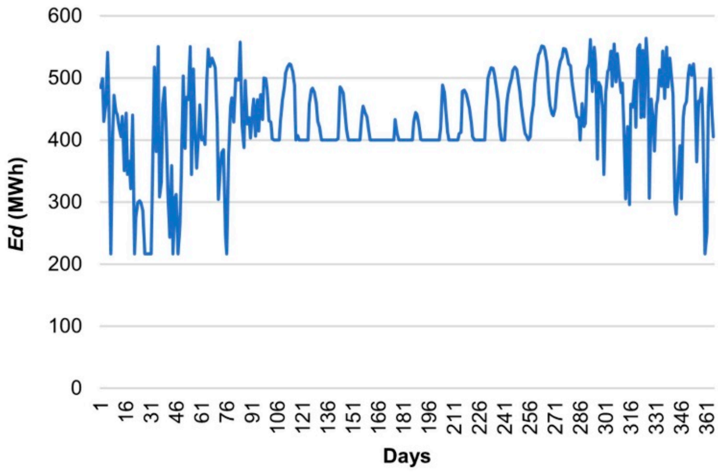


Figure 6. Daily dispatched energy, *Ed*, from a tidal-solar PV farm with 624 MWh shared energy storage. The minimum value of *Ed* is 216 MWh, equal to *Eth*.

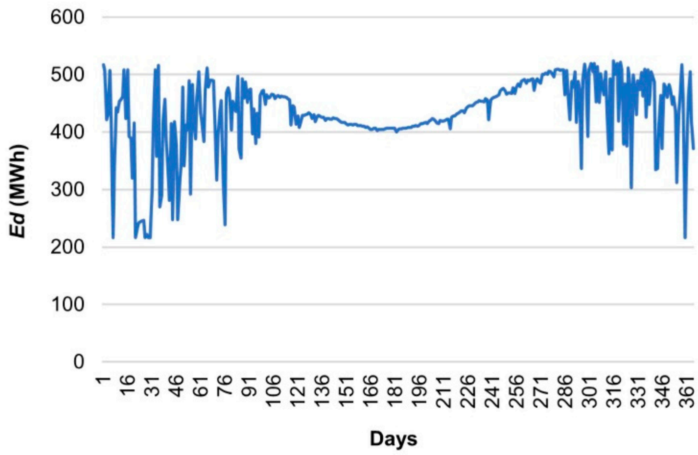


Figure 7. Daily dispatched energy, *Ed*, from a tidal-solar PV farm with a 624 MWh shared battery energy capacity. The chart averages 30 tests with phase differences between the solar and tidal energy minima ranging from 0 to 29 days. The improvement in *Ed* exceeds or equals *Eth*.

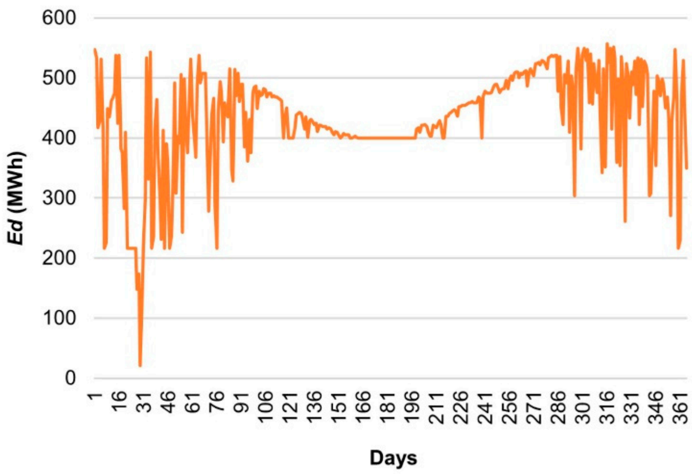


Figure 8. Daily dispatched energy, *Ed*, from a solar PV farm with 624 MWh battery energy capacity and no tidal energy component. The minimum value of *Ed* is 21 MWh.

The principal factors that reduced intermittency in the electricity supplies associated with Figures 6 and 7 were the regularity of tidal power and sharing energy storage to manage phase coincidences between the solar and tidal power minima. Algorithms that predicted the coincidence of tidal or solar minima did not further mitigate intermittent power drops below *Pth*.

2.4. Energy Storage and Cost

Vanadium batteries were projected to be more cost-effective than lithium, where more than six hours of energy storage were required [28,29]. Consequently, lithium batteries were only used where the tidal energy resource had short periods of low power during neap tides. Small scale pumped hydro was approximately the same cost per kilowatt-hour as lithium batteries in coastal Australia, where cliffs seldom rise above 200 m [29].

The battery CAPEX included two components: costs related to power rating and costs related to energy storage. Table 3 provides the CAPEX) values for the most cost-effective energy storage options projected for 2025 [12,28,29].

Table 3. Energy storage option costs CAPEX (2025).

Energy Storage Mode	$\$E_{battery}$ (A\$/kWh)	$\$P_{battery}$ (A\$/kW)
Lithium batteries (2 × 10 year life)	792	425
Vanadium redox flow battery (20 year life)	347	2810
Pumped hydro (100 MW, 6 h, 100 m head)	-	5108

Equation (4) combined the battery cost components. $\$E_{battery}$ was the capital-cost per kilowatt-hour, $E_{battery}$ was the battery energy storage capacity, $\$P_{battery}$ was the capital-cost per kilowatt, and $P_{battery}$ was the battery power rating.

$$\$_{battery} = \$E_{battery} \times E_{battery} + \$P_{battery} \times P_{battery}. \quad (4)$$

The cost estimate for vanadium redox batteries included construction, commissioning, and vanadium electrolyte costs in the energy storage component and power conversion, stack, and balance of plant costs in the power component [29,30]. The lithium battery cost estimate included construction, commissioning, and all stack costs in the energy storage component and power conversion and balance of plant costs in the power component. A factor of two is included in the lithium battery cost to account for the longer lifecycle of vanadium compared to lithium batteries [28].

In the case studies, the energy component of cost was five to ten times greater than the power component because of the extended periods of low power that needed to be managed. The vanadium constituent of vanadium redox batteries was the greatest contributor to this cost, and the price of vanadium is volatile [31]. This price uncertainty impacts the projected case study estimates of CAPEX reduction as they were based on a relatively low present-day price for the vanadium electrolyte. Increases in the price may increase the projected CAPEX savings.

2.5. Evaluating the CAPEX Reduction for Tidal Hybrid Farms

Equation (5) evaluated the difference in CAPEX for dispatchable power generated with or without tidal power. 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 tidal power (*Ptidal*) that governed the tidal and wind or solar PV generator costs. The energy component (*E*) included the battery energy storage costs. The *CF* variables are capacity factors.

$$CapexSaved = P_{th} \times \left(\begin{array}{c} \left(\$P_{BatterySolarWind} - \$P_{BatteryTidal}\right) + \\ \left(\tau_{SolarWind} \times \$E_{BatterySolarWind} - \tau_{TidalHybrid} \times \$E_{BatteryTidalHybrid}\right) \end{array} \right) + P_{Tidal} \times \left(\frac{\$P_{SolarWind}}{CF_{SolarWind}} - \frac{\$P_{Tidal}}{CF_{Tidal}} \right), \quad (5)$$

where:

The "SolarWind" subscript identifies solar PV or wind turbine arrays.
The "Tidal" subscript identifies TEC arrays.
The "TidalHybrid" subscript identifies tidal-solar or tidal-wind hybrid arrays.
The low power periods (τ) are evaluated from their respective battery energy.

Capacities and the dispatchable power threshold (*Pth*), using Equation (6):

$$\tau = \frac{E_{Battery}}{P_{th}}. \quad (6)$$

Figures 9–11 are derived from Equation (5). Each graph is evaluated for 1.0 MW average power, and the CAPEX saving scales linearly with average power. There is a change from lithium to vanadium batteries at a tidal low power duration equal to or greater than six hours. Figure 9 shows a critical boundary with CAPEX saving depending on increases in the dispatchable power threshold *Pth* and wind low power duration $\tau wind$.

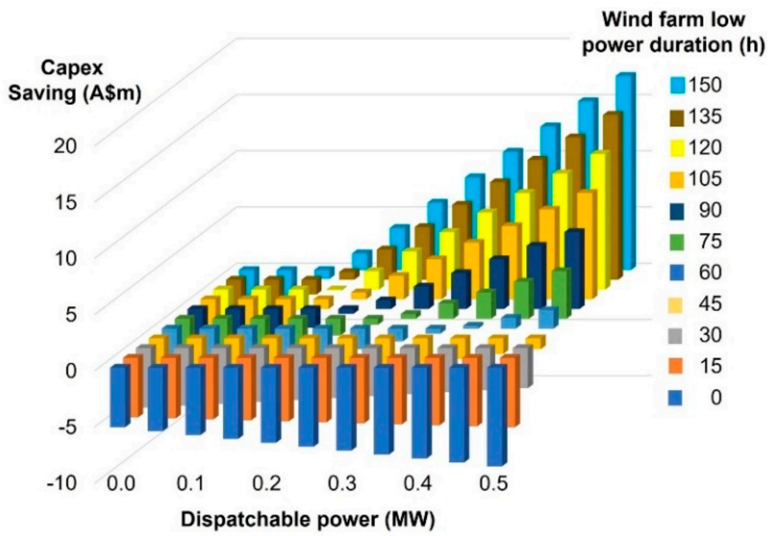


Figure 9. The CAPEX saving dependence on the dispatchable power threshold and low power duration in a standalone offshore wind farm, (Equation (5) with: P = 1 MW, P_{tidal} = 0.5 × P, τ_{tidal} = 20 h, $CFtidal$ = 0.18, $CFwind$ = 0.45).

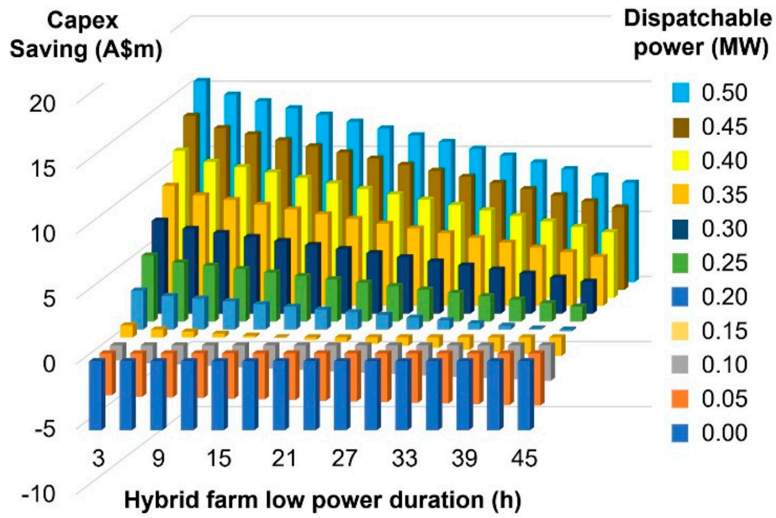


Figure 10. The CAPEX saving dependence on dispatchable power and low power duration in a tidal-offshore wind farm. (Equation (5) with: P = 1 MW, $P_{tidal} = 0.5 \times P$, τ_{wind} = 119 h, $CFtidal$ = 0.18, $CFwind$ = 0.45).

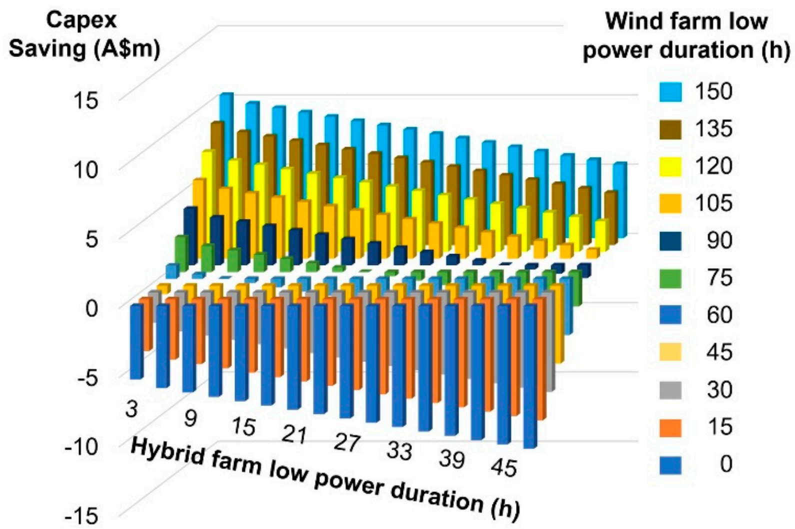


Figure 11. The CAPEX saving dependence on low power duration in a tidal-offshore wind farm and in a stand-alone offshore wind farm. (Equation (5) with: P = 1 MW, $P_{tidal} = 0.5 \times P$, Pth = 0.3 MW, $CFtidal$ = 0.18, $CFwind$ = 0.45).

Figure 10 describes the CAPEX savings dependence on tidal hybrid farm low power periods; for example, during neap tides or where there is tidal asymmetry. There is a critical boundary for Pth at 0.15 MW (15% dispatchability). The figure suggests that CAPEX saving should be possible for a broad range of tidal hybrid farm low power durations if the standalone wind farm has extended periods of low power.

Figure 11 indicates the range of low wind farm power durations that can be managed using tidal energy. It shows that CAPEX savings increase as hybrid farm low power duration reduces and standalone wind farm low power duration increases.

3. Results

The case studies demonstrate that incorporating tidal energy in wind farms or solar PV farm designs may improve energy security and reduce CAPEX. Preliminary versions of these case studies were described in an ARENA-AUSTEn project report [6] with estimates limited to tidal hybrid farms using a three-hour energy storage battery to manage the tidal ebb and flood power. The case studies described here extend the range of energy storage, dispatchability and CAPEX reduction, introduce a battery sharing technique, and account for neap tides and asymmetric tide cycles. They also include performance tests for case studies 1 and 2 using solar exposure and wind velocity data and the methods described in Section 2.

Case Study 1 demonstrates a reduction in CAPEX from replacing the wind energy and high-capacity energy storage with a tidal hybrid farm and lower-capacity energy storage. Case Study 2 demonstrates improved dispatchability and reduced CAPEX by sharing energy storage between tidal and solar PV energy generators, despite the impact of extended period neap tides. Case studies 3 and 4 describe potential applications where tidal energy by itself may provide dispatchable electricity.

The average wind farm power was set equal to the tidal farm power in Case Study 1, to demonstrate the separate and independent contributions of tidal and wind farms to dispatchability (Table 4). This contrasts with Case Study 2, where the solar and tidal energy resources share the battery capacity because the extended period neap tides mean that tidal power has no competitive advantage over solar power. Nevertheless, the temporal complementarity of the solar and tidal farm powers ensures that when they share a storage battery, they will provide more cost-effective dispatchability than either could provide separately.

Table 4. Specifications for an offshore wind farm in Banks Strait with and without tidal energy.

Specification Parameter	Wind Farm with No Tidal Energy	Wind and Tidal Hybrid Farm	Hybrid Farm Tidal Component	Hybrid Farm wind Component
Number of turbines	~5	~60	57	~3
Rated power (MW)	36	62	44	18
Capacity Factor (%)	45	26	18	45
Average power (MW)	16	16	8	8
Energy per annum (GWh)	140	140	70	70
Dispatchable power (MW)	6.4	6.4	4	2.4
Daily dispatched energy (MWh)	154	154	96	58
Dispatchability (%)	40	40	50	30
Battery energy capacity (MWh)	842	294	24	270

In both case studies, alternative configurations and optimisations are possible depending on a client's specification. Potential optimisations can be assessed using charts such as Figures 9–11 or by applying Equations (1)–(5).

Case studies one and two used the maximum economically available tidal power, and cost estimates were 2025 projected costs. Economies of scale and the need to compete cost-effectively with wind and solar power farms mandated the use of hypothetical 26 m turbines with a power cut out at tidal flow rates of 2 m/s [6]. Using a greater number of smaller TECs [22] might have achieved economies of volume (EoV); however, there was insufficient Australian data to estimate them. If CAPEX EoV's were achievable a factor of 0.9 would indicate an installed CAPEX of A$4065/kW for TECs with 20 m rotors, comparable with A$4076/kW for TECs with 26 m rotors. In case study 2, this would have increased the available tidal farm power to 12 MW.

3.1. Case Study 1. Incorporating Tidal Power into Wind Farms in Banks Strait

3.1.1. Overview

The Tasmanian government plans to generate 200% of its electricity from renewable energy, including wind, solar PV and hydropower, by 2040 [32]. The Musselroe wind farm located next to Banks Strait is a significant resource contributing to this plan; it has 56 wind turbines with a total rated power of 168 MW, an average power of 57 MW, and from 2016 to 2020 produced on average 575 GWh/year [33–35]. However, it can experience intermittent drops in wind energy for durations of up to six days [4,15]. In contrast, tidal stream energy in Banks Strait may require as little as three hours of energy storage to provide dispatchability.

This case study describes the performance and cost impacts of introducing tidal energy into wind farms. The first example is an offshore wind farm; the second example is a land-based wind farm. The tidal-wind farms are hypothetical, drawing on wind energy data from Swan Island in Banks Strait [15], wind turbine data from the Musselroe wind farm [4,33–35], and tidal stream data from the AUSTEn project (Figure 12) [20]. The offshore and land-based farms have the same dispatchability and average power ratings but different capacity factors. The capacity factors are estimated values typical in this region [33] and reflect the average energy delivered but not the maximum period of low wind power. This region's maximum period of negligible wind power was six days per year for both the land-based and offshore wind farms [4,15].

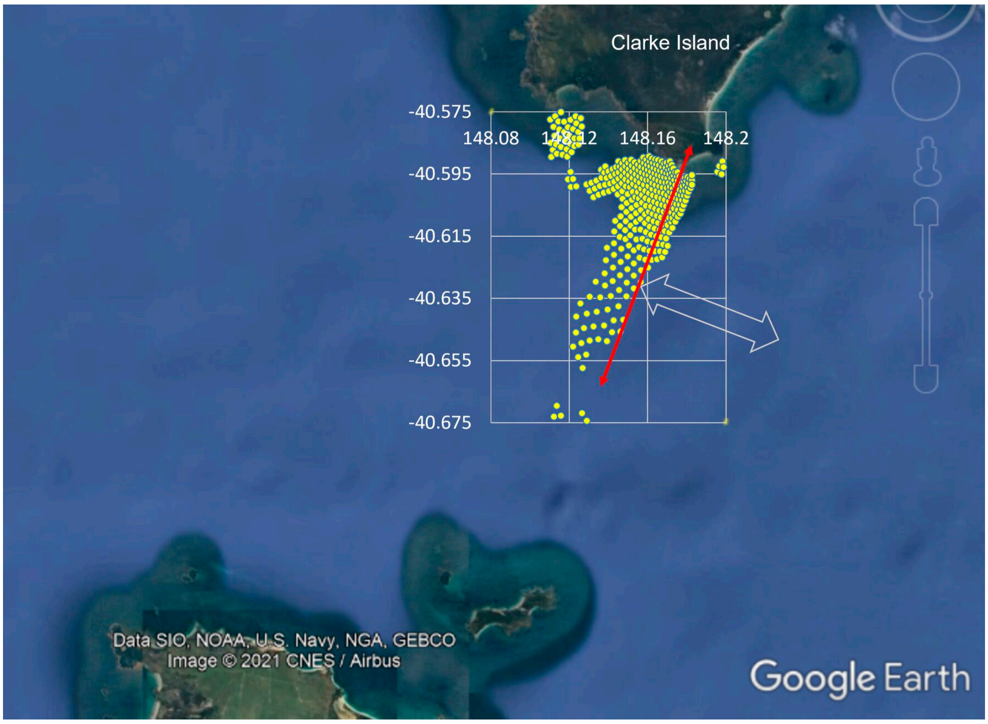


Figure 12. Regions with a moderate to high flow rate in Northeast Banks Strait. Average tidal flow rates: 0.81 m/s, bearing 294°; 0.96 m/s, bearing 110°. The red line indicates an energy flux transect, and the grey arrow indicates an average flow direction [20]. Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image © 2021 CNES/Airbus.

3.1.2. The Neap Tide Influence on Battery Storage

The neap tide average power generation in Banks Strait had a minimum of approximately 50% of the rated average power. Consequently, the battery capacity to support up to 50% TEC array dispatchability was only needed for semidiurnal variability and was not required to support neap drops in tidal power. With wind power, the reverse is the case where variability does not need to be supported, but intermittency does. This suggests that the storage batteries required for wind and tidal power dispatchability may not need to be shared. Setting the hybrid farm dispatchability at 40% instead of 50% allowed the contributions of wind and tidal farms to dispatchability to be readily observed (Table 4).

3.1.3. System Specification, Performance, and Costs

The performance comparison in Figure 13 applies to both the offshore and land-based wind farm examples. It describes four configurations for the wind farm: with and without tidal energy support and with two energy storage levels. The required dispatchable energy threshold (*Eth*) is 154 MWh that is 40% dispatchability.

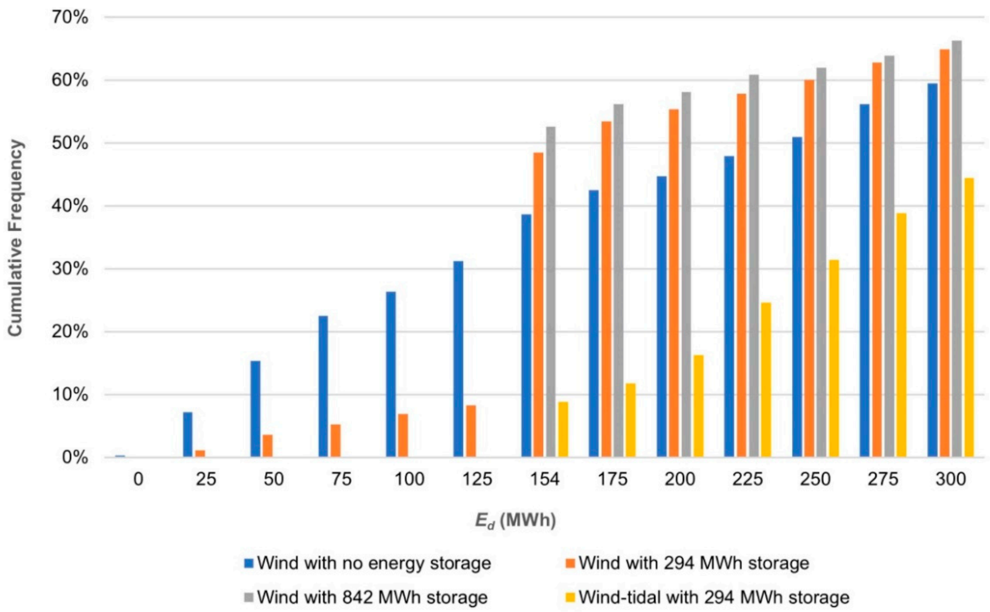


Figure 13. Performance comparison of four configurations for a Banks Strait wind farm: (1) wind only, (2) wind with 294 MWh storage, (3) wind with 842 MWh storage, and (4) tidal and wind with 294 MWh storage. *Eth* is 154 MWh. In configurations 3 and 4, *Ed* equals or exceeds *Eth* (the cumulative frequency of *Ed* is zero below *Eth*). In configurations 1 and 2, *Ed* fails to equal or exceed *Eth* for 31% and 8% of the time, respectively.

Figure 13 shows that the wind farm's daily dispatched energy (*Ed*) requires 842 MWh energy storage to reach the *Eth* threshold value. Replacing 50% of the wind energy with tidal energy reduces the required battery energy capacity to 294 MWh, lowers the frequency of *Ed* values that are less than 400 MWh, and ensures that *Ed* exceeds *Eth*.

3.1.4. Tidal-Offshore Wind Specification and CAPEX

Tables 4 and 5 compare the specifications and costs for an offshore wind farm using wind turbines with and without tidal energy. Both farm configurations produce an average power of 16 MW, of which 40% is dispatchable. The CAPEX reduction for the tidal-wind farm is 20% (A$105m), principally due to a reduction in the battery energy capacity needed for dispatchability.

Table 5. Comparison of CAPEX (2025) for an offshore wind farm in Banks Strait with and without tidal energy.

Capital Cost without Tidal Energy	A$m	Capital Cost with Tidal Energy	A$m
Wind turbines (36 MW)	193	Wind turbines (18 MW)	97
Battery (842 MWh)	310	Tidal turbines (44 MW)	181
Subsea cables (33 km)	33	Battery (294 MWh)	120
		Subsea cables (33 km)	33
Total	536	Total	431

3.1.5. Tidal-Onshore Wind Specification and CAPEX

The second example estimates the cost of a land-based wind farm with and without a tidal component. The wind farm uses wind turbines with capacity factors typical of land-based farms in the region. The average power and dispatchability for the land-based farm are identical to the offshore farm in the first example. However, the reduced capacity factor changes the rated peak power needed to achieve the required average power rating and alters the CAPEX saving associated with the tidal-wind farm. These changes are shown in Tables 6 and 7.

Table 6. Specification for a land-based wind farm in Banks Strait with and without tidal energy.

Specification Parameter	Wind Farm with No Tidal Energy	Wind and Tidal Hybrid Farm	Hybrid Farm Tidal Component	Hybrid Farm wind Component
Number of turbines	~15	~65	57	~8
Rated power (MW)	46	67	44	23
Capacity Factor (%)	35	24	18	35
Average power (MW)	16	16	8	8

Table 7. Comparison of CAPEX (2025) for a land-based wind farm in Banks Strait with and without tidal energy.

Capital Cost without Tidal Energy	A$m	Capital Cost with Tidal Energy	A$m
Wind turbines (46 MW)	87	Wind turbines (23 MW)	44
Battery (842 MWh)	311	Tidal turbines (44 MW)	181
		Battery (294 MWh)	120
		Subsea power cables (10 km)	10
Total	**398**	**Total**	**355**

The CAPEX saving also depended on how the tidal component of the tidal-wind farm was connected to the end-user. If the connection was via a 33 km subsea power line to the national grid, the saving was 5% (A$20m). If it was connected to a local grid via a 10 km subsea power line, the saving increased to 11% (A$43m).

3.2. Case Study 2. Reducing Intermittent Power Failures in Clarence Strait

3.2.1. Overview

Case Study 1 illustrated how replacing high-capacity wind energy storage with tidal energy and lower-capacity energy storage can reduce the CAPEX required for dispatchable power. However, this may not be possible in regions where extended duration neap tides with low tidal velocity last more than a day. Under these circumstances, a battery sharing strategy may be helpful. Case study 2 illustrates how introducing tidal energy and battery sharing into a solar PV farm could mitigate solar power loss during the wet season while managing neap tides with negligible kinetic energy for one or two consecutive days per month. The application is for a chemical plant where a constant electricity supply can be critical, for example a plant for converting hydrogen and carbon dioxide to fuel.

For this case study the maximum available TEC power was used combined with enough solar power to provide a similar production capacity compared to projects that did not use tidal power. For example, the George Olah plant in Iceland, which produces 4000 tons of renewable methanol per year [36]; or the proposed Heroya project in Norway, designed to produce 8000 tonnes of e-fuel per year [36]. The dispatchability was set at 50 per cent, as a minimum requirement for cost-competitive power to efuel conversion [36].

3.2.2. Dispatchable Renewable Power for a Clarence Strait Power to Liquid Electro-Fuel Plant

In Darwin, a liquefaction plant at Wickham Point processes natural gas from the Ichthys gas field in the Timor sea. The plant could produce 278 Mt of carbon dioxide during its 40-year life, and about 30% of this would be concentrated carbon dioxide stripped from the natural gas by its liquefaction [37,38]. The proximity of this plant to tidal stream and solar energy resources suggests an opportunity to recycle some of this waste carbon dioxide as electro-fuel (e-fuel).

The car manufacturer Audi pioneered carbon dioxide recycling in a 6 MW power to e-fuel conversion plant in Werlte, Germany. The Audi plant used electricity from four North Sea wind turbines, each rated at 3.6 MW peak power, and could produce up to 1000 t/year of synthetic methane from 2750 t/year of carbon dioxide [39]. The liquid fuel industry is also testing prototypes for producing e-fuels such as synthetic methanol, diesel or kerosene from hydrogen and waste carbon dioxide. The largest of the proposed commercial-scale projects aimed to produce 8000 t/year of liquid e-fuel in Heroya, Norway [36]. The intermittency of wind farm power may compel the plant operators to consider electricity price arbitrage strategies. For example, the Audi Werlte plant may use electricity purchased from the spot market on an hourly trade basis [40], reducing the cost of electricity and improving grid stability during periods of surplus renewable energy production. Including tidal energy in such a plant could further improve such strategies or lessen the need for them.

A power to liquid e-fuel plant near Glyde Point north of Darwin could receive concentrated waste carbon dioxide by pipeline from the natural gas liquefaction plant at Wickham Point. The plant could run on power from a solar PV farm at Glyde Point and TECs in Howard Channel 4 km offshore. Figure 14 shows the distribution of tidal energy along the Howard Channel. Combining 4.5 MW average tidal power from the Howard channel with 13.5 MW average solar power from the solar PV farm could provide 158 GWh/year to run the power-to-fuel conversion plant. The plant could produce 8830 t/year liquid e-fuel and avoid 20,751 t/year carbon dioxide from transport fuel.

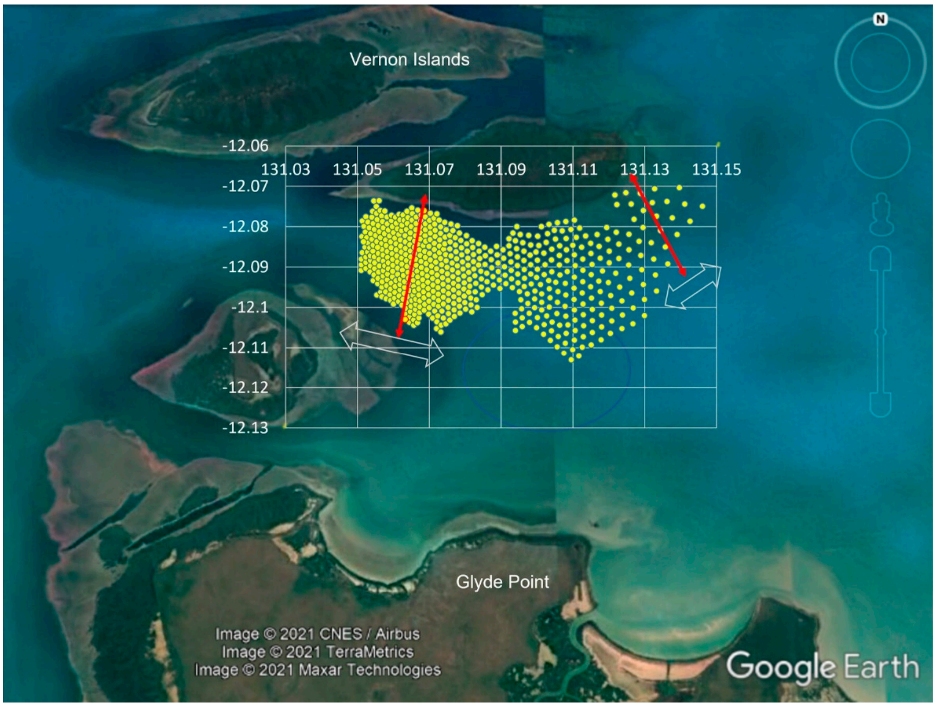


Figure 14. Regions of moderate to high flow rate in Howard Channel. Average tidal flow rates: 1.1 m/s, bearing 286°; 0.99 m/s, bearing 102°. The red line indicates an energy flux transect, and the grey arrow indicates an average flow direction [21]. Image © 2021 CNES/Airbus. Image © 2021 TerraMetrics. Image © 2021 Maxar Technologies.

3.2.3. System Specification, Performance, and Costs

Figure 15 shows the power supply time series for a tidal farm in Howard Channel comprising TECs with power curves that have been modified to reduce their rated power and the associated CAPEX. The solar PV panels are equipped with a single-axis tracking unit to provide about eight hours a day of solar power generation. The tidal and solar PV generators share a 624 MWh battery: to reduce solar power intermittency, provide electricity for continuous plant operation during the low power phase of tidal ebb and flow, and manage low tidal power during neap tides. The phase difference between the tidal and solar power time series was varied from 0 to 30 days in one-day increments to include potentially coincident tidal and solar power minima.

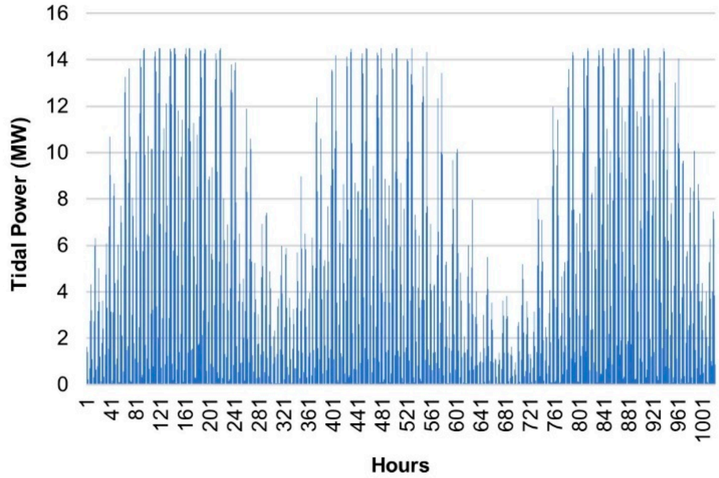


Figure 15. Hourly average tidal power generation in Howard Channel using TECs with reduced rated power (uncropped).

During the wet season in Clarence Strait, daily solar PV electricity generation can randomly drop from an average of 432 MWh to as little as 21 MWh [27]. The assessment was carried out for 2018, the worst-case solar intermittency scenario between 2015 and 2020.

For this case study, Figure 16 shows that the daily energy supplies (*Ed*) from solar PV farms with either zero or 624 MWh storage capacity do not reach the *Eth* threshold value of 216 MWh. Increasing the solar PV farm's energy storage to 1015 MWh ensures that *Ed* exceeds the 216 MWh threshold. Alternatively, replacing 25% of the solar PV energy with tidal energy also ensures that the tidal-solar PV farm exceeds that threshold, reducing the required energy storage to 624 MWh and lowering the frequency of *Ed* values that are below 300 MWh.

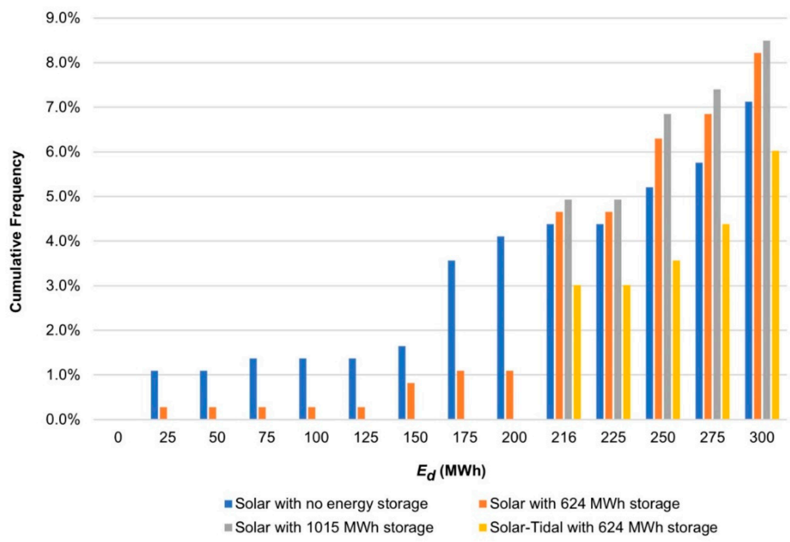


Figure 16. Performance comparison of four configurations for a Clarence Strait solar PV farm: (1) Solar PV only, (2) Solar PV with 624 MWh storage, (3) Solar PV with 1015 MWh storage, and (4) Solar PV and tidal hybrid with 624 MWh storage. *Eth* is 216 MWh. In configurations 3 and 4, *Ed* equals or exceeds *Eth* (the cumulative frequency of *Ed* is zero below *Eth*). In configurations 1 and 2, *Ed* fails to equal or exceed *Eth* for 4.1% and 1.1% of the time, respectively.

Tables 8 and 9 compare the specifications and cost of the standalone solar PV farm with a 1015 MWh battery against a tidal hybrid farm with a smaller 624 MWh battery and 25% of the solar energy replaced by tidal energy. Both farm configurations produce an average power of 18 MW, of which 50% is dispatchable. The tidal hybrid farm also reduced low power events delivering 94% of *Ed* at levels greater than 300 MWh, and it reduced the system CAPEX by 18% (A$83m). The CAPEX reduction was principally due to a reduction in the battery energy capacity needed for dispatchability.

Table 8. Specifications for a solar PV farm in Clarence Strait with and without tidal energy.

Specification Parameter	Solar PV Farm No Tidal Energy	Solar PV and Tidal Hybrid Farm	Hybrid Farm Tidal Component	Hybrid Farm Solar PV Component
RE farm area (km^2)	0.8	1.1	0.5	0.6
Rated power (MW)	82	76	15	61
Capacity Factor (%)	22	24	30	22
Average power (MW)	18	18	4.5	13.5
Energy per annum (GWh)	158	158	39	118
Dispatchable power (MW)	9.0	9.0	shared	shared
Daily dispatched energy (MWh)	216	216	shared	shared
Dispatchability (%)	50	50	shared	shared
Battery energy capacity (MWh)	1015	624	shared	shared

Table 9. Comparison of CAPEX (2025) for a solar PV farm in Clarence Strait with and without tidal energy.

Capital Cost without Tidal Energy	A$m	Capital Cost with Tidal Energy	A$m
Solar PV farm (82 MW)	71	Solar PV farm (61 MW)	54
Battery (1015 MWh)	378	Tidal farm (19 × 0.8, 15 MW)	61
		Battery (624 MWh)	242
		Subsea power cable (10 km)	10
Total	**449**	**Total**	**367**

Given that the tidal-solar PV farm supplies energy to a chemical plant, it is also worth comparing annual values for the alternative products, including electricity, hydrogen, liquid e-fuel, and carbon dioxide (Table 10). The carbon price has been set at the level recommended for transformational change by the IMF and World Bank. Hydrogen has an additional value not given in the table as its production can be rapidly controlled and used to take advantage of power peaks. The price values given are projected for 2025.

Table 10. Alternative products from the Clarence Strait tidal-solar PV farm.

Product Quantities	Quantity	Value
Generated electricity per year [12]	158 GWh	8.01 A$m/year
Equivalent hydrogen [41,42]	3667 t/year	7.33 A$m/year
Avoided CO_2-e (e-fuel from waste CO_2) [36,43,44]	20,751 t/year	1.24 A$m/year
Liquid e-diesel [36,45]	8830 t/year	11.56 A$m/year

3.3. Case Study 3. Yampi Sound, Tidal Energy for Cockatoo and Koolan Islands

3.3.1. Overview

Case Study 3 describes how tidal energy could supply power for mining or remediation operations at Koolan and Cockatoo Islands (Figures 17 and 18). Both islands have significant reserves of high-grade iron ore, and both rely on sea walls to facilitate mining access to these resources. Over several decades the Cockatoo mine has been closed for long periods and, on two occasions, has flooded. Leaving the mine flooded or dewatering the flooded area too quickly and without adequate control risks breaching the sea wall [46]. A local community has raised concerns that such a breach would result in silt covering nearby coral reefs [47]. Access to a continuous electricity supply could allow pumps to counter water seepage through the sea wall, saving the months needed to pump out the flooded mine and maintain it. Tidal powered pumps may be a cost-effective and more reliable alternative to diesel-powered pumping that could otherwise cost several hundred thousand dollars a month.

Figure 17. Koolan Island mine site. Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image © 2021 Maxar Technologies, Image © 2021 TerraMetrics.

Figure 18. Cockatoo Island mine site. Image ©2020 CNES/Airbus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image © 2021 Maxar Technologies, Image © 2021 TerraMetrics.

The ARENA National Tidal Model did not have a sufficiently high spatial resolution to detect strong tidal streams in the Cockatoo and Koolan Islands, despite the powerful tidal currents in the neighbouring King Sound and Yampi Sound. However, environmental assessments of islands in the Buccaneer Archipelago describe tidal ranges of 4 m to 11 m and tidal currents up to 5 m/s [48]. A local study (Atlantis Resource Corporation, personal communication) has recorded flow rates of up to 3 m/s in The Gutter, southeast of Koolan Island. High-resolution surveys to the north and south of Koolan Island (Figure 17) and Cockatoo Island (Figure 18) would be needed to determine if tidal streams are strong enough to power the Koolan mine's offices, workshops and accommodation, and for mine-dewatering on Cockatoo Island.

3.3.2. Renewable Power Plant Options, Specification, and Cost

Options 1 and 2 in Table 11 are for deep channels north and south of Koolan Island. Option 3 is for a tidal turbine reef of eight TECs, each with 4 m rotor diameters [49] that may be suitable for locations near Round Island adjacent to the southeast coast of Koolan Island. Option 4 is for a small tidal farm in deeper water either north or south of Cockatoo Island. In this option, the rate of water seepage requiring pump out may fall during neap tides, so the energy storage required to manage neap tides has been reduced, compared to options 1 to 3. The four suggested options are contingent on further high-resolution surveys finding suitable tidal streams with maximum flow velocities of at least 2.5 m/s.

Table 11. Koolan Island and Cockatoo Island tidal farm specification options.

Location Options	Option 1	Option 2	Option 3	Option 4
Rotor diameter (m)	26	10	4	26
Number of TECs	1	4	8	6
Power per TEC (MW) (2 m/s tidal flow)	0.78	0.12	0.07	0.78
Tidal farm rated power (MW)	0.78	0.46	0.56	4.69
Capacity factor (%)	20	20	10	20
Average power (MW)	0.16	0.09	0.06	0.94
Annual electricity production (GWh)	1.37	0.81	0.49	8.22
Dispatchable power (Pth) (MW)	0.08	0.05	0.03	0.31
Dispatchability (%)	50	50	50	33
Battery energy capacity (MWh)	2.35	1.39	0.84	9.38

Table 12 shows the performance and cost data for a range of potential locations and site depths. The first three options were to supply office and accommodation power on Koolan Island. The fourth option is to supply electricity to dewater the mine on Cockatoo Island.

Table 12. CAPEX (2025) for Koolan Island and Cockatoo Island tidal farm options.

Configuration		Cost (A$m)
Option 1. Koolan Island north of Mullet Bay		
Tidal turbine (0.8 MW, 1 × 26 m rotor)		3.4
Subsea power cable (1.5 km to 5 km)		1.5 to 5
Energy storage (2.4 MWh)		1.0
	Total	**5.9 to 9.4**
Option 2. Koolan Island south of Arbitration Cove		
Tidal turbines (4 × 116 kW, 10 m rotor)		10.7
Subsea power cable (1.5 km to 5 km)		1.5 to 5
Energy storage (1.4 MWh)		0.6
	Total	**12.8 to 16.3**
Option 3. Koolan Island southeast (The Gutter)		
Tidal Turbine Reef (8 × 70 kW, 4 m rotor)		8.8
Power cable (4 km)		4.0
Energy storage (0.8 MWh)		0.4
	Total	**13.2**
Option 4. Cockatoo Island northeast of North Bay		
Rated power (4.7 MW, 6 × 26 m rotor)		20.6
Power cable (1.5 km to 5 km)		1.5 to 5
Energy storage (9.4 MWh)		4.1
	Total	**26.2 to 29.7**

Options 1 and 2 are for deep channels north and south of Koolan Island. Option 3 is for a tidal turbine reef of eight TECs, each with 4 m rotor diameters [49] that may be suitable for locations near Round Island adjacent to the southeast coast of Koolan Island. Option 4 is for a small tidal farm in deeper water either north or south of Cockatoo Island. In this option, the rate of water seepage requiring pump out may fall during neap tides, so the energy storage required to manage neap tides has been reduced, compared to options 1 to 3. The four suggested options are contingent on further high-resolution surveys finding suitable tidal streams with maximum flow velocities of at least 2.5 m/s.

3.4. Case Study 4. Port Melville: High-Security Tidal Energy Electricity Supply

3.4.1. Overview

Port Melville is a remote defence and shipping service facility located at the northern end of Apsley Strait between Melville and Bathurst Islands. It is a security regulated port operated by Northern Territory Port and Marine and can house 150 personnel. It provides a range of services and storage facilities for civilian and defence shipping. This case study describes the contribution tidal energy could make to meet a demand for reliable emergency power at the port. The tidal energy resource being considered is located 2 km to 3 km south of Port Melville at a narrow section of Apsley Strait.

The Port Melville tidal assessments suggest that tidal streams in this area may be suitable for electricity generation. However, the tidal flow is significantly stronger for an ebb tide than for a flood tide. The peak flooding tide from the north, at Melville Port wharf, is generally 0.75 m/s and 1.25 m/s during spring tides. The ebbing tide can rise over two hours to flow rates of 1.5 m/s to 2 m/s and up to 2.5 m/s during spring tides. The ebbing tide flow rates persist for three hours, after which they rapidly slow [50,51].

The ARENA National Tidal Model identified a strong tidal stream south of Harris Island at (11°25.8′ S, 130°24.6′ E,) (Figure 19), but this may be located too close to Port Melville and interfere with its operations. The hypothetical installation is at the south end of a 45 m deep 500 m wide channel from Port Melville wharf to 2.5 km south of Port Melville. The channel narrows and becomes shallower at its southern end, which may increase the tidal stream flow rate. A hypothetical tidal farm was evaluated for this location (11°26.60′ S, 130°24.78′ E).

Figure 19. Potential TEC site southwest of Port Melville, Apsley Strait. Image © 2021 Maxar Technologies, © 2021 Google, Image © 2021, CNES/Airbus, Image © 2021 TerraMetrics.

3.4.2. Port Melville Tidal Power Generator-Specification and Costs

Three TEC configurations are given. The 10 m and 26 m rotor turbine arrays are for deeper sites about 1.6 km south of Harris Island, and a tidal turbine reef [49] is proposed for shallower locations. Vanadium flow cell batteries are suggested to accommodate an estimated 60 h, half power, neap tide phase. Table 13 shows the specification, and Table 14 gives indicative capital costs for the three tidal turbine options. Each of these is contingent on confirming that the tidal stream resource has a semidiurnal peak velocity of at least 2.5 m/s.

Table 13. Port Melville, Apsley Strait tidal farm specification options.

Configuration	Option 1	Option 2	Option 3
Rotor size (m)	26	10	4
Number of TECs	1	4	8
Rated power per TEC (kw, 2 m/s tidal flow)	782	116	70
Tidal farm rated power (MW)	0.78	0.46	0.56
Capacity factor (%)	10	10	10
Average power (MW)	0.08	0.05	0.06
Annual electricity production (GWh)	0.69	0.41	0.49
Dispatchable power (Pth) (MW)	0.04	0.02	0.03
Dispatchability (%)	50	50	50
Battery energy capacity (MWh)	1.11	0.66	0.80

Table 14. CAPEX (2025) for Port Melville, Apsley Strait tidal farm options.

Configuration		Cost (A$m)
Option 1		
Tidal turbines (1 × 782 kW, 26 m rotor)		3.4
Power cable (5 km)		5.0
Energy storage (1.1 MWh)		0.5
	Total	**8.9**
Option 2		
Tidal turbines (4 × 0.116 MW, 10 m rotor)		10.7
Power cable (5 km)		5.0
Energy storage (0.66 MWh)		0.3
	Total	**16.0**
Option 3		
Tidal Turbine Reef (8 × 70 kW, 4 m rotor)		8.8
Power cable (1.5 km to 5 km)		1.5 to 5.0
Energy storage (0.8 MWh)		0.36
	Total	**10.7 to 14.2**

4. Discussion

Despite Australia's moderate tidal stream flow velocities, tidal power's regularity makes it a renewable energy resource worth considering for critical applications. These might include chemical processing, emergency power, security, or supplying regional microgrids where intermittent power shutdowns may not be tolerable.

Case Study 1 described the use of tidal-wind farms to supply dispatchable power. Replacing 50% of the wind farm power with tidal power made it possible to provide 40% of the average power generation as dispatchable power. The replacement also reduced low power events above the dispatchability threshold and provided a CAPEX reduction of 20% (A$105m) for an offshore tidal-wind farm and 5% (A$20m) to 11% (A$43m) for a land-based hybrid farm depending on its location. The cost savings were principally due to the continuity and regularity of tidal power in Banks Strait and the reduced charge and discharge periods required for tidal-wind farm energy storage compared with 132 h of energy storage needed for a standalone wind farm.

Case Study 2 demonstrated that even with extended period neap tides and the much cheaper cost of solar power, using tidal power to replace 25% of a solar PV farm's capacity may provide cost-efficient dispatchability. The tidal and solar PV farm exceeded a 50% dispatchability threshold. It reduced low power events delivering 94% of *Ed* at levels greater than 300 MWh. It also reduced the system CAPEX by 18% (A$83m).

Case studies 3 and 4 suggested opportunities to provide small scale emergency power from standalone tidal energy converters. The principal advantages would be the ability to supply electricity for long periods from unattended remote or transportable TECs, or the potential for a renewable electricity supply on islands where a solar PV farm might cover too great an area.

The case studies are hypothetical and require a more detailed assessment of the tidal resource, capital, and operation and maintenance costs before implementation. Case studies such as those presented here are not conclusive, but they suggest directions for further work. Future studies could extend databases on the intermittency characteristics of solar and wind resources for high-security power in remote regions. They could also assess prototypes of the large rotor, reduced rated power, TECs outlined in this study for moderate tidal stream flow environments. If such TECs proved viable, they would significantly expand the global potential for using tidal stream power.

5. Conclusions

We have shown that the cost of supplying dispatchable power from variable sources, such as wind and solar energy farms, may be significantly reduced if tidal energy is also available and is exploited. Hybrid tidal-wind or tidal-solar energy farms may provide cost savings, power availability and levels of dispatchability that are higher than can be achieved by using any of these resources by themselves. Table 15 compares tidal-solar hybrid and tidal-wind hybrid examples, based on data measured from moderate power tidal sites in Australia.

Table 15. Comparison of tidal-wind and tidal-solar farms.

RE Farm Type	Annual Energy Production	Dispatchability	Energy Storage Mode	Battery Capacity	CAPEX Saving
Offshore Tidal-Wind	140 GWh	40%	Independent	294 MWh	A$105m
Tidal-Solar	158 GWH	50%	Shared	624 MWh	A$83m

The improved dispatchability shown in Table 15 is because wind, solar and tidal energy have high levels of temporal complementarity; that is, when one resource is not available, it may in whole or part be replaced by another. The cost savings are primarily due to the reduced battery capacity needed for dispatchability. A novel algorithm has been described that allows combinations of tidal and wind or tidal and solar energy resources to be optimised for specified levels of dispatchability, power, battery capacity or capital cost.

Author Contributions: Conceptualisation, I.P., P.O., J.A.H., M.A.H. and P.M.; Methodology, P.O., J.A.H. and M.A.H.; Software, U.R. and P.M.; Validation, P.O., J.A.H. and M.A.H.; Formal analysis, P.O., J.A.H., P.M., M.A.H. and M.H.; Investigation, P.O., J.A.H., M.A.H., P.M., S.S., J.-R.N., R.C., I.P. and A.G.; Resources, I.P.; Data curation, P.M., M.A.H. and D.G.; Writing—Original Draft Preparation, P.O.; Writing—Review and Editing, P.O., I.P., J.A.H., M.A.H., D.G. and A.G.; Visualisation, P.O.; Supervision, I.P.; Project administration, I.P., J.-R.N.; Funding acquisition. I.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Australian Renewable Energy Agency grant G00902], the Australian Maritime College (University of Tasmania), the University of Queensland, CSIRO, our industry partners MAKO Tidal Turbines, Sabella and SIMEC Atlantis Energy and our international collaborators Richard Karstens from Acadia University, Canada, and Matt Lewis from Bangor University, UK.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The tidal data collected as part of the Banks Strait and Clarence Strait field campaigns can be found by searching on the keyword 'AUSTEn' at https://portal.aodn.org.au/, (accessed on 8 December 2021) an open-source online data repository hosted at the Integrated Marine Observing System Australian Ocean Data Network (AODN) data repositories database (2021). Three AUS-TEn National Tidal model data sets have been published by Herzfeld M, Griffin D, Hemer M, Rosebrock U, Rizwi F, Trenham C. AUSTEn National Tidal model data. (2020): v3. CSIRO. Data Collection. https://doi.org/10.25919/q8dw-c732: The data sets include: (a) The first 59 of the 365 days of COMPAS output hourly time series, at all cell centres, for all state variables (b) 13 har-monic constituents of the COMPAS velocity and height fields, derived from the 365-day model run (c) 13 (11 in places) harmonic constituents of the current's validation dataset, along with sub-tidal ellipse parameters for 95 locations.

Acknowledgments: The authors wish to acknowledge the technical advice received from our industry partners, our international collaborators, and James Murray, Orbital Marine Power, and Ralf Starzman, Schottel Hydro GmbH.

Conflicts of Interest: The authors declare the following financial interests/personal relationships that may be considered as potential competing interests: Our industry partners in the Australian Renewable Energy Agency project that funded this research included: MAKO Tidal Turbines, Sabella and SIMEC Atlantis Energy. Each industry partner contributed funding and expertise to the project under the terms of the Australian Government's Grant G00902. Additional advice and data were received from Orbital Marine Power, and Schottel Hydro GmbH.

References

1. Australian Energy Regulator. Retailer Reliability Obligation. 2019. Available online: https://www.aer.gov.au/retail-markets/retailer-reliability-obligation (accessed on 20 February 2021).
2. Tasmanian Economic Regulator. 2020 Report into the Reliability of Electricity Network Services in Tasmania. 2020. Available online: https://www.economicregulator.tas.gov.au/Documents/2020%20Report%20into%20the%20Reliability%20of%20Electricity%20Network%20Services%20in%20Tasmania.pdf (accessed on 29 July 2021).
3. Pommeret, A.; Katheline, S. Optimal energy transition with variable and intermittent renewable electricity generation. *J. Econ. Dyn. Control.* **2021**, *134*, 104273. [CrossRef]
4. Aneroid Energy. Australian Energy Market. 2021. Available online: https://anero.id/energy/ (accessed on 20 February 2021).
5. Coles, D.; Angeloudis, A.; Goss, Z.; Miles, J. Tidal Stream vs. Wind Energy: The Value of Cyclic Power When Combined with Short-Term Storage in Hybrid Systems. *Energies* **2021**, *14*, 1106. [CrossRef]
6. Penesis, I.; Hemer, M.; Cossu, R.; Nader, J.R.; Marsh, P.; Couzi, C.; Hayward, J.; Sayeef, S.; Osman, P.; Rosebrock, U.; et al. *Tidal Energy in Australia: Assessing Resource and Feasibility in Australia's Future Energy Mix*; Australian Maritime College, University of Tasmania: Hobart, Tasmania, 2020. Available online: https://arena.gov.au/projects/tidal-energy-australia-assessing-resource-feasibility-australias-future-energy-mix/ (accessed on 20 February 2021).
7. Kempener, R.; Neumann, F. *Tidal Energy Technology Brief*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2014; Available online: https://irena.org/-/media/Files/IRENA/Agency/Publication/2014/Tidal_Energy_V4_WEB.pdf (accessed on 24 August 2021).
8. Twidell, J.; Weir, T. *Renewable Energy Resources*, 2nd ed.; Taylor and Francis: Oxon, UK, 2006; pp. 447–449. ISBN 0-419-25330-0.
9. International Energy Agency. *Electricity Information: Overview*; Statistics report; IEA: Paris, France, 2021; Available online: https://www.iea.org/reports/electricity-information-overview (accessed on 20 February 2021).
10. Gazzo, A.; Perez, J. Ocean Energies, Moving towards Competitiveness: A Market Overview. Seanergy, Ernst and Young. 2016. Available online: https://arena.gov.au/assets/2016/10/1605SG797-Etude-Seanergy-lowres.pdf (accessed on 17 August 2021).
11. Noonan, M. Tidal Stream: Opportunities for Collaborative Action. Offshore Renewable Energy (ORE) Catapult. 2019. Available online: https://tethys-engineering.pnnl.gov/publications/tidal-stream-opportunities-collaborative-action-0 (accessed on 20 February 2021).
12. Graham, P.; Hayward, J.; Foster, J.; Havas, L. GenCost; Final Report, 2020–2021. CSIRO Publications Repository, Australia. 2021. Available online: https://publications.csiro.au/publications/publication/PIcsiro:EP2021-0160(accessed on 1 June 2021).
13. Stehly, T.; Philipp, B.; Duffy, P. 2019 Cost of Wind Energy Review. National Renewable Energy Laboratory, NREL/TP-5000-78471. 2020. Available online: https://www.nrel.gov/docs/fy21osti/78471.pdf (accessed on 2 December 2021).
14. Smart, G.; Noonan, M. Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit. Offshore Renewable Energy (ORE) Catapult. 2018. Available online: https://tethys.pnnl.gov/publications/tidal-stream-wave-energy-cost-reduction-industrial-benefit-summary-analysis (accessed on 20 February 2021).
15. Swan Island Banks Strait. *Wind Velocity Data*; Bureau of Meteorology: Melbourne, Australia, 2018.
16. Simec Atlantis Energy. Tidal Stream Projects MeyGen. 2021. Available online: https://simecatlantis.com/projects/meygen/ (accessed on 20 February 2021).

17. Coles, D.S.; Angeloudis, A.; Greaves, D.; Hastie, G.; Lewis, M.; Mackie, L.; McNaughton, J.; Miles, J.; Neill, S.; Piggott, M.; et al. 2021 A review of the UK and British Channel Islands practical tidal stream energy resource. *Proc. R. Soc.* **2021**, *477*, 20210469. [CrossRef]
18. Coles, D.S.; Blunden, S.; Bahaj, S. The energy yield potential of a large tidal stream turbine array in the Alderney Race. *Phil. Trans. R. Soc. A* **2020**, *378*, 20190502. [CrossRef] [PubMed]
19. Griffin, D.A.; Herzfeld, M.; Hemer, M.; Engwirda, D. Australian tidal currents–assessment of a barotropic model (COMPAS v1.3.0 rev6631) with an unstructured grid. *Geosci. Model Dev.* **2021**, *14*, 5561–5582. [CrossRef]
20. Cossu, R.; Penesis, I.; Nader, J.-R.; Marsh, P.; Perez, L.; Couzi, C.; Grinham, A.; Osman, P. Tidal energy site characterisation in a large tidal channel in Banks Strait, Tasmania, Australia. *Renew. Energy* **2021**, *177*, 859–870. [CrossRef]
21. Marsh, P.; Penesis, I.; Nader, J.-R.; Couzi, C.; Cossu, R. Assessment of tidal current resources in Clarence Strait, Australia including turbine extraction effects. *Renew. Energy* **2021**, *179*, 150–162.
22. Goss, Z.L.; Coles, D.S.; Piggott, M.D. Identifying economically viable tidal sites within the Alderney Race through optimisation of levelized cost of energy. *Phil. Trans. R. Soc. A* **2020**, *378*, 20190500. [CrossRef] [PubMed]
23. Novo, P.G.; Kyozuka, Y. Tidal stream energy as a potential continuous power producer: A case study for West Japan. *Energy Convers. Manag.* **2021**, *245*, 114533. [CrossRef]
24. Lewis, M.; McNaughton, J.; Márquez-Dominguez, C.; Todeschini, G.; Togneri, M.; Masters, I.; Allmark, M.; Stallard, T.; Neill, S.; Goward-Brown, A.; et al. Power variability of tidal-stream energy and implications for electricity supply. *Energy* **2019**, *183*, 1061–1074. [CrossRef]
25. Jurasz, J.; Canales, F.A.; Kies, A.; Guezgouz, M.; Beluco, A. A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. *Solar Energy* **2020**, *195*, 703–724. [CrossRef]
26. ABP Marine Environmental Research Ltd. *Quantification of Exploitable Tidal Energy Resources in UK Waters*; Report R1439; 2007. Available online: https://www.iow.gov.uk/azservices/documents/2782-FF5-Quantification-of-Exploitable-Tidal-Energy-Resources-in-UK-Waters.pdf (accessed on 20 February 2021).
27. Daily Global Solar Exposure. Climate Data Online. Available online: http://www.bom.gov.au/climate/data/ (accessed on 26 September 2021).
28. Baxter, R. *2018 Energy Storage Pricing Survey*; SAND-2019-14896; Sandia National Lab: Albuquerque, NM, USA, 2019. [CrossRef]
29. Pacific Northwest National Laboratory. *Energy Storage Technology and Cost Characterization Report*; PNNL-28866; PNNL: Richland, WA, USA, 2019. Available online: https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf (accessed on 20 February 2021).
30. Noack, J.; Wietschel, L.; Roznyatovskaya, N.; Pinkwart, K.; Tübke, J. Techno-Economic Modeling and Analysis of Redox Flow Battery Systems. *Energies* **2016**, *9*, 627. [CrossRef]
31. Ciotola, A.; Fuss, M.; Colombo, S.; Poganietz, W.-R. The potential supply risk of vanadium for the renewable energy transition in Germany. *J. Energy Storage* **2021**, *33*, 102094. [CrossRef]
32. Tasmanian Government, Department of State Growth. The Draft Tasmanian Renewable Energy Action Plan. 2020. Available online: https://renewablestasmania.tas.gov.au/policies_and_plans (accessed on 20 February 2021).
33. Australian Energy Market Operator. 2020 Costs and Technical Parameter Review, Revision 3, Reference 510177. 2020. Available online: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/aurecon-cost-and-technical-parameters-review-2020.pdf?la=en/ (accessed on 20 February 2021).
34. Australian Renewable Energy Agency. Musselroe Wind Farm Lessons Learnt. Progress Report, Milestone 2A. 2019. Available online: https://arena.gov.au/assets/2018/03/mussleroe-wind-farm-lessons-learnt-progress-report-2019.pdf (accessed on 20 February 2021).
35. Office of The Tasmanian Economic Regulator. Energy in Tasmania Report 2019-20. 2020. Available online: https://www.economicregulator.tas.gov.au/Documents/Energy%20in%20Tasmania%20Report%202019-20.pdf (accessed on 29 July 2020).
36. Soler, A. Role of e-Fuels in the European Transport System-Literature Review, Concawe Report no. 14/19. 2020. Available online: https://www.concawe.eu/publication/role-of-e-fuels-in-the-european-transport-system-literature-review/ (accessed on 13 July 2021).
37. Reuters staff. FactBox: Projected CO2 Emissions from Top Australia LNG Projects. Reuters, Green Business News. 2011. Available online: www.reuters.com/article/us-australia-lng-carbon-fb/factbox-projected-CO2-emissions-from-top-australia-lng-projects-idUSTRE7491FU20110510/ (accessed on 12 May 2021).
38. Jacobs Australia. North West Shelf Project Extension Greenhouse Gas Benchmarking Report. Revision 4. 2019. Available online: https://www.epa.wa.gov.au/sites/default/files/PER_documentation2/NWS%20Project%20Extension%20-%20Appendix%20F%20-%20Greenhouse%20Gas%20Benchmarking%20Report.pdf (accessed on 12 May 2021).
39. Audi. Audi e-fuels, Audi Media Centre. 2015. Available online: https://www.audi-mediacenter.com/en/audi-future-performance-days-2015-5097/audi-e-fuels-5104 (accessed on 21 May 2021).
40. Lambert, M. Power-to-Gas: Linking electricity and gas in a Decarbonising World? Oxford (UK): Oxford Institute for Energy Studies. 2018. Available online: https://www.oxfordenergy.org/publications/power-gas-linking-electricity-gas-decarbonising-world/ (accessed on 20 February 2021).
41. USDOE, Hydrogen and Fuel Cell Technologies Office. Technical Targets for Hydrogen Production from Electrolysis. 2021. Available online: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis/ (accessed on 6 May 2021).

42. Australian Renewable Energy Agency. Australia's Pathway to $2 Per kg Hydrogen. 2020. Available online: https://arena.gov.au/blog/australias-pathway-to-2-per-kg-hydrogen/ (accessed on 6 May 2021).
43. IMF; OECD. Tax Policy and Climate Change: IMF/OECD Report for the G20 Finance Ministers and Central Bank Governors. 2021. Available online: https://www.oecd.org/tax/tax-policy/tax-policy-and-climate-change-imf-oecd-g20-report-april-2021.pdf (accessed on 29 July 2021).
44. World Bank. Carbon Pricing: Results Briefs. 2019. Available online: https://www.worldbank.org/en/results/2017/12/01/carbon-pricing (accessed on 6 May 2021).
45. Australian Renewable Energy Agency. Biofuels and Transport: An Australian Opportunity. ARENA. 2020. Available online: https://arena.gov.au/knowledge-bank/biofuels-and-transport-an-australian-opportunity/ (accessed on 18 August 2021).
46. Powell, C.L.; Hall, J. Cockatoo Island: Pit dewatering and wall depressurisation behind critical seawall infrastructure. In *Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*; Dight, P.M., Ed.; Australian Centre for Geomechanics: Perth, WA, Australia, 2020; pp. 1359–1372. [CrossRef]
47. Dambimangari Aboriginal Corporation. New threat to Cockatoo Island, Dambinangari News. 2018. Available online: https://www.dambimangari.com.au/new-threat-to-cockatoo-island/ (accessed on 17 June 2021).
48. Purcell, S. Intertidal reefs under extreme tidal flux in Buccaneer Archipelago. Western Australia. *Coral Reefs* **2002**, *21*, 191–192. [CrossRef]
49. O'Neill, L.; Barker, B. The Tidal Turbine Reef (TTR) Feasibility Study; 2016/ARP002; ARENA. 2016. Available online: https://arena.gov.au/projects/tidal-turbine-reef-feasibility-study/ (accessed on 20 February 2021).
50. Northern Territory Port and Marine. Port Procedures and Information for Shipping. 2018. Available online: https://www.ntportandmarine.com/wp-content/uploads/2018/11/Port-Melville-Port-Procedures-and-Information-for-Shipping.pdf (accessed on 20 February 2021).
51. Northern Territory Port and Marine, Port Melville Information. 2017. Available online: https://amgmarine.com.au/assets/pdfs/port_melville_information_handbook.pdf (accessed on 20 February 2021).