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TECHNO-ECONOMIC ASSESSMENT OF DEVELOPING COMBINED OFFSHORE WIND AND WAVE ENERGY IN AUSTRALIA

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ABSTRACT

Australia has significant offshore wind and wave energy potential that can provide a long-term solution to the ever-increasing power demand and contribute to the future energy mix. The integration of offshore wind and wave energy has been proposed previously, but considered to be difficult due to the high cost and high intermittency of developing ocean renewable energy sources. In addition, the economic analysis of the integrated offshore wind and wave systems, considering life cycle cost, energy benefits, market regulation costs and future carbon price, has not been studied thoroughly in Australia. Therefore, this paper aims to investigate the economic feasibility of a co-located offshore wind and wave energy farm in multiple key locations around the Australian coastline. The high-fidelity life-cycle cost and economic benefit models are developed under different technical deployment constraints. Furthermore, the paper studies the impact of electricity market regulation cost and future carbon prices on deploying the proposed combined energy farm. The results of this paper provide a guideline for industry leaders, investors and policymakers at the pre-planning stage of ocean renewable energy system development and deployment.

Keywords: Offshore wind, Wave energy, Techno-economic analysis, Combined system, Australia

1. INTRODUCTION

Net-zero emission by 2050 is legislated by the Australian government. As reported in [1], the method of electricity generation is the largest source of emission (34% of the total in 2019) in Australia. Therefore, renewable energy is the most likely candidate to offer a smooth energy transition towards the net-zero emission target. AEMO (Australian Energy Market Operator) report published in 2022 [2] has provided a comprehensive pathway toward 100% renewables for Australia's National Electricity Market (NEM), which also highlights possible engineering challenges on renewable energy utilisation. It was concluded in [2] that enhancing the renewable energy resource mix and the transition between various renewables plays a key role in smoothing out intermittency as well as providing an affordable and reliable energy supply.

In [3], offshore wind and wave have been identified as potential energy resources, which can provide a long-term contribution to the national energy mix during the energy transition. Moreover, the integration of offshore wind and wave energy is emerging, which can more efficiently capture largely untapped ocean renewables. As it was reported in [4], the combined wind and wave energy systems can be divided into two categories: co-located system and hybrid system. The co-located system utilizes the independent platforms but shares the common grid transmission infrastructure in the same marine area. The hybrid system accommodates both offshore wind turbine (WT) and wave energy converter (WEC) on a single platform which further reduces the overall cost by sharing multiple system components.

As it was studied comprehensively, the combined offshore wind and wave energy conversion systems can reduce intermittency and variability [3, 5], can increase the energy dispatchability [6, 7], can reduce the costs (hence the levelized cost of energy, LCOE) [8, 9] and can enhance the energy production [3, 10]. Moreover, other synergies [11] were observed between the two renewable sources, which include the improvement for operation and maintenance [12].

However, the development of the offshore renewable industry is still in its infancy in Australia, although the local workforce and industry are mature enough in onshore renewables (including wind, solar and hydro). In addition, whilst multiple locations around the Australian coastline have been identified with great potential for future hybrid development [3, 13], a detailed analysis of the feasibility and economic potential of combined offshore wind and wave energy has not been performed for Australia's Exclusive Economic Zone (EEZ). This also hinders the practical implementation of development strategies for policymakers and project developers.

In general, LCOE and LACE (the levelized avoided cost of

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energy) are the most common fundamental matrices to evaluate the economic potential for new energy technologies. Note that LCOE defines the total cost of energy production over the expected economic lifetime of a generation unit and is usually expressed in dollars per megawatt-hour ($/MWh). However, LCOE does not capture the energy benefits and is insufficient to value the power system attributed to a particular generation source. Therefore, LACE is proposed [14, 15] as it captures revenue available to a generating source by considering the marginal generation price in the electricity market. However, LACE does not consider the energy market and environmental sector regulations, such as regulation penalties from the local electricity market and the impact of future carbon pricing.

Therefore, this paper aims to investigate the high-fidelity life-cycle cost of a co-located offshore wind and wave energy farm in multiple key locations in Australia's EEZ. Then, the economic feasibility of developing the proposed combined energy farm is studied by integrating the electricity market regulation cost and future carbon offset benefits based on a new LACE matrix.

The structure of this paper is as follows: Section 2 introduces the data collection, system configuration and energy generation and variability. The detailed life-cycle cost models and economic matrix of an offshore energy farm are developed in 3. Section 4 analyses the primary results of this study and conclusions are drawn in Section 5.

2. DATA COLLECTION AND SYSTEM DESCRIPTIONS

2.1 Site Selection and Data Sources

In order to assess the techno-economic feasibility of offshore energy systems and to cover the wind and wave climate diversities in Australia [3], multiple key locations in the Australian coastal region were selected as shown in Fig. 1 and geographic information is listed in Table. 1. These locations have been identified with good potential for developing offshore renewables [3, 16] in terms of either industry interests, state government energy policies or renewable energy zones and targets.

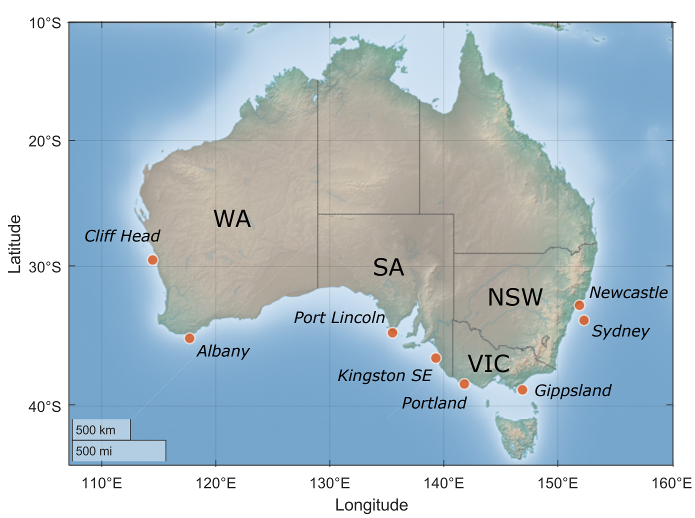

FIGURE 1: THE MAP OF CHOSEN LOCATIONS IN THIS STUDY

The wind and wave resources in the studied areas are obtained from wind-wave hindcast data (by the WaveWatch III model) [17]. This hourly data operates on a series of nested grids of 4 arcminutes (~ 7 km) in Australian regions and has been validated by in-situ wave buoy and satellite altimeter observations [18]. The main parameters of the data set considered in this paper include the wind speed v_w at 100 m height, significant wave height H_s, wave peak period T_p and the bathymetry (water depth d_{water}).

TABLE 1: GEOGRAPHIC INFORMATION OF EIGHT OFFSHORE SITES AROUND AUSTRALIA

Locations	State	Coordinates	Depth	Distance
Newcastle	NSW	32.9°S 151.9°E	$\sim 80\ m$	$\sim 15\ km$
Sydney	NSW	34.0°S 152.3°E	$> 100\ m$	$\sim 117\ km$
Gippsland	VIC	38.9°S 146.9°E	$\sim 25\ m$	$\sim 16\ km$
Portland	VIC	38.5°S 141.8°E	$\sim 50\ m$	$\sim 23\ km$
Kingston SE	SA	36.7°S 139.3°E	$\sim 45\ m$	$\sim 49\ km$
Port Lincoln	SA	34.9°S 135.5°E	$\sim 70\ m$	$\sim 10\ km$
Albany	WA	35.3°S 117.7°E	$\sim 70\ m$	$\sim 23\ km$
Cliff Head	WA	29.5°S 114.8°E	$\sim 50\ m$	$\sim 46\ km$

To evaluate the economic benefits and viability of developing offshore energy in multiple locations, historical data of different States in Australia with the hourly resolution, such as demand information, electricity market price and regulation service cost, are obtained from AEMO [19]. In addition, the transmission network and substation geographic information data were obtained from [20]. Note that the same analysis method described in this paper can be applied to other sea locations in Australia.

2.2 System Configurations

In this paper, a DC-linked hybrid power unit is considered based on the study [4, 21] as illustrated in Fig. 2. The direct-drive (DD) technology is used for offshore WT (see Fig.2a) as it eliminates the traditional gearbox hence greatly reducing the risk of drive-train failure in the harsh marine environment. The WEC conversion system is illustrated in Fig. 2a. Note that the buoy and the Power-take-off (PTO) system convert the kinetic energy in the incident wave to mechanical energy in the form of shaft power which is coupled with the conventional rotating generator.

A DD brushless permanent magnet synchronous generator (PMSG) is considered with a DC-DC converter. Note that the topology can easily be integrated into WECs to provide a common coupling point for a DC link within and among the hybrid power units. In addition, the rotor side converter (RSC) is needed to achieve maximum power tracking, and the grid side converter (GSC) is required for the main grid connection either at the offshore or onshore substations.

Figure. 2c shows the layout of the hybrid power unit (HPU), which integrates one WT with four WECs. The four WECs are evenly distributed around WT with a distance of 300 m to reduce the hydrodynamic impact between conversion devices. WEC power is delivered to the common coupling point at the WT platform via WEC-to-WT cables. In addition, the power of the HPU is transformed to the offshore substation via inter-array cables (Fig.2b). In terms of transmission technology selection, a break-even distance between HVDC and HVAC is about 56 km as reported in [22].

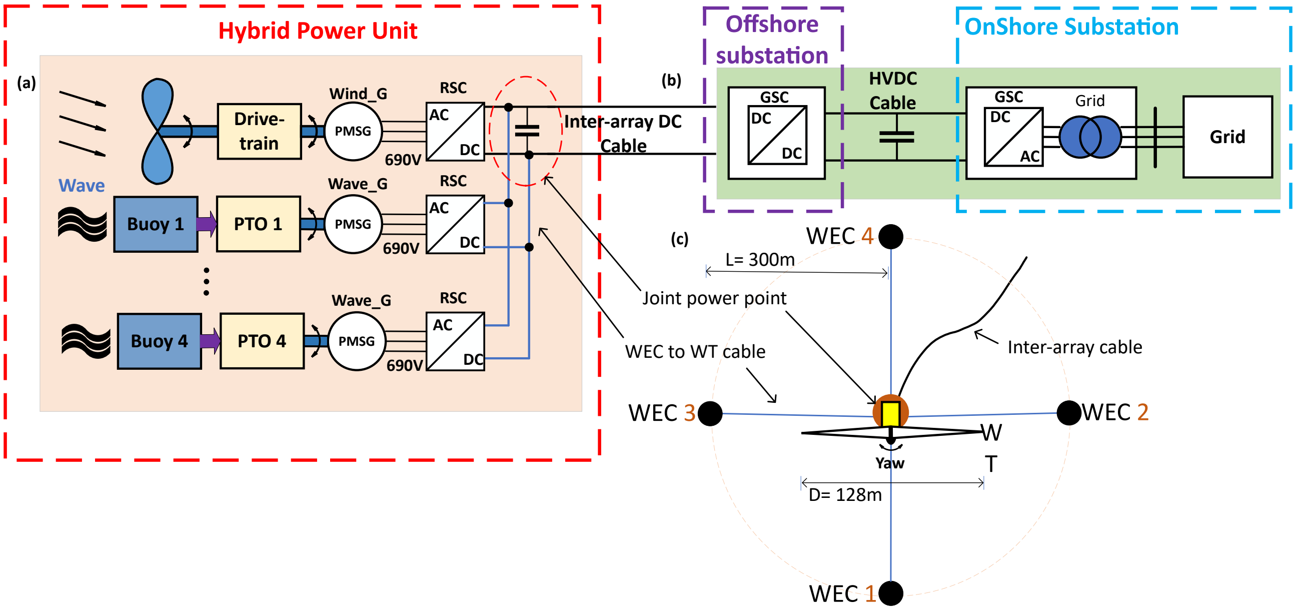

FIGURE 2: SYSTEM DIAGRAM OF: A) HPU, D) TRANSMISSION TOPOLOGY AND C) THE TOP VIEW OF HPU.

2.3 Assessment of Energy Resources, Generation and Variability

It is known that the wind power density (P_{wind}) is proportional to the cube of the wind speed (v_w) at hub height, given by:

$$P_{wind} = \frac{1}{2}\rho_a v_w^3. \tag{1}$$

where ρ_a is the air density (assuming 1.15 kg/m^2 at 15 °C) at hub height. The power density (power per unit of crest width, kw/m) of irregular wave (P_{wave}) can be defined based on the linear wave theory and assumption of deep water [18], given by:

$$P_{wave} = \frac{\rho_w g^2}{64\pi} H_s^2 T_e \tag{2}$$

where H_s and T_e are the significant wave height and wave energy period ($T_e = 0.857T_p$). ρ_w and g are the water density and gravity acceleration constant respectively.

The energy generation of wind and wave can be estimated by the power curve of a WT and the power matrix of a WEC (given the wind hub speed and wave statistics). These methods have been widely used to assess the energy availability, variability and economic analysis for offshore energy farms [3, 23], to avoid costly simulation studies and to obtain a quick assessment. In this analysis, a commercial WT, Gamesa G128-5 MW, is selected as a reference WT. A typical WEC type (WaveStar C6 600 kW) is used to represent the generic wave energy generation. The power curve and the power matrix of the benchmark turbine can be found in the study [3]. Note that the hydrodynamic analysis of foundation types is applied to the WT, hence the impact of the platform on the WT power curve and the direction information are ignored in this paper.

To evaluate the power variability of offshore wind energy, a normalized variability index, coefficient of variability (CV), is used in this paper, given by:

$$CV = \frac{\sigma_x}{\mu_x}. \tag{3}$$

where σ_x and μ_x are the standard deviations and the mean power of generation time series.

3. ECONOMIC MODELLING

3.1 Life-cycle Cost Models

To evaluate the life-cycle cost (LCC) of offshore wind-only systems and combined wind and wave (WW) systems, two exemplar energy farm configurations with the same 500MW installed capacity are considered in this study. The offshore farm includes 100 5 MW WT in a standalone wind farm and 67 combined WW generation units (5 MW + 2.4 MW) in a combined energy farm. Therefore, both options can utilize the same electrical transmission infrastructure.

The life-cycle cost model of offshore wind and wave farms is illustrated in Fig. 3, where the LCC models of an offshore wind farm can be divided into two different subsystem costs: generation systems and connection systems. In terms of the project development procedure, LCC can be categorized by capital expenditure (CAPEX in cyan), operational expenditure (OPEX) (in green) and decommissioning expenditure (DCPEC in grey). The details of these cost capsules are described in the following subsections.

The LCOE used in this paper is given by:

$$\text{LCOE} = \frac{\text{CRF} \cdot (\text{CAPEX} + \text{DCPEX}) + \text{OPEX}}{\text{AEP}}, \tag{4}$$

where CAPEX is the overnight capital cost. OPEX and DCPEX are the annual operational expenditure and the total decommissioning cost. CRF is the capital recovery factor [24], which is defined at 7.1% based on the interest rate (5% p.a.) and 25 years

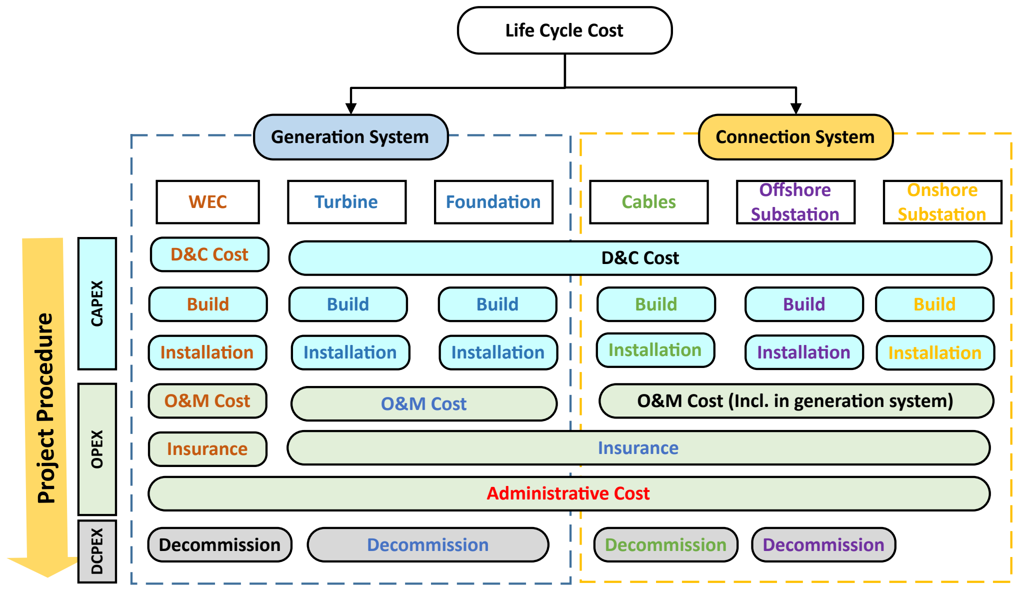

FIGURE 3: THE LIFECYCLE COST DIAGRAM IN AN OFFSHORE ENERGY FARM: 1) BY DIFFERENT SUBSYSTEMS, SUCH AS GENERATION SYSTEMS AND CONNECTION SYSTEMS; 2) BY VARIOUS PROJECT PERIODS, SUCH AS CAPEX, OPEX AND DCPEX.

of the project's economic life. The Annual Energy Production (AEP) from 2017 to 2021 is calculated by:

$$\text{AEP} = \alpha \cdot \eta \cdot \left(\sum_{t=2017}^{2021} E_t \right) / 5. \tag{5}$$

Here E_t is the energy generation at year t. α is the energy farm availability, estimating at 94% [25] for wind-only system and 96.3% for combined system [26]) and η is the energy conversion efficiency, estimating at 90.5% (1.8% of electrical losses and 7.7% of aerodynamics losses [27]).

3.1.1 CAPEX. The CAPEX for an offshore energy farm compromises the development and consenting cost ($C_{D\&C}$), the equipment building cost (C_{Build}), the installation cost ($C_{install}$) and the power connection cost ($C_{Connection}$), which is represented by:

$$\text{CAPEX} = C_{D\&C} + C_{Build} + C_{Install} + C_{Connection}, \tag{6}$$

The D&C cost includes but is not limited to site selection, survey, characterization, permitting and array design. In this paper, the $C_{D\&C}$ of a 500 MW offshore energy farm is estimated at 157.5 MA$, which is in line with the values of 105 M€ (assumed a currency exchange rate of 1.5) for an exemplar 500 MW offshore wind farm in the studies [25, 28]. Note that the D&C cost is assumed to be the same for the bottom-fixed wind farm and floating wind farm. In addition, due to the lack of wave projects being commercialized, the $C_{D\&C}$ for a WEC array is estimated by 12% of the total initial investment of WEC farm [29].

The WT equipment cost includes the turbine cost ($C_{turbine}$) and foundation cost (C_{found}) which usually are the biggest share of the total CAPEX of the offshore wind farms. In this paper, the generic turbine (including tower, nacelle, hub and blades) cost is estimated at 1300 A$/KW based on the average wind turbine pricing from most market orders received by [30].

The foundation type selection is primarily based on the water depth of the selected sea site. In this paper, both bottom-fixed and floating foundations are considered to accommodate various water depths in different locations, being deployed at the depth below and above 55 m, respectively. The cost of the monopile foundation is estimated by a parametric expression reference to the hub height (h), turbine diameter (Dturbine) and water depth ($d$water) in study [31], given by:

$$C_{found}^{fixed} = 480 \cdot P_{WT} \left[1 + 0.02(d\text{water} - 8)\right] \cdot \left[1 + 0.8 \cdot 10^{-6} \left(h \left(\frac{D\text{turbine}}{2} \right)^2 - 10^5 \right) \right] \ [\text{kA\$/turbine}] \tag{7}$$

The floating foundation provides benefits in manufacture, transmission and installation procedures. Since this is a novel platform, the cost matrix cannot be found in the public domain. Therefore, in this paper, the semi-submersible floating platform is considered and its cost has been estimated by the steel material cost (1500 A$/t), platform mass (550 t/MW, estimated by [32]) and manufacturing process (cost factor of 2 [27]).

The installation cost of an offshore WT is highly determined by the travel distance to the shore and installation vessels. Due to the lack of large-scale offshore wind farm deployment in Australia, the installation costs of the turbine and foundation in this paper are estimated by the installation vessel rent cost and the number of days needed for installation, which is given by:

$$C_{install} = N_{unit} \left(\frac{(T_{turbine} + T_{found} + 2 \cdot T_{trip}) \cdot C_{vessel}^{\text{Jack-up}}}{N_{vist}^{\text{Jack-up}}} \right), \tag{8}$$

$$Day_{trip} = \frac{2 \cdot d_{shore}}{V_{vessel}^{\text{Jack-up}} \cdot h_{work}}, \tag{9}$$

where N_{unit} is the number of generation units in the offshore farm. $T_{turbine}$ and T_{found} are the number of days for turbine and foundation installation. T_{trip} is the days for travelling from the shore to the installation sea site which is estimated by the specific vessel speed (V_{vessel}) and working hours (h_{work}, 16 working hours for one day in this paper). The installation day cost of the Jack-up vessel ($C_{vessel}^{\text{Jack-up}}$) and vessel travel speed are estimated at 350k A$ and 20 km/h [33]. The WEC installation cost is normally estimated at 8-17% of the initial investment and hence, the WEC installation cost in this paper is estimated at 13% of the initial WEC investment [34].

The weather window (which the offshore site has to be accessible) significantly impacts the offshore energy farm installation procedure and specialized vessel charter period. Therefore, this paper considers the weather limitations of vessels with maximum operability at 1.65 m for H_s and 16 m/s for v_w. In addition, the standby cost of vessels is estimated by the time ratio ($\text{TR}_{weather}$ is defined by comparing the available time of operation a year and the total hours in a year) and the percentage of the standard day rate (25% is used in this paper to reflect the OPEX of the shipowner), which is given by:

$$C_{standby} = 0.25 \cdot C_{install} \left(\frac{1}{\text{TR}_{weather}} - 1 \right) \tag{10}$$

It should be noted here that subject to the availability of specialized installation vessels in the global market, the optimal schedule of using such vessels for installing large offshore WT is expected to become critical in the future.

The connection costs are divided into the substation cost (C_{sub}) and cabling cost (Ccable). The substation cost is estimated by:

$$C_{sub} = N_{\text{off-sub}} \left(C_{\text{off-sub}}^{\text{equip}} + C_{\text{off-sub}}^{\text{install}} \right) + N_{\text{on-sub}} C_{\text{on-sub}}. \tag{11}$$

Here, $N_{\text{off-sub}}$ and $N_{\text{on-sub}}$ are the number of offshore substations and onshore substations (2 and 1 are used for HVAC and HVDC substations for a 500 MW energy farm). $C_{\text{off-sub}}^{\text{equip}}$ and $C_{\text{off-sub}}^{\text{install}}$ are the equipment cost and installation costs of offshore substations. The key cost parameters of substations are shown in Table. 2. Note that all the values in Euro are converted to Australian dollars based on the average currency exchange rate (1.5 between AUD and Euro) in 2021.

TABLE 2: THE INPUT PARAMETERS FOR SUBSTATION COST [8, 22, 31, 35].

Substation	AC offshore	DC offshore	DC onshore
Equipment	34 M€	142 M€	84 M€
Installation			
Fixed foundation	23.8 M€		
Float foundation	18.6 M€		

The cabling cost includes inter-array cable cost ($C_{\text{inter-cable}}$) which is estimated by a regression equation in [36] and the transmission cable cost (Ctrans-cable) which can be estimated by:

$$C\text{trans-cable} = (C_{\text{cable}}^{\text{equip}} + C_{\text{cable}}^{\text{install}}) \cdot D_{trans}. \tag{12}$$

Here, $C_{\text{cable}}^{\text{equip}}$ and $C_{\text{cable}}^{\text{install}}$ are the unit price of cable acquisition cost (kA$/km) and installation cost (kA$/km). D_{trans} is the transmission distance to the nearest onshore transmission substation. The input parameters are shown in Table. 3.. Note that the costs of the utilization of AC compensators and Static Synchronous Compensator (STATCOMs) have not been directly analysed and it is assumed to be covered in the HVAC substation cost if selected in this work.

TABLE 3: THE INPUT PARAMETERS FOR TRANSMISSION CABLES [27, 36, 37].

Transmission Cables	HVAC	HVDC
Equipment	1036 k€/km	443 k€/km
Installation	624k €/km (single cable, single trench)	

Note that dismantling WTs will require the use of specialised vessels, cranes and other heavy equipment. Therefore, due to the limited knowledge of decommissioning offshore wind farms, this cost has been estimated in relation to the installation cost with ratios of 70%, 90% and 10% for the completed WT (incl. foundations), substations and undersea cables respectively. In addition, the return value of a WT is assumed at approximately 375 kA$/MW (250 k€/MW [22, 27]), 112.5 kA$/MW for a semi-submerged floating WT and Jacket based WT, respectively.

3.1.2 OPEX. The O&M services for an offshore energy farm include the operations related to the management (such as health and safety, control and operation) of the asset, including the WTs, monitoring and vessels and quayside infrastructure, and the maintenance activities, such as planned maintenance and unplanned service in response to system faults. In light of this, the associated annual operational expenditure (OPEX) comprises the operation and maintenance cost ($C_{O\&M}$), insurance cost (Cinsurance) and administrative cost (C_{admin}), which is given by:

$$\text{OPEX} = C_{O\&M} + C_{Insurance} + C_{admin}, \tag{13}$$

Unlike onshore operations, offshore energy O&M are more complex and highly influenced by the weather conditions and availability of specialised vessels. Due to the lack of large-scale offshore farm projects, in this paper, a first-order estimation of $C_{O\&M}$ is estimated at about 137 A$/kW (86 £/kW in [35]) which is close to the average value between 89 A$/kW and 200 A$/kW [23, 28, 30, 35, 38]. Note that, an additional cost at a value of 60 A$/MW/kW per year (the variable cost which is associated with distance to the shore, d_{shore}) is used in this paper for far shore distance (> 60 km). The O&M cost of the WEC system is estimated to be 4% of its total CAPEX [34]. Note that, due to the coordinated efforts such as the shipping vessel, storing and labour costs, the total installation cost and OPEX of the combined wind and wave system have 10% and 12 % reduction, respectively [26].

The insurance cost (Cinsurance) relies on the development phase of the project and different calculation methods have been proposed, such as 15% of O&M cost in [26], 22.5 to 30 A$/kW [25] and about 1% of the initial cost of WT [39]. In this study, the unit insurance cost of 26.5 A$/kW/year is used for the selected WT. The insurance cost of a WEC is estimated as 2% of the O&M

cost of co-located farm [28]. Furthermore, the fixed annual labour (such as technician and managers services) and administrative cost (C_{admin}) is estimated at 7.15 MA$ in this study based on the 500 MW benchmark wind farm [25].

3.2 Economic Matrix

To evaluate the economic potential of offshore energy farms with consideration of grid regulation and carbon price on developing offshore energy, a novel LACE model has been developed, given by:

$$\mathrm{LACE} = \frac{\left(\frac{\sum_{j=1}^{j=60}\mathrm{Price}_j\cdot\mathrm{MEP}_j}{5\cdot Pinstalled} + \mathrm{REGC}\right)\mathrm{ECF} + CC(CP + \mathrm{COB})}{\mathrm{AEP}/Pinstalled}, \tag{14}$$

where Price_j and MEP_j are the average electricity marginal price (in A$/MWh) and the amount of energy generation (in MWh) at month j. In this study, 60 months of price and generation profiles have been considered between 2017 and 2021. The REGC represents the annual regulation cost which is estimated by generation profiles, demand profiles and annual average regulation price (19.31 A$/MWh and 12.94 A$/MWh obtained from AEMO [40]) and the calculation method is based on the study [33].

The CC and CP are the capacity credit (in %) and the capacity payment (in A$/kW) with an estimated value at 25% [14] and 750 A$/kW (capital cost for large gas turbine [38]). It is noted that CC represents the ability of the unit to provide system reliability reserves and the CP represents the value to the system of meeting the reliability reserve margin.

To immune the significant price fluctuations due to rare events or conditions, the Escalation Calibration Factor (ECF) is proposed to capture the long-term (10 years) price variation pattern. It is calculated by the geometric mean of price variations (in %) of each year from 2012 to 2021.

In terms of environmental sector regulations, a carbon price would be an effective mechanism to support the ambitions of 100% renewables by 2030 and net zero goals by 2050 in Australia. In this paper, the annual carbon offset benefit (COB, unit in A$/kW) can be estimated from the emission factors and annual energy produced (AEP, MWh) by the offshore wind farm, which is given by:

$$\mathrm{COB} = \frac{P_{carbon}\cdot\mathrm{EMF}\cdot\mathrm{AEP}}{P_{\mathrm{installed}}}. \tag{15}$$

Here, P_{carbon} and EMF are the carbon price (56.4 A$/MWh [41]) and emission factor (dimensionless) which is a coefficient to convert the generation activity into greenhouse gas (GHG) emission with values of 0.70, 0.21, 0.83 and 0.55 for NSW, SA, VIC and WA, respectively [42].

Therefore, the economic potential (EP) can be assessed by comparing LACE and LCOE, given by:

$$\mathrm{EP} = \mathrm{LACE} - \mathrm{LCOE}. \tag{16}$$

It is noted that the net value between LCOE and LACE shows the initial understanding of the economic feasibility of an offshore wind energy farm in a given location. The positive value of difference indicates better economic potential for developing offshore wind energy and vice versa.

4. RESULTS

This section analyses the major results of offshore wind and wave energy resources assessment, LCC cost breakdown and economic potential of both standalone offshore wind farm and combined energy farm.

4.1 Resources Assessment

Table. 4 shows the main parameters of offshore wind and wave resources in 8 sea locations in Australia. In general, the offshore wind resources are abundant in these locations (most above 8.5m/s defined as medium to high wind by IEC wind Turbine classes [43]), particularly in the Sydney site, Kingston SE and Cliff Head with power density above 0.85 kW/m^2. Wave energy has great potential in the southern and western parts of Australia, such as Portland, Kingston SE, Port Lincoln, Albany and Cliff Head, with wave power density above 40 kW/m. This makes a unique possibility for integrating offshore wind and wave energy in a multi-purpose platform. It is noted that, due to the shallow water and geographic barrier of Bass Strait, the wave resource is not rich in Gippsland.

TABLE 4: OFFSHORE WIND AND WAVE ENERGY RESOURCES IN EIGHT SITES FROM 2017 TO 2021.

Locations	Wind resource		Wave resource		
	$\overline{v}_w$ (m/s)	$\overline{P}_{wind}$ (kW/m^2)	$\overline{H}_s(m)$	$\overline{T}_p(s)$	$\overline{P}_{wave}$(kW/m)
Newcastle	6.7	0.30	1.50	9.3	11.6
Sydney	10.2	1.03	2.04	9.1	19.1
Gippsland	8.5	0.64	1.02	9.7	4.5
Portland	8.6	0.63	2.79	14.0	57.5
Kingston SE	9.6	0.90	2.62	13.7	47.3
Port Lincoln	8.1	0.54	2.38	14.1	42.8
Albany	9.1	0.80	3.07	13.7	65.9
Cliff Head	9.8	0.88	2.76	13.9	53.5

The WT foundations and transmission technologies highly rely on the site specifications such as water depth and the distance to the point of common coupling (PCC) of the onshore grid. Therefore, the various foundation types and transmission topologies are selected in this study, as shown in Table. 5. It can be seen that the floating platform is used in locations with a water depth of more the 55 m (such as Newcastle, Sydney and Albany) and the HVDC technology is more economic for transmission distances over 56 km (such as in Sydney, Kingston SE and Cliff Head).

TABLE 5: TECHNICAL CONFIGURATIONS AND ENERGY PRODUCTION CHARACTERISTICS IN EIGHT SITES FROM 2017 TO 2021.

Locations	Technical parameters			System Configs. (WT/WW)		
	Found	D_{Trans}	Trans.	AEP (TWh/yr)	Capacity Factor	CV
Newcastle	Floating	22 km	HVAC	1.22/**1.43**	0.30/**0.34**	0.99/**0.69**
Sydney	Floating	118 km	HVDC	2.46/**2.54**	0.60/0.60	0.60/**0.49**
Gippsland	Fixed	39 km	HVAC	**1.88**/1.67	**0.46**/0.39	0.79/**0.74**
Portland	Fixed	21 km	HVAC	1.87/**2.12**	0.45/**0.50**	0.77/**0.49**
Kingston SE	Fixed	127 km	HVDC	2.25/**2.37**	0.55/**0.56**	0.66/**0.47**
Port Lincoln	Fixed	7 km	HVAC	1.74/**1.96**	0.42/**0.46**	0.79/**0.52**
Albany	Floating	34 km	HVAC	2.07/**2.29**	0.50/**0.54**	0.71/**0.45**
Cliff Head	Fixed	72 km	HVDC	2.43/**2.57**	0.59/**0.60**	0.60/**0.45**

In terms of energy generation characteristics, the combined wind and wave energy farm has more annual energy production compared to the standalone wind farm except for the Gippsland location, as shown in Table. 5. Also, the capacity factors (CFs, which are defined by the ratio of total annual energy generation and theoretical maximum annual energy generation) in most offshore locations are greater than 0.40 (except Newcastle) which is higher than the typical onshore wind energy farm in Australia (normally less than 0.35). In addition, the combined system has the advantage of reducing energy variability but presents different levels in all locations. For example, the combined system in Albany has the best power smooth effect with 36% reductions of energy variability while Gippsland presents the lowest performance (4% reduction).

4.2 Economic Assessment

To evaluate the economic feasibility of developing an offshore energy farm in Australia, the results of major parameters of LCC breakdowns (such as CAPEX, OPEX and annual expenditure, AnEXP), annual regulation cost (REGC), carbon offset benefits (COB) and overall economic potential index (such as LACE, LCOE and EP) are analysed and given in Table. 6.

In general, the CAPEX of offshore energy farms in these locations are between 4307 A$/kW and 6452 A$/kW for a standalone wind system and between 4747 A$/kW and 6197 A$/kW for a combined system. The wide CAPEX range significantly depends on the locations deployed and the technologies used. For example, due to the expensive floating foundation and long-distance transmission, the Sydney location has the highest CAPEX compared to other locations. In contrast, Port Lincoln has the lowest CAPEX resulting from cheaper fixed foundations and adjacency to the PCC of the grid. It is noted that the CAPEX of the combined system in Sydney and Albany are slightly lower than that of a standalone wind system. The possible reasons for cost reduction are the significant shared opportunities (such as infrastructure, installation and O&M costs).

The values of OPEX are calculated similarly in most locations (except Sydney) as their estimations are based on the power capacity and are located less than 60 km from the shoreline. Sydney location has higher OPEX due to the additional variable cost for far shore operation (greater than 60 km). The annual expenditure (defined by $AnEXP = CRF \cdot (CAPEX + DCPEX) + OPEX$) covers the impact of the financial loan and economic lifetime on an offshore energy farm. Typically, the value for a combined system is higher than the standalone wind system (in most locations) unless significant cost-sharing (such as in Sydney).

Due to the variability involved in the offshore renewables, the estimated REGC for offshore wind-only farms account for 7.1% of total annual expenditure (AnEXP) which could be a maximum of 21 mA$ per year in Gippsland and a minimum of 15 mA$ per year in Newcastle. As it was summarised in Table. 6, REGC for the combined system has been reduced by an average of 25% compared to that of wind only system. It is also found that the magnitudes of these regulation reductions are proportional to the values of CV in different locations. For example, Albany has the most significant regulation reduction and Gippsland has a minimal regulation reduction.

The carbon offset benefits significantly depend on the annual energy production and emission factor of the electricity grid in different Australian States. Kinston SE and Port lincoln have low COB as SA has the lowest EMF due to all generation capacity from gas, while Gippsland, Portland, Newcastle and Sydney locations show high COBs due to high EMF (attributed to the dominated coal power plant) in VIC and NSW. The value of COB indicates the significance and potential for developing low-emission generation (such as ocean renewables) in the future carbon market to meet the net zero.

It is shown that the combined offshore wind and wave energy farms in most locations have more competitive LCOE compared to the standalone wind farm (excluding Gippsland). In addition, due to the increased energy production and lower energy variability (less regulation penalty), the combined WW system has better LACE than the standalone wind farm. In general, Kingston SE, Gippsland and Portland have the best economic potential for developing offshore wind energy. However, Portland, Kingston SE, Sydney and Port Lincoln have a great potential for developing combined energy farms due to the abundant wind and wave resources n these locations. However, due to the insufficient wave resource, the LCOE of the combined energy farm in Gippsland is 21% higher than the value of the wind-only energy farm. It should be noted that Newcastle has the highest LCOE and lowest economic potential for developing both offshore wind and wave energy compared to other studied locations. Finally, this study aims to provide a preliminary techno-economic assessment of developing offshore wind and wave energy in Australia. However, the detailed evaluation highly relies on specific projects, locations, local supply chains, labour markets, etc.

5. CONCLUSION

This paper investigates the feasibility of combined wind and wave energy farm and compares it with a standalone offshore wind farm via a techno-economic assessment. The results in this paper indicate that compared with the standalone wind farm, the combined wind and wave energy farm has unique advantages, such as lower LCOE, a lower regulation penalty from the electricity market and higher energy production and carbon offset benefits. In terms of location, Portland in VIC and Kingston SE in SA present better feasibility than other locations for developing combined energy farms. In addition, the analysis models developed in this paper can be easily applied to study offshore wind-only or wave-only farms in other Australian sea locations. The future work will apply this analysis method to develop a detailed mapping of combined wind and wave energy across all Australian exclusive economic zones.

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REFERENCES

[1] "Australia's Long Term Emissions Reduction Plan." Technical report no. Commonwealth of Australia. 2021.

TABLE 6: ECONOMIC PARAMETERS OF OFFSHORE WIND AND WAVE ENERGY FARMS IN EIGHT SITES FROM 2017 TO 2021.

Locations	LCC cost breakdown (WT/WW)			Regulation and carbon offset (WT/WW)		Overall economic parameters (WT/WW)		
	CAPEX (A$/kW)	OPEX (A$/kW/yr)	AnEXP (A$/kW/yr)	REGC (A$/kW)	COB (A$/kW)	LACE (A$/MWh)	LCOE (A$/MWh)	EP
Newcastle	**5648**/5653	176/186	577/587	31.1/24.5, -21%	103/117	152/162	**261/224**	-109/-62
Sydney	6452/**6197**	**180/188**	**638/628**	40.4/32.3, -20%	206/207	120/130	143/135	-23/**-4**
Gippsland	**4462**/4853	176/186	493/530	41.1/32.3, -21%	188/160	130/152	**145/175**	**-15**/-23
Portland	**4619**/4958	176/186	504/538	38.3/27.1, -29%	186/204	131/142	149/139	**-18/3**
Kingston SE	**5027**/5234	176/186	533/557	41.8/30.7, -26%	57/58	116/127	131/129	**-14/-2**
Port Lincoln	**4307**/4747	176/186	482/523	36.6/26.9, -27%	44/48	127/136	153/146	-26/**-10**
Albany	6023/**5907**	176/186	604/605	40.1/27.1, -32%	137/146	90/100	161/145	-71/-45
Cliff Head	**4830**/5101	176/186	519/548	38.8/29.0, -25%	160/164	85/95	118/117	-33/-22

[2] AEMO. "Engineering Roadmap to 100% Renewables." Technical report no. AEMO. 2022.

[3] Gao, Qiang, Khan, Salman Saeed, Sergiienko, Nataliia, Ertugrul, Nesimi, Hemer, Mark, Negnevitsky, Michael and Ding, Boyin. "Assessment of wind and wave power characteristic and potential for hybrid exploration in Australia." *Renewable and Sustainable Energy Reviews* Vol. 168 (2022): p. 112747.

[4] Gao, Qiang, Ertugrul, Nesimi, Ding, Boyin and Negnevitsky, Michael. "Offshore Wind, Wave and Integrated Energy Conversion Systems: A Review and Future." *2020 Australasian Universities Power Engineering Conference (AUPEC)*: pp. 1–6. 2020. IEEE.

[5] Gao, Qiang, Ertugrul, Nesimi and Ding. "Method and Analysis of Short-term Intermittency in Hybrid Wind and Wave Power Unit." *2022 Australasian Universities Power Engineering Conference (AUPEC)*: pp. 1–6. 2022. IEEE.

[6] Osman, Peter, Hayward, Jennifer and Foster, James. "Dispatchability and energy storage costs for complementary wave, wind, and solar PV systems." .

[7] Gao, Qiang, Bechlenberg, Alva, Vakis, Antonis I., Ertugrul, Nesimi, Jayawardhana, Bayu and Ding, Boyin. "Techno-economic Assessment of Offshore Wind and Hybrid Wind-Wave Farms with Energy Storage Systems." *Submitted to Renewable and Sustainable Energy Reviews* .

[8] Gao, Qiang, Yuan, Rui, Ertugrul, Nesimi, Ding, Boyin, Hayward, Jenny and Li, Ye. "Analysis of Energy Variability and Costs for Offshore Wind and Hybrid Power Unit with Equivalent Energy Storage System." *Submitted to Applied Energy* .

[9] Shah, Kamran Ali, Meng, Fantai, Li, Ye, Nagamune, Ryozo, Zhou, Yarong, Ren, Zhengru and Jiang, Zhiyu. "A synthesis of feasible control methods for floating offshore wind turbine system dynamics." *Renewable and Sustainable Energy Reviews* Vol. 151 (2021): p. 111525.

[10] Ferrari, Francesco, Besio, Giovanni, Cassola, Federico and Mazzino, Andrea. "Optimized wind and wave energy resource assessment and offshore exploitability in the Mediterranean Sea." *Energy* Vol. 190 (2020): p. 116447.

[11] Clemente, Daniel, Rosa-Santos, P and Taveira-Pinto, F. "On the potential synergies and applications of wave energy converters: A review." *Renewable and Sustainable Energy Reviews* Vol. 135 (2021): p. 110162.

[12] Ren, Zhengru, Verma, Amrit Shankar, Li, Ye, Teuwen, Julie J.E. and Jiang, Zhiyu. "Offshore wind turbine operations and maintenance: A state-of-the-art review." *Renewable and Sustainable Energy Reviews* Vol. 144 (2021): p. 110886.

[13] Rasool, Safdar, Muttaqi, Kashem M, Sutanto, Danny and Hemer, Mark. "Quantifying the reduction in power variability of co-located offshore wind-wave farms." *Renewable Energy* Vol. 185 (2022): pp. 1018–1033.

[14] Beiter, Philipp, Musial, Walter, Kilcher, Levi, Maness, Michael and Smith, Aaron. "An assessment of the economic potential of offshore wind in the United States from 2015 to 2030." Technical report no. National Renewable Energy Lab.(NREL), Golden, CO (United States). 2017.

[15] Beiter, Philipp, Musial, Walter, Smith, Aaron, Kilcher, Levi, Damiani, Rick, Maness, Michael, Sirnivas, Senu, Stehly, Tyler, Gevorgian, Vahan, Mooney, Meghan et al. "A spatial-economic cost-reduction pathway analysis for US offshore wind energy development from 2015–2030." Technical report no. National Renewable Energy Lab.(NREL), Golden, CO (United States). 2016.

[16] Government, Victoria State. "Wind Offshore Implementation Statement." https://www.energy.vic.gov.au/renewable-energy/offshore-wind-energy (2022). Accessed: 2022-10-03.

[17] CSIRO. "CAWCR Wave Hindcast aggregated collection." https://data.csiro.au/collections/collection/CI46550 (2020). Accessed: 2022-06-30.

[18] Hemer, Mark A, Zieger, Stefan, Durrant, Tom, O'Grady, Julian, Hoeke, Ron K, McInnes, Kathleen L and Rosebrock, Uwe. "A revised assessment of Australia's national wave energy resource." *Renewable Energy* Vol. 114 (2017): pp. 85–107.

[19] AEMO. "Aggregated price and demand data." https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data (2022). Accessed: 2022-11-30.

[20] Australian Government. "Electricity Transmission Substations." https://data.gov.au/dataset/ds-ga-13be62a4-4fe3-f812-e053-12a3070a22be/details?q= (2022). Accessed: 2022-11-30.

[21] Gao, Qiang, Ding, Boyin, Ertugrul, Nesimi and Li, Ye. "Impacts of mechanical energy storage on power generation in wave energy converters for future integration with offshore wind turbine." *Ocean Engineering* Vol. 261 (2022): p. 112136.

[22] Martinez, A and Iglesias, G. "Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic." *Renewable and Sustainable Energy Reviews* Vol. 154 (2022): p. 111889.

[23] Martinez, A and Iglesias, Gregorio. "Multi-parameter analysis and mapping of the levelised cost of energy from floating offshore wind in the Mediterranean Sea." *Energy Conversion and Management* Vol. 243 (2021): p. 114416.

[24] Aldersey-Williams, John and Rubert, Tim. "Levelised cost of energy–A theoretical justification and critical assessment." *Energy policy* Vol. 124 (2019): pp. 169–179.

[25] Myhr, Anders, Bjerkseter, Catho, Ågotnes, Anders and Nygaard, Tor A. "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective." *Renewable energy* Vol. 66 (2014): pp. 714–728.

[26] Astariz, S, Perez-Collazo, C, Abanades, J and Iglesias, G. "Co-located wave-wind farms: Economic assessment as a function of layout." *Renewable Energy* Vol. 83 (2015): pp. 837–849.

[27] Bjerkseter, Catho and Ågotnes, Anders. "Levelised costs of energy for offshore floating wind turbine concepts." Master's Thesis, Norwegian University of Life Sciences, Ås. 2013.

[28] Clark, Caitlyn E, Miller, Annalise and DuPont, Bryony. "An analytical cost model for co-located floating wind-wave energy arrays." *Renewable Energy* Vol. 132 (2019): pp. 885–897.

[29] Dalton, Gordon J, Alcorn, Raymond and Lewis, T. "Case study feasibility analysis of the Pelamis wave energy converter in Ireland, Portugal and North America." *Renewable Energy* Vol. 35 No. 2 (2010): pp. 443–455.

[30] IRENA. "Renewable power generation costs in 2022." Technical report no. International Renewable Energy Agency. 2022.

[31] Ioannou, Anastasia, Angus, Andrew and Brennan, Feargal. "A lifecycle techno-economic model of offshore wind energy for different entry and exit instances." *Applied Energy* Vol. 221 (2018): pp. 406–424. DOI 10.1016/j.apenergy.2018.03.143.

[32] Banister, Kevin. "WindFloat Pacific Project, Final Scientific and Technical Report." Technical report no. Principle Power, Inc., Emeryville, CA (United States). 2017.

[33] Gao, Qiang, Hayward, Jenny, Sergiienko, Nataliia, Saeed Khan, Salman, Hemer, Mark, Ertugrul, Nesimi and Ding, Boyin. "Detailed Mapping of Technical Capacities and Economics Potential of Offshore Wind Energy: A Case Study in South-eastern Australia." *Submitted to Renewable and Sustainable Energy Reviews* .

[34] Têtu, Amélie and Fernandez Chozas, Julia. "A Proposed Guidance for the Economic Assessment of Wave Energy Converters at Early Development Stages." *Energies* Vol. 14 No. 15 (2021): p. 4699.

[35] BVG Associates. "A Guide to an Offshore Wind Farm." Technical report no. The Crown Estate. 2019.

[36] Timmers, Victor, Egea-Àlvarez, Agustí, Gkountaras, Aris, Li, Rui and Xu, Lie. "All-DC offshore wind farms: When are they more cost-effective than AC designs?" *IET Renewable Power Generation* .

[37] Nationalgrid. "Appendix E, Electricity Ten Year Statement." https://www.nationalgrideso.com/research-publications/etys/archive (2022). Accessed: 2022-11-03.

[38] Aurecon. "2021 Costs and Technical Parameter Review." Technical report no. AEMO. 2021.

[39] Castro-Santos, Laura, Martins, Elson and Soares, C Guedes. "Cost assessment methodology for combined wind and wave floating offshore renewable energy systems." *Renewable energy* Vol. 97 (2016): pp. 866–880.

[40] AEMO. "MARKET DATA." 'https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/market-data-nemweb' (2021). Accessed: 2022-10-03.

[41] Graham, Paul, Hayward, Jenny, Foster, James and Havas, Lisa. "GenCost 2021-22 Consultation draft." Technical report no. CSIRO. 2021.

[42] Department of Industry, Energy, Science and Resources. "Australia's emissions projections 2021." .

[43] International Electrotechnical Commission. "Wind Turbine Generator WTG classes." *IEC 61400* .

[44] IRENA. "Renewable Capacity Statistics 2022." Technical report no. International Renewable Energy Agency. 2022.

[45] Gideon, Roan A and Bou-Zeid, Elie. "Collocating offshore wind and wave generators to reduce power output variability: A Multi-site analysis." *Renewable Energy* Vol. 163 (2021): pp. 1548–1559.

[46] AEMO. "2022 Integrated System Plan for the National Electricity Market." Technical report no. 2022.