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Ocean renewable energy: 2015-2050

An analysis of ocean energy in Australia

July 2012

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1. Executive Summary

1.1 Introduction

Ocean waves, tidal and non-tidal ocean flows, collectively known as Ocean Renewable Energy (ORE), are attracting increasing interest in Australia as a potentially viable source of renewable energy. Recently, the CSIRO Wealth from Oceans Flagship (WfO) was commissioned by the Department of Sustainability, Environment, Water, Population and Community (DSEWPaC) to produce maps of wave, tidal and non-tidal ocean flow energy distributions around the Australian coastline. These preliminary energy distribution maps, produced from the best available existing information, provide evidence of substantial, but imprecisely quantified, potentially extractable energy. Several Australian and overseas companies have initiated ventures to use ORE for grid-connected electricity generation and/or related uses such as desalination. With this growing interest, WfO and the CSIRO Energy Transformed Flagship (ETF) jointly conducted a study to assess the potential of ORE in Australia and to identify research and development gaps and opportunities CSIRO could investigate for the country's benefit.

The study begins with an assessment of Australian ORE resources and their potential for providing accessible forms of renewable energy (e.g., magnitudes, extent of variability and forecasting). Ocean energy conversion devices and their characteristics are then considered, together with specific examples of devices for which performance data are available. Issues in setting up "farms" of multiple devices are described, along with an assessment of how much energy might be extracted from specific coastal locations identified by the resource survey. The analysis concentrates particularly on wave energy as the most likely form of significant ORE in Australia. This information is then used to develop scenario projections of the possible market share of wave energy in Australia up to 2050. Facilitation issues, including competing uses such as shipping and fishing are considered, with a brief commentary on broad environmental aspects of significant ORE activity. Finally, there is a brief survey of Australian (including recent R&D) and international ORE developments and activities.

1.2 Findings

1.2.1 Australian Resources

Wave Energy

Australia has considerable wave energy resources in reasonable proximity to population and potential industry users. For example, the total wave energy crossing the 25 metre depth isobath between Geraldton and the southern tip of Tasmania is over 1300 TWh/yr, about five times the country's total energy requirements. Wave energy in Australia is not resource limited. Other factors such as the economics of energy extraction, transmission, environment and social impacts will determine its future exploitation. We caution that the wave assessment in this study was preliminary, and needs to be augmented by further investigation.

Tidal Energy

Of the three main sources of ORE, tidal flows appear to be the Australian resource with the smallest upper limit (and the most isolated from end users). An 8TWh/yr estimate exists for a King Sound (Kimberley, Western Australia) barrage scheme and 0.13TWh/yr at most for a Banks Strait (Tasmania) tidal stream project. Nonetheless, there are Australian developers currently active in the planning stages of large tidal projects and the resource should not be ignored. Some additional work needs to be done to better quantify the available extractable power from tidal flows.

Non-Tidal Ocean Current

This form of ORE is the furthest from being technically and economically viable. However, the potential is large enough (the order of 44TWh/yr) to attract commercial interest.

1.2.2 Availability of ORE

Wave Energy

As with many forms of renewable energy, ORE is a variable source and this must be taken into consideration when assessing its availability. Some comparisons of wave with wind energy reveal that: hourly-average wave energy varies at about one-third the speed of hourly-average wind energy; a wave forecast for 36 hours is nearly as accurate as a wind forecast for 12 hours; the incidence of low values of extractable energy is much less for wave energy (for example, 13 per cent at Cape Sorell) than it is for wind (42 per cent). This gives a higher degree of certainty and consistency for wave energy compared with wind.

Tidal Energy

The nature of the variability of tidal current energy is distinct from wave sources in that it is highly predictable both in temporal (hourly) and magnitude (weeks, months) variation. However, the daily variation is great, going from essentially zero up to a maximum when the tide goes full flood to full ebb. This variation needs to be accommodated by storage or use management in some form.

Ocean Flow

A great deal less is known about the temporal variability of energy from Australian non-tidal ocean currents as there are no long term, reliable records of the flow speed and variability for locations of interest such as the East Australian Current (EAC) off Southeast Queensland. An initial analysis of the flow statistics shows that the mean output and intermittency of the EAC are of the order of 450W/m^2 and 10 per cent (per cent of time that the power is less than one quarter of the mean) respectively. These are broad brush estimates only. It will take considerable effort to obtain more accurate estimates.

1.2.3 Ocean Energy Conversion Devices

Over 200 devices that have been proposed for the extraction of ORE. Of these only a few have actually been constructed or are near demonstration or commercial size for testing in actual operating conditions. Wave energy extraction devices largely fall into three categories — oscillating water columns that drive air turbines, oscillating bodies (floats, buoys) that drive generators or produce pressurised water; and overtopping systems that drive water turbines. Tidal and ocean flow devices consist of turbines placed in either constricted or unrestricted water flows. There are other types of extraction devices that draw energy from ocean thermal and salinity gradients, but there are few locations in Australia where they would be applicable at a reasonable scale and cost.

Wave power remains potentially the single greatest ORE source for Australia. For commercial operation, wave devices will need to be built in "wave farms": collections of devices in specific areas. The areas can be quite large; for example, a 250MW wave farm designed to extract 20 per cent of the incoming wave energy could occupy an area of 50km^2. This would be an extreme case and most wave farms will be smaller than this. Nonetheless, there will be issues with anchorage of large, multiple devices, particularly in designing for extreme sea conditions. Gear breakage and resulting debris colliding with farm elements (and other infrastructure in the vicinity) is a distinct possibility that needs further investigation, along with maintenance of the individual units throughout their producing life.

1.2.4 Competing Uses

To supply 10 per cent of Australia's total grid-based electricity demand by 2050 it will be necessary for ORE to generate 46TWh. Depending on the technology, this could take as little as 150km of coastline segmented into a number of regions. However, this might need to be extended by up to a factor of five if for environmental reasons it proved desirable to limit the extraction from waves to 20 per cent. Gaining access to these coastal waters for renewable energy development is at least as complex an issue as for land based sites. Considerations include:

- Native title and land rights
- Marine Protected Areas
- Fishing, aquaculture and fisheries
- Oil, gas and mineral resource development
- Shipping
- National security
- Tourism, recreation and visual amenity

1.2.5 Environmental Impact

The environmental impact of various types of ORE extraction devices is not well known and will not be for some time — until large commercial farms are operating. The influence of wave calming, for instance, could have both adverse and advantageous effects in the local area — protection from coastal erosion and/or changes in local current flows are cases in point. The prediction and management of these influences will have to form part of the environmental impact statements for each intended facility.

1.2.6 Economic Projections

The uptake of ORE in Australia was modelled on the basis of several scenarios, assuming particular global backgrounds, a range of Greenhouse Gas (GHG) targets imposed by the federal government (CPRS-5, CPRS-15 and Garnaut-25) with their attendant carbon prices rising over time and using a range of capacity factors as a measure of electricity production per wave energy converter.[1] Simulations were done for generic technologies and for actual technologies for which operating data were available.

1 Capacity factor is defined as (average power/rated power) and is widely used in energy economic projections as a measure of electricity production per generator. However, in the marine context the rated power component of capacity factor can be too arbitrarily defined for meaningful comparison, for example wave energy has a huge dynamic range that contributes to a non harmonised approach to generator nameplate rating. The rated power component was therefore removed from all comparative assessments made by the model where capacity factor was a parameter.

One important finding was that tidal and ocean current technologies will not contribute to Australian electricity generation out to 2050 under any scenario examined. This was a surprising result, considering that large investments are planned. We should handle this conclusion with care and need to fully understand the factors behind it.

The economic modelling has defined the overall conditions under which wave electricity generation is viable in Australia. The generation areas are restricted to the southern coastline and each state has special circumstances that make wave energy more or less attractive. This is the first time that such a comprehensive modelling study of ORE has been done for Australian conditions.

The scenario modelling indicates that wave energy has the potential to make a significant contribution to global and Australian renewable electricity generation. The extent depends on many factors. For instance, a carbon price and associated policy stability is essential globally and in Australia for wave energy uptake. Operations and maintenance (O&M) cost reductions, comparable with wind energy, are also essential for wave energy uptake in Australia. While, globally, wave energy contributes to electricity generation under all of the scenarios tested, uptake in Australia shows more variation. Three example scenarios which describe wave energy uptake in Australia were considered. All of the scenarios modelled use realistic values, and show the range of variability that can be expected with the current state of knowledge.

(i) Low uptake: this occurs under the lowest carbon price scenario (CPRS-5), for generic (hypothetical) Wave Energy Convertors (WECs), with early capital cost reductions. Under this scenario wave energy would contribute 1 per cent of total Australian electricity generation by 2038.

(ii) Average uptake: this occurs under the highest carbon price scenario (Garnaut-25), again for generic (hypothetical) WECs, with gradual but substantial capital cost reductions. Wenergy convertors were set with a capacity factor 25 per cent higher than under the low uptake scenario. Under this scenario wave energy would contribute 6 per cent of Australia's total electricity generation by 2050.

(iii) High uptake: this occurs under any carbon price scenario for commercially available prototype WECs, with a continuously low capital cost, a capacity factor set modelled under Australian wave conditions, and with an estimated 25 per cent dispatchable power. Under this scenario wave energy would contribute 11 per cent of Australia's total electricity generation by 2050.

The vast majority of wave farms were taken to be constructed in Victoria (VIC), up to the limit of the sustainably-extractable resource. When the dispatchable power capability was assumed in the model there were increases in generation in states with good wave resources, most notably VIC, Western Australia (WA) and South Australia (SA).

1.2.7 Australian and International Developments

There is increasingly significant ORE activity, worldwide. Device research is centred in Europe with Ireland, Portugal and the UK making large investments into the development of "wave hubs". These are sea-based test centres that serve the dual purpose of testing developer's devices and providing experience in integrating the outputs into local grids. There is also active work in the US and Canada.

Development activity in Australia is fragmented, relying mainly on entrepreneurs and the formation of small companies to raise funding through public offerings and government grants. As a result, those companies are highly competitive and protective of their technology. While this might not be a conducive environment for Australian innovation, there are some home-grown technologies being offered to the market. The two most advanced are the CETO submerged buoy system and the OceanLinx oscillating water column system. The largest ORE project in Australia (recipient of a $66 million grant from the federal government) is the construction of a wave farm off the coast of Victoria by Ocean Power Technologies Australasia Pty Ltd (OPTA), a company with a US-based parent.

This study identified 16 Australian companies that are either actively developing ORE projects, have received significant government and/or private funding or have announced ORE plans.

1.3 Recommendations

The main conclusion from the study is that there is likely to be a significant role for ORE in the form of wave energy in Australia (the prospects for tidal and ocean flow devices are less buoyant) provided there is a price on carbon and the specific technology remains within appropriate capital and operating cost thresholds.

1. The modelling showed that, under some circumstances, wave energy take up is disadvantaged by increasing carbon prices. This was an unexpected result which could possibly affect other emerging renewable energy technologies. It is recommended that this observation be subjected to further analysis across the entire spectrum of energy technologies and the results published in the open literature.
2. The temporal and spatial variability of wave energy analysis showed that the combination of the electricity output of several sites achieves a degree of overall smoothing. This would also be true for other combinations of ORE and renewable energy. It is recommended that consideration be given to an examination of optimal mixes of renewable energy sources for Australia to assist the integration of variable sources of energy into the electricity grid.
3. Addressing the issues associated with competing/alternative uses of the marine environment will be a major factor in the success of the ORE industry in Australia. It will at least be of equivalent importance to the technical/engineering aspects. It is recommended that consideration be given to the type of research needed to ensure that these aspects are appropriately covered in the early stages of project development.
4. It is recommended to increase the accuracy and detail of Australia's wave energy resource by developing a time-stepping, high-resolution wave model on a single boundary-free mesh that becomes progressively finer as the coast is approached.
5. It is recommended to develop the model further to ensure that energy models express capital and O&M costs for regionally located wave energy generators formally with a new term in place of the commonly used but problematic term "capacity factor" and to propagate this practice through an international energy standards body.
6. It is recommended to develop the model to include the impact of interstate inter-connections to allow cost effective export and import of renewable energy across state borders.
7. It is recommended to assess the engineering feasibility of mooring very large wave energy convertors to withstand extreme wave conditions.
8. It is recommended the current modelling be used to conduct a sensitivity analysis to establish where improvements need to be made in ORE technology to increase its viability in Australia. This should include "tuning" of devices for Australian conditions, such as wave height distributions and wave periods.
9. It is recommended to enhance the now sparse array of wave buoys. This should include upgrading the buoys to include measurement of wave directional information to enable more accurate estimates of wave power to be made.
10. The modelling returned the unexpected result that under all scenarios investigated, tidal and ocean flow energy was not competitive in Australia out to 2050. Further investigation is recommended to more clearly define the conditions and technological changes required to make it a competitive technology in Australia.
11. It is recommended there be direct *in situ* measurements of specific tidal flows in areas of maximum prospectivity to verify our model estimate tidal flow.
12. It is recommended there be a predictive model study of a "fence" of tidal turbines to establish whether the power generated would be as much as indicated by the unimpeded, freely resonating natural flows. The study should also examine how this would affect the local tidal amplitudes.
13. It is recommended that we refine our current model of the extractable energy from open ocean flows by making continuous *in situ* measurements of the flow speeds and model the impact on the flow of installing large turbines in water at depths of up to 1km.
14. It is recommended an assessment be made of the engineering feasibility and synergies of mooring large ORE devices, shared with oil wells and offshore wind turbines.

2. Australian Resources

Australia has access to most forms of ORE, sufficient to provide a significant proportion of Australia's electricity supply.

Ocean current is widely available, but no devices, let alone economic ones, presently exist to exploit it. Ocean thermal, osmotic gradient and tidal power are all available in significant quantity within restricted areas of Australia and have the potential to supply a useful niche market. The machinery required to harness tidal power is the most developed of the technologies; however, its environmental impact may be the least understood. Wave power is ubiquitous to the south west, south and south east coasts and provides potentially the greatest resource of energy with a preliminary estimate [1] of the extractable energy suggesting that it could supply up to 10 per cent of Australia's electricity needs by 2050. We give an overview of the magnitude and location of Australia's tidal, non-tidal current and wave energy resources, with particular focus on the driving question of where future research is both possible and most likely to be of value to the nation. For a more technical discussion of the wave resource of the southern seaboard see [1].

2.1 Tidal Current

The rotation of the Earth and the gravitation field gradients associated with the sun and moon cause the ocean basin oscillations known as tides. Most people are aware that tides are highly predictable because of their intrinsic periodicity. However, the complexity of the spatial structure of tidal oscillations is less well understood. Computer models of global ocean tides can simulate gross features, such as that Perth has only one high tide per day while Sydney has two, but the models need to use satellite and tide gauge observations of the actual tides in order to become accurate enough for practical use. The models then function more as sophisticated interpolation systems than predictive computer simulations.

The importance of this background information is that predictive computer simulations are required in order to estimate the power output of a major tidal energy project. The design studies for the Severn Estuary Barrage, for example, found that extracting power from the tides on the English side of the Irish Sea would actually increase the range of the tides on the Irish side. The reason unexpected results occur is basically that interest in tides for renewable energy purposes inevitably focuses on regions where the tides have very high amplitude. High amplitudes only occur where the tide is in resonance, which only happens when the natural oscillation frequency of a semi-enclosed body of water coincides perfectly with one of the astronomical forcing frequencies. Anything that changes the geometry of the water body will slightly change the resonant frequency of the basin, possibly making a disproportionately large change to the nature of the oscillations. Secondly, and perhaps more importantly, extracting energy from a resonating system can rapidly damp the oscillations. This is a corollary of the fact that only a small amount of energy is required to make a resonant system undergo large-amplitude oscillations if the energy is supplied at exactly the right frequency. If we aspire to extract only a tiny fraction of the tidal energy, then maps of the natural, or existing, amplitude of the tidal height and current are certainly indicative of the extractable energy resource. But if we wish to extract significant quantities of energy, maps of the natural amplitudes can be misleading for the reasons given above. A map of the extractable energy can be produced but is beyond the scope of the present study. (The design and impact study for the Severn Barrage was a major undertaking.) This review gives preliminary estimates of the extractable energy density using existing information on the natural tidal amplitude.

To augment the information available from the limited number of locations where tidal measurements have been made, the National Tidal Centre of the Bureau of Meteorology uses a fairly coarse-resolution (~12km grid) tidal model for predicting tides all around Australia. One traditional way of portraying a map of tides is to show the tidal range, which is defined as the sum of the amplitudes of all the tidal frequencies. The tidal excursion only reaches this range when all the tidal components coincide in phase, which is just once every 19 years. Another method is to map the tidal harmonic constituents separately but there are up to 64 of these, with periods ranging from annual, through daily and twice-daily, to just several hours. Neither of these traditional methods is convenient for estimating the tidal energy resource.

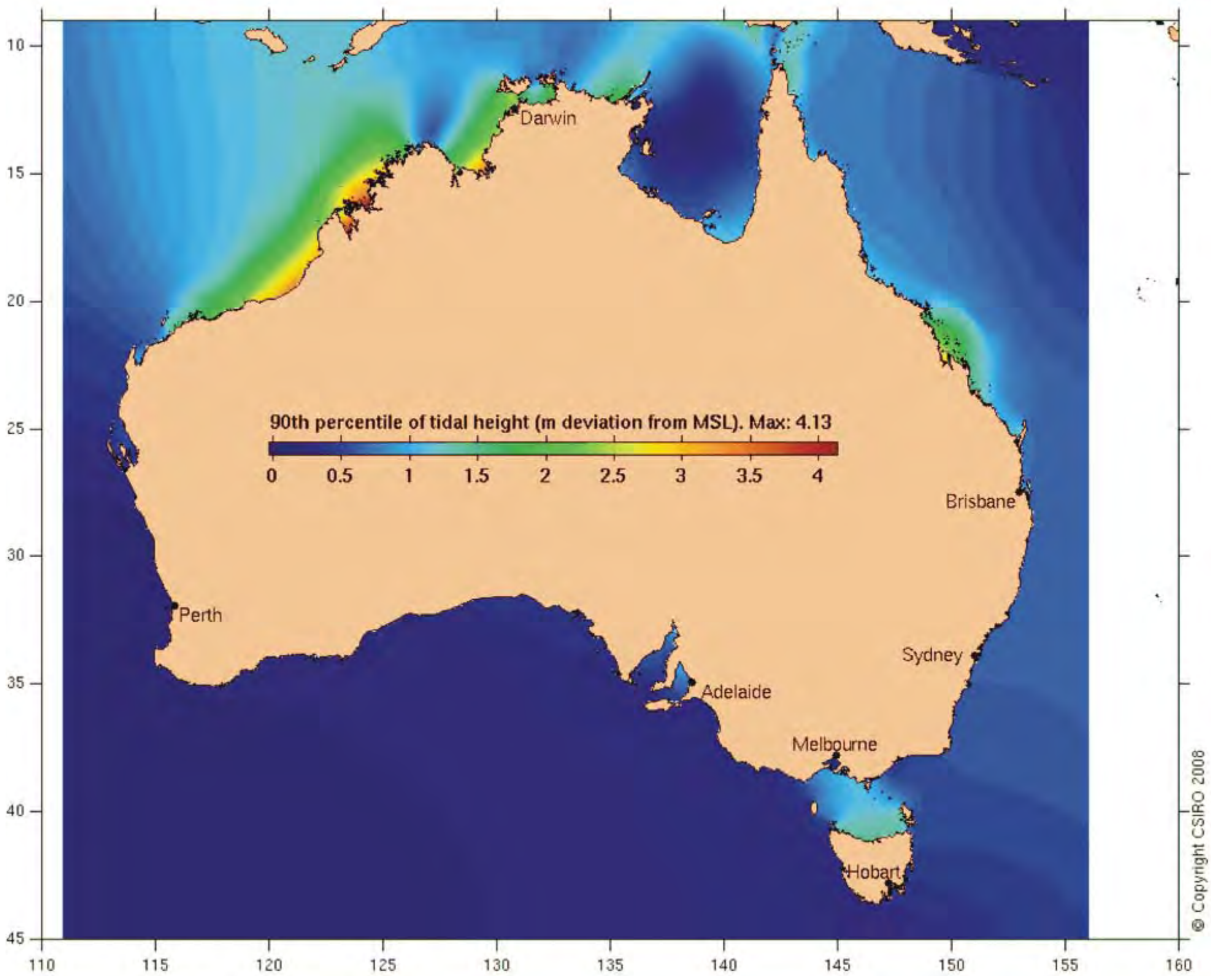


Figure 2-1 Map of the 90th percentile value of the instantaneous tidal height amplitude for Australia, based on the 1/12 degree tidal model of the National Tidal Facility of the Bureau of Meteorology.

An alternative way to succinctly describe the spatial distribution of tidal variability is to compute the Cumulative Distribution Function of the tidal height, speed and/or power. Since tides vary regularly on both a within-day basis (due to the rotation of the Earth) and on a fortnightly and monthly basis (known as the spring-neap cycle, and due to the relative position of the sun and moon), we have computed the statistics of both the instantaneous values and the averages over the daily tidal cycle. The statistics we have chosen to report are the 10th, 50th and 90th percentile values; i.e. the values below which 10 per cent, 50 per cent and 90 per cent of the observations fall.

In Australia, the highest amplitudes (Figure 2-1) of tidal height occur on the Kimberley and Pilbara coasts of northern WA, with King Sound being well-known for having Australia's largest tides. Consequently there have been several proposals for tidal energy schemes in the Kimberley region. A 48MW Derby Tidal Power Project was proposed for King Sound in 1999 but rejected on the grounds of its potential environmental impact. This was followed in 2008 by a proposal [2], which quoted the World Energy Council with saying that Secure Bay (Derby) and Walcott Inlet could produce 2.9TWh/yr and 5.4TWh/yr, respectively, from an installed capacity of 4.3GW. To verify these estimates is beyond the scope of the present study.

There is also a well known tidal resonance in Broad Sound, Queensland. Bass Strait has a weak maximum on the Tasmanian side. At spring tides (characterised here by the 90th percentile) the tidal height amplitude (approximately half the "tidal range") exceeds 4m in the Kimberley, 3m in Broad Sound and 1.2m off northern Tasmania.

These values are not particularly large by global standards but certainly represent opportunities for tidal energy extraction schemes based on the impoundment, or "tidal barrage" principle, like the one proposed for the Severn Estuary. It should be recognised, of course, that in terms of environmental impact, these schemes are utterly transformational because they necessarily involve the construction of a dam across the mouth of an estuary or bay. This changes the nature of the estuary completely, from being an extraordinarily macro-tidal regime to a much more moderate tidal range, with less exchange of waters between the estuary and the ocean. Such projects are therefore much less acceptable now than when, for example, La Rance was commissioned in 1966. The Severn Estuary project is facing strong opposition because of the impacts it will have on the tidal wetlands. South Korea's Lake Sihwa tidal power station is the biggest tidal barrage scheme since La Rance, with an installed capacity of 254MW.

The other way of extracting energy from the tides is to focus on the places where the tidal energy is manifest as kinetic, rather than potential energy. In their purest form, these schemes are known as "free stream" tidal energy projects since there is no attempt to alter the flow field other than via its interaction with the installed device. The first commercial installation of a free stream turbine is the SeaGen in Strangford Lough, UK. The "tidal fence" concept is essentially the same as the free-stream concept but resembles a barrage to the extent that the water is denied the option of avoiding the turbines.

While high tidal heights can only occur at the antinodes of the tidal oscillations, strong tidal streams can occur at a wider range of locations, wherever the topography steepens the gradient of the sea level by constricting the flow- creating opportunities for tidal power extraction using free-stream turbines. For example, neither Torres nor Banks Strait (between NE Tasmania and Flinders Island) has high tidal height amplitude, but both have strong tidal currents (Figure 2-2).

Figure 2-2 shows the two Australian locations with the highest tidal current speeds. These are the mouth of King Sound and Banks Strait. The resolution of the computational grid is about 9km, so narrow straits with even higher velocities do not feature on these maps. BioPower commissioned CSIRO to construct a set of nested higher-resolution models of the Banks Strait region. In the 4km-resolution model, the tidal current speed in Banks Strait routinely reaches 2.6m/s. The correct value may be either higher or lower but observations have not yet been made to validate these model estimates.

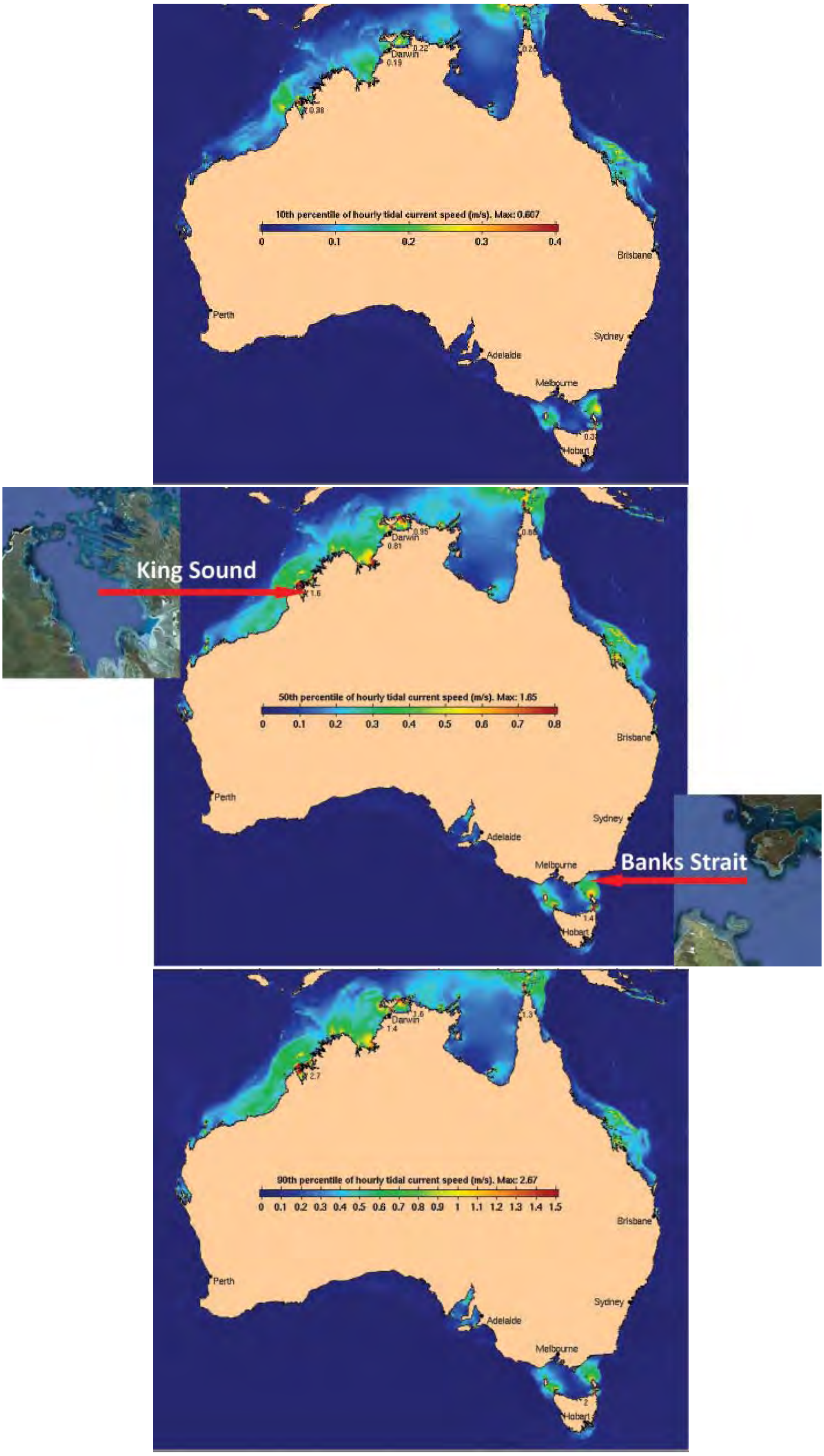


Figure 2-2 Maps of the 10th, 50th and 90th percentile values of instantaneous tidal current speed for Australia based on the 1/12 degree (~9km) tidal model of the National Tidal Facility of the Bureau of Meteorology.

Energy Equations for Tidal Flows

The energy flux density P (in W/m^2) of a moving fluid is,

$$P = \frac{\rho \cdot v^3}{2} \qquad 2\,1$$

where ρ=1023 kg/m3 is the density of seawater and v is the velocity of the fluid normal to the plane of the area measured. The extractable power is,

$$Pe = \varepsilon \cdot \alpha \cdot P \qquad 2\,2$$

P_e is limited to about half of P because of the combined effect of the mechanical efficiency ε and the hydrodynamic extractability coefficient α [3]. The power output P_o of a device is,

$$Po = A \cdot Pe \qquad 2\,3$$

where A is the swept area.

According to SeaGen, their dual-16m-diameter SeaGen ocean current turbine ($A=400m^2$) generates 1.2MW when v = 2.4m/s, suggesting that ε.α = 0.4. This would be the instantaneous (i.e. flood or ebb tide) peak output of a SeaGen deployed in Banks Strait. Averaged over time, the power output would be about 40 per cent of this (the average value of $|\sin(x)|^3$), or 500kW. According to the coarse-resolution National Tidal Facility model (run for a year with all harmonic constants) the time-average power density would be less again at just $1.7kW/m^2$ (see Figure 2-3). Assuming these figures are accurate, then a SeaGen would only produce a time-average of 280kW. This is almost certainly an under-estimate.

2.1.1 Summary and Future Work

As indicated, all estimates of tidal power here are approximations based on a model estimate of the free-stream velocity. To make estimates of the extractable power, two additional studies are required:

1. *In situ* observations of the tidal current speed for verification of the model estimate of the existing natural tidal flows.
2. A predictive model study of the tidal flows in the presence of a "fence" of tidal turbines. Would the power generated be as much as indicated by the unimpeded, freely resonating natural flows? Would the tidal amplitudes of northern Tasmania be influenced? The ability of the flow to just divert around the turbines will depend on the detailed design of the fence with respect to the local and the large-scale topography.

Once this work is done, the resulting predictive model of the interaction of the flow with the tidal devices could form the basis for studies of the environmental impacts of the tidal energy farm.

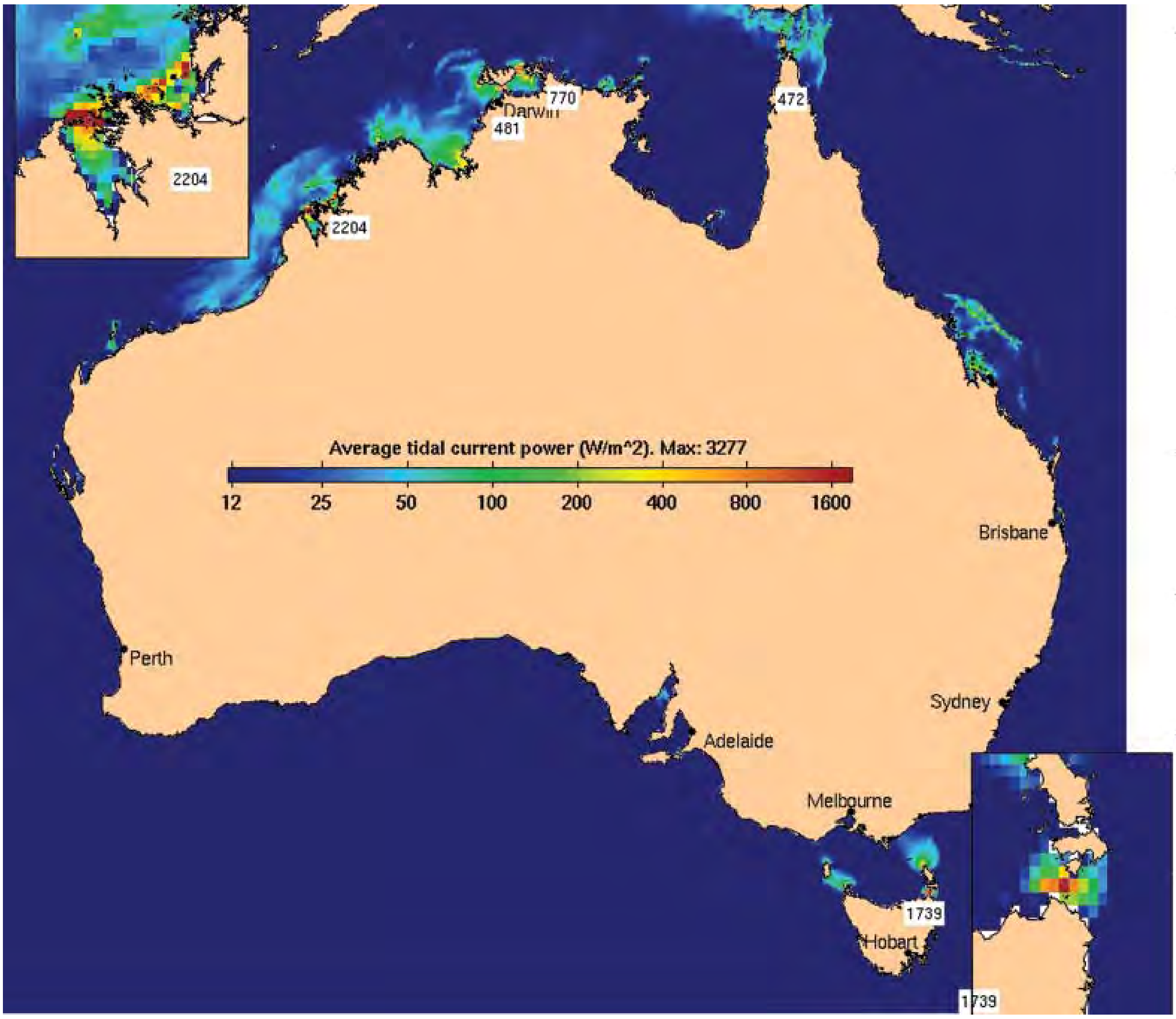


Figure 2-3 Map of the time-average tidal current power, based on the 1/12 degree (~9km) tidal model of the National Tidal Facility of the Bureau of Meteorology. Insets show zoom-ins on the King Sound and Banks Strait regions.

2.2 Non-Tidal Ocean Currents

The East Australian Current flows southwards from Queensland into New South Wales, with a small fraction of its flow continuing past eastern Tasmania. While the current flows mostly as a fast narrow jet along the upper continental slope between Fraser Island and northern NSW, from then onwards it is best characterised as an unstable, meandering flow that creates or flows around a complex field of large (hundreds of km) clockwise and anti-clockwise rotating eddies (for example see [4]), making the northern NSW-southern Queensland stretch of coast the most promising location in Australian waters for extracting energy from non-tidal currents.

Off Brisbane, the flow speed has been observed to exceed 2m/s in the vicinity of the 1000m depth contour but continuous measurements to document the frequency of this have yet to be made. Analysing the 15-year BRAN2.1 data archive generated by the Bluelink $0.1^0 \times 0.1^0$ resolution ocean model [5, 6], we find that the 10th, 50th and 90th percentile values of the current speed are about 0.2, 0.9 and 1.3m/s respectively (Figure 2-4).

The power density at these velocities is quite low (P=500W/m^2 at 1m/s, see equation 2.1), so very large diameter devices are required in order to extract significant quantities of power. It should also be remembered that a turbine can extract no more than half the kinetic power of the ocean (see equation 2.2), in which case the power generation is just 250W/m^2. The total width of the fast region of the current is about 20km, so a dense fence of 200 100m-diameter turbines across that could potentially produce about 250W/m^2*100m*20km=500MW when the flow speed is 1m/s. A more precise calculation of the time-average power density follows in the next section.

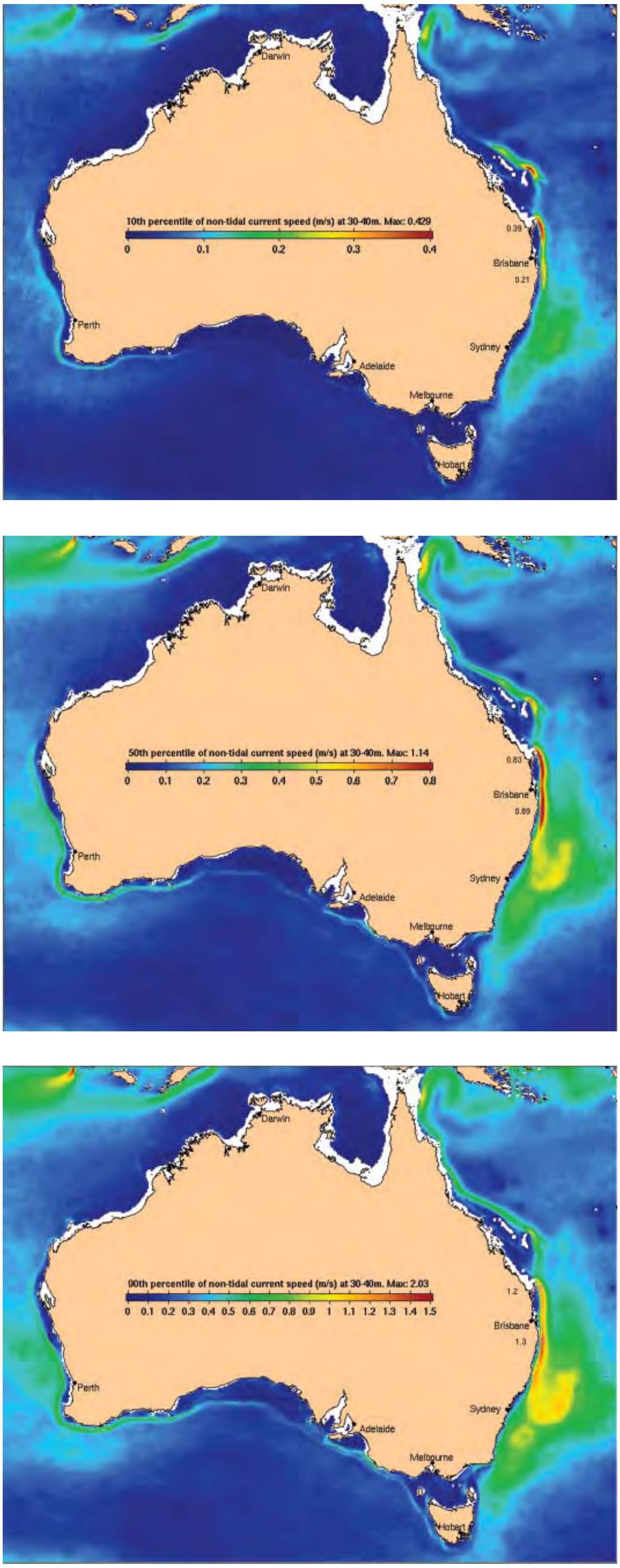


Figure 2-4 Maps of the 10th, 50th and 90th percentile values for non-tidal, near-surface (30-40m depth) ocean current speeds for Australia based on the 1/10 degree (~11km) resolution CSIRO Bluelink ocean circulation model.

2.2.1 Summary and Future Work

This form of ORE is possibly the furthest from being technically or economically viable. The potential size of the resource is large enough, however, to justify research projects to:

1. Refine our model estimate of the extractable energy: for example by making continuous *in situ* measurements of the flow speed, and by modelling the impact on the flow of installing large turbines.
2. Assess the engineering feasibility of mooring large devices in such deep water, amidst heavy shipping traffic.
3. Assess the environmental impacts of installing turbines, which may cause upwelling of cold nutrient-rich waters into the photic zone, triggering growth of plankton.

The first study could augment deployments of current meters off Brisbane, scheduled to form part of Australia's Integrated Marine Observing System in 2012.

2.3 Waves

The southern ocean is well known for its large waves. This is recognised in global atlases of the wave energy resource [7]. Waves are generated by the wind and can travel large distances in the deep ocean because the rate of energy loss is very small until the waves reach shallow water and start experiencing frictional drag on the seafloor. In deep water, the energy flux P (inkW per m of wavefront) is approximately (see [8] here corrected);

$$P = 0.49 \cdot Te \cdot Hs^2 \qquad 2.4$$

where T_e is the mean wave energy period (approximately equal to 0.86 times T_p, the period of the waves at the spectral energy peak) and Hs is the significant wave height (or average height of the upper third of the instantaneous wave field). This equation is an approximation because it assumes a certain spectral shape, which, in the real world, varies by location and time depending on the fetch[2] of the waves.

The height and period of these southern ocean waves have been measured by wave buoys for many years at a few Australian locations. Off Cape Sorell on Tasmania's west coast, the long-term average wave height, period and energy flux are 3m, 12.3s and 51kW/m respectively, at a site in 100m of water [9]. The 51kW/m value is derived from the buoy's burst-sampled[3] wave observations. It is therefore more accurate than the 56kW/m resulting from equation 2.4 based on the integral parameters T_e and H_s. Burst-sampled observations are not available for most of Australia, so we are obliged to base estimates on the integral wave parameters in order to make a map of the resource. Here, we will follow [1] (see below) whose method is in principle more accurate than equation 2.4. It yields an estimate of 48kW/m from the archives of T_p and H_s for this particular location. All these estimates of the observed energy flux are significantly lower than the 70kW/m value shown south of Australia by the World Energy Council 2007, but are nevertheless indicative of a very significant resource. The west coast of Tasmania is about 300km long and the waves are incident nearly normal to the coastline, so the total energy incident on the west coast over a year is about 134TWh, or 12.2 times Tasmania's present consumption (11TWh/yr , of electrical energy [10]).

A global map such as that of the World Energy Council 2007 is potentially misleading if used as an indicator of the resource available to a near-shore wave farm somewhere in southern Australia, unless attenuation of the deep ocean waves as they cross the continental shelf is taken into account. While estimates of the near-shore wave height are available from satellite-based radar altimetres embarked on ESA and NASA/CNES missions (ENVISAT, TOPEX/Poseidon, Jason-1, OSTM, etc), these measurements are only indirect estimates, along discrete track lines. As a first step towards serving the needs of the wave energy sector, and to reconcile these various model and observed data sets, Hemer and Griffin [1] have recently produced a wave energy atlas for southern Australia with fine spatial resolution ($0.01^0 \times 0.01^0$, i.e. about 1km), by running the SWAN wave model with offshore boundary conditions specified by three percentile levels of the NOAA WaveWatchIII operational model, after Hemer *et al* [11] showed that this was the most accurate data set presently available to describe

2 The uninterrupted distance travelled by a nearly constant wind crossing a body of water and interacting with waves.
3 Burst sampling is very frequent sampling for a restricted interval.

the offshore wave climate. To reduce the computational cost of this task, Hemer and Griffin [1] ran the fine resolution models for just a small (3×13) number of representative wave states, defined by three (the 10th, 50th and 90th) percentile levels of the wave energy during i) all of 1997-2006 (Figure 2-5), and ii) each of the 12 months in that period. The resulting atlas, comprising maps of wave height, period, direction and energy is to be included in the Australian Government's *Atlas of Renewable Energy* [12]. The domain of the wave energy atlas is restricted to the stretch of coast (Geraldton WA to the southern tip of Tasmania) where the offshore wave climate is fairly uni-modal[4], and therefore adequately described by the NOAA WaveWatchIII archive of integrated wave parameters.

2.3.1 Summary and Future Work

As mentioned above, the total wave energy incident on Tasmania's west coast far exceeds the state's energy requirements. Hemer and Griffin [1] made a more accurate model-based calculation of the total amount of energy crossing the 25m isobath between Geraldton, WA and the southern tip of Tasmania. This came to 1329TWh/yr (without attempting to correct for the possibility that the model slightly over-estimates the energy flux), about five times the energy requirements of the whole nation. Turning just 10 per cent of that into electricity would be a massive investment but would provide half the country's electricity.

Clearly, the energy content of the resource is great enough that it does not place an upper bound on the future of the wave energy sector. Other factors, such as the economics of energy extraction, storage and transmission, are what will decide the future of wave energy, assuming environmental and social impacts can be shown to be acceptable.

Hemer and Griffin caution that their latest assessment of the (southern) Australian wave energy resource [1] was a preliminary study and recommend that their research be followed by tasks 1 and 2 of the following recommendations for future work:

1. Development of a time-stepping, high-resolution wave model implemented on a single boundary-free mesh that gets progressively finer as the coast is approached. The shallowest grid points need to be closer to shore than was possible with the one kilometre spacing of the Hemer and Griffin [1] model. The domain of the model should span all of Australia.
2. Enhancement of the existing sparse array of wave buoys, and upgrading of the buoys to include measurement and storage of wave directional spectra to enable accurate estimates of extractable power to be made. We understand that Sustainability Victoria is deploying two wave buoys off western Victoria for exactly these purposes.
3. Commencement of the research necessary to support future environmental and competing use impact assessments [13].

2.4 Conclusion

Our estimates of the natural energy fluxes are approximate, particularly for tidal energy, but are probably accurate enough to make some very general conclusions about the relative contributions to Australia's energy requirements that the three forms of ORE could make.

We have looked least closely at tidal power since this appears to be the resource with the smallest upper limit. An 8TWh/yr estimate exists for a King Sound barrage scheme, while we estimate that 0.13TWh/yr at most could be produced by a Banks Strait, tidal stream project. Both projects are technically possible. It is the environmental impact and economic considerations that are the major concern.

Non-tidal ocean currents potentially constitute a greater resource at 44TWh/yr but no device has ever been built to harvest this form of energy. The challenge is that the energy density is low, so the devices have to be very large, and moored in very deep (400-1000 metres) water.

Of the three forms of energy, wave is the only one that is of massive magnitude (i.e. more than Australia's total consumption) and also technically feasible. For this reason, the remainder of this report will focus mostly on wave power, starting with an examination of its temporal variability, a critical parameter for renewable energy resources.

4 Seas with a single predominant direction and canonical spectrum.

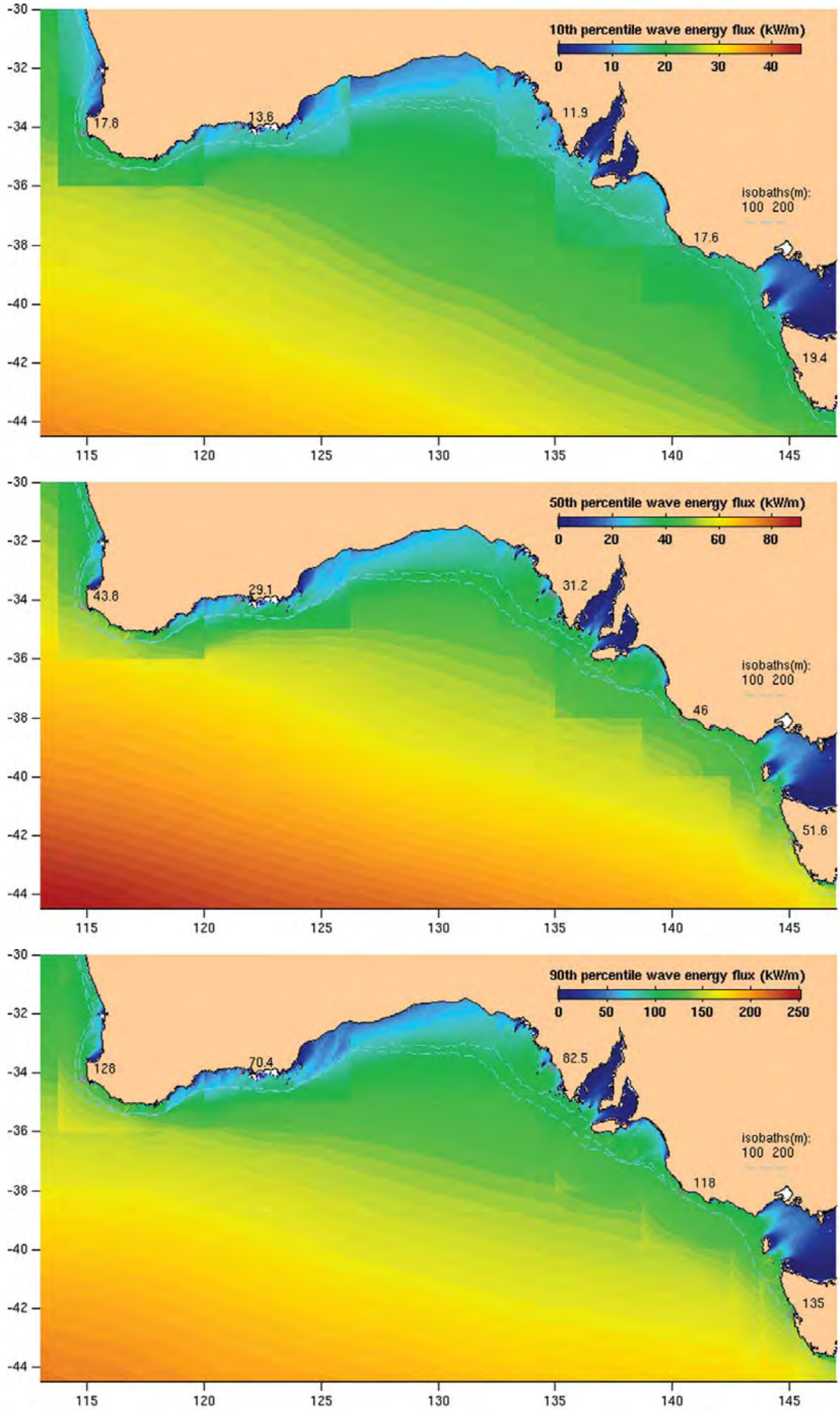


Figure 2-5 Maps of the 10th, 50th and 90th percentile values for the 1997-2006 wave energy flux south of Australia, based on the NOAA WaveWatchIII operational wave model and nested high-resolution implementations of SWAN [1].

3. Availability of ORE

The major problem with several forms of renewable energy is that they are highly variable, unpredictable, or both. In this section we first look briefly at the spatio-temporal variability of the tidal and non-tidal ocean current energy resources off the East coast of Australia. We then take a closer look at the statistics of the wave resource, with a focus on how this compares with the statistics of the more familiar wind energy resource, with which wave energy will have to compete.

3.1 Intermittency of Tidal and Non-Tidal Currents, Waves and Wind Energy

3.1.1 Tidal Currents

The nature of the temporal variability of tidal current energy is very distinct from that of wave or non-tidal current, in that it is highly predictable, as discussed in the previous section. While being predictable, the daily variation is still a drawback of this energy source since it necessitates the use of either storage or companion production. On a daily basis the energy production will go from essentially zero to maxima when the tide is either in full flood or full ebb. To smooth out production, the amount of energy that needs to be either stored or produced otherwise is more than half the total daily usage, since the productive time is only a few hours duration during each flood and ebb.

The fortnightly and monthly variation poses a similar problem. In Banks Strait (Tasmania), for example, the 10th, 50th and 90th percentiles of the daily-average power, according to the National Tidal Centre tidal model, are 1.1, 1.7 and 2.5kW/m^2. Compared with the other forms of ORE this is a very narrow range of variability (65-145 per cent of the median) but is still far from being a constant energy source. While the energy storage capacity required to smooth out the daily variability is a large fraction of the 12 hours periodicity, this only amounts to several (~8) hours of demand. In contrast, the slower-varying spring-neap variability requires storage of about 35 per cent of a few days, which might be as great as 24 hours of demand, and therefore constitute the greater energy management issue.

3.1.2 Non-Tidal Currents

So long, reliable records of the flow speed of the East Australian Current do not exist for the locations of interest it is not possible to validate the maps shown in Figure 2-5, or do detailed analyses of observed temporal fluctuations of the current. A measurement program is planned to start off Brisbane in 2012 as part of the Integrated Marine Observing System (IMOS) but the number of locations sampled will be very limited. In the meantime we have performed a brief analysis of the statistics of the temporal variability of the flow using the long archive (1994-2004) of daily-averaged current flow velocities simulated by the Bluelink model. Figure 3-1 shows the time-series of modelled flow speed at five locations chosen using a simple procedure to design an array of five ocean current turbine farms producing a combined output that has as few "outages", or periods of low output, as possible.

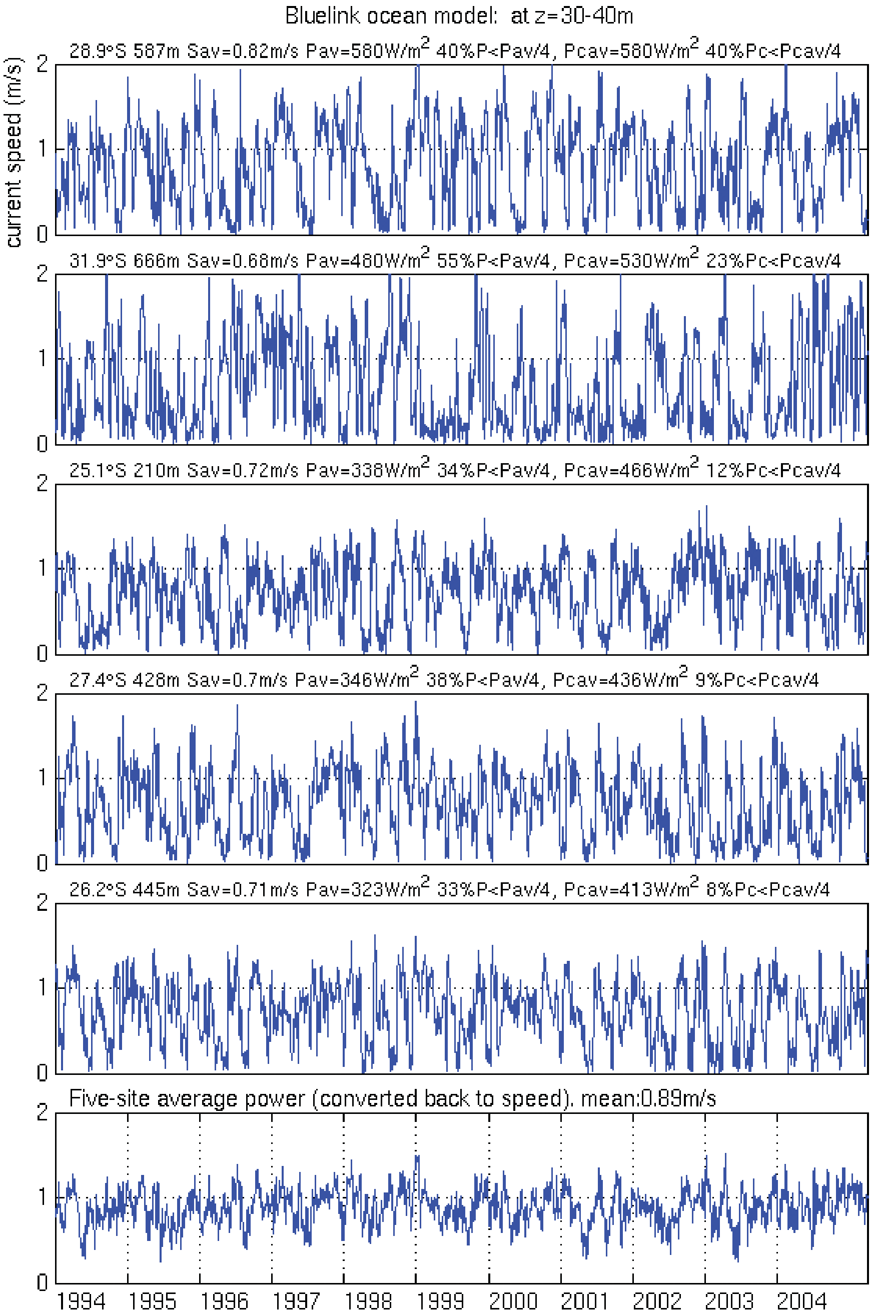


Figure 3-1 Time series of modelled non-tidal current speed. Data are from the Bluelink ocean model in the depth stratum from 30-40m. Panels 1 to 5 from the top show the daily-average speed from 1994 to 2004 at five locations discussed in the text, each annotated with the latitude, total water depth, average speed, average power, intermittency (= per cent time that the power is less than ¼ of the mean), then the cumulative average power and intermittency. The bottom panel shows the 5-site mean power (converted back to current speed) for comparison.

This procedure takes only the flow speed magnitude and covariance into account, as follows:

The first choice ("site 1" in Figure 3-2a) is the location where the time-average power is the greatest (according to the Bluelink model). This location has a mean power (580W/m²) and a (moderately) low per centage of the time (40 per cent) that the power is less than ¼ of the mean. Site 2 was then chosen using Figure 3-2b. This shows the average flow speed for the days when the power at site 1 was less than ¼ of the mean. Sites 3, 4 and 5 were then chosen similarly, using maps (not shown) of the average power for the days when the combined power at sites 1 and 2 (then 1, 2 and 3 …) was less than ¼ of the combined mean.

As the number of sites increases from 1 to 5 the percentage of time that the power is less than a quarter of the mean reduces from 40 per cent to 23 per cent, then 12 per cent, 9 per cent and finally 8 per cent. The bottom panel of Figure 3-1 shows how much smoother the combined output is than in any of the individual sites. The average power, unfortunately, also reduces (from 580 to 530, 466, 436 and 413W/m²) but this is the inevitable cost of not concentrating all the farms in the one region where the average power density is highest. The benefit of including sites 4 and 5 may not prove to be cost effective but many other factors need to be considered before any such statements can be made. We may, however, conclude that indicative numbers for characterising the mean output and intermittency (defined here as the per cent time that the power is less than ¼ of the mean) of non-tidal current energy are ~450W/m² and 10 per cent, respectively.

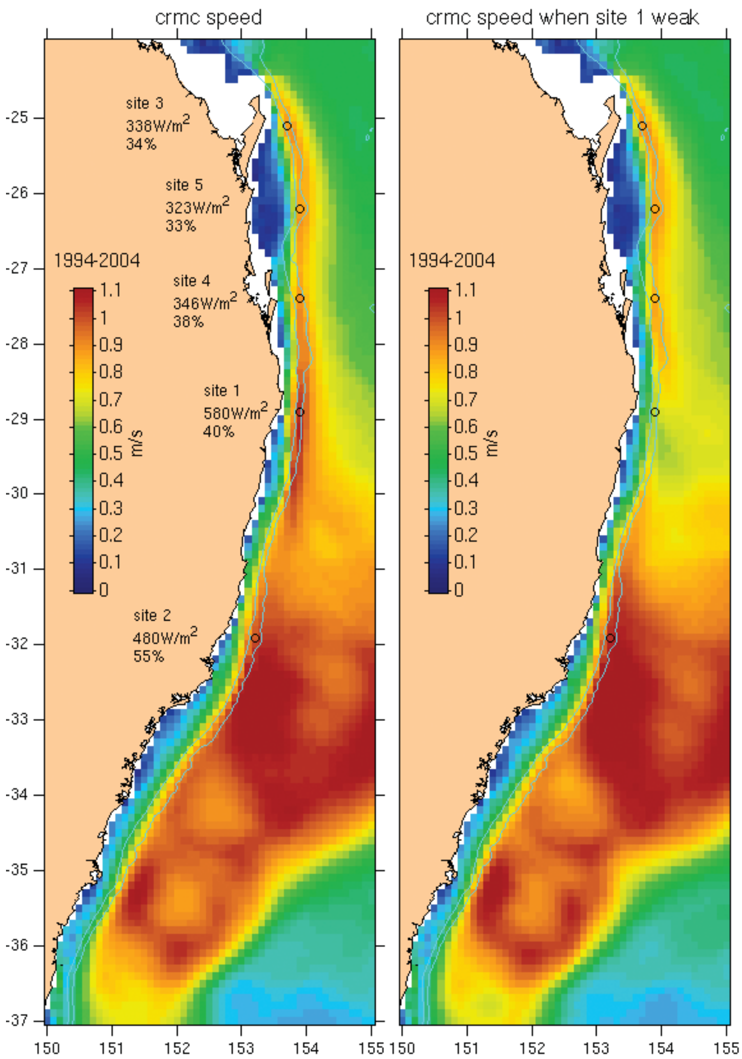


Figure 3-2 Maps of the time-mean non-tidal current power (shown as the corresponding "cube root mean-cubed" speed). The time period of the averaging for the left panel (a) is the entirety of 1994-2004; while for the right panel (b) it is just the days when the power at site 1 is less than ¼ of the long-term mean at that location. The long term means and intermittencies are annotated for all five stations.

3.1.3 Wave and Wind Energy

In contrast with tidal and non-tidal ocean currents, some long records of observations are available. We have conducted a brief analysis of these in order to make some comments on the intermittency of single-site and multi-site power generation. As above, we have not attempted to compute the optimal weighting factors for combining the production from various rregions, but simply show the result of adding together the power densities at the small number of sites for which the long records of observations exist, then renormalising by the new mean, for comparison with the time series of the single-site data (Figure 3-3).

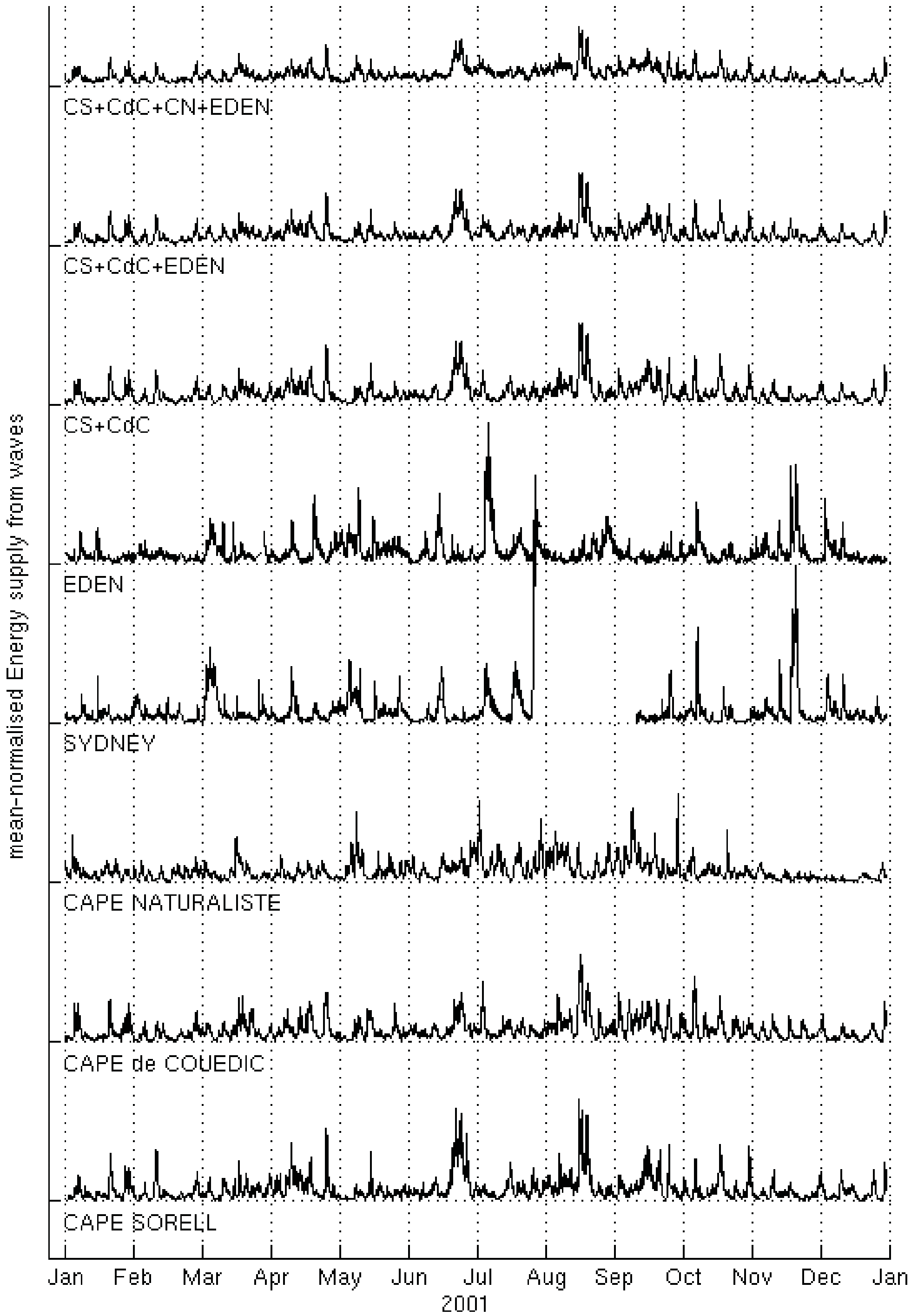


Figure 3-3 Time series of wave energy computed from wave buoy records. The summations from all sites are given in the top two records and from individual sites in the records below the summation.

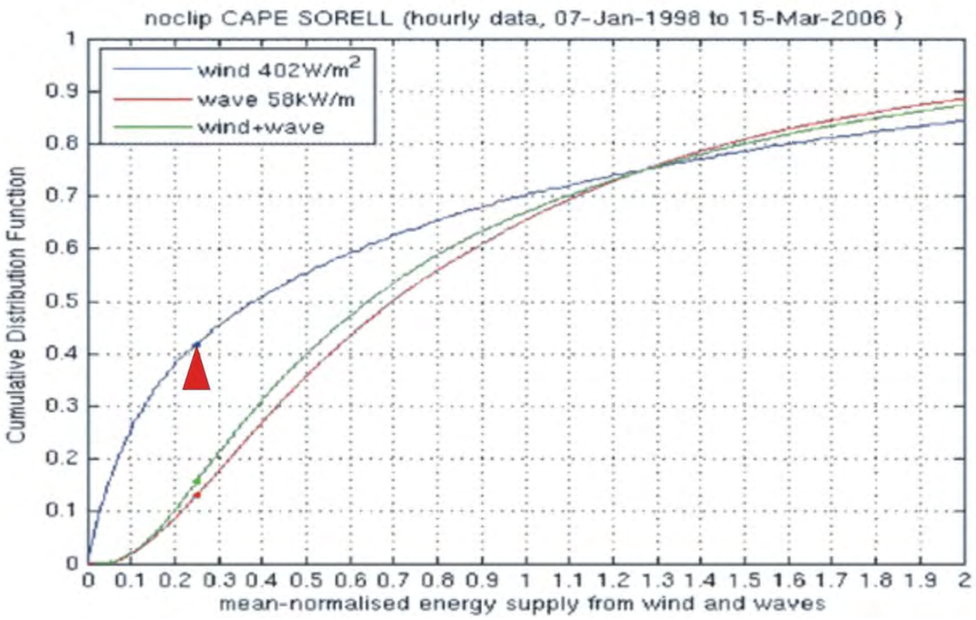


Figure 3-4 Cumulative distribution function of the wave and wind energy (normalised by the mean value shown in the key) at Cape Sorell, western Tasmania.

Statistics of Energy Fluctuations from Single Sites and Interlinked Sites

The cumulative distribution functions (CDF) (Figure 3-4) of the wave energy fluxes, each normalised by their means, show the statistics of their variability. Wind measurements are also included to provide a more familiar basis for comparison.

To address the vital question of the contribution ORE can make to dispatchable energy demand, the graph can be read in two ways. The 10th percentile of the normalised energy is that value of the normalised energy for which the CDF is 0.1. Since this is the value that is exceeded 90 per cent of the time it provides a potential definition of the dispatchable energy supply from the source. The other way of using the CDF (as shown in Figure 3-4) is to read off the percentage of time (defined above as the "intermittency") for which the normalised power P' is less than a critical value. The red marker indicates the percentage of time that P is less than a quarter. Also listed are statistics for the combined energy fluxes from several sets of sites.

For wave farms the benefit of interlinking Cape Sorell and Cape de Couedic is relatively low — the drop in per cent times of low output is from 13 per cent to 10 per cent. Connecting these sites with Eden, however, makes a big difference because the waves are of very different origin (and therefore timing) from those reaching the south coast. Table 3-1 also shows the potential for improved availability from bringing wave and wind farms together in a form of cogeneration as proposed by a number of European centres. The synergies between wind and wave power generation will be the topic of a separate study.

The value of combining wind and wave energy sources can also be assessed from Figure 3-4.

Figure 3-5 Location of measurement sites [14].

Site	Mean wind W/m²	Mean wavekW/m	per cent time P_n<1/4		
			Wind	Wave	Wind+Wave
Cape Sorell	402	58	42	13	16
Cape de Couedic	563	47	26	11	8
C. Naturaliste	372	51	25	12	7
Sydney	253	14	35	14	15
Eden	421	14	37	8	11
CS+CdC	447	55	29	10	9
CS+CdC+Eden	436	39	19	5	4
CS+CdC+CN+Eden	422	42	12	2	2

Table 3-1 Statistics of hourly wind and wave power computed from observations throughout the year at several sites from 1998 to 2005.

Site	Mean wind W/m^2	Mean wavekW/m	per cent time P_n<1/4		
			Wind	Wave	Wind+Wave
Cape Sorell	502	70	41	8	14
Cape de Couedic	805	68	24	9	6
C. Naturaliste	500	77	35	5	9
Sydney	255	17	37	23	20
Eden	416	15	42	13	16
CS+CdC	562	67	30	6	9
CS+CdC+Eden	510	47	20	2	4
CS+CdC+CN+Eden	512	54	12	1	1

Table 3-2 Statistics of hourly wind and wave power computed from winter-only observations (June-August) at several sites from 1998 to 2005.

Site	Mean wind W/m^2	Mean wavekW/m	per cent time P_n<1/4		
			Wind	Wave	Wind+Wave
Cape Sorell	325	43	42	13	14
Cape de Couedic	444	33	20	8	6
C. Naturaliste	329	29	14	6	3
Sydney	256	11	33	6	9
Eden	436	12	30	3	6
CS+CdC	370	39	25	10	7
CS+CdC+Eden	392	30	15	4	3
CS+CdC+CN+Eden	377	30	9	2	1

Table 3-3 Statistics of hourly wind and wave power computed from summer-only observations (December-February) at several sites from 1998 to 2005.

Some of the spread between the low and high values of wave energy flux is due to the annual cycle (Figure 3-6). Comparing Table 3-2 and Table 3-3 we see that in winter the mean wave energy levels are nearly twice the summer values. With the annual cycle removed from the statistical analysis by windowing the data set, the distribution of values is slightly tighter. The percentage time of relatively low wave power for Cape Sorell, for example, drops from its all-year value of 13 per cent to 8 per cent for winter-only data. In summer, however, this fraction is the same as the all-year value.

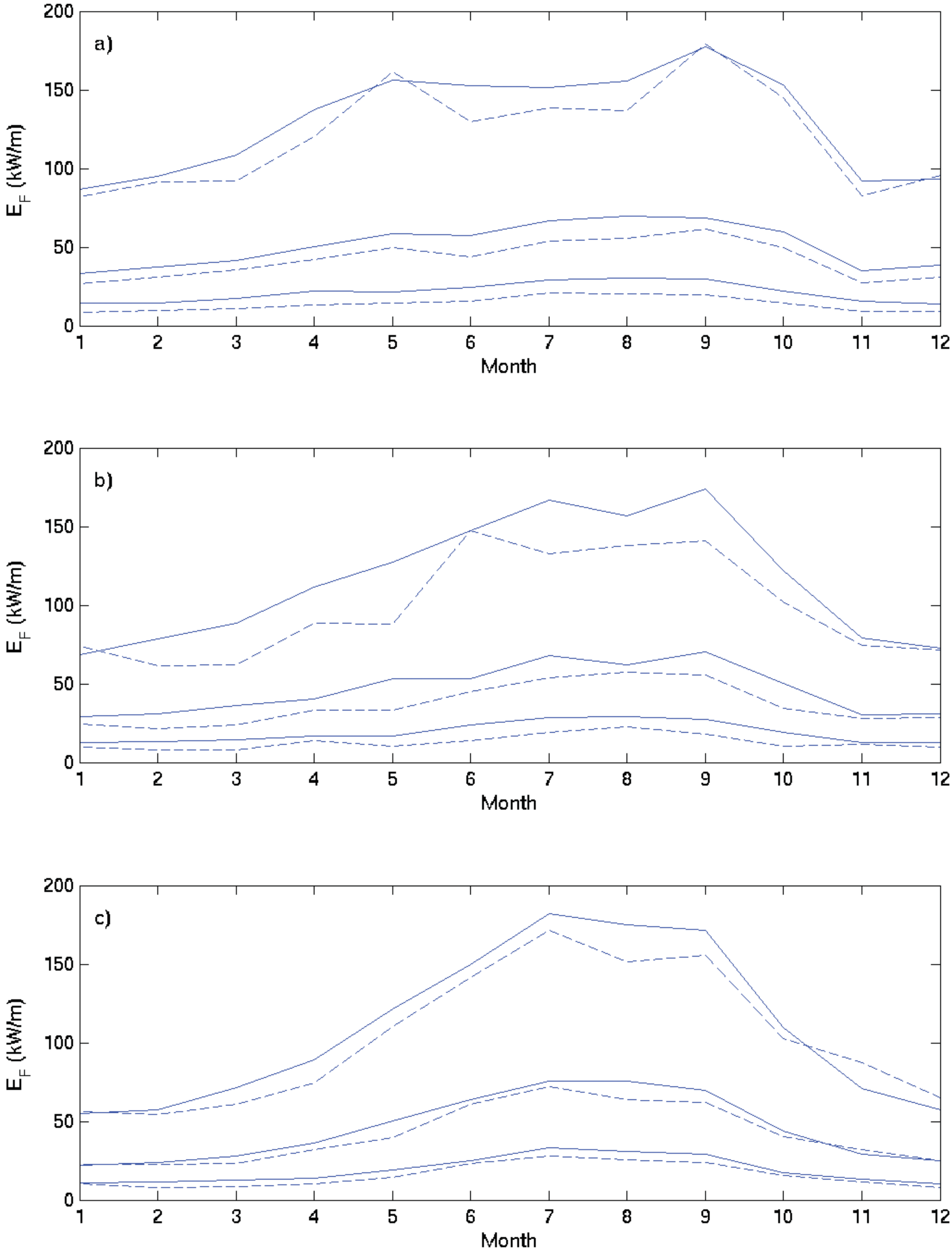


Figure 3-6 Annual cycle of wave energy flux estimated by the SWAN model [1] output (solid line) and waverider buoy data (dashed line) at Cape Sorell (top); Cape de Couedic (middle); and Cape Naturaliste (bottom). Upper two curves of each plot correspond to 90th percentile values. The middle two curves correspond to the 50th percentile values, and the lower two curves correspond to the 10th percentile values.

Interestingly, the winter increase of wave energy is fairly well synchronised with the winter 10 per cent increase in Tasmanian power demand (Figure 3-7). This extra winter demand (equal to about 115MW) is equal to the wave energy flux crossing 115MW / 70kW/m = 1.6km of wavefront. A 16km wave farm capturing 10 per cent of the incident energy would therefore meet this extra demand. In contrast, there is no synchronisation of the daily cycle (Figure 3-8) of energy demand, which features morning and evening peaks, with wave energy, which has no daily cycle.

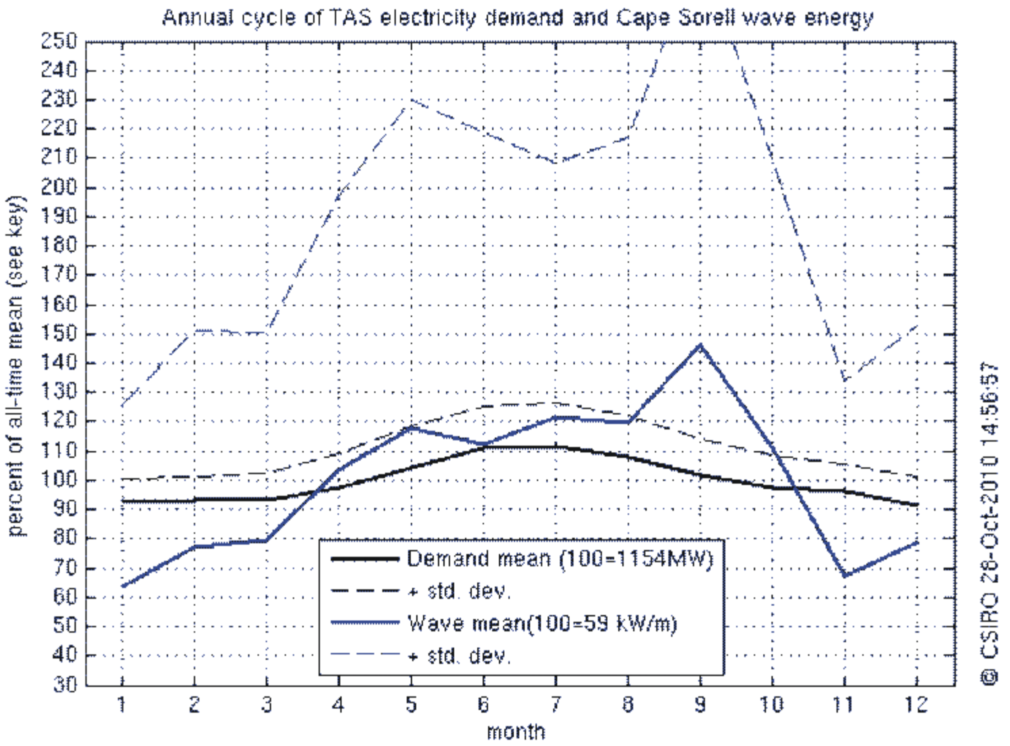


Figure 3-7 Annual cycle of Tasmanian electricity demand and west coast (Cape Sorell) wave energy, each normalised by their respective means (given in the key).

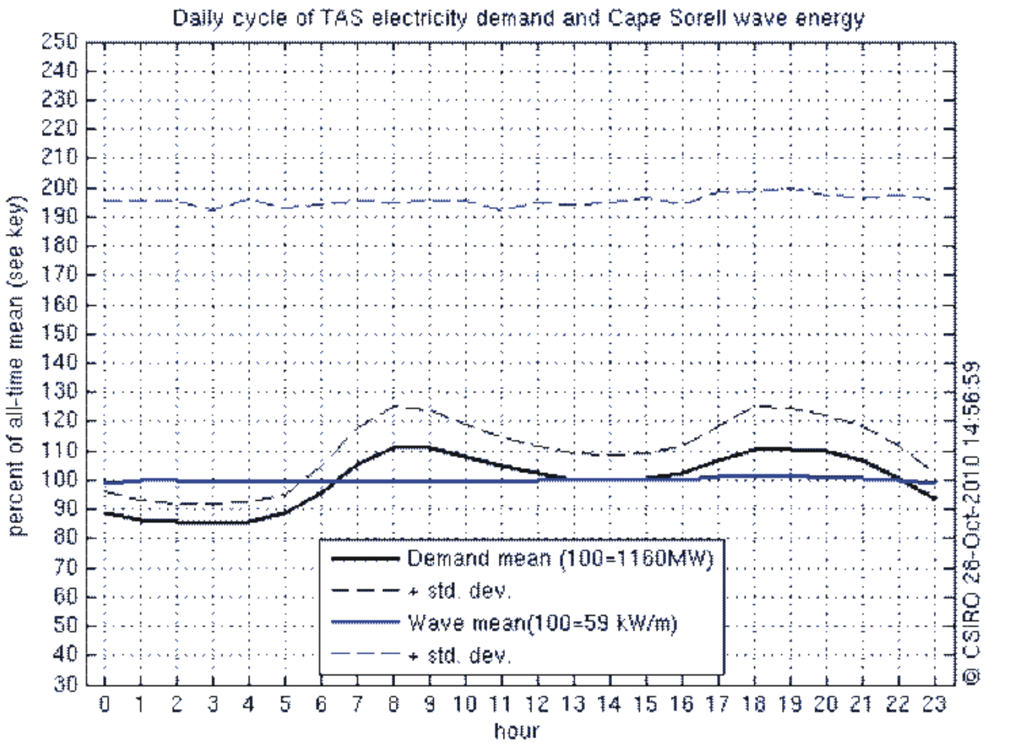


Figure 3-8 Daily cycle of Tasmanian electricity demand and west coast (Cape Sorell) wave energy, each normalised by their respective means (given in the key).

Increasing Availability by Spatial Averaging

The wave energy at Cape Sorell is significantly correlated with that at Cape de Couedic (Figure 3-9), reducing the benefit of combining the production from these two sites. The correlation is not perfect, of course, and we find that the average value of the energy at Cape de Couedic for times when the energy at Cape Sorell is in the lowest quartile is 2.5 times as great as the Cape Sorell value. The wave energy incident on the NSW coast comes from a totally different direction and is therefore totally uncorrelated with the Cape Sorell wave energy; so there is a bigger advantage, as far as smoothing production is concerned, of combining NSW wave energy with Tasmanian (west coast) wave energy. Figure 3-10 shows where electricity generation infrastructure exists that could allow the coupling of uncorrelated wave energy and renewable energy resources to improve availability and by omission where that infrastructure is still needed.

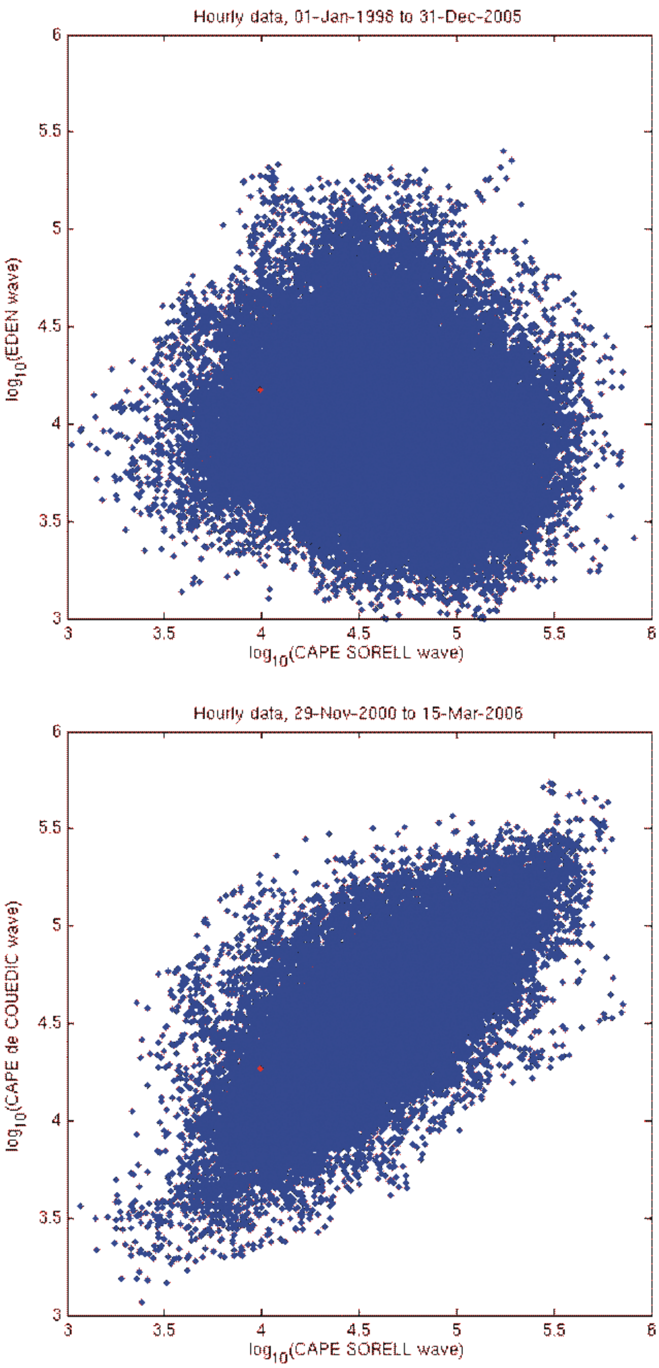


Figure 3-9 Scatter plot of Cape de Couedic (lower panel) and Eden (upper panel) wave energy vs. Cape Sorell wave energy. The red dot shows the average value for the times when the Cape Sorell energy is less than ¼ of the mean.

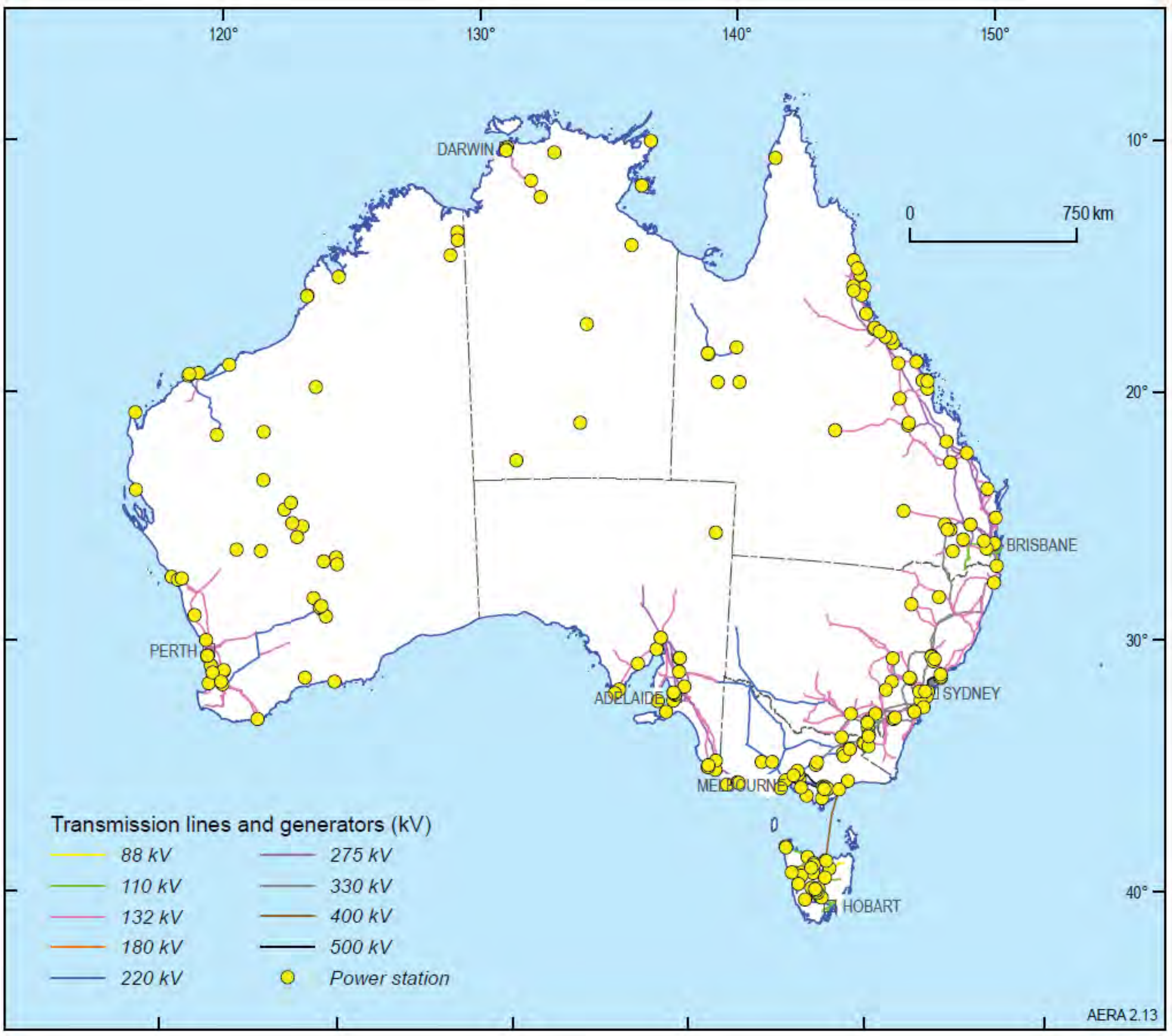


Figure 3-10 Australia's electricity infrastructure [15].

(cc) BY © Commonwealth of Australia (Geoscience Australia) 2012.

3.2 Forecastability

Waves are generated over time by winds over large regions. Consequently, the wave energy in a region is the result of the accumulated influence of the wind field at many locations possibly far away, at correspondingly earlier times. This is effectively an averaging and delaying process, making wave energy inherently more slowly changing as well as more forecastable than wind energy. This averaging process applies from the timescales of individual gusts (seconds-minutes) to the passage of fronts (hours).The impact of the averaging process on hourly (consideration of the minute-by-minute variations due to wind gusts and wave groups is beyond the scope of this study) values of power can be summarised by comparing the autocorrelation functions (Figure 3-11) which show that even after an interval of 24 hours, the wave energy is still moderately correlated (r^2=0.25) with the initial value, while the wind energy is not (r^2=0.02), although wind is still well forecastable at 24 hours. The production of energy from a wave farm at Cape Sorell would clearly be more slowly-changing than that from a wind farm.

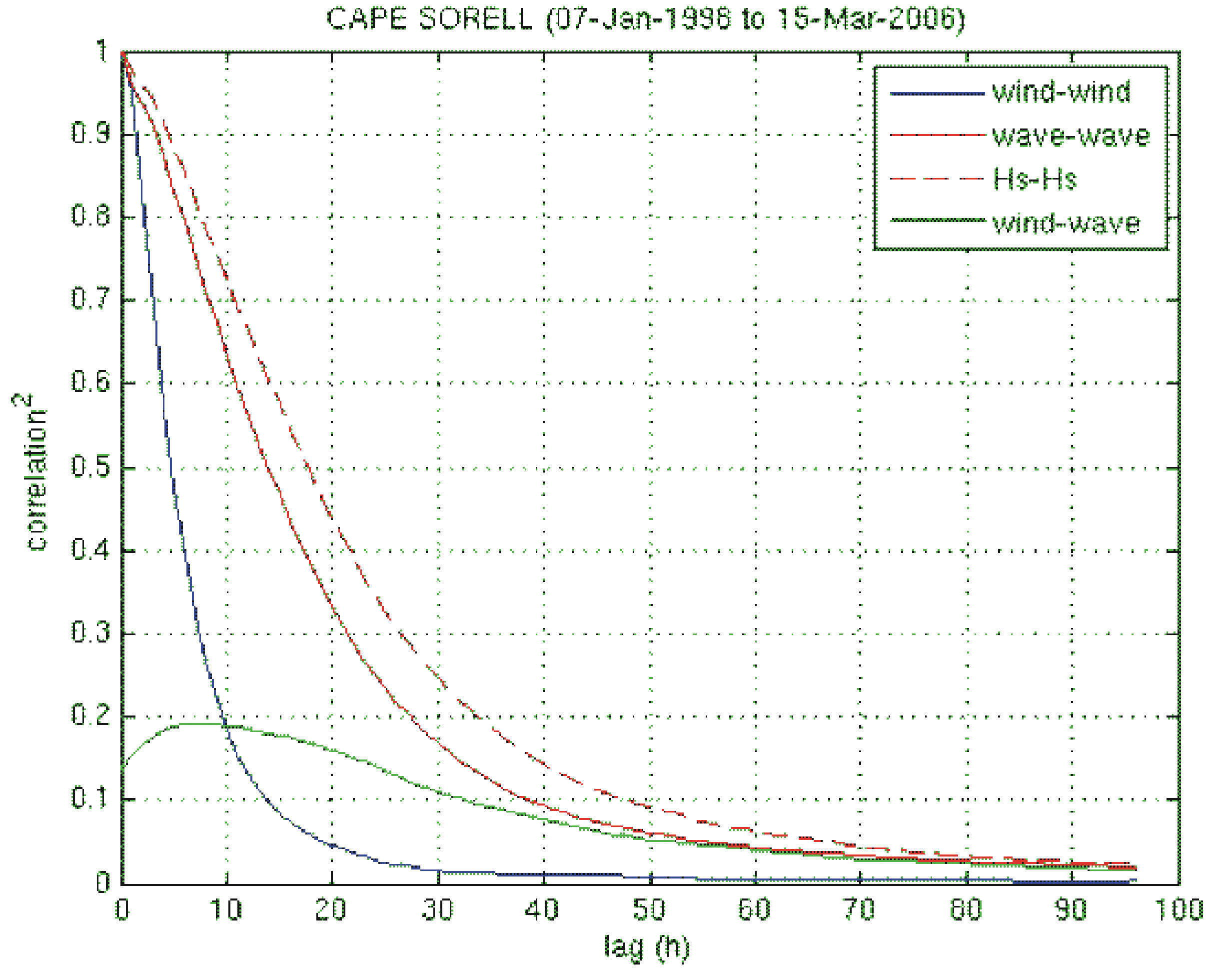


Figure 3-11 Autocorrelation functions of wind and wave energy at Cape Sorell, and the cross-correlation function. The auto-correlation of the wave height is also shown for reference and to make a link with Figure 3-12.

Looking as far ahead as 24 hours, however, the autocorrelation value is not the most relevant statistic. At that sort of time interval, the error of persistence as a forecasting technique is about as great as that of climatology (see Figure 3-12). Indeed, for forecast intervals greater than about 5 hours (also Figure 3-12), the best estimate of the future wave energy production would be derived from a wave forecasting system. This is because it can exploit the fact that waves travel at a well-known speed, so knowing the present state of the wave field over a large region is a good basis for a prediction into the future. At the intermediate lead time of 12 hours, the forecast skill (measured by r^2) for Cape Sorell wind speed is 0.9 while for wave height it is 0.94 [16]. The corresponding estimates of the standard-deviation-normalised RMS errors of speed and height for Cape Sorell are 0.3 and 0.25, respectively (and here it must be remembered that wind power depends on v^3 while wave power depends on $T.H^2$).

The four methods for estimating forecasting error are: 1) persistence of observations (i.e., same information as Figure 3-11 but here we look only at wave height, not energy), 2) the all-time mean, 3) mean for the time of year (climatology), 4) the (new) AUSWAVE forecast about to be declared operational at the Bureau of Meteorology. Note that these data provide the average performance for all buoys and that the error for Cape Sorell is less than average.

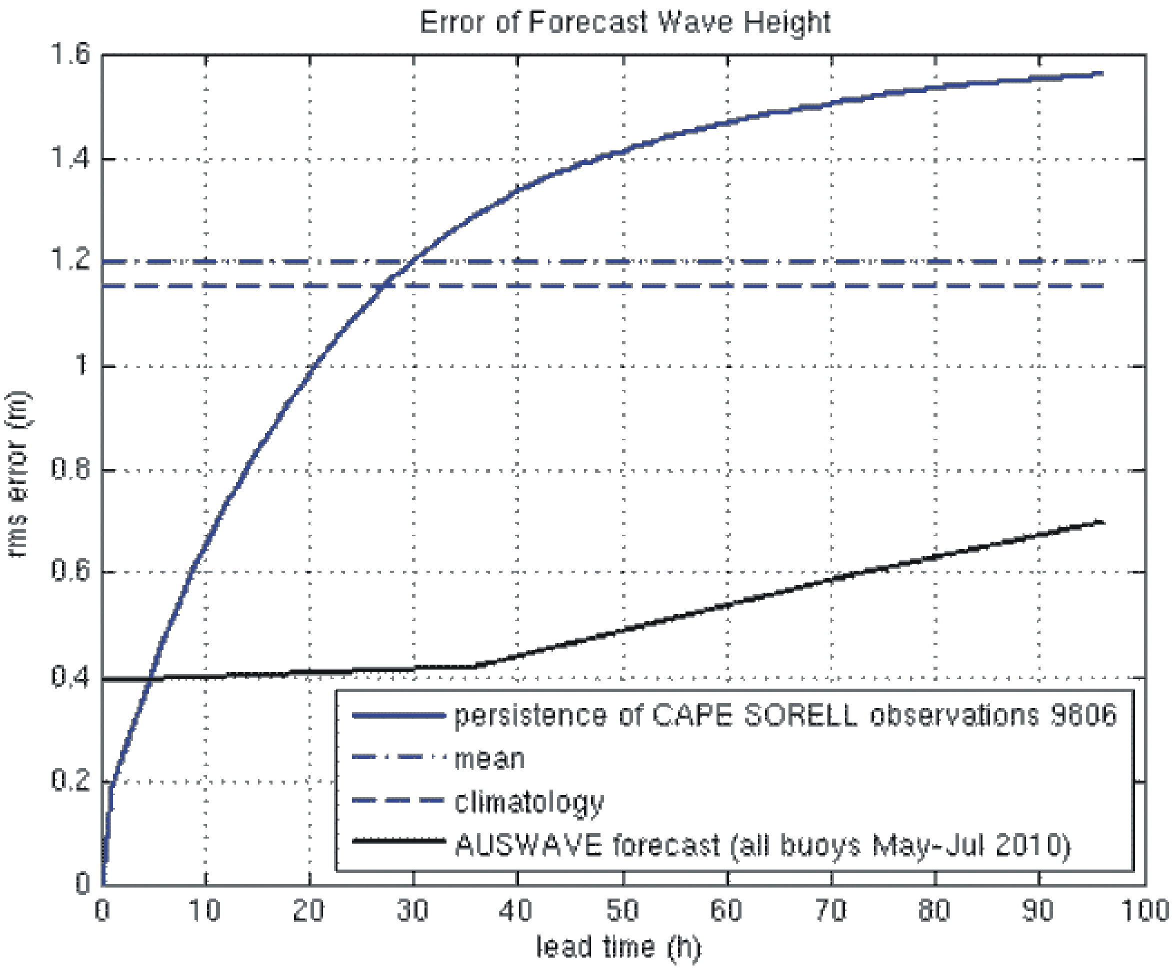


Figure 3-12 Estimating error of forecast wave height at Cape Sorell by four methods.

3.3 Conclusion

The temporal variability of wave energy has three useful properties:

1. Hourly-average wave energy varies at about one-third the speed of hourly-average wind energy, i.e. the time for the autocorrelation function to drop to any particular value (in the 0.95 – 0.3 range) is about three times as great.
2. The same 1:3 ratio applies to the reliability of the respective forecasts generated by the Bureau of Meteorology — a wave forecast for 36 hours is nearly as accurate as a wind forecast for 12 hours. This is particularly relevant for the recently proposed technologies that will allow converters to tune their performance to optimise performance for synoptic scale variability.
3. The incidence of low (less than ¼ of the mean) values of energy is much less for wave (13 per cent at Cape Sorell) than it is for wind (42 per cent).

Whether these advantages compensate for the inevitably greater costs associated with operating in the marine environment is discussed in chapter 7. We also examined the spatial variability of wave energy and found that combining the production of several sites does achieve a degree of smoothing, especially when the sites are exposed to waves from different directions. The wave climate off NSW, for example, is totally different from that off western Tasmania or western Victoria where the highest energy densities are to be found. A closer examination of the characteristics of particular devices would need to be undertaken to further evaluate the benefits of combining the production of high-mean (south coast) and low-mean (east coast) wave farms, where different types of devices might be appropriate.

What we have not done, but believe should be done, is to address the question of the optimal mix of renewable energy sources, with both cost and temporal variability taken into account.

4. Ocean Energy Conversion Devices

This chapter describes a number of options for harvesting energy from the oceans.

For 50 years scientists and engineers have been exploring the reserves of ocean energy stored in waves, tides, currents, thermal gradients and salt concentration [17] [18]. This diversity of energy resource is matched by an extraordinary range of techniques, particularly in accessing wave energy. Of 200 devices currently being developed about half a dozen have been scaled up, partially tested at sea and the data publicly reported. They range in size from devices the size of an oil drum to structures weighing hundreds and potentially as much as fifty thousand tonnes, the weight of a loaded bulk freighter.

This chapter will take each energy resource and provide an overview of the principles for extracting energy and describe the many devices that can be used. It will briefly give examples of devices that have been analysed, constructed and sea tested to some level. Most importantly, selection will be restricted to devices with model data and if possible measurement data that are publicly available.

The principal focus will be wave energy, as wave energy resources are of an order of magnitude greater than tidal in Australia, while techniques using ocean current, ocean thermal and salt gradients are in their infancy. Some of the issues in setting up wave farms will also be described, using three devices that represent a range of size and techniques, and whose data is in a form that allows comparison. Finally, an assessment will be made of how much energy might be extracted from the south, south west and south east coasts of Australia. This information will be used in chapter 7 to make projections of market share for wave energy over the period 2015 to 2050 and to determine whether or not ORE can make a significant contribution to the Australian economy.

4.1 Ocean Waves and Energy Converters

4.1.1 Wave Properties and Power Generation

Wave energy is derived, ultimately, from the wind. The transfer of energy from the wind to the waves occurs locally over short distances (kilometres) resulting in "wind waves", or remotely over long distances (thousands of km) resulting in ocean swell. Swell periods range from about 8 to 14 seconds with wavelengths in the deep ocean of 100-300 metres. The maximum wave height measured in Australian waters, over an approximately 30-year record, was approximately 18 metres.

In the southern coastal regions of Australia wind waves typically range in height from a few centimetres to 2 or 3 metres with wave periods from about 2-8 seconds, while swell can typically range in height from a few centimetres to 7 metres or more. The average height of swell off the southern coast of Australia is 2.5 to 3.5 metres. The period is 11 seconds and the direction predominantly from the south-west. In contrast, swell off the coast of New South Wales has an average height of 1 to 2 metres, an average period of 6 seconds and can occur either from a south-easterly or north-easterly direction.

Waves and Energy Conversion

The Power flux "P" (watts per metre) along an ocean swell front in the deep ocean has already been described in chapter 2. However, the variation of power flux and wavelength with depth are also key considerations in designing Wave Energy Convertors (WECs). These are briefly described below.

Wave power profile with depth and converter design

The operation and design of WECs depend very much on water depth, because the movement in a wave offshore is essentially circular and progressively changes to a linear surge as the water depth reduces below about half the wavelength. The profile of wave power with depth is described as:

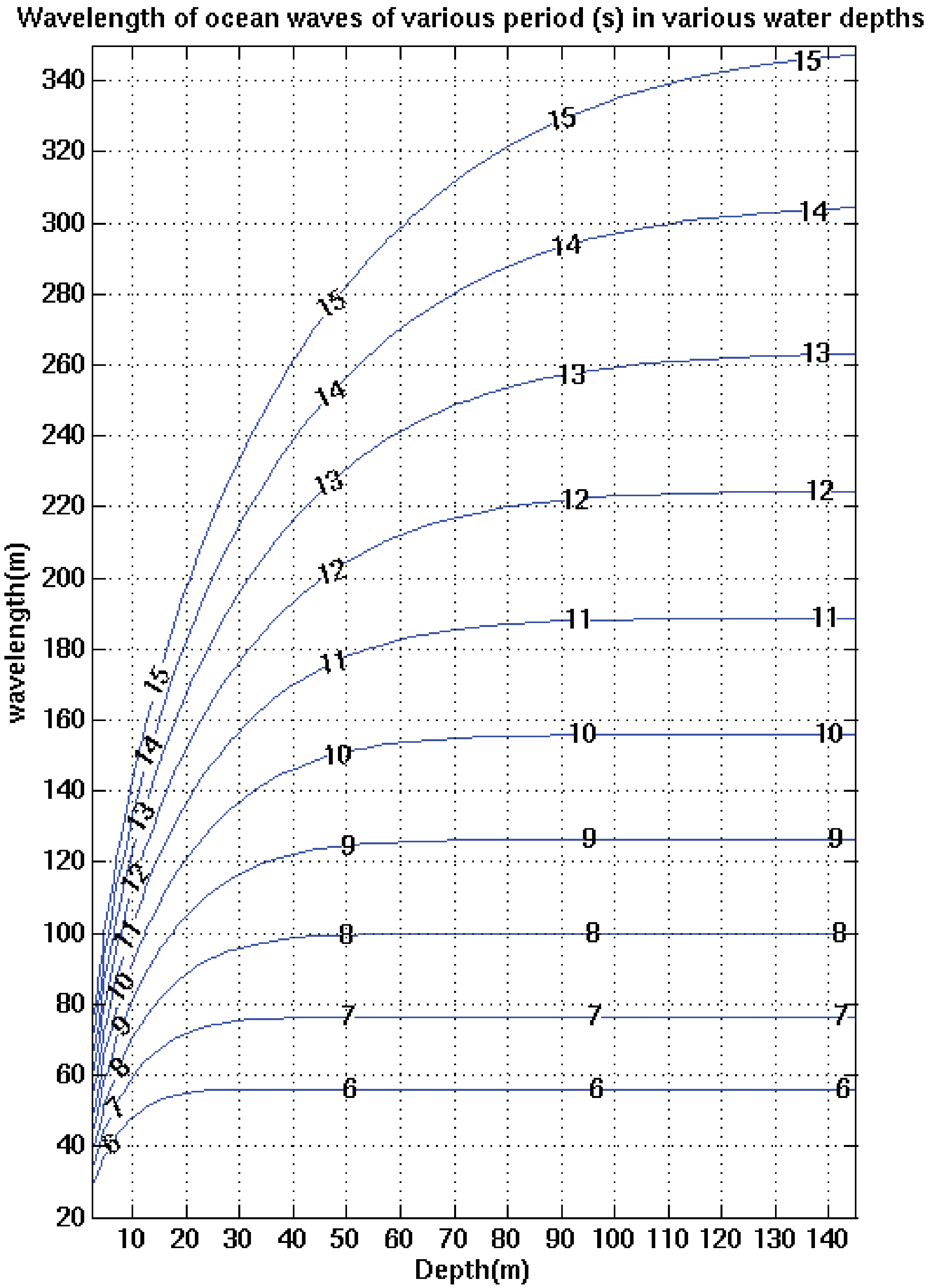
$$P = Ps \cdot e^{-\frac{d}{\lambda}} \qquad 4.1$$

Where Ps is the power per metre at the sea surface, d is the depth below the surface and λ is the wavelength.

This decline in wave power with depth means that it can be useful to place expensive components on the sea floor where they have a degree of protection against poor weather conditions. It can also be practical to place large converter components that receive the energy, such as a buoy or flap, sufficiently far below the surface to allow small boats to pass over a device or wave farm. The associated reduction in power with depth is not necessarily a disadvantage as there may well be an environmental requirement to restrict energy absorption from a wavefront: see section 6.1 Sea Calming Effects (taking energy from the sea).

Period, wavelength and sea depth

As waves traverse the continental shelf they lose about 10 per cent of their energy. The transition from the deep ocean to the shallower continental shelf reduces the group velocity, resulting in an increase of the wave height and reduction of the wavelength (see Equation 4.2 and Figure 4-1). These changes and the subsequent effect on energy conversion are key design issues. Despite the loss of energy, this increased wave height and reduced wavelength may be better matched to practical designs for a WEC.



$$\omega^2 = g \cdot k \cdot \tanh(k \cdot h) \qquad 4.2$$

Where $\omega = 2\pi/T$; $k = 2\pi/\lambda$

Figure 4-1 Chart and equations for the wavelength λ of ocean waves vs. period T and water depth h.

4.1.2 Classifying WECs

The classification of WECs is not harmonised; there are many systems in use and each shares subsets of techniques and nomenclature. Two commonly used broad classifications are described here, together with their associated techniques [19-23]:

- Collector Surface Orientations: (point absorber, attenuator and terminator).
- Wave Energy Transfer Mechanism: (oscillating water column, overtopping and oscillating bodies).

Classification by Collector Surface Orientation

Point Absorber

The term point absorber refers to devices that incorporate a float that is small compared with the swell wavelength. The float is free to follow the movement of the wave and accept wave energy from any direction. It can be tethered so that it is submerged and moved by the pressure of the wave passing overhead, or it can float on the surface and track or "heave" with the movement of the sea surface, as shown in Figure 4-2.

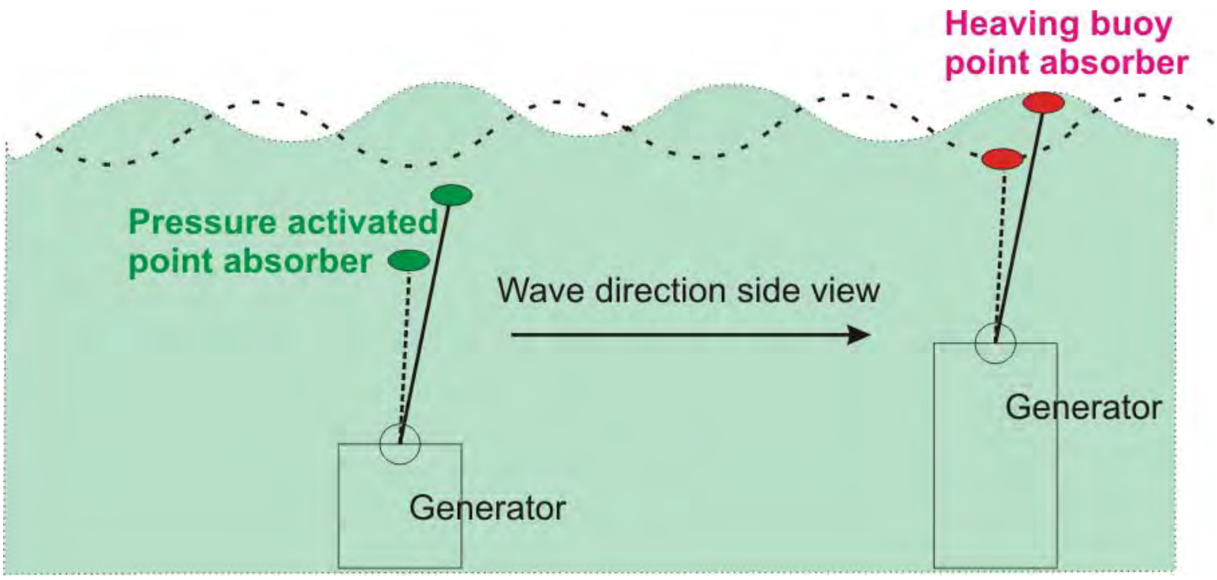


Figure 4-2 Pressure activated and heaving buoy point absorbers.

Linear Absorbers or Attenuators

These devices incorporate a float, or a number of floats that are shaped or distributed to be aligned in the direction of wave travel. Their overall length may be large compared with the swell wavelength. However, they are also wavelength-dependent. Unlike a point absorber they need to be slack moored so that they can turn to maintain their principal axis normal to the oncoming waves (see Figure 4-3).

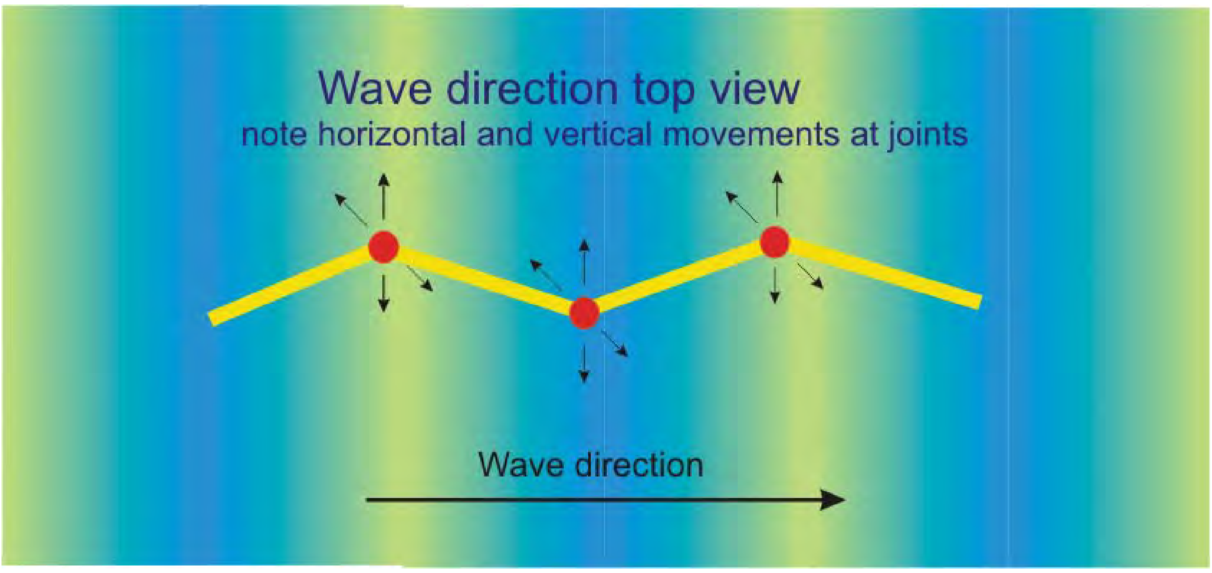


Figure 4-3 Linear attenuator absorber. Adapted from Pelamis schematic [24].

Terminators

Terminators are designed to collect energy from waves by directly facing them. They may include passive devices such as a tapered channel to focus energy from a wide section of wavefront. Examples of terminators include oscillating water column and overtopping classes of device (see Figure 4-4).

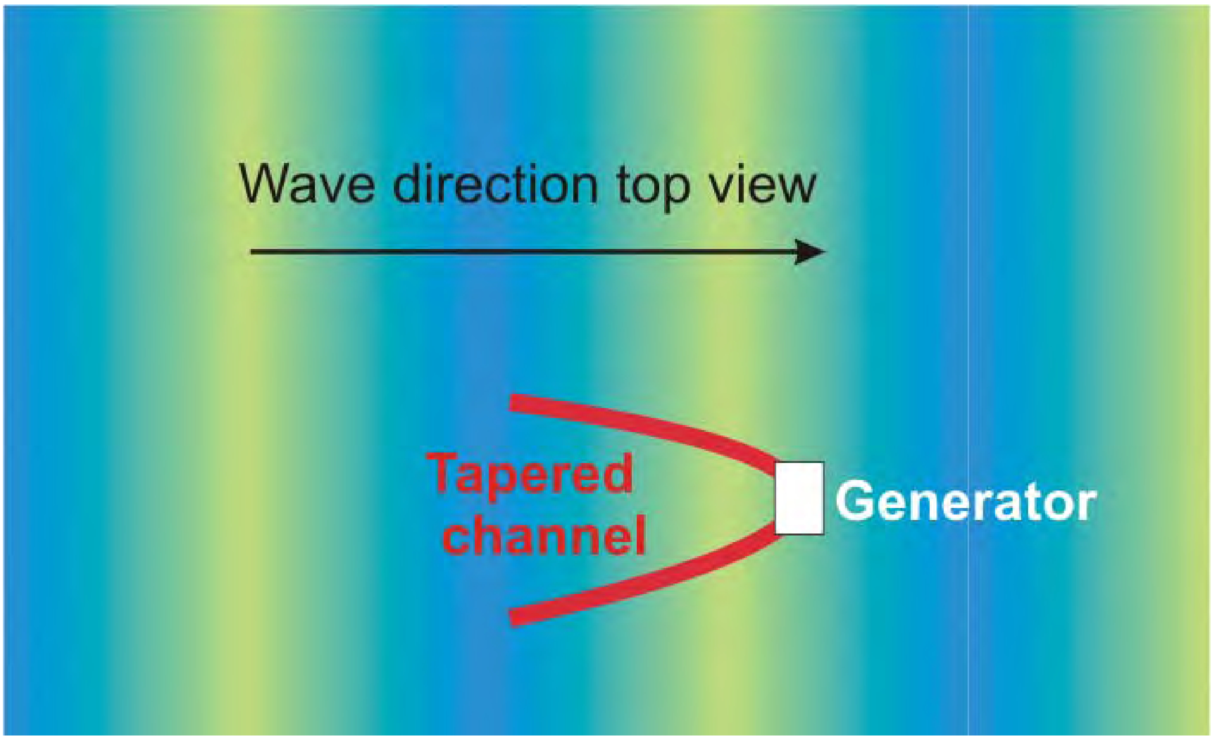


Figure 4-4 Tapered channel terminator.

Classification by Wave Energy Transfer Mechanisms

Overtopping

Overtopping devices are terminators. They face into the wave direction and direct waves up a ramp and into a catchment tank. These devices are designed to concentrate wave energy from a wide area to the narrow collecting ramp to effectively increase the wave height at the ramp. The ramp converts the waves' horizontally directed kinetic energy into vertically directed potential energy by "focusing" and lifting the incoming water, which can rise high enough to pass over a wall and into the catchment tank where it forms a head of several metres of water pressure. The water then flows down through a bank of "low head" turbines to turn a generator. These devices can be attached to the sea bed or shoreline, or be designed to float. The Wave Dragon is an example of a floating overtopping WEC and is described in more detail later in this chapter.

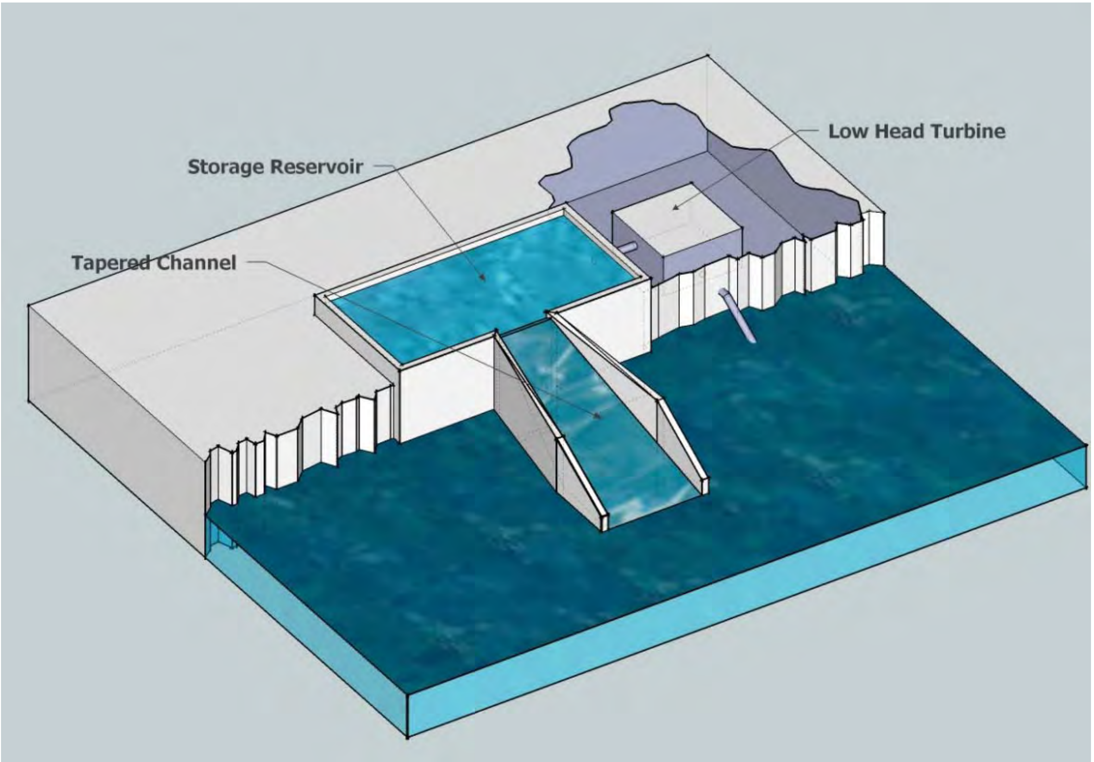


Figure 4-5 Terminator with tapered channel and overtopping ramp [25].

Oscillating Water Column

These devices are terminators in which energy transfers from the wave to the converter via a pneumatic intermediate stage. The principle is analogous to a blow hole and is shown in Figure 4-6. Waves enter a chamber with a horizontal opening facing the sea. The wavefront traps a volume of air and pushes it through a funnel or chimney containing a turbine. The turbine is designed to rotate in one direction only, independent of the direction of the air flow. Two designs for this are the Wells turbine that uses symmetric airfoils to allow unidirectional rotation and the Denniss-Auld turbine which uses blade pitch control to achieve unidirectional rotation with a higher efficiency than the Wells turbine. These devices are usually fixed to the seabed or coastline. However, they can be built such that the whole of the device floats on the ocean and is moored away from shore. Examples of such converters are the Pico and the Limpet, both of which are shore-based fixed installations respectively in Portugal and on the Isle of Islay Scotland; and the Oceanlinx developed in Australia and the Mighty Whale developed in Japan, are both offshore floating oscillating wave converters.

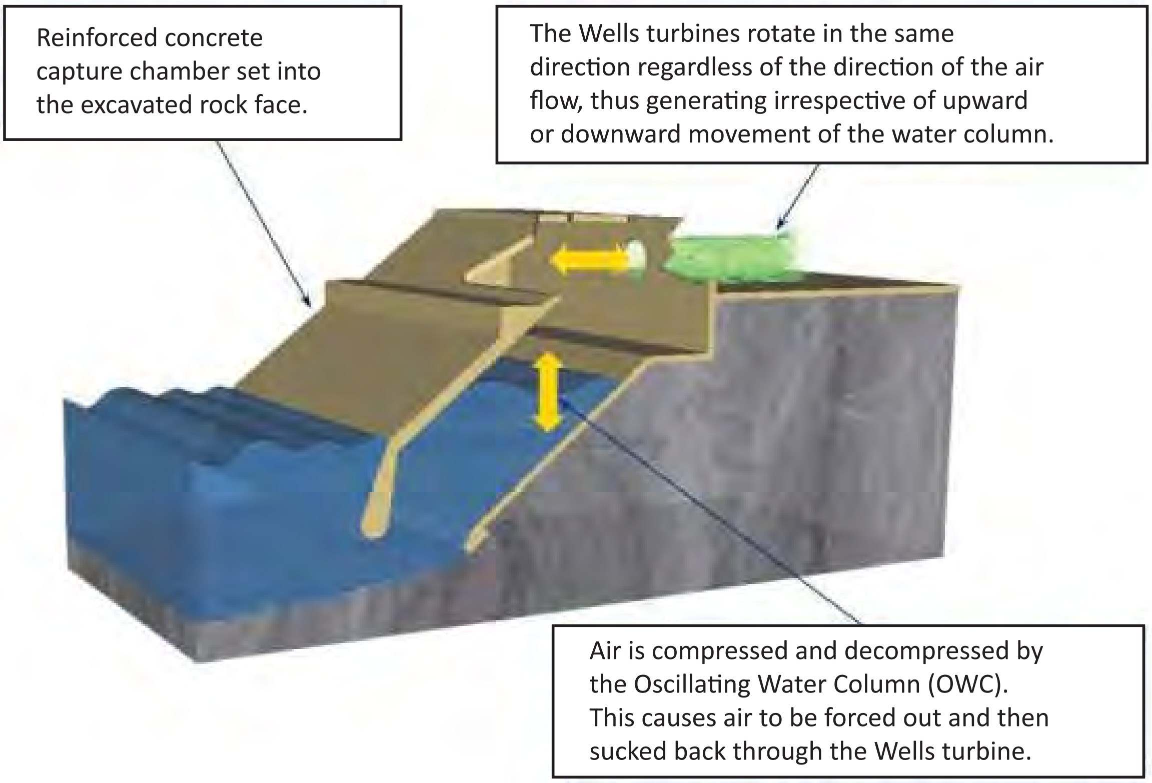


Figure 4-6 OWC operating principle. Image courtesy of Voith Hydro Wavegen Ltd.

Oscillating body

The oscillating body classification outlines how wave energy that is harvested using floating or submerged barriers or buoys can be transferred to the energy converter using mechanical levers or pistons. There are a number of sub classifications. These include:

Single-body: fixed frame

A buoy or other floating body (wave-buoy) on the sea surface picks up wave energy and transfers it to a converter that turns it into electrical or hydraulic energy (as in Figure 4-2). The converter is set in a fixed frame of reference such as the seabed or a point on a nearby shore. The mechanical connection between the buoy and converter is usually a taut cable connected to a moving actuator in the converter. The actuator may also incorporate elastic loading and active or passive damping to assist with load matching. Consequently both the damping and the time constant of the WEC must be tuned to match the spectrum of the wave environment in which it will be located. An example is the Sea Based linear electrical generator developed at Uppsala University.

Two-body: inertial

The principal difference between a single-body and two-body WEC is that the converter is contained within or adjacent to the wave-buoy instead of being attached to a fixed frame on land or the sea floor. The two bodies considered here are the wave-buoy and a converter component. These are arranged so that they move differentially in response to waves. This can be achieved by arranging for a local mass of water to react against a damping plate attached to the converter. The resulting differential movement allows the transfer of mechanical energy from the wave-buoy to the converter.

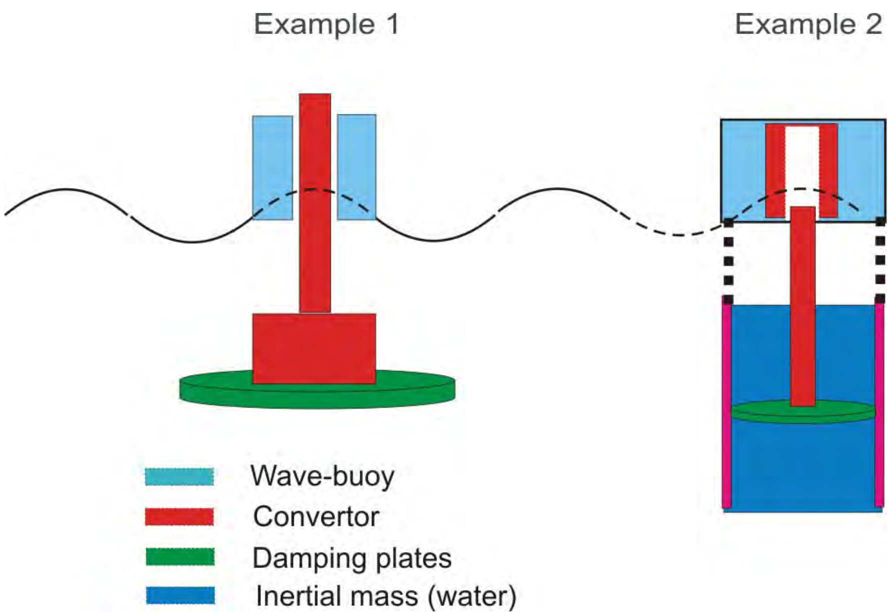


Figure 4-7 Two examples of inertial two body WECs.

The wave float and converter may be arranged coaxially, such as the L-10 linear electrical generator developed at Oregon State University. Or they may be connected by a mechanism such as a piston and inertial mass (water) as in the IPS buoy developed by Uppsala University. As with the single body fixed frame devices the connection may be associated with an elastic component to assist in load matching between the wave-buoy and the generator. There is a consequent need to tune the converter to match the spectrum of the wave environment.

Multi-body: inertial and fixed frame

The two body systems described above can be combined to include multiple sets of generators and wave harvesting floats connected together. Examples include the WaveStar with 20 floats connected to hydraulic pistons set in a fixed frame converter; and the Pelamis which has four power modules linked together with a wave-buoy in each module operating a converter in the adjacent module making up a multi-body inertial converter.

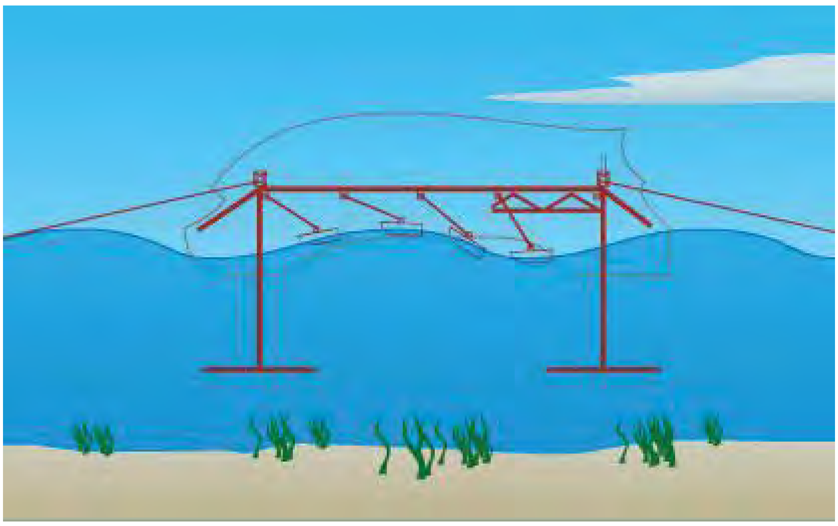


Figure 4-8 Wave Star, multi-body fixed frame absorber. Image courtesy of Perpetuwave Power.

Pitching devices

These devices are tethered buoys designed to rock back and forth in the waves picking up energy from the horizontal movement of the wave. One of the earliest examples is the Salter Duck. The difficulty of adapting tether arrangements for changing wave directions means that these devices are best used where the wave direction does not vary significantly.

Hinged systems — Pendulum — Oscillating Wave Surge Converters

The pendulum category of WEC describes devices which form a wall in the water, arranged to hinge around a horizontal axis located either near the surface (for example the Pendulor), or near the sea floor (as in an inverted configuration like Aquamarine Power's Oyster). These devices capture energy from the horizontal movement of the wave as it surges near the shore. Some are designed to be attached to a floating platform so that they can self-align to the direction of the wave.

4.1.3 Summary of WEC Energy Transfer Mechanisms

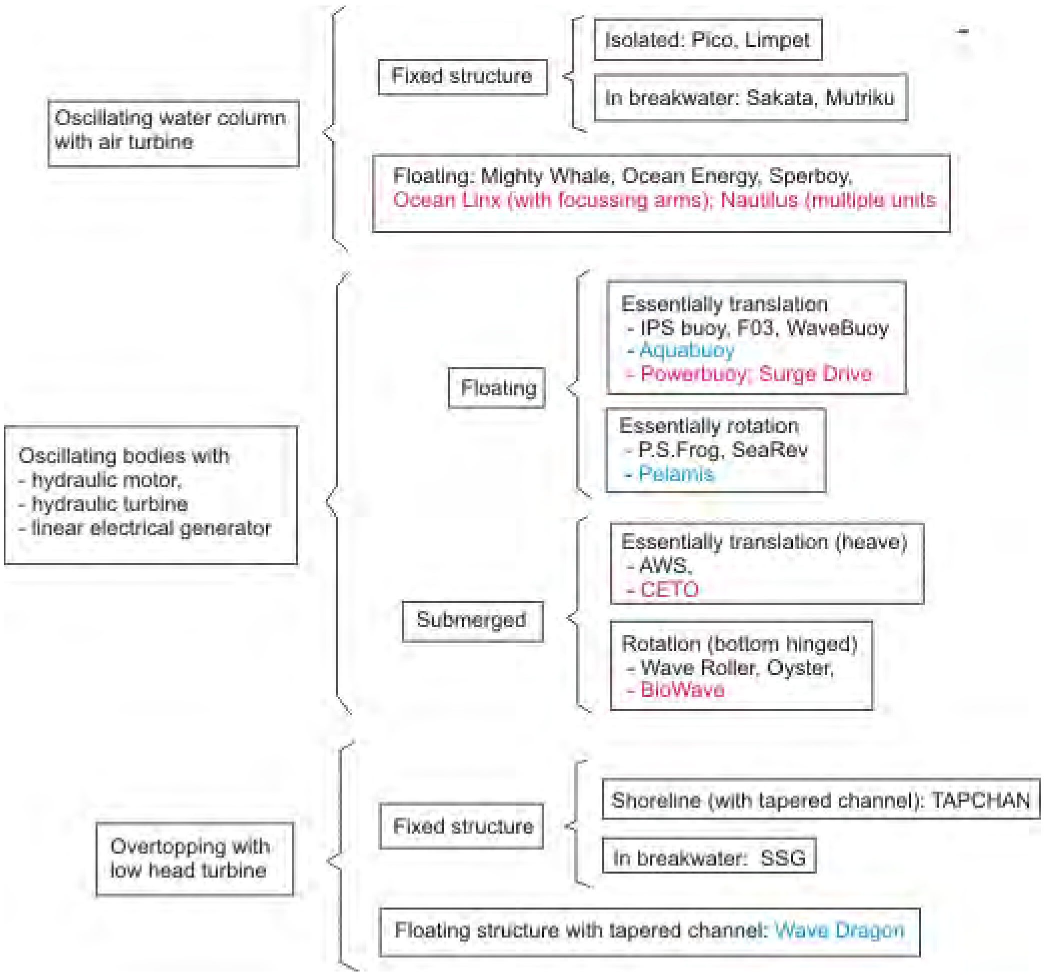


Figure 4-9 Various Wave Energy Technologies classified by energy transfer mechanism. The blue text shows models used in analysis. The red text shows devices being further developed in Australia. Adapted from A.Falcao [22].

Some WECs operate on principles that cannot be covered by the classifications described here. An example is the Ocean WaveMaster converter which is a submerged device that uses the differential pressures below wave peaks and troughs to drive submerged turbines.

4.1.4 Some Key Design Constraints

Geographic Location

Ocean WECs can be designed for most ocean environments. However, the location has a considerable impact on the cost effectiveness of a design approach. Some of the key design considerations are briefly described below:

Deep Ocean (greater than 500 metres depth)

While ocean waves at these depths have lost very little energy, the difficulties of anchorage, the limitations on design imposed by longer wavelengths and smaller wave heights, and logistical costs are all likely to preclude this option, except where there may be a local need for power such as for island communities or drilling rigs.

Offshore (greater than 50 to 70 metres depth)

As waves reach the continental shelf overall wave energy is lost. However the wave heights increase and the wave lengths decrease, expanding the range of WEC design and anchorage options. In addition, the relative proximity to land would reduce capital and operations and maintenance costs.

Onshore

Locating a WEC onshore has the advantages of accessibility for maintenance, limited power transmission costs and the potential for designers to use the land as part of the structure of the device. However, wave energy decreases in magnitude the closer to the shoreline the wave gets. There may also be difficulty in finding suitable onshore sites for WECS. This could be owing to competing land uses as well as correct land profile, access to reasonable waves, environmental impact and proximity to necessary infrastructure, among other factors.

Near Shore (less than 50m)

A WEC located near shore trades off the advantages and disadvantages of offshore and onshore systems. The power and consistency of wave energy may have been lost by the time a wave is close to shore. However, the capital, operation and maintenance costs are likely to be lower and design options increased. These might include placing a wave buoy in the sea and mechanically coupling it to a land based generator.

Power Transmission

To provide electrical energy to the main power grid, a WEC must transport energy to the shore either as electrical energy, or as some other form which can be converted onshore. Energy transportation methods include via direct current electrical energy, alternating current electrical energy, or hydraulic power (as pumped sea water). Using pumped sea water as a method of transmitting power provides further potential for storing energy, or alternative uses of the energy, as outlined below. In general, if a significant distance is involved (as for offshore installations) the option of transmitting electrical energy is likely to be the most cost effective.

Energy Storage

For smooth delivery of power from a WEC, some amount of energy storage or “capacitance” is required to help offset the cyclical nature of wave energy. Devices to do this might take the form of flywheels, hydraulic accumulators, a head of water, batteries, mechanical or pneumatic springs or salinity gradient systems, to take a few examples. It seems that most WECs include some form of capacitance for short-term power smoothing, while some could potentially use capacitance for the long-term storage of energy.

As mentioned above, some wave energy generators can pump water directly to shore (for example Carnegie CETO). This not only provides the ability to smooth the power output, but also the potential to store energy during times when the electrical energy is not needed. This might be achieved by simply pumping the sea water into an elevated reservoir, or accumulator, which can be released at some later point.

Directional Dependency/Independency

Some types of WEC work equally well in waves from any direction, including any point absorber. Other types of WEC work best when wave energy is from a given direction. Pendulums, pitching devices and terminator style converters are commonly directionally dependent.

With suitable anchorage, some directionally dependent WECs, such as the Pelamis and the Wave Dragon, are able to realign their orientation to the wave direction for optimal energy conversion.

Strategies for Coping with Extreme Sea States

A key issue for Wave Farms and WECs, which may comprise a hundred or more converters about the size of a bulk carrier, has been the need to withstand storms and extreme wave conditions, while remaining cost-effective. However, WECs are usually designed for best performance in average or predominant wave conditions, and are sized and manufactured accordingly. The devices are therefore not necessarily designed to work optimally in high wave energy sea states. But they must be designed to survive extreme wave heights that may occur only once in twenty years [Figure 4-10].

Wave buoy measurements at eight sites around the southern coast show that a maximum wave height of between 15 to 17 metres has been observed at least once over a twenty year period at each of these sites. The latest was an 18 metre wave on 16 September 2010, 10km off Cape Sorrell on the west coast of Tasmania.

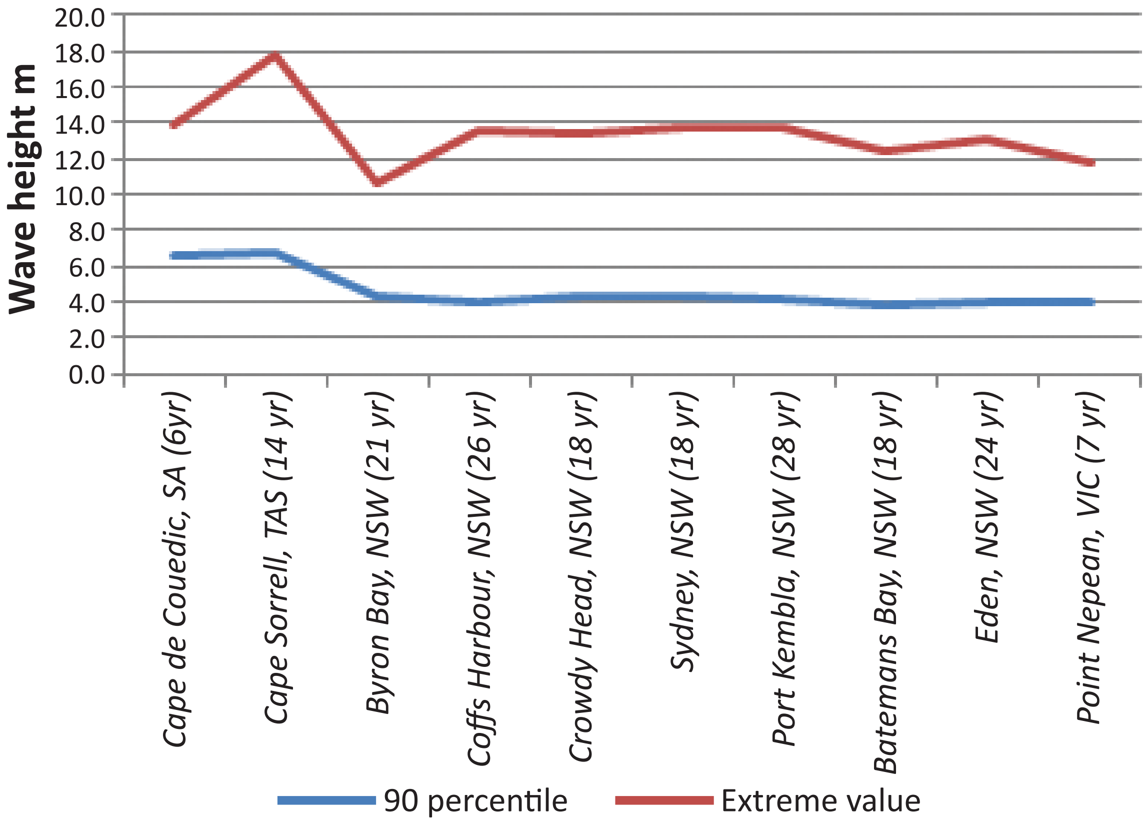


Figure 4-10 Twenty year extreme wave heights.

Strategies for coping with such extreme waves include:

- Providing protection mechanisms such as automated lowering of expensive components to the sea floor when extreme conditions are forecast.
- Using low cost redundant equipment such as buoys on the sea surface with the expensive equipment placed on the sea floor or onshore.
- Making the device and the farm sea worthy enough to cope with the extreme conditions.
- Installing energy relief mechanisms that limit loads through the system in extreme sea states.
- Folding or moving the device to the sea floor (appropriate, for example, for inverted Pendulums and other near shore devices).
- Shutting down the devices to simply "ride the waves".
- Designing devices large enough to withstand extreme conditions.
- Designing a device as a potentially disposable or recyclable element. This would be appropriate if a device or its components were cheap enough for energy and economic costs to be paid back between extreme wave events. This approach has been adopted by The Wave Power Project at Lysekil where a relatively low cost and easily replaced wave buoy is deemed sacrificial, while the high cost generation equipment is located on the sea floor so that it is not exposed to damaging wave energy [26].

Conversion Efficiency and Capacity Factor

An unintended consequence of the strategies used to cope with extreme sea states is the impact on the device capacity factor, i.e. the ratio of average power generated at a location to the converter's nameplate rated power (that is, the maximum continuous rated power output of the converter). The extraordinary dynamic range of ocean wave power flux, ranging from a few watts per metre to average values between 20 and 50kW/m and extreme values of about 1.5MWh/m, means nameplate ratings may be of an order of magnitude greater than average operating powers. This may in part depend on the strategy used to protect against extreme conditions. It is one of the reasons that using capacity factors to compare energy production between devices is dubious; it would be more appropriate to use wave to wire energy efficiency for quick assessments and the methodology we describe in Figure 4-19 for more detailed assessments.

4.1.5 Sea Trialled WECs with Publicly Available Data

About 200 wave energy conversion devices have been conceived, marketed, designed or built. A few dozen have been trialled as scale prototypes at sea. We found six that have published model data; four of these have also published a limited amount of electrical power test data from trials at sea. We now briefly describe the six devices.

Pelamis [27-31]

Pelamis is a 750kW rated WEC that has undergone extensive design and testing, including sea testing off the Orkneys and Portuguese coasts. Sea tests on a commercial prototype commenced in September 2010. Model and test data have been made available but they do not yet include electrical power output test data from sea trials.

The Pelamis operates as a multi-body inertial attenuator. It is made up of four segments, each of which attaches to other segments via an articulated joint (Figure 4-3). The segment lengths are designed to match a predominant wave length. The total length is 150m, and the diameter 3.5m. This design approach allows the device to operate in the mid-range of power for typical WECs, while reducing anchorage stresses by presenting a low profile to the wavefront.

The Pelamis floats on the surface of the ocean in waters typically 50m-70m deep. It moves with the water a little like a writhing snake, oscillating in harmony with the waves. Not only do the waves cause the Pelamis to articulate in the vertical plane, but also in the horizontal plane (such that it oscillates in top view as well as side view). The Pelamis is moored in a manner that allows it to change direction to suit the prevailing wave direction, within limits.

As each segment articulates against its neighbour, it drives hydraulic rams which provide fluid (biodegradable oil) flow to a hydraulic motor, which in turn drives an electrical generator. Accumulators are attached to the hydraulic lines to provide a small amount of energy storage to smooth the power flow to the motor/generator. Electrical energy is transferred to shore via a seabed cable.

Figure 4-11 Pelamis P2 on Tow in the Firth of Forth, Scotland [29]. Image courtesy of Pelamis Wave Power.

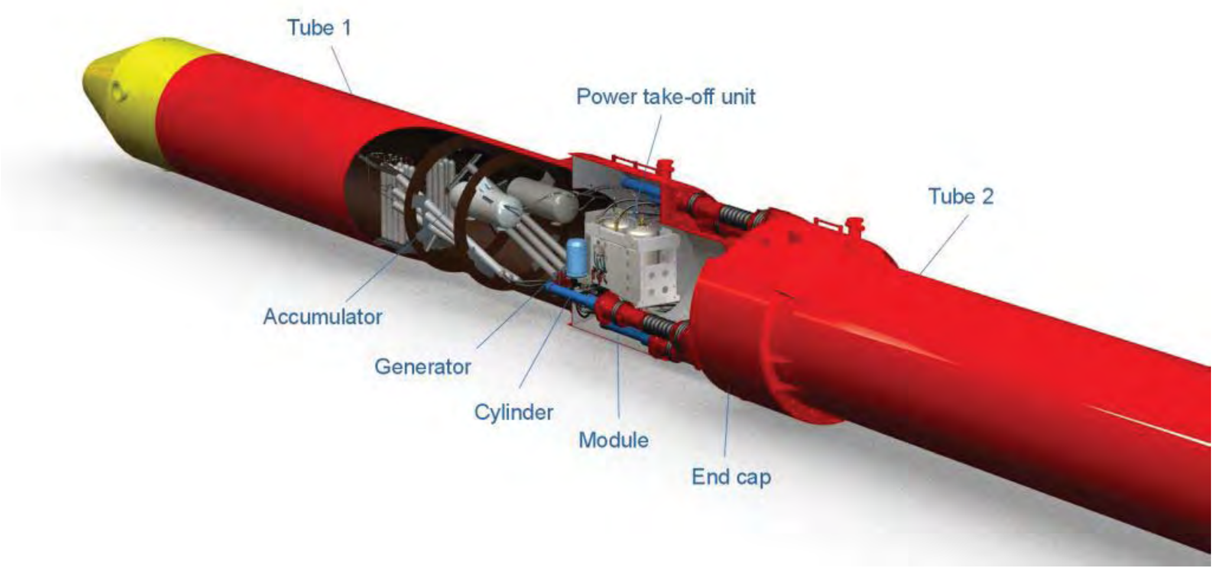


Figure 4-12 Internal Views of a Pelamis Power Conversion Module [29]. Image courtesy of Pelamis Wave Power.

Wave Dragon [30, 32-35]

The Wave Dragon WEC can be supplied in three power ratings: 4MW, 7MW and 11MW. A 270 tonne 4.5:1 scale model has undergone extensive design and development over three years of sea testing off the coast of Denmark at Nissum Bredning. This has included storm conditions. The company is now about to test a full scale device. Model and test data have been made available, including electrical power output test data from sea trials. Wave Dragon is one of only four devices we found for which such data have been made public.

The Wave Dragon operates as an overtopping, tapered channel, terminator type of WEC (Figure 4-13 and Figure 4-14). It uses a “low head” turbine which is able to generate power from a small pressure differential. It is a floating device intended to work in depths greater than 25m. It has an automatically adjustable float height, operated via a pressurised air system, to allow the device to tune itself to the predominant wave height; and an anchorage system designed to allow it to face into the waves. The design approach allows very large power devices to be constructed but also requires moorings capable of withstanding extremely high stresses. One of its greatest advantages is the relatively straightforward operation and maintenance, with only a few devices required to make up a wave farm and with all generator components accessible on a large floating structure. The devices have inbuilt redundancy because of the multiple turbines used for each.

Figure 4-13 Wave Dragon prototype showing tapered channel and ramp. Image courtesy of Wave Dragon [34].

Figure 4-14 Wave Dragon prototype with an overtopping wave. Image courtesy of Wave Dragon [34].

AquaBuOY [30, 31, 36-40]

AquaBuOY is a WEC originally based on a combination of designs from Sweden: the IPS buoy and the hose-pump. It has been proposed for supply in a number of power ratings for a variety of sea conditions, with the larger version reportedly capable of producing up to 250kW [41]. 1/50th scale, half scale and full scale models have been tested although the full scale model sank on completion of the tests. Model data, and a very limited amount of electrical power output test data from wave tank tests on a 1/50th scale model, have been made publicly available.

A two body inertial point absorber WEC, AquaBuOY uses sea water as an inertial mass to slow the movement of a piston connected to a hose pump, while wave action moves the piston tube up and down. The sub-surface float pumps sea water, on both upward and downward movements, through a turbine to turn a generator. The wave-buoy and converter is 6 metres diameter and about 30 metres long. It is intended to operate in waters of typically 50 metres depth. Modelling predicts a maximum power production of 200kW in five metre waves. The design approach allows AquaBuOY to be readily adapted to provide pressurised sea water for desalination.

Lysekil "Sea Based" Linear Generator [43-45]

The Lysekil Seabased AB WEC is being tested in units with power ratings of 10kW, 20kW and 50kW. The technology has undergone extensive design and development since 2002 and full scale sea testing of prototypes at Lysekil off the coast of Sweden since 2005. Commissioning has now commenced of a wave farm that will incorporate ten WECs of from 20kW to 50kW rating as well as a number of buoys for taking wave measurements and monitoring environmental impact. Model data and electrical power output test data have been made available.

The Seabased WEC is a single body point absorber comprising a floating buoy tethered to a linear permanent magnet generator set on the sea floor. The tether connects the buoy to a neodymium-iron-boron permanent magnet actuator. The converter is held in place by a concrete foundation. The system could be made to withstand extreme weather or wave conditions by incorporating a sacrificial link between the floating buoy and the more expensive generator.

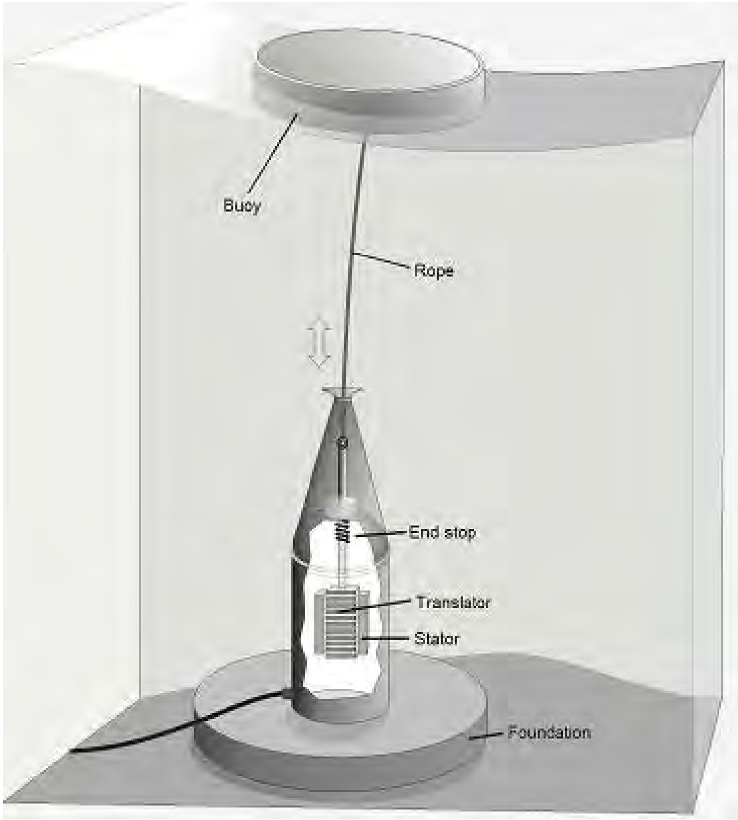


Figure 4-15 Seabased AB Generator Layout [26]. Image courtesy of Seabased Industry AB.

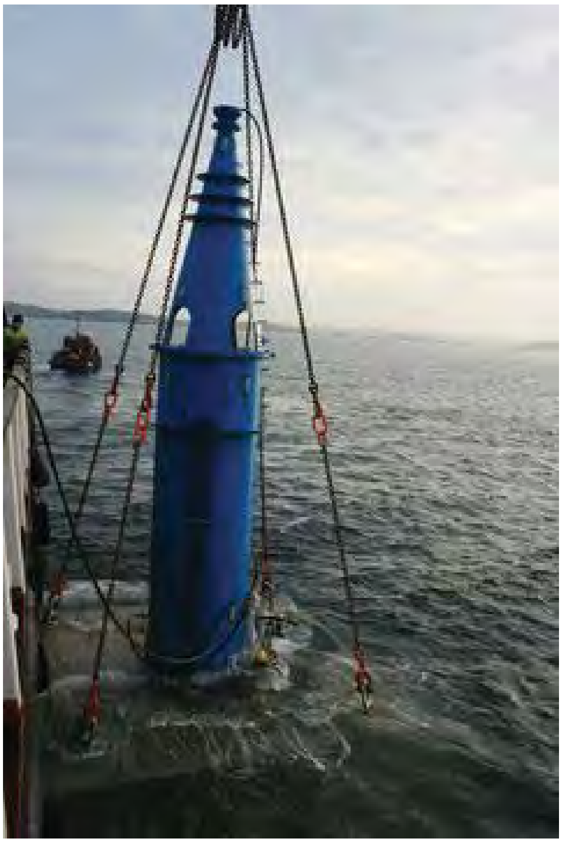


Figure 4-16 Prototype Seabased AB Linear Generator [26].

The float used in the prototype is three metres in diameter. The converter is eight metres long and intended for use in waters of about 25 metres in a near shore location. An advantage of this system is the ease with which different float designs can be incorporated into the device and the protection afforded by setting the converter well below the sea surface (Figure 4-15). The electrical energy generated by a number of the devices is transferred to an underwater “Medium Voltage” or “Low Voltage Marine Substation”. The underwater substation rectifies, inverts and transforms the electrical energy for transmission as an AC signal to the grid.

Seabased AB is currently installing a wave farm of devices capable of delivering electrical energy to the grid, off the coast near Lysekil, Sweden.

Land Installed Marine Powered Energy Transformer (LIMPET) [46]

The LIMPET, a 75kW WEC prototype, was commissioned on the Island of Islay, off the west coast of Scotland, in 1991 and was operated until 1999. Model data and electrical power output test data have been made publicly available.

Voith Hydro Wavegen, the owner of the LIMPET technology, describes the unit installed on Islay as “the world’s first commercial-scale wave energy device that generates wave energy for the grid” [46]. It uses the oscillating water column method of operation. A particular advantage of this type of WEC is that all moving parts of the device are out of the water and on dry land where accessibility for maintenance and repair is maximised.

The LIMPET is built into the cliffs on the shoreline (Figure 4-17). The water column is set at an angle to the vertical, unlike many other oscillating water columns. This may be to take advantage of the predominant direction of kinetic energy in waves near shore. The installation is 21 metres wide with a capture width of 35 metres and rated for 500kW of power. The average power during the period of operation was 50kW. This poor power factor had several causes, principally that the grid connection was limited to 150kW and the location had a relatively poor wave energy resource. In addition the progressive introduction of debris into the water column path at one stage limited the wave energy that could enter the converter. Nevertheless, on several occasions during storms and periods of high wave activity, the WEC was observed to reach the 150kW limit.

Figure 4-17 LIMPET WEC [25]. Image courtesy of Voith Hydro Wavegen Ltd.

4.1.6 Wave Farms

For WECs to prove economically feasible, it will be necessary to install them in large groups to provide useful quantities of electrical energy to the grid. The impact of wave farms on the environment, competing users, capital and costs is particularly affected by their size shape and structure. The key determinants are:

1. The need to accommodate other uses for any given area of sea water, along with ecological and geographical constraints.
2. The fraction of wave energy allowed to be extracted from the wavefront as it passes through the wave farm. We have set this at 20 per cent. However, the extraction limit will vary as wave calming might be desirable in some locations and not in others.
3. Anchorage and the safe spacing of devices to eliminate entanglement or collision during high energy sea states. This will also determine the effect that the wake of one device might have on another device positioned behind it relative to wave direction.
4. The type of WEC, in particular its size, conversion efficiency, packing density and the number of converters needed to deliver the required energy.
5. Maintenance considerations, particularly the need for access space.

Points 1 and 2 are covered in Chapter Five, "Competing Uses" and Chapter Six, "Environmental Impact". Points 3, 4 and 5 are described in more detail below, using examples selected from three test devices of radically different design size and shape. We have labelled these: a Point Absorber1, Linear Attenuator1 (absorber) and Terminator1. Examples were selected based on devices which had been extensively sea-tested and for which publicly available data was in a mutually consistent form. The examples we have used include a low powered point absorber, a mid-range power linear attenuator and a high powered terminator. These tend to represent the power levels achieved by the generic approaches to device design but should not be regarded as definitive. All three devices can be built in a wide range of sizes and power capacity.

Anchorage and Layout [20]

The mooring system is a non-trivial key to wave farm performance and security of investment. There is unlikely to be any precedent for moorings for a wave farm large enough to deliver hundreds of megawatts. Consider two types of farm: the first in which the number of devices and therefore anchorage points is minimised; the second in which the size of devices is reduced to lower anchorage stresses.

A wave farm capable of delivering 200MW, and using the largest converters available, rated at 7MW to 11MW, would require one hundred or more devices weighing 33,000 tonnes. The failure of a front line anchor point in a storm would be a disaster for a significant proportion of the whole farm and would happen too quickly for a remedial response. It is likely that such large converters will be designed as terminators that are either oscillating water column or overtopping devices. Such a farm is analogous to anchoring 150 bulk freight carriers in close proximity. However, there is a key difference. Ships at anchor are moored so as to minimise their profile to a wavefront. WECs of the terminator class will be oriented to present a maximum profile to the wavefront so as to gather most energy. The stresses on anchorage in a storm are considerable and may well demand new design techniques.

At the other extreme, a wave farm capable of delivering 200MW might comprise 5000 point absorber devices typically sized as a three metre diameter wave buoy and rated at 100kW. Such a farm would require innovative system and component design, both to minimise handling during operations and maintenance and to retain the integrity of the connection to the seafloor mini-grid.

Linear absorbers typically rated at a, provide a useful compromise between these extremes and they minimise the anchorage stresses by being oriented in the wave direction rather than across the wavefront. Further, their dimensions are of necessity comparable with the wave length being typically three metres diameter by 150 metres length. Devices of this size and capacity would require about a factor of five fewer anchorage points than point absorbers to make up a wave farm of a given capacity.

An outline of anchorage design considerations and options is given by Harris *et al* [51] who discuss three classes of mooring: i) Spread, in which multiple anchor points are used and in which it may not be possible for the WEC to weather vane; ii) Single Point mooring in which it is possible for the WEC to weather vane; and iii) Dynamic Mooring, which relies on either servo-controlled tensioning of mooring lines or computer controlled propellers to hold the device in position above a point on the sea bed. The most suitable options in these classes are outlined in Table 4-1. While dynamic positioning is an intriguing option it consumes power and is unlikely to adequately withstand the transient forces of a storm. For our purposes it is necessary to maximise availability of power and therefore the ability to weather vane is critical, this reduces the options to catenary anchor leg mooring or multi-catenary mooring.

Mooring Configuration	Description
SPREAD MOORINGS	
Catenary Mooring	A free hanging catenary relies on the weight of a mooring chain rather than the anchor point.
Multi-Catenary Mooring	The mooring lines use weights and buoys (clumps) to create slack floating regions in the chain.
SINGLE POINT MOORINGS	
Catenary Anchor Leg Mooring (CALM)	The floating structure is moored to a single anchored taut buoy This allows the moored structure to weather vane.
Single Anchor Leg Mooring (SALM)	The floating structure is moored to a buoy which is catenary moored to the sea bed. This allows the moored structure to weather vane.

Table 4-1 Some suitable mooring configurations [51].

Wave Farms and WEC Type

Some of the compromises needed for wave farm design are:

- The point converter is of necessity a low capacity device. It therefore requires a very large number of moorings for a wave farm to supply a comparable amount of power as a small coal fired power station, with consequent environmental and operations and maintenance issues.
- At the other extreme, the terminator type of converter is typically a large device requiring comparatively very few moorings and taking up a moderate area. However, as described earlier, it requires moorings capable of withstanding substantial anchorage forces.
- The linear converter represents a useful compromise between the two extremes described but because of its relatively poor packing density it takes up the largest wave farm area of all three types of converter.

The type or mix of types of converter used for a wave farm will depend on the local environmental and power demand requirements, as well as local operations and maintenance costs.

Wave Farm Size Estimates

Published estimates tend to show greater energy densities and more densely packed wave farms than our estimates given below. This is because we have required that devices can rotate ±180° without collision and have taken into account the performance of each device under Australian sea conditions. It is possible that devices tuned for these conditions might achieve higher energy densities.

Seabased AB [52] estimate that a wave farm might take up an area of one square kilometre of water space, comprising 1000 WECs rated at 10kW each. This could potentially supply about 25GWh/yr, at 10 per cent energy extraction from a wave power environment of 5kW/m to 10kW/m if the area of sea was distributed in a rectangle of, for example, 4km x 250m.

Pelamis Wave Power [24] estimate that a one square kilometre wave farm made up of 40 Pelamis P750 devices would be rated at 30MW, or 30W per square metre. This might for example be based on an array of devices extracting 30 per cent of the energy along a 2000 metre long, 50kW/m wavefront.

Beels [53] gives estimates based on 99 Wave Dragon devices at 25 per cent energy extraction, delivering a total of 2MW power, for sub-optimal and optimal layouts in which transmission line costs have been optimised. The systems deliver 185 and 146 TWh/y. Beel's optimisation takes into account the diffraction and changes in absorption of wave energy as it passes through the farm, shown on the top left hand side of the graph. It also describes some of the synergies from combining wind farms with wave farms. The layouts we have used allow more clearance with an area about 30 per cent greater. Sørenson suggests a spacing of 600 metres between devices [32], which is slightly less than our value as we provide for the mooring catenary to become taut. The authors have made estimates for corresponding wave farm sizes under Australian conditions, based on three configuration approaches together with assumptions listed below.

Configurations

Close Spaced: A spacing suggested by reports of wave farm layouts installed in an overseas context.

Close Spaced for an Australian Wave Resource: The wave farm uses spacing derived using the layout as in the first case but with the number of devices required determined by their response to Australian southern coast wave energy resource. We have taken standard device characteristics of energy produced vs. wave height and wave period, as reported by Dunnett and Wallace [30] and used them to assess energy production over the southern coast of Australia.

Conservatively Spaced for an Australian Wave Resource: The number of devices required was determined by their response to Australian southern coast wave energy resource. In addition, the spacing used allows clearance between devices under all wave conditions likely to be encountered over a 20-year period (Figure 4-10). The estimate includes a length of cable free to drag on the sea floor, with the friction of the cable on the sea floor adding to the mooring stability (the sea floor cable drag length was calculated as 1.5 times the square root of depth) and a depth of 50 metres was assumed. Each row was offset with respect to the preceding row to maximise packing density. For the Linear Attenuator1 case we changed the mooring layout to using a single line at one end of the device. This has the additional benefit that the devices are freer to orient relative to wave direction, an essential requirement along the south east coast of Australia, where wave direction can be quite variable.

Minimising Coastline Length: In the case of the Wave Dragon, the coast length could be reduced without compromising spacing by increasing the separation between devices along the wavefront; this allowed an additional row to be incorporated without stepping over the limit of 20 per cent for energy removal from the wavefront.

Assumptions for tables 4.3 to 4.6:

- A maximum farm capacity of 270MW was assumed so that 20 such farms would supply the estimated maximum likely market penetration for Australia by 2050.
- The number of devices required was determined by their response to Australian southern coast wave energy resource.
- No wave farm was allowed to extract more than 20 per cent of wave energy from incoming waves.
- The length of the coastline traversed by the wave farm was to be minimised.
- No account was taken of diffraction effects between devices; this requires further research.
- Devices were conservatively spaced as described above to allow clearance between them under all wave conditions likely to be encountered over a 20 year period.
- In the Linear Attenuator1 case we changed the mooring layout to using a single line at one end of the device; it was free to orient ±180 degrees with respect to wave direction.
- Each row was offset with respect to the preceding row to maximise packing density.

Table 4-3 gives projections for 2050 of electrical power demand, available resource and extractable wave power from the southern coast of Australia. Tables 4.4, 4.5 and 4.6 provide more details on the size of wave farms capable of meeting these extraction requirements using examples of a relatively low power point absorber, a mid power range linear absorber, and a high powered terminator.

Australian Ocean Power Requirements			
Percentage of Demand >	2.5 per cent	5 per cent	10 per cent
Total Wave resource (line integral) (GW)	131	131	131
Total power extraction from 20 farms (GW)	1.35	2.7	5.4
Power per farm (MW)	67.5	135	270

Table 4-2 Projected Australian ocean power requirements by 2050.

Point Absorber1 Wave Farm			
Percentage of Demand >	2.5 per cent	5 per cent	10 per cent
Number of devices required	1112	2224	4447
Coastline/wavefront length (km)	6.7	13.3	27
Width (depth in plan view) (km)	0.15	0.15	0.15
Total area of farm, conservatively spaced (square km)	1.00	2.00	4.0
Average Power Density, conservatively spaced (W/m^2)	67	67	67

Table 4-3 Point Absorber1 wave farm conservative estimates for wave farm size by 2050.

Linear Attenuator1 Wave Farm			
Percentage of Demand >	2.5 per cent	5 per cent	10 per cent
Number of devices required	402	804	1607
Coastline/wavefront length (km)	13.2	18.6	26.3
Width (depth in plan view) (km)	3.3	4.6	6.6
Total area of farm, conservatively spaced (square km)	43	86	172
Average Power Density, conservatively spaced (W/m^2)	1.6	1.6	1.6

Table 4-4 Linear attenuator1 wave farm conservative estimates for wave farm size by 2050.

Terminator1 Wave Farm			
Percentage of Demand >	2.5 per cent	5 per cent	10 per cent
Number of devices required	31	62	124
Coastline/wavefront length (km)	19	26	37
Width (depth in plan view) (km)	0.7	1.0	1.4
Total area of farm, conservatively spaced (square km)	12	25	50
Average Power Density, conservatively spaced (W/m^2)	5.4	5.4	5.4

Table 4-5 Terminator1 wave farm conservative estimates for wave farm size by 2050.

Wave Farm Operations and Maintenance

Costs

The feasibility of maintaining a large wave farm power station centres on questions of cost, downtime, the ability to forecast failure modes and the logistics of working in remote locations to identify and repair breakdowns. Annual operations and maintenance have been estimated at about 40 per cent of the total cost of electricity generated from wave converters.

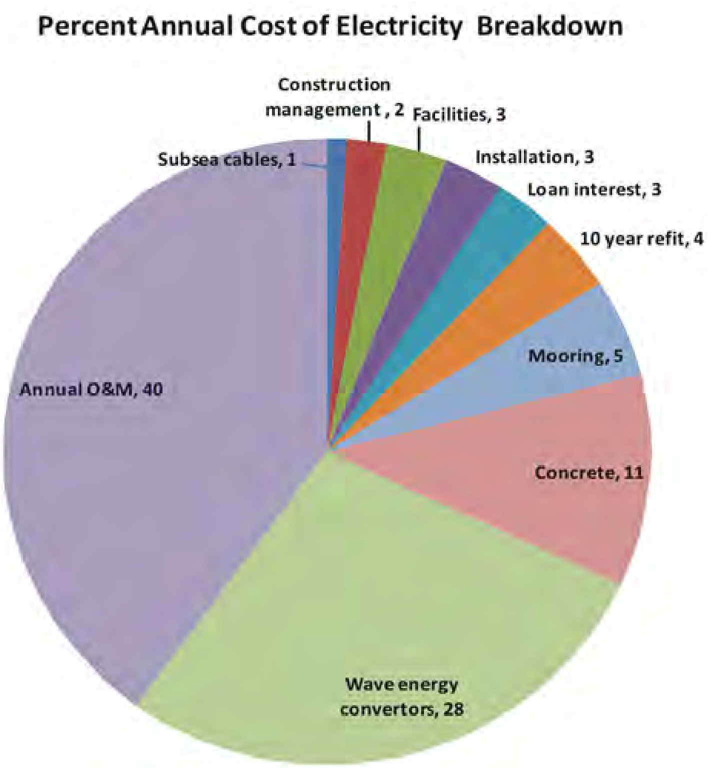


Figure 4-18 Annual operations and maintenance cost breakdown. Adapted from Bedard [28].

Maintenance operations

Scheduled maintenance downtime may not be a key issue for two reasons: i) wave power stations large enough to make a significant impact on the grid are likely to be designed as a "farm" of many subunits that can be individually disconnected and taken to shore for maintenance offline; ii) there is the possibility of scheduling maintenance during periods of low wave activity when little power is lost by removing machines for maintenance. On the other hand, the potential for catastrophic breakdown suggests the need for strategic telemetry to provide notification of the impending breakdown as well as a manned repair facility associated with the wave farm.

The ease with which converters and wave farms can be maintained depends on their number and accessibility: i.e. their proximity to the surface and whether divers are needed to manage components on the sea floor. A floating oscillating water column, for example, is likely to be easier to maintain than a point absorber with a float on the surface and the converter on the sea floor. The Oscillating Water Column (OWC) would have most of its moving components above water on a relatively stable and large platform with the potential for routine maintenance to be carried out *in situ*, whereas the converter for the point absorber would need to be removed by a diver and taken aboard ship. The intermediate case inertial systems have floating main moving parts which still need to be removed either to a supporting framework or to a ship, but without the need for a diver. Approaches to maintenance schedule options include:

- Fit and forget.
- Two year — blast clean, repaint and minor repairs together with a ten year major refurbishment.
- Five year — blast clean, repaint, strip down and refurbishment.
- Removing key components while leaving the main structure at sea; for example removing one turbine at a time from the Overtopper for maintenance and separately scheduled maintenance of main structure.

Failure modes

Well known failure modes anticipated or recorded in the literature include:

- Corrosion — this is conventionally managed using:
  - Cathodic protection, in which an electric current or a sacrificial anode made from magnesium or zinc, is used to counter corrosion current. Sacrificial anodes need to be monitored for replacement and have to be managed carefully to avoid the build up of chalky deposits in regions of stagnant water.
  - Use of specialised coatings and selection of material not susceptible to corrosion.
  - Regular maintenance that is typically scheduled for between two to five year intervals.
- Marine growths — these can add weight or friction to moving surfaces or restrict the movement of mechanisms such as levers or pistons. Such "biofouling" is not restricted to static surfaces; there are many marine organisms that require substrate movement to grow. Biofouling and corrosion are both likely to be worse for components at the sea surface where movement and air encourage oxidation and the growth of marine organisms. Prevention and remediation involves:
  - Survey of each site where a wave farm is to be constructed, to determine the composition of local flora and fauna.
  - Use of specialised coatings that discourage growth and are self polishing; there is usually a trade-off between durability and the self polishing characteristic.
  - Regular maintenance that is typically scheduled for between two to five year intervals concurrent with corrosion management.
- Leakage — this can result in biofouling and corrosion as well as sinking of the device. It is generally thought to be a more severe problem for devices located on the sea floor due the increased water pressure. However, constant exposure to wave impact may create similar pressure stresses at the sea surface. This kind of damage has compromised several wave energy development projects.
- Broken moorings — this kind of failure is most likely to occur in storm conditions when it has the potential to disrupt the whole wave farm as well as local shipping. Prevention would seem to be the only solution in this case, using appropriate design and quality control measures. It may also be possible to use backup buoys to facilitate retrieval.

4.1.7 Summary of Wave Farm Considerations

In principle it should be possible to set up wave farms that can be satisfactorily maintained. Some early investigation to demonstrate this on individual devices has been carried out and published [27]. However, large scale maintenance of wave farms has the potential to be a major cost affecting the competitiveness of ORE. It is also the least investigated and documented aspect of ORE technology. A relatively high power Terminator1 device has the potential for relatively straightforward maintenance logistics because of the small number needed for a substantial (250MW) wave farm. On the other hand, a substantial wave farm of point absorbers or linear converters might require thousands of devices to be maintained. The logistical requirements for such an exercise have not been investigated and publicly documented. If these two converter modes are to be seriously considered as significant contributors to Australia's electricity supply, a comprehensive investigation is required into their maintenance requirements and costs.

4.1.8 WEC Assessment and Placement

Background

An assessment was carried out on three WECs to provide data for market share projections from 2015 to 2050, starting with state of the art devices selectively located along the southwest, south and southeast coasts of Australia. The assessment combined an evaluation of device performance and a selection process for optimum cost per kWh at each location. The devices were selected because they provided a consistent data set for a wide range of size, technology and cost. They all operated at reasonable capacity factors in the regions selected by the economic model and necessary data were in the public domain.

It should be emphasised that of necessity the device data and costs used are derived from publicly available model data and estimates, supported by a limited amount of device testing. Technologies change and adapt, so while the results provide a useful basis for an economic analysis, they should not be used to compare specific technologies as part of a purchasing program. It was also noted that while the Linear Attenuator1 device operated at typically 250kW in the regions selected, it had the potential to be higher given appropriate redesign to adjust the frequency response and impedance matching for the wave environments selected by the model.

The process undertaken to determine the potential of wave energy conversion in the waters surrounding Australia is outlined below.

Modelling was performed using performance data gathered for three devices, including a Point Absorber1, Linear Attenuator1 and Terminator1. The examples for these devices were selected because:

- All three were at an advanced stage of development, having undergone a long period of analysis and development including sea trials of full scale devices.
- They had all provided detailed model data of the device electrical power output versus wave height and period. This level of detail allowed the ambiguities and inconsistencies arising from oversimplified specifications to be removed from our assessment.
- The data had been collected together with cost estimates that as far as possible were based on similar assumptions.

In its present form the Linear Attenuator1 was found during the assessment to be sub-optimal for Australian south coast conditions. This does not reflect on the potential of either the example or the linear attenuator principle of operation, which might possibly be retuned for Australian conditions. For example, the example Linear Attenuator1 generates just 149kW in three metre, 12.5s waves, but generates 340kW from three metre, 7.5s waves. This suggests it is tuned for high efficiency for European conditions rather than for the longer wavelengths found on the southern coasts of Australia.

Assumptions

No energy would be lost due to directional changes in wavefronts. Point absorbers are insensitive to direction and both the Linear Attenuator1 and the Terminator1 could be anchored so that they were free to rotate ±180 degrees and face the wavefront.

Capacity Factor is based on average power at a location referenced to the device nameplate power rating. As previously discussed, comparing capacity factors is too arbitrary and inconsistent to provide a useful assessment of WECs and the assessment here is based on costs and device power output characteristics as a function of wave period and height and the statistics of available wave energy in specific locations.

Maps of Australia's wave energy are discussed in section 2. The modelling and calculations discussed here used the 50th percentile wave energy estimates of Hemer and Griffin (2010). The data describing the significant wave height and significant wave period were derived from the 50th percentile wave power flux levels. That is, 50 per cent of the time, the waves possess more power, and for 50 per cent of the time less power. The assumptions made were that WECs would be tuned to work optimally in median wave conditions, and that performance in these conditions is defined as the average performance of a device over time, that power output at these wave conditions could be multiplied across a year to give the energy output per annum. These data were supplied in the form of a map encompassing an area from the equator to 50 degrees south, and from 90 degrees east to 180 degrees.

Method

The performance characteristic data (Figure 4-20, Figure 4-21 and Figure 4-22) were used to calculate the local power output and corresponding annual energy production, and cost of electricity (LCOE) for each device at each data point on the map. White patches on some areas of the maps are because of a lack of device performance data for the wave conditions. Where the surface reaches a plateau it is due to device rating. We also plotted local capacity factors for the economic projection model to effectively cancel out its device nameplate power ratings. Apart from the need to remove these arbitrary parameters from the model, the capacity factor had no other use. Figure 4-19 shows the process flow for device assessment. Figure 4-23 to Figure 4-30 show the results.

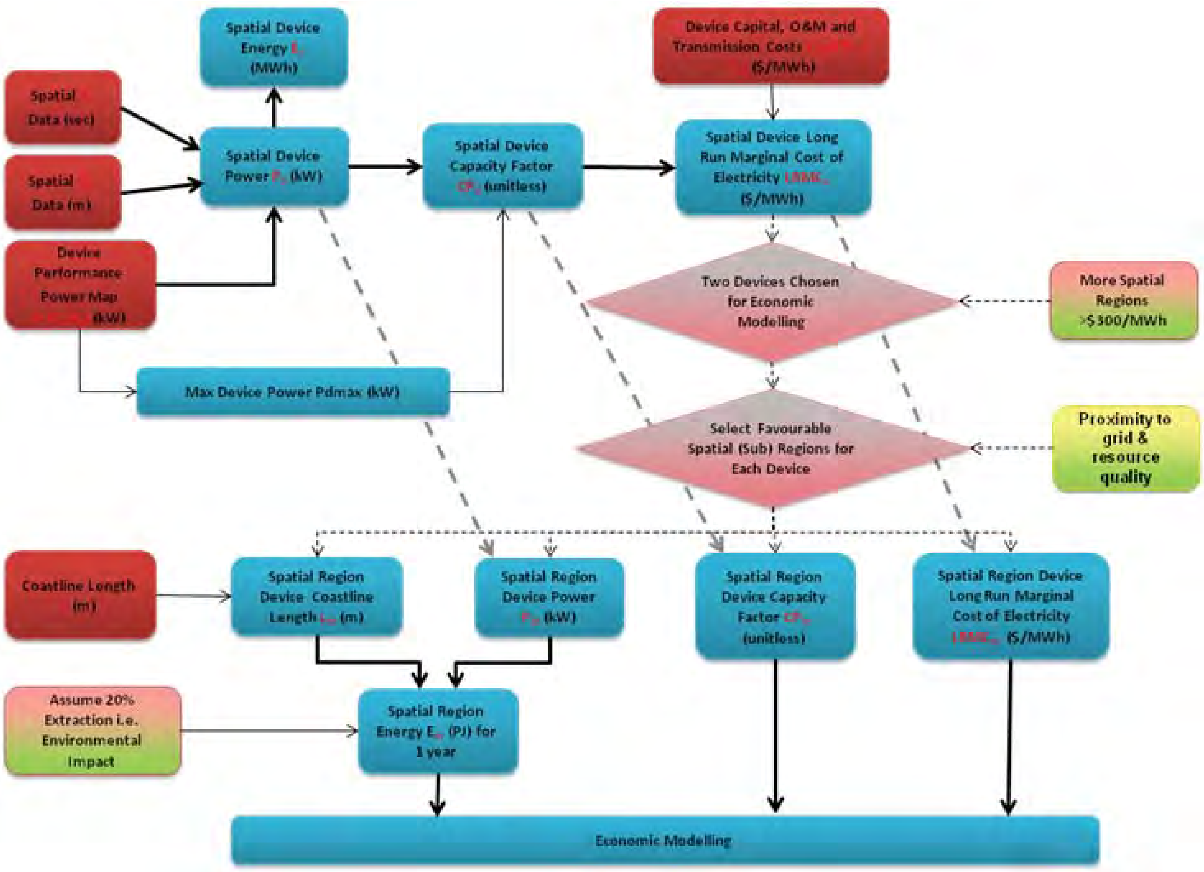


Figure 4-19 Process flow for assessing wave converter performance in Australian waters.

Results

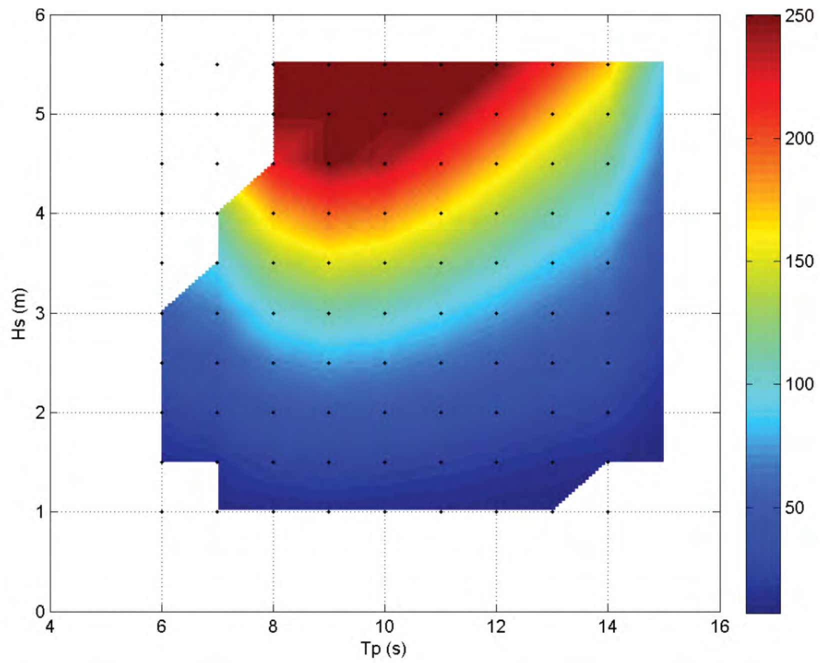


Figure 4-20 Point Absorber1 performance curve — power (kW).

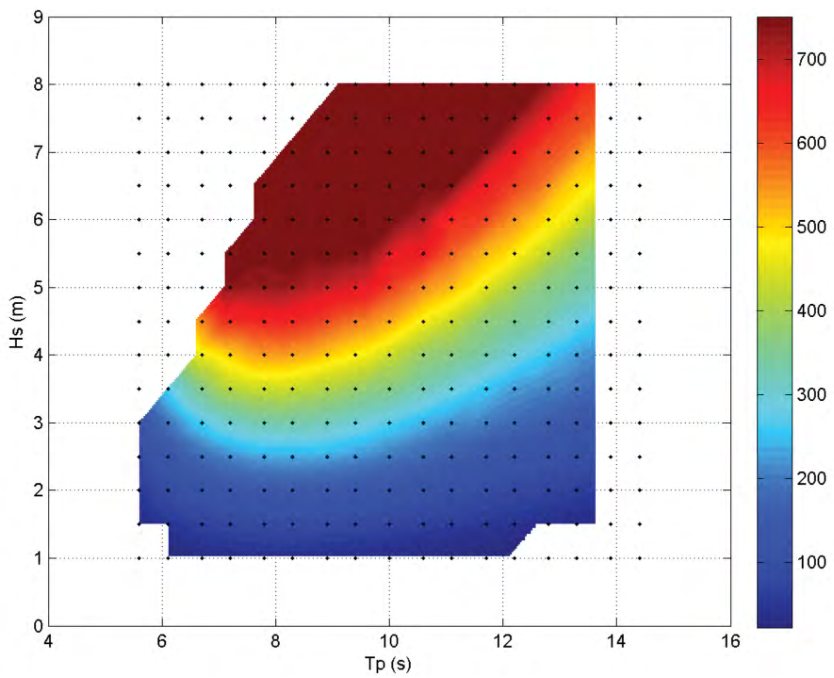


Figure 4-21 Linear Attenuator1 performance curve — power (kW).

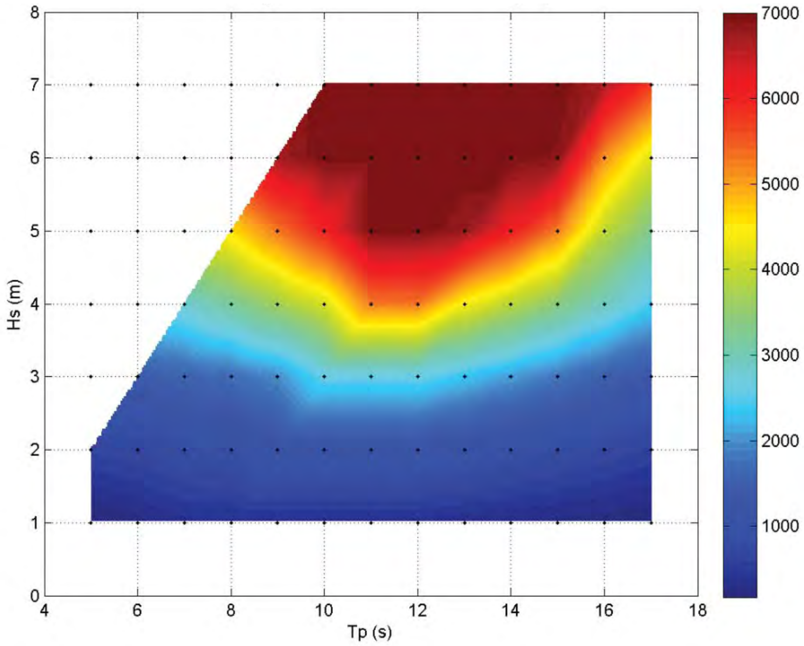


Figure 4-22 Terminator1 performance curve — power (kW).

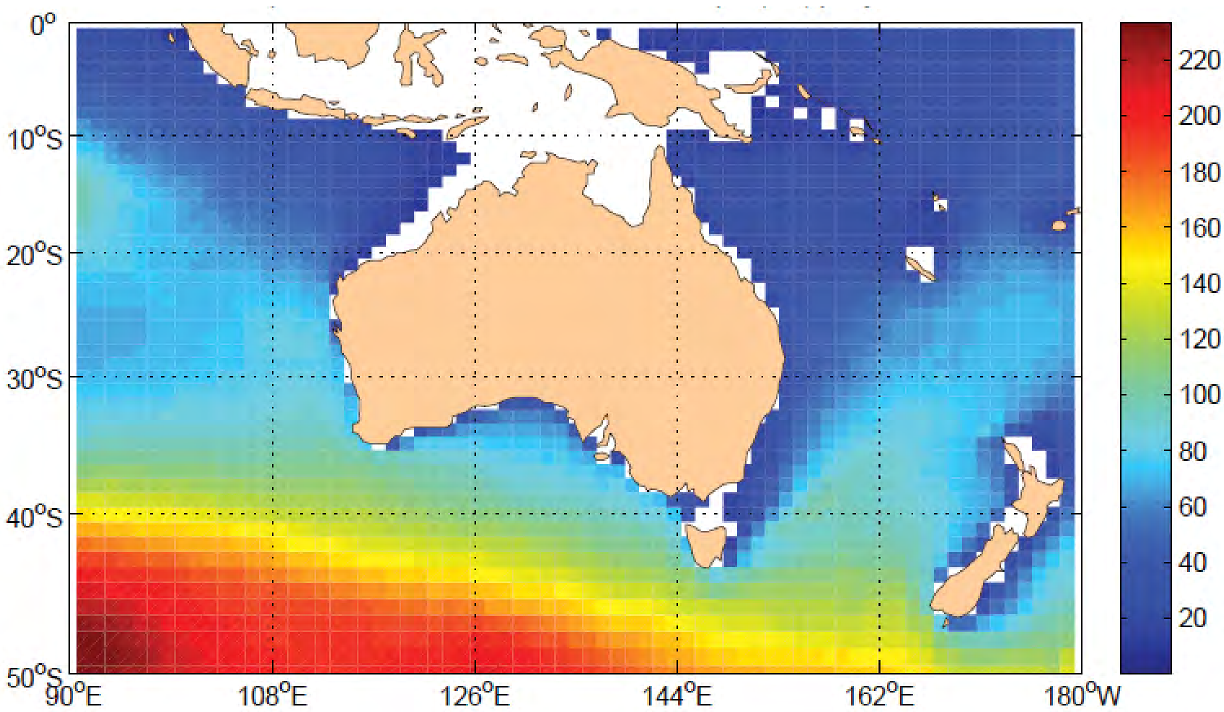


Figure 4-23 Point Absorber1 power output map — 50th percentile for power output (kW) per year.

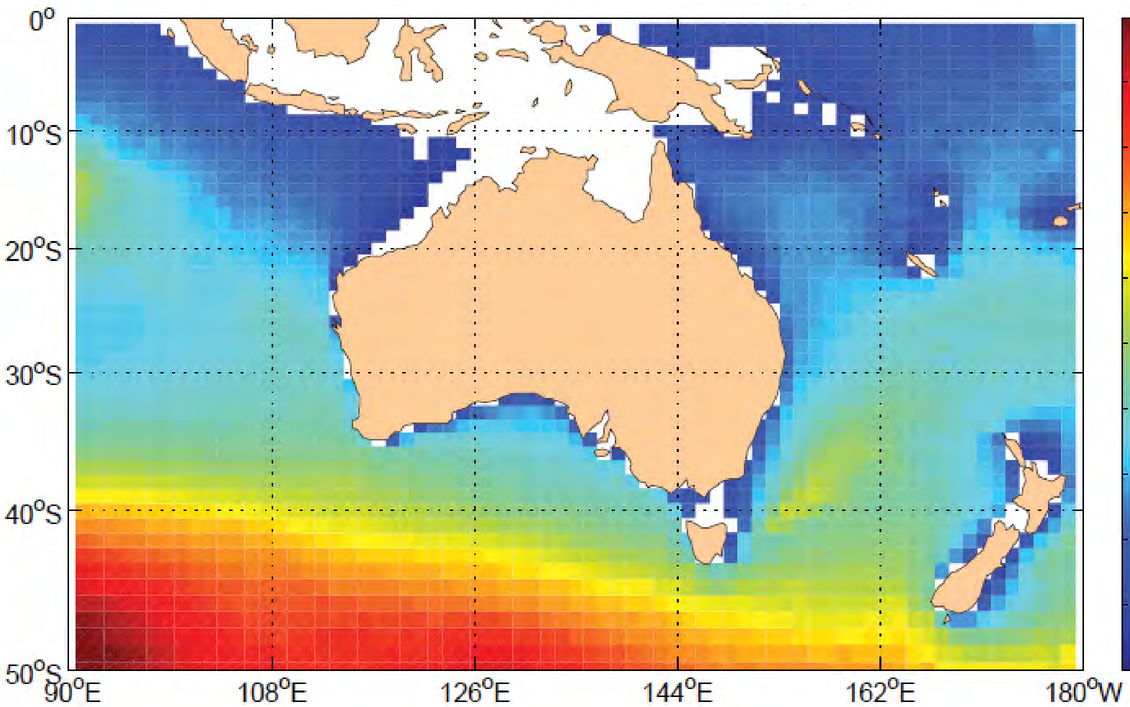


Figure 4-24 Linear Attenuator1 power output map — 50th percentile for power output (kW) per year.

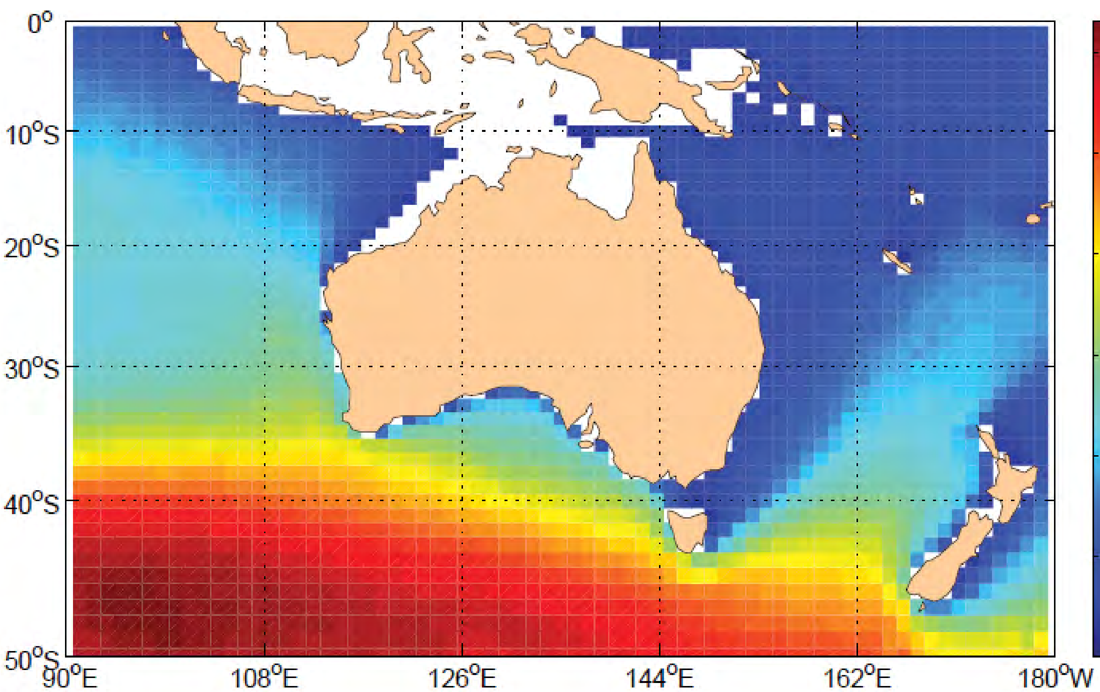


Figure 4-25 Terminator1 power output map — 50th percentile for power output (kW) per year.

Using the power outputs from the above device power maps, three device energy per annum maps were produced, by multiplying power maps by time (of 1 year). Units are MWh/year.

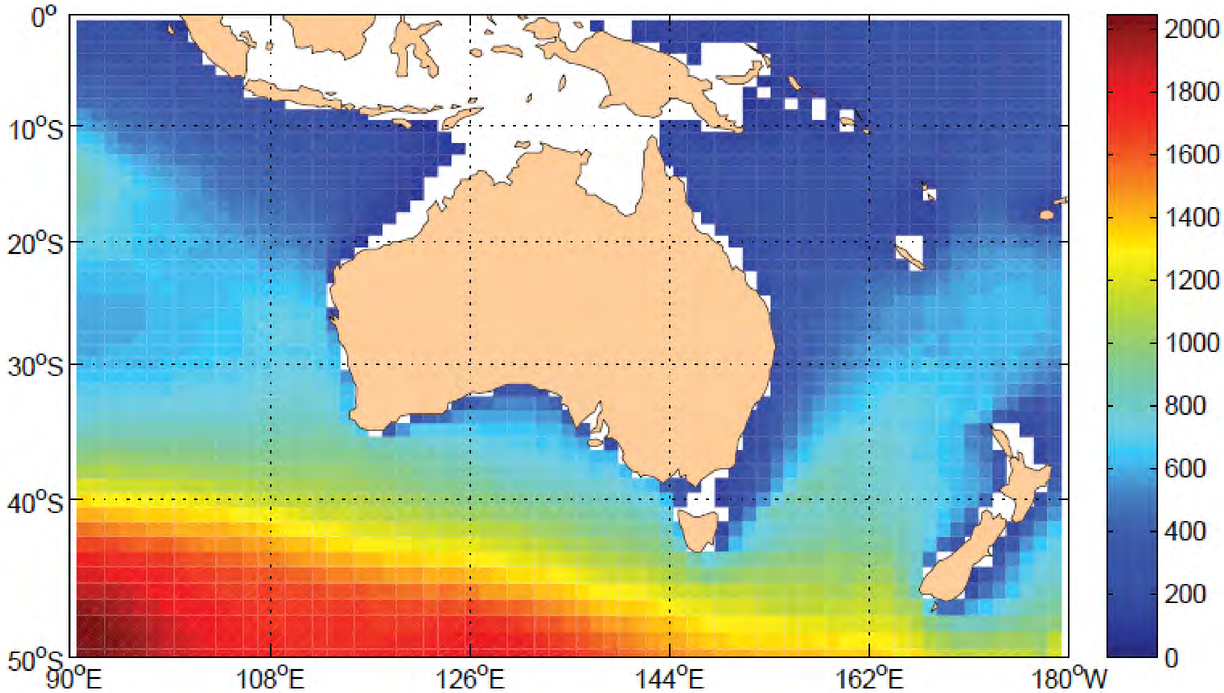


Figure 4-26 Point Absorber1 — 50th percentile for energy output (MWh) per year.

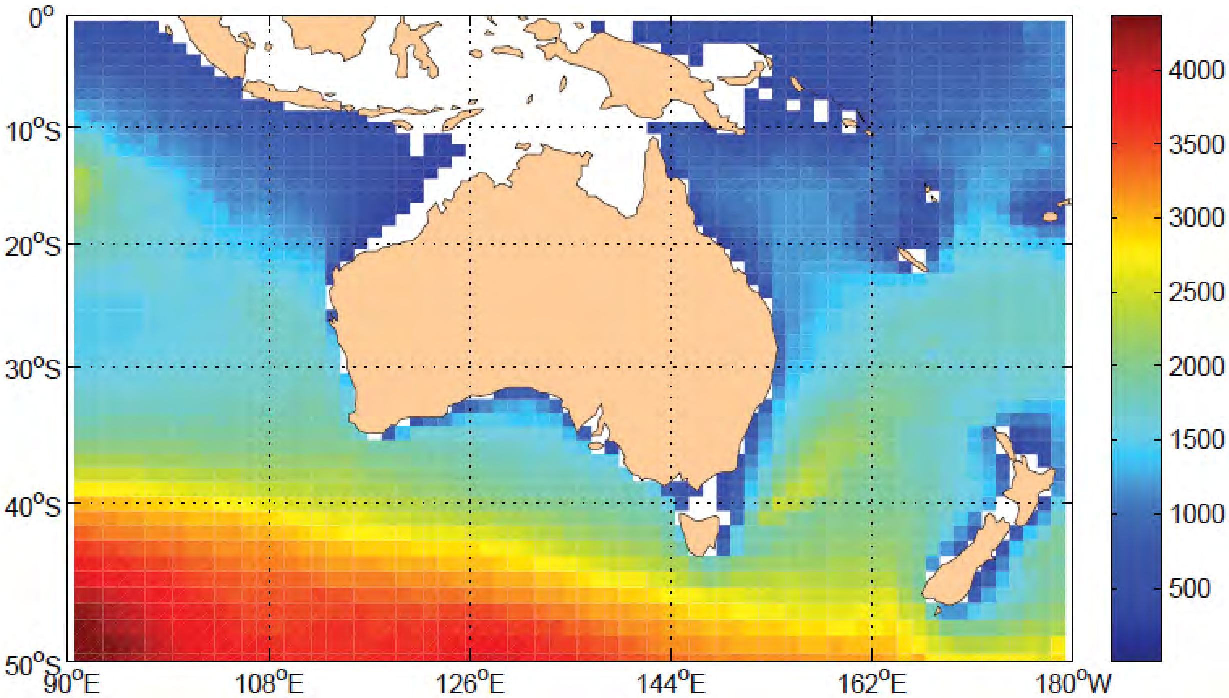


Figure 4-27 Linear Attenuator1 — 50th percentile for energy output (MWh) per year.

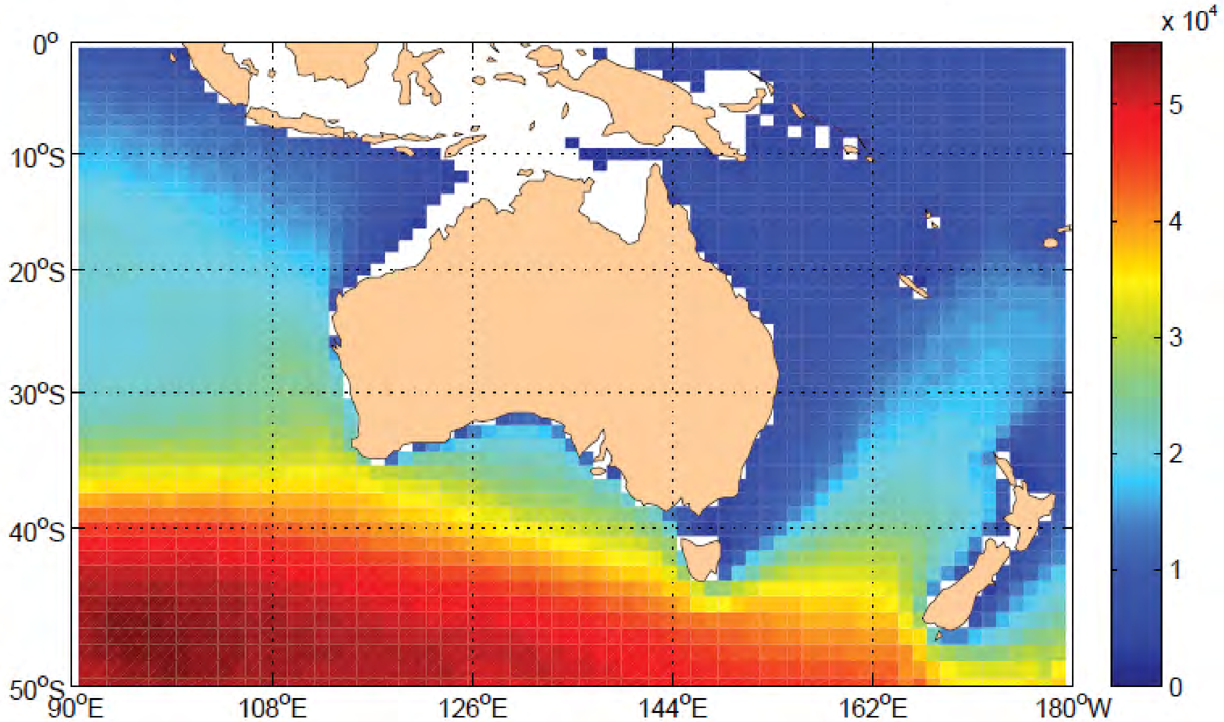


Figure 4-28 Terminator1 — 50th percentile for energy output (MWh) per year.

Levelised cost of electricity (LCOE) maps were produced for each of the three devices, using the power and energy production maps generated above and equation and cost elements as described in Section 7.

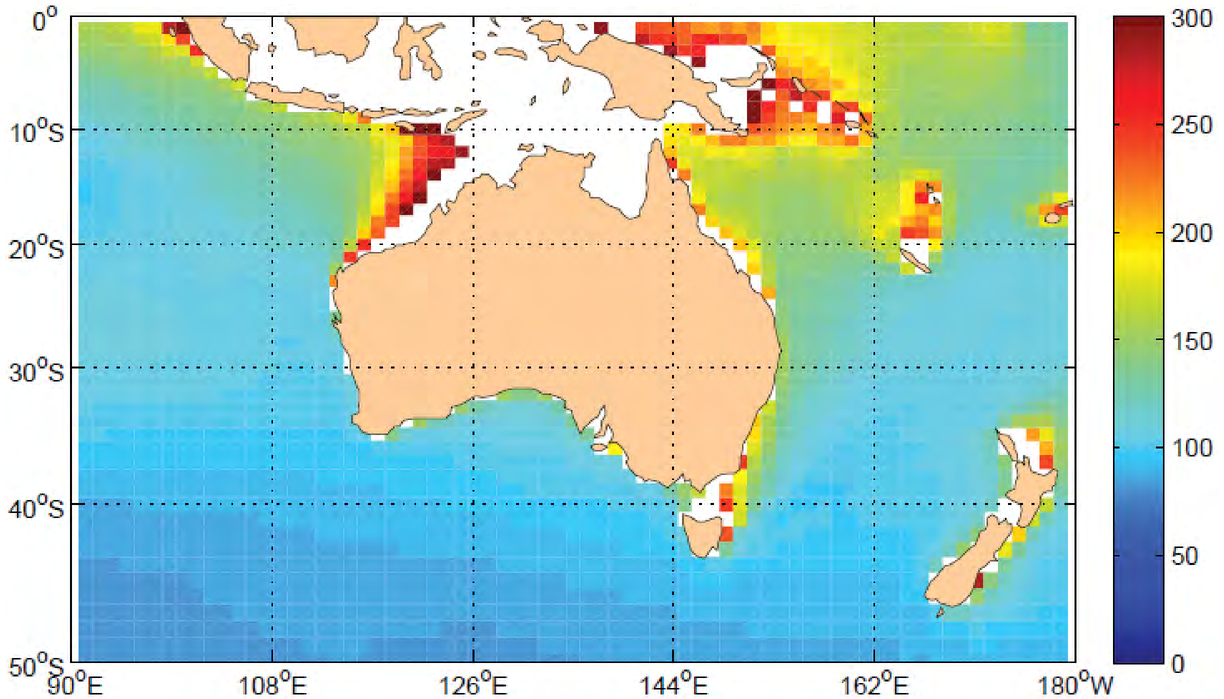


Figure 4-29 Point Absorber levelised cost of electricity (LCOE) ($/MWh) per annum map.

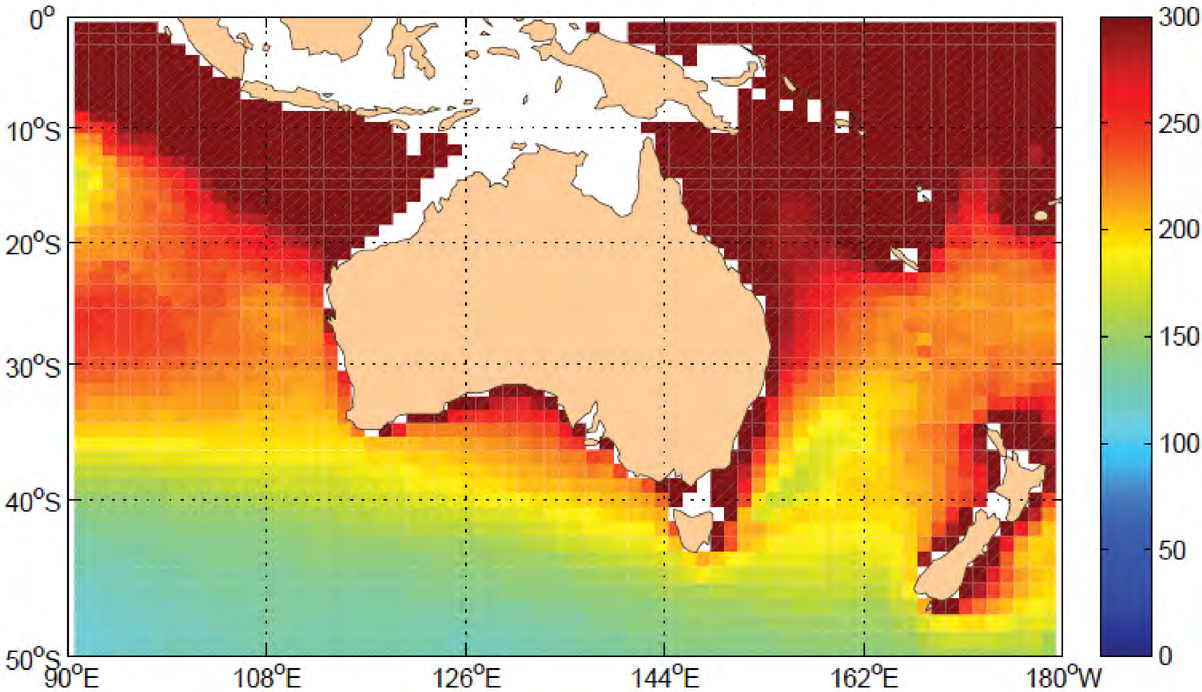


Figure 4-30 Linear Attenuator1 levelised cost of electricity (LCOE) ($/MWh) per annum map.

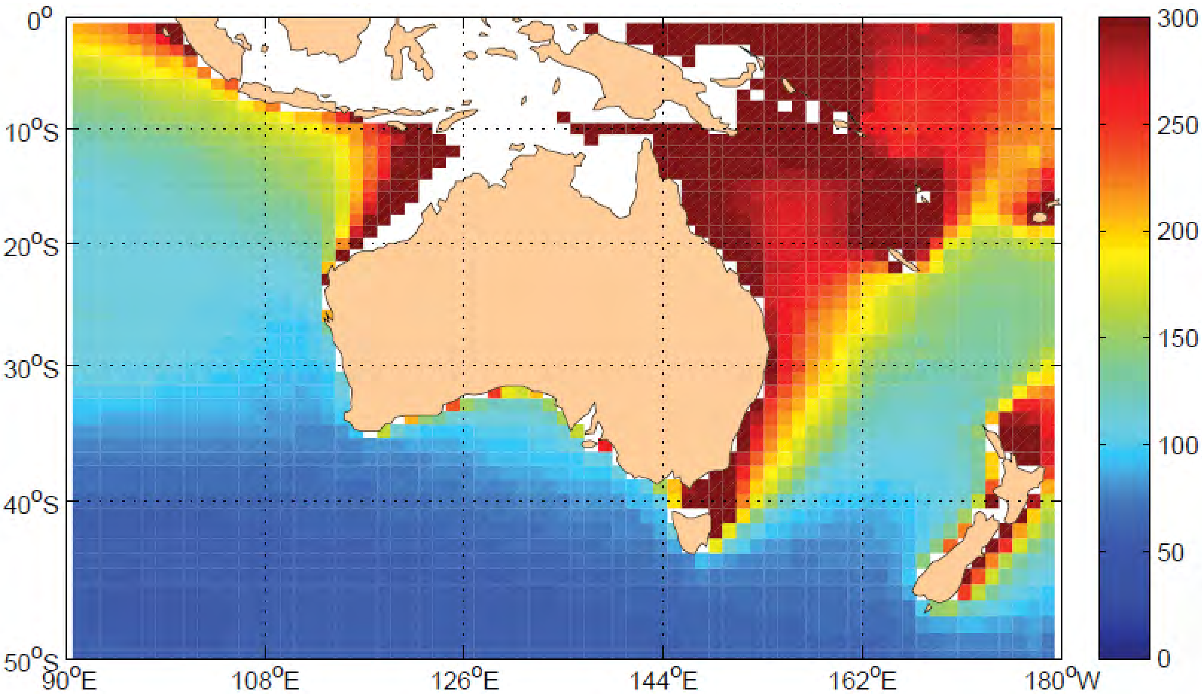


Figure 4-31 Terminator1 levelised cost of electricity (LCOE) ($/MWh) per annum map.

Selecting Regions

As required by the model used for economic analysis, regions and sub-regions were selected from various parts of the Australian coastline. At present large electricity consumers such as aluminium smelters and desalination plants have ready access to the grid. However, parts of the Australian coastline that are not close to major population centres and, existing electrical grid infrastructure could provide reasonable levels of wave energy. This is particularly true for the coastline north of Geraldton in WA, and to a lesser extent between Albany in WA and Port Lincoln in SA. These regions also contain potentially valuable mineral deposits that are not currently being exploited. For example, a number of mineral deposits that are currently not mined lie on or near the coast of WA east of Albany. In particular the area near Trilogy and Hillsborough includes deposits of gold, silver, copper, nickel, tungsten and tin. Other metals, bauxite, coal and mineral sands are also evident along this stretch of coastline.

There may be an opportunity along these coastlines, and possibly others, to provide electrical power from WECs to future industry or consumers who are not near major population centres or connected to the grid.

In this study regions were selected, based on the quality of 50th percentile wave energy and proximity to an existing electrical grid. Sub-regions were selected based on consistency of wave energy along the coast, such that each sub-region had little variance in wave energy. Those regions selected included:

- WA The coastline from Geraldton in the north to south around the tip to Albany in the east, broken into three sub-regions covering Geraldton to the southwest tip, the tip itself, and from the tip to Albany.
- SA Port Lincoln to the Victorian border, broken into two sub-regions.
- VIC From the SA border to Cape Otway.
- TAS The west coast and southern tip, broken into three equal sized sub-regions.
- NSW From the Victorian border to the Queensland border.

Estimating Device Performance across the Regions

The 50th percentile wave power flux of each of the regions or sub-regions was found, by taking the median wave power flux (kW/m) value for each region/sub-region as read from maps, and multiplying by the length (km) of the wavefront for each region/sub region, to give answers in MW.

From these raw wave power values for each region/sub-region, the power was multiplied by time to determine energy produced over one year, in petajoules (PJ).

An assumption was made that no more than 20 per cent of raw wave energy ought to be harvested or converted, to limit potential environmental and ecological effects. As such, only 20 per cent of the energy found via the previous step was used to determine maximum WEC extraction levels for each region or sub-region. Additionally, a lower bound case of approximately 5 per cent extraction and an upper case of 30 per cent were determined for economic modelling and sensitivity analysis. It was found that the resource was used to its limit in Victoria under each of the sensitivity cases. Under the 30 per cent case some additional wave farms in Western Australia and Tasmania compared with the 20 per cent case.

LCOE figures ($/MWh) for each region/sub-region were read from 50th percentile maps. These were used in the model to determine which regions should be included in the economic projection for greatest impact.

4.1.9 Summary of WEC Assessment

A summary of the values determined for economic modelling is given in Table 7-1 to Table 7-3 of Section 7.3.1. It was decided to use only the Terminator1 and the Point Absorber1 values as the examples of Linear Attenuator1 technology did not match closely enough to the long period swells of the south coast to allow cost effective energy transfer. Future work might consider whether adapting such linear attenuators is practical for these long wave period conditions.

4.2 Tidal and Ocean Current Conversion Devices

Tidal energy has been used for centuries as a local power source for such purposes as milling grain. It is a consistent and relatively accessible resource with the potential to provide about 0.5 per cent of Australia's electricity. A particular advantage is the ability to provide relatively constant power using:

- Arrangements of tidal ponds to store energy at the expense of increased environmental impact.
- Incoming and outgoing tidal flow.
- Geographically disparate tidal converters to supply energy at different times of the day.

For large scale tidal power to be practical the range in water depth from high tide to low tide would generally need to be greater than seven metres. Ideally the tidal power station would be located near a natural restriction in the tidal flow, and near a centre with a significant demand for electricity. A number of regions in Australia have been proposed as having suitable tidal resources. They include Banks Strait, Tasmania; Port Phillip Heads, Victoria; Derby and Clarence Strait, Northern Territory.

There do not appear to be significant technological barriers to the development of tidal power generators. The basic technology principles are well understood. The main focus for new research is likely to be in the improvement of efficiency and cost-effectiveness and in analysing the type of system most appropriate for a particular environment. The impact of large scale energy extraction is less well understood. While tides ebb and flow in response to the moon and to local geography, the frequency and timing of their flow can be greatly affected by resonance effects caused by coastal land forms and the extraction of tidal energy.

4.2.1 General Approaches to Tidal Power Conversion

Tidal power converters operate by placing turbines in a strong tidal current. The placement can be as part of a dam wall in which sluice gates are opened to fill the dam and closed to divert flow through a turbine. Or they can be part of an open wall that traverses a tidal flow gradient, or supported on a bridge-like structure so that only the turbine and bridge supports are in the tidal stream; or the turbines can be individually supported in the tidal stream.

Barrages

The dam wall approach, known as a barrage, has the dual advantages of providing energy storage and intensifying flow rates so that energy can be extracted with fewer turbines and/or smaller turbine blades. Well-known examples are the Rance Tidal Power Station in France which generates 240MW and the Sihwa scheme in South Korea, where an artificial lake intended to supply fresh water became polluted and was abandoned. Turbines are now built into the dam wall to allow sea water to exchange with the lake water and improve its quality while supplying an estimated 254MW of power generation capacity. An issue with barrage tidal power converters are the significant environmental impacts caused by restricting tidal flow rates and extent. This together with cost has seen the cancellation of the 8GW $A15 billion Severn tidal barrage project in the United Kingdom.

Free Stream Tidal Turbine

Free stream turbines are stand-alone, self supporting devices. Their advantages are reduced infrastructure cost and reduced environmental impact. However, they operate in a relatively limited range of tidal velocities with a lower economic limit of two metres per second and an engineering limit of three metres per second due to stresses on the turbine blade. At present there is a strong research focus on optimising turbine shrouds to increase the turbine's capture width and flow velocity. A number of small units (tens of kilowatts) are being installed and assessed in Canada, China, Norway and the United Kingdom.

Tidal Fences

A trade-off between the "free stream" and "barrage" methods is the use of a bridge-like structure known as a "fence" or "caisson", which supports a set of turbines across the flow of sea water. This approach provides some freedom for marine life to pass between the turbines and less restriction on tidal flow and area. It can also serve the dual function of a bridge and a tidal power plant. There are no examples of large scale tidal fences in use today, although a substantial number of proposals have been made with one of the largest advanced being for a 2.2GW, $A2.8 billion across the San Bernardino Strait in the Philippines.

Dynamic Tidal Power

A new concept in tidal power energy involves constructing a long wall from the coast into the ocean so that it traverses a tidal flow gradient at an angle that does not excessively compromise tidal influx to a bay or estuary. The wall may be "T" shaped, terminating on the seaward side in a shorter wall at right angles. A pressure differential head forms across the wall to provide current flow through a turbine.

4.2.2 Hydraulic Turbines

Hydraulic turbines are usually either vertical axis or horizontal axis devices. Each has advantages and disadvantages and is used for different conditions and locations.

Horizontal Axis Turbines (Axis parallel to flow)

Horizontal axis turbines spin around an axis parallel to a horizontal fluid flow. They are generally the most efficient method for converting the energy from a laminar, unidirectional fluid flow. These devices are generally used where the direction of flow is well known, or constrained, mostly in deep water. Some devices are able to automatically align to cope with slow changes in flow direction. The Atlantis Resources Corporation "AK" device is an example, illustrated in Figure 4-32.

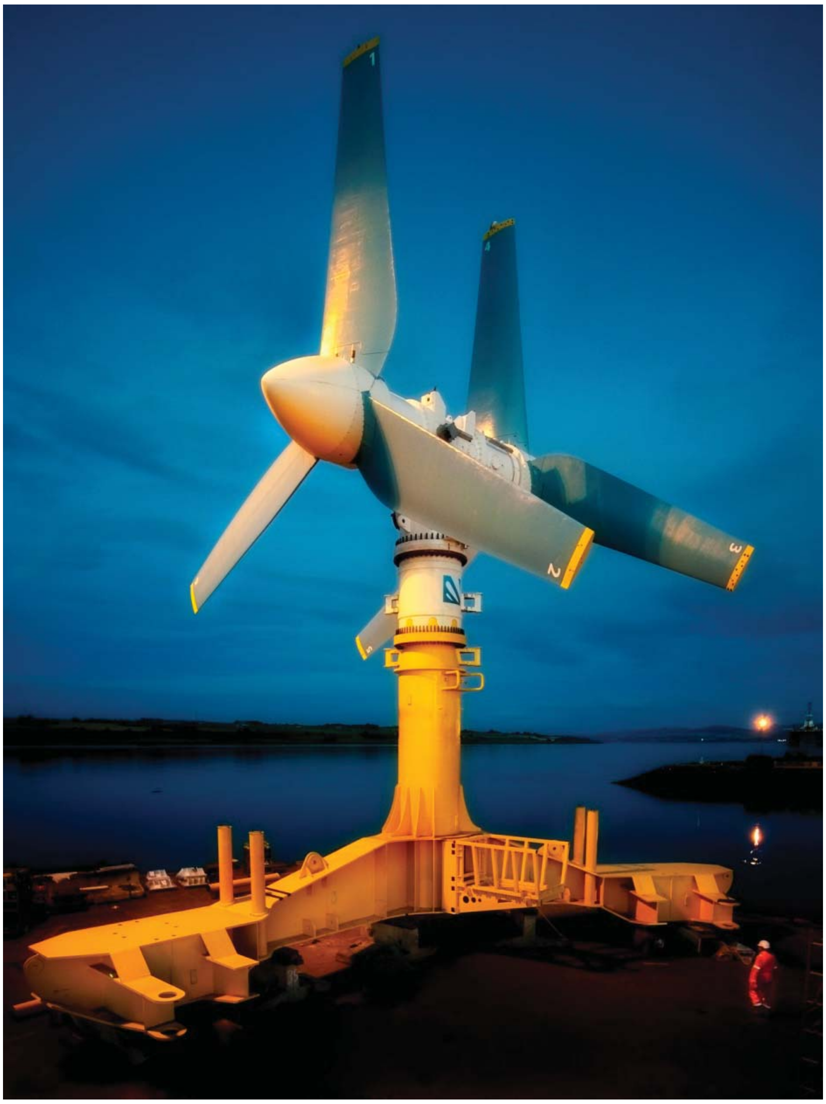


Figure 4-32 Atlantis Corporation AK turbine illustration [54]. Image courtesy of Atlantis Resources.

A shroud or duct can be used to increase the turbine's capture area and efficiency. A ducted example is shown in Figure 4-33.

Figure 4-33 Atlantis Resources Corporation, AR1000 tidal turbine installation [54]. Image courtesy of Atlantis Resources.

The largest operating free stream turbine is the SeaGen device, which produces up to 1.2MW of power and is located in Strangford Lough, in Northern Ireland [55].

Vertical Axis Turbines (Axis orthogonal to flow)

Vertical axis turbines are so named as the axis of rotation of the turbine is generally vertical, in relation to a horizontal fluid flow. It should be noted that a vertical axis device could be arranged with its axis horizontal and still operate effectively, so long as the axis was orthogonal to the direction of the flow. One of the advantages of a vertical axis is that there is no requirement for a separate support pole, post or structure supporting the turbine, as it can be supported on its own axis from the sea floor, or suspended from above the surface of the water.

In the vertical orientation such turbines are insensitive to flow direction, and this can be a significant advantage where the flow may be turbulent, or where the flow direction changes are unpredictable or occur frequently. An example of a GKC Technology is shown at [56].

Other Turbines and Devices

Not all designs operate by rotating around an axis. Two alternatives are outlined below:

Several companies have conceived and tested oscillating hydrofoil devices. Two examples are the BioPower "bioStream" and the "Stingray" from IHC Engineering. BioPower state on their website [57]: "Due to the single point of rotation, this device can align with the flow in any direction, and can assume a streamlined configuration to avoid excess loading in extreme conditions. Systems are being developed for 250kW, 500kW, and 1000kW capacities to match conditions in various locations."

Figure 4-34 BioPower bioStream oscillating hydrofoil. Copyright BioPower [57].

A second design is the Atlantis Resources Corporation "AN" device. It is a current turbine similar to a horizontal axis turbine, but uses blades arranged on a chain, such that those blades don't rotate around a point, but follow a path perpendicular to the current flow. It is designed to extract a maximum amount of energy from shallow flowing water. [52].

4.3 Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) supplies energy by taking advantage of the difference in temperature between an ocean's surface and depths greater than a kilometre. The surface temperature varies seasonally with solar intensity while temperatures at one kilometre depth are relatively constant at about 4°C.

Ocean Thermal Resources

For OTEC to be worth considering, the converter and the resource should be close enough to the coast for economic transport of electricity, operations and maintenance, typically less than 100km. The ocean should have a mean surface-bottom temperature difference greater than about 25°C, which usually requires traversing depths greater than a kilometre. These conditions are found in regions beyond the continental shelf, such as sub-tropical and tropical islands in the deep ocean. Thirty-two suitable regions have been evaluated worldwide. Although Australia is not included, a region that might be suitable lies 100km off the coast of Queensland and about 150km from Cairns, between latitudes 13°S to 16°S, and has ocean surface temperatures that vary seasonally between 24°C to 30°C.

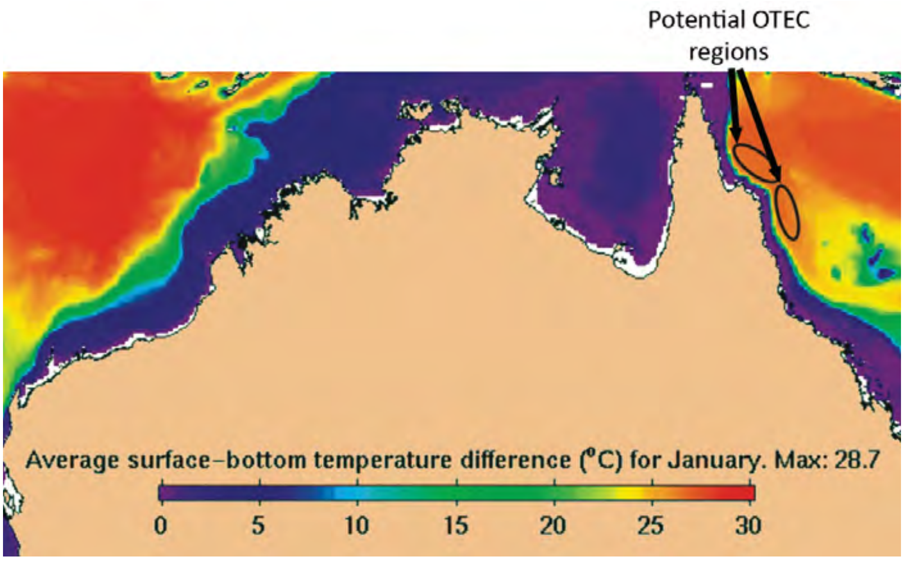


Figure 4-35 Potential regions on the Queensland coast for OTEC [58].

Offshore distance (km)	Capital cost ($/kW)
10	4200
50	5000
100	6000
200	8100
300	10200
400	12300

Table 4-6 Future cost projections based on the analysis of a 100MW conceptual design [59].

Conversion Methods — Closed Cycle Systems

OTEC operates by using warm sea water to vaporise a working fluid so that the relatively high pressure vapour can turn a turbine. The process suggested originally by Jacques d'Arsonval is a closed loop cycle, using a working fluid such as ammonia. The working fluid is evaporated using warm sea water and recondensed using the cold sea water. The closed loop cycle is estimated to be capable of providing up to 100MW of power. The limit is set by the technology available to construct the cold water pipe [60].

Conversion Methods — Open Cycle Systems

It is possible to use warm sea water as the working fluid and this is known as an open cycle system. A fraction of the warm sea water is evaporated by passing it through jets into a chamber with a pressure lower than the saturation pressure for the sea water temperature. This has less environmental impact in the event of a leak of the working fluid and produces desalinated water as well as energy. However, the practical limit for an open cycle system is estimated to be 2.5MW [60].

Net and Gross Energy Production

OTEC takes advantage of the high energy density of warm sea water, which is typically of an order of magnitude greater than tidal energy and two orders of magnitude greater than wave energy. The OTEC process for extracting energy from the temperature differential between an ocean surface at 25°C and an ocean floor at 4°C has a Carnot efficiency of 7 per cent. A conservative upper bound on the conversion efficiency that takes account of the finite times required for energy conversion is 4 per cent [61]. The converter itself has a much higher efficiency, where:

$$\text{Convertor Efficiency} = \frac{\text{Net Power exported from the convertor}}{\text{Gross Power}}$$

$$\text{Gross Power} = \text{Net Power} + \text{Power used for Convertor}$$

This is because the converter efficiency doesn't include in the gross power the solar energy needed to raise the sea water temperature. Consequently, despite its low Carnot efficiency, OTEC continues to attract interest as a renewable energy resource and several prototypes have been tested at sea demonstrating converter efficiencies of up to 39 per cent with significant volumes of desalinated water as a by product.

	Method	Gross Power (kW)	Net Power (kW)
Georges Claude Cuba 1930	Open cycle	22	Nil
National Energy Authority Hawai'i 1979	Closed cycle	53	18
Toshiba Nauru 1982	Closed cycle	120	31
National Energy Authority Hawai'i 1993-98	Open cycle	255	100

Table 4-7 Key examples of sea tested OTEC devices [62].

Research Issues and Foci [62, 63]

Research has been accelerating since 1980 with significant learning around the scaling up of technology for issues such as biofouling of heat exchangers, frequency instabilities in generators and violent out-gassing of cold seawater in condensers. Ongoing research includes:

- cold-water pipe design;
- electric riser power transmission; and
- deployment and survivability.

Currently there are three proposals to build OTEC plants. One is a 13MW unit for the US Navy which will also supply about 5ML of potable water a day. The second is a 10MW closed cycle unit for Guam. The third is a 10MW expandable to 100MW closed cycle system for Hawai'i.

4.4 Salinity Gradient Energy Conversion

The Resource

The salinity difference between seawater and the relatively fresh water returned to the sea by the world's rivers and flood pumping stations, represents two to three TW of resource and 150 GW of extractable power. This is not likely to be relevant to Australia, except perhaps as a means of energy storage in remote, reversible desalination plants. However, it may provide a significant opportunity for neighbouring countries such as East Timor or others in Southeast Asia. For this reason it is covered here very briefly [64].

Operating Principles

When water mixes with saline the mean free path of the ions and the entropy of the solution increases, while the Gibbs free energy associated with electrostatic, polar and hydrogen bond forces between sodium and chloride ions, and water molecules, is released. For this reason the solar energy that creates freshwater streams by evaporating water from the oceans can be retrieved by remixing that freshwater with sea water.

Two methods for accessing this energy are "Pressure Retarded Osmosis", a hydraulic method used to drive a turbine; and "Reverse Electrodialysis", a method for directly producing electric power by using a battery of ion selective membranes to separate the seawater solution and the freshwater solvent.

Pressure Retarded Osmosis Method [65, 66]

Pressure retarded osmosis uses flow cells of filtered seawater and fresh water separated by a semi-permeable membrane that will pass water, but not solutes such as sodium chloride. The difference in solute concentrations between the two cells means that the osmotic pressure gradient drives water from the fresh water cell through the membrane to the seawater cell. Sufficient freshwater can be move into the seawater cell to build up a pressure of 120 metres head of water (11.76 bar) [67]. This is used to drive a turbine to generate electricity. Continuous flows of brine and fresh water are passed through the flow cells to maintain the concentration difference. Powers of up to 3W/m^2 have been achieved with this method.

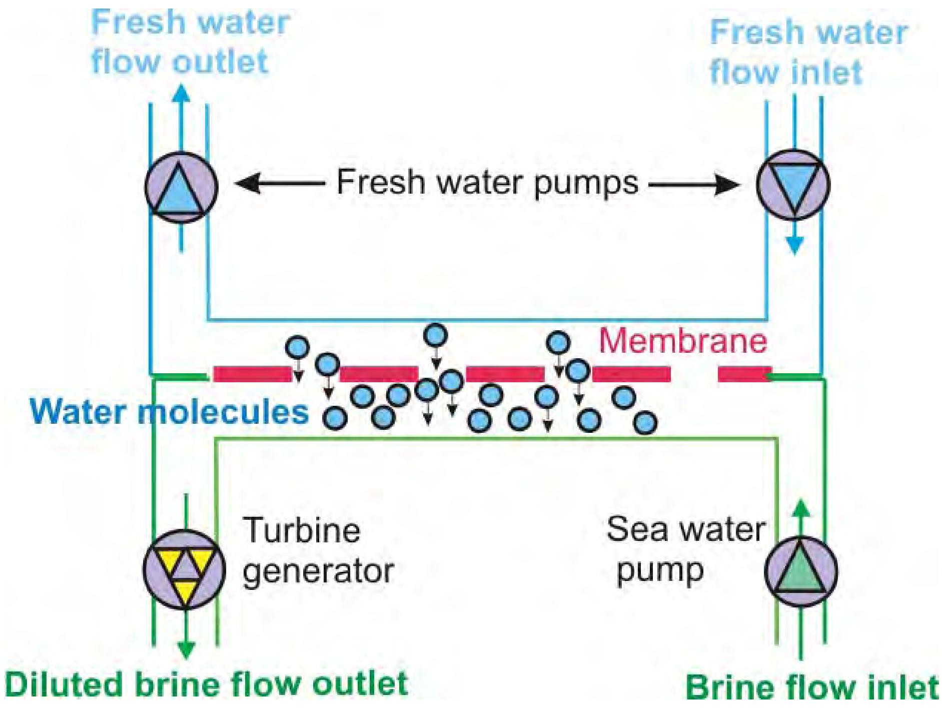


Figure 4-36 Pressure retarded osmosis schema. Adapted from S.Skilhagen *et al* [65].

Reverse electro-dialysis [65, 66]

A second approach is to use an ion selective membrane to separate the seawater and freshwater cells. Sodium (cation) or chloride (anion) membranes can be used separately or connected in series. To illustrate the principle, if one takes a single membrane that is selective (for example, to a sodium cation), then the sodium will move from the saline to the fresh water solution under the influence of the osmotic pressure gradient. The cation can then release its electronic charge in return for an anion that it receives from a "redox" electrode such as silver/silver chloride. Similarly the chloride anion in the seawater solution will move to a redox electrode in the brine solution and react with a cation in the electrode to release its negative charge. The power density of dialysis membranes at present is about 1.2 W/m².

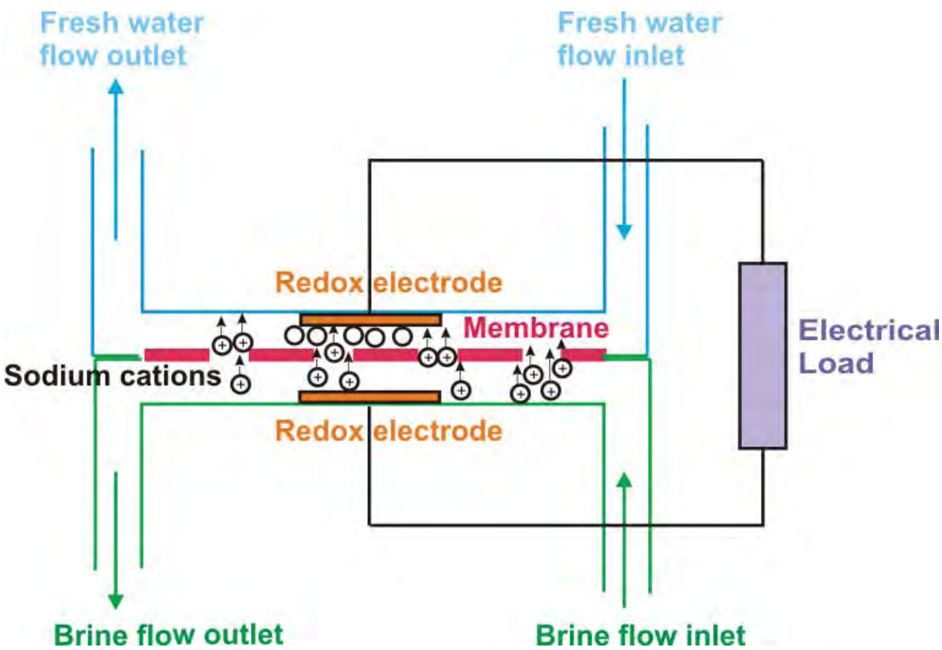


Figure 4-37 Reverse electro-dialysis schema. Adapted from S.Skilhagen *et al* [65].

Ongoing Research

As membrane performance has improved, so has the ability to extract energy from salinity gradients. In the last decade the powers achievable for a given membrane area have increased from a few 100mW/m^2 to between 1-3W/m^2 at the present time. Research goals for commercialisation to be achievable include:

- 5W/m^2 membrane capacity;
- overcoming biofouling issues and water contamination issues;
- structural strength of the membranes; and
- efficiency improvement and reduction of cell internal resistance.

Looking to the future

- A Dutch company REDstack is running a 10kW plant at a salt refinery in Harlingen and planning a 50kW unit.
- Norway has a pressure retarded osmosis prototype plant in Tofte, south of Oslo. It uses 200m^2 of membrane to produce 1kW to 2kW. This will be expanded to a 1 to 2MW pilot plant and if this proves viable then a 25MW generator using 5 million m^2 will be built in the next five years. [65, 67]
- It may be worth assessing an application in remote Australia for energy storage in desalination plants using combined and reversible desalination. The advantage over using water reservoirs is being the much higher energy density and the potential for dual use of components in the desalinator.

4.5 Desalination

In addition to electricity production, wave power can supply energy as high pressure brine for specific processes, thus removing load from electricity generators. Desalination is a particularly useful example.

Desalination plants are becoming more common globally. Within Australia alone there are three operating desalination plants (Perth, Gold Coast, Sydney) with three more under construction (Binningup WA, Wonthaggi Vic, Port Stanvac SA), and at least one other planned.

The reverse osmosis process is currently considered the most energy efficient method for desalination and is used by most modern plants. The energy requirements for various options are to:

- supply fresh water in Newcastle, on average, typically 0.43Wh/L [68];
- run a reverse osmosis desalination plant between 3 to 6Wh/L [69-72];
- run a vapour compression desalination plant 6 to 16Wh/L [73]; and
- run a distillation type desalination plant 22Wh/L. [52]

A number of state governments are purchasing renewable energy to offset the carbon footprint of their desalination plants. For example, Sydney's desalination plant is indirectly powered by 100 per cent renewable energy from Capital Wind Farm at Bungendore.

As an alternative to providing a carbon offset, wave energy could contribute to desalination directly by supplying high pressure sea water for the reverse osmosis desalination technique, or indirectly by supplying hydraulic or electrical power to transport groundwater or treated water from a sewage plant for desalination or purification. Whether it is more efficient to use a WEC to provide hydraulic pressure or electricity depends on the plant's elevation and distance from the converter. It is significantly more expensive to transport hydraulic pressure than electricity over long distances. Pumping pressures for typical reverse osmosis desalination plants include:

- Hadera, Israel pumping 275ML per day and requiring a pressure of 67 to 75 Bar (6.7 to 7.5MPa), [74]; and
- Tampa Bay USA, pumping 95ML per day and requiring a pressure of 625 to 1050psi (4.3 to 7.2MPa) for USA. [75]

Such pressures may be considered "high", but if an existing ocean energy converter is unable to generate these pressures directly, due to design or to a low energy ocean state, a "pressure intensifier" can be utilised. Such a system has been proposed [76] to allow an Oyster WEC to be used to pump water to a reverse osmosis desalination process.

There are currently several operational examples of WECs used to desalinate water. In one case an oscillating water column is used to create electrical energy for powering the electric pumps in a reverse osmosis desalination system (Vizhinjam, India, 2004 [77]). Devices have also been developed for using wave energy to directly pump sea water through a reverse osmosis desalination system (e.g. The DELBUOY™, by ISTS Delaware Inc [78] and the CETO convertor, by Carnegie Wave Energy Ltd).

4.6 Conclusions

Summary of the Options

Tidal energy is worth considering as a useful option for two or three sites in Australia. However, it is essential that these be developed progressively with ongoing environmental impact studies.

Ocean thermal energy — once fully developed — as to enable an assessment of its economic potential. The abundance of this resource in Southern Queensland and New South Wales suggests that further study would be worthwhile.

Salinity gradient techniques may be useful at a very small scale in remote locations for local site production of electricity. For example, where they may be combined with wave power desalination and using the same filter banks.

Ocean thermal energy once fully developed could make a useful contribution to both water desalination and electricity production in the vicinity of Cairns. However, it still faces significant technical issues, particularly with the management of the kilometre-long pipe needed to supply chilled water from the abyss.

Wave power remains as potentially the single greatest ocean renewable resource.

Wave Power Devices and Farms

The classification and operating principles of a number of wave energy devices have been described and assessed as individual entities and connected together as wave farms. The following conclusions were made from the assessment:

- Any device used in Australia will need to be tuned for Australian wave characteristics — particularly amplitude and period. There are currently about six devices worldwide that show sufficient data to be assessed as promising for use in Australia.
- Capacity factor is an inadequate parameter for assessment of wave energy devices due to the huge dynamic range of wave energy leading to a non-harmonised approach to nameplate rating. An alternative assessment process is described that can readily be implemented as a user friendly computer program.
- There is a trade-off between anchorage and the logistics of operations and maintenance for wave farms. If wave converter devices rated at several megawatts are used the logistics are relatively simple for about 100 freighter-sized devices. However, the anchorage stresses are substantial and require significant research and development. If devices rated at a few hundred kW are used, several tens of thousands of devices will be required with corresponding complexity in operations and maintenance.
- In respect of environmental impact and competing use it is worth considering wave farms based on both small and large energy convertors. Large (MW) convertors have a poorer packing density and their wave farms take up significantly greater areas of sea. A 200MW wave farm of large multi-megawatt convertors, might typically take up 50km^2; whereas a 200MW farm, based on small convertors rated at a few 100kW, would take up 10km^2 to 20km^2, although many more of them would be required to supply the same power.

In both cases there is the potential to either disrupt or benefit other uses. Anchor cables might interfere with sea life and their number would increase by one or two orders of magnitude where the smaller energy convertors are used; whereas the area of the wave farm might intrude on other activities; this would be a greater issue where larger energy convertors are used. On the other hand, wave farms may prove beneficial to other users; for example in sea calming and the provision of local power, synergistically with oil-gas drilling platforms, offshore wind turbines or for protecting eroding coastline.

- The design of the subsea mini-grid is a technical and research challenge at least as great as the design of converter devices. It is unclear where the boundary for such research and development lies between device manufacturers and electricity utilities. This area of research and devlopment is a key to successful development of an ORE industry, but is neglected except in Denmark, Sweden and the United Kingdom.

5. Competing Uses

To supply 10 per cent of Australia's total grid based electricity demand by 2050 it will be necessary for ORE to generate 46TWh.

Depending on the technology, this could take as little as 150km of coastline segmented into a number of regions. However, the process might need to be extended by up to a factor of five if for environmental reasons it was desirable to limit the extraction from waves to 20 per cent. For our estimates we have selected seven regions each traversing about 50km of the coast along the southern perimeter of Australia. Gaining access to these coastal waters for renewable energy development is at least as complex an issue as for land-based sites. The federal and state Departments of Crown Lands can provide guidance [79] to the developer on the many stakeholders, licences and issues to consider including:

- native title and land rights;
- Marine Protected Areas;
- fishing, aquaculture and fisheries;
- oil, gas and mineral resource development;
- shipping;
- national security; and
- tourism, recreation and visual amenity.

This chapter will examine each of these in turn and outline some of the key issues and opportunities.

5.1 Indigenous Land (Native Title and Land Rights)

The land rights and cultural resources of Indigenous communities are maintained and developed through mechanisms such as:

- Indigenous protected areas;
- Indigenous Land Use agreements;
- Regional agreements; and
- Native Title and Land Rights.

Indigenous Protected Areas are lands for which the Indigenous owners have agreed with the federal or state Governments to promote biodiversity and cultural resource conservation. Such land joins the National Reserve System [80, 81].

Indigenous Land Use agreements are agreements between Indigenous groups and others that are derived from a broad range of issues related to land rights. These agreements may become part of a process towards determining Native Title.

Regional agreements are usually between governments or industry and relate to policy, administration or public services involving Indigenous people in a defined territory of land or sea.

Native Title and Land Rights are two separate mechanisms for recognising the rights and interests of aboriginal communities to land [80, 81]. Native Title is based on the recognition by Australian law of rights and interests arising from the traditional laws and customs of Indigenous people. It was first recognised in Australia through the Mabo vs. Queensland ruling in 1992. Subsequent determinations are shown in Figure 5-1 and ongoing applications in Figure 5-2. These include regions of both land and sea. Land rights are provided by a grant of title from the Australian government. Both may provide rights such as:

- possessing and occupying an area to the exclusion of all others;
- controlling access and use of the area;
- living or camping on land;
- access to food, water and resources such as wood, fibre and natural dyes;
- using land for traditional purposes such as ceremonies; and
- protecting cultural resources and sites of cultural significance.

Negotiations with communities to access Indigenous Land (where native title may or may not exist) may provide mutual benefits in addition to the required permissions. These might include co-investment opportunities in renewable power generation together with associated training, employment and business opportunities to meet the critical need for ongoing maintenance of ORE farms. Such Indigenous interests are exemplified in activities such as the “Bushlight” program promoting solar power in remote communities through the Centre for Appropriate Technology in Alice Springs; or the recent negotiations between CSIRO and the Wajarri Yamatji people of Western Australia for development of the Square Kilometre Array [82].

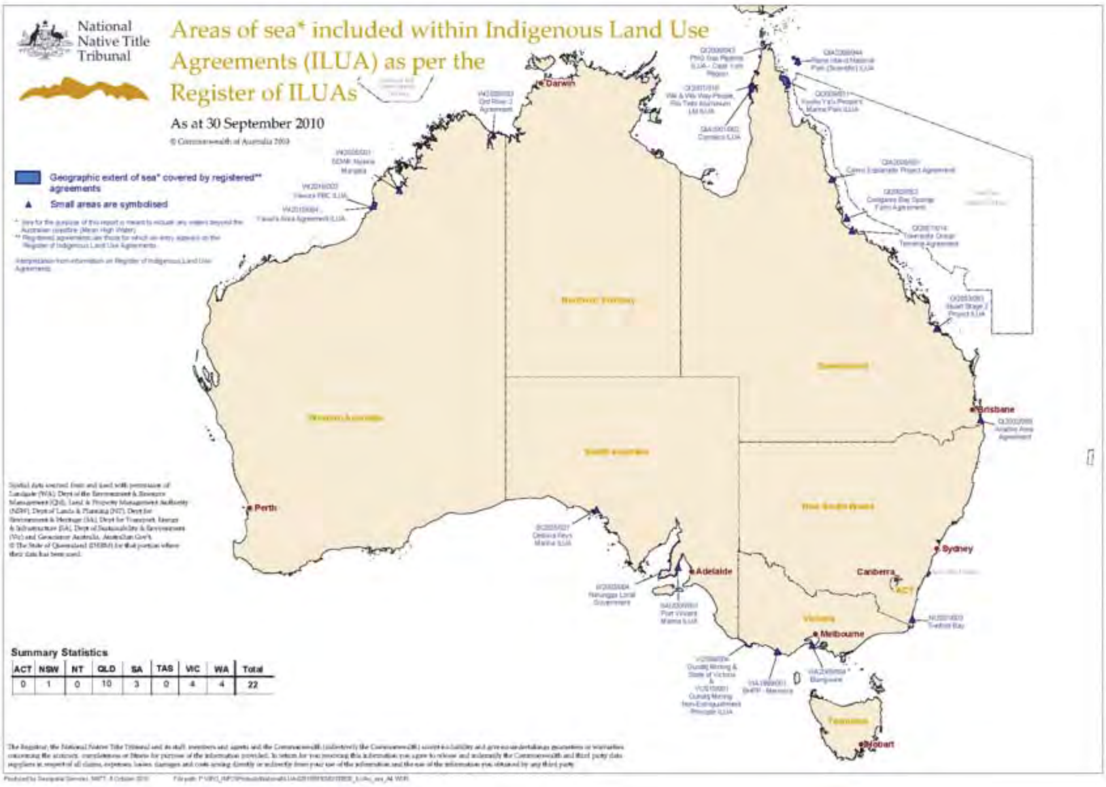


Figure 5-1 National Native Title Tribunal: Areas of sea included within Indigenous Land Use Agreements [80].

These maps have been produced by the National Native Title Tribunal. These maps are regularly updated and can be accessed through the Tribunal's website at www.nntt.gov.au.

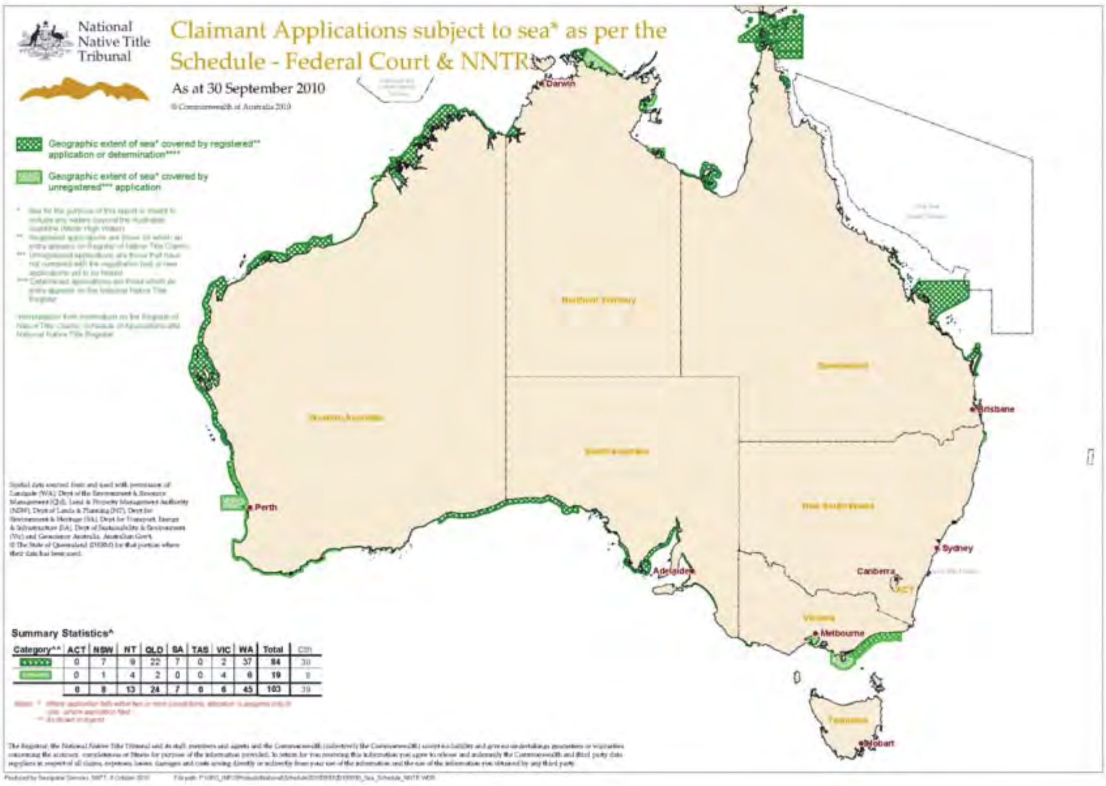


Figure 5-2 National Native Title Tribunal: Claimant Applications subject to sea as per the schedule [80].

These maps have been produced by the National Native Title Tribunal. These maps are regularly updated and can be accessed through the Tribunal's website at www.nntt.gov.au.

5.2 Marine Protected Areas

A Marine Protected Area (MPA)[83, 84] is "an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity and of natural and associated cultural resources, and managed through legal or other effective means". It can include:

- seabeds in deep water;
- mangroves;
- reefs;
- rock platforms;
- seagrass beds;
- shipwrecks;
- tidal lagoons;
- archaeological sites;
- mudflats;
- underwater areas on the coast;
- salt marshes; and
- seabeds in deep water.

The types of MPA protection in Australia are formally described using the International Union for Conservation of Nature (IUCN) categories [85] [84].

Type of area	IUCN	Explanation
Strict nature reserve	Ia	Managed primarily for scientific research or environmental monitoring.
Wilderness area	Ib	Protected and managed to preserve its unmodified condition.
National park	II	Protected and managed to preserve its natural condition.
Natural monument	III	Protected and managed to preserve its natural or cultural features.
Habitat/species management area	IV	Managed primarily, including (if necessary) through active intervention, to ensure the maintenance of habitats or to meet the requirements of specific species.
Protected landscape/seascape	V	Managed to safeguard the integrity of the traditional interactions between people and nature.
Managed resource protected area	VI	Managed to ensure long-term protection and maintenance of biological diversity with a sustainable flow of natural products and services to meet community needs.

Table 5-1 Classification of Marine Protected Areas.

Less formal categorisations, more oriented to describing levels of protection, are sometimes used in state government or privately managed MPA's. These may include terms describing high levels of protection such as "no take zone" or "sanctuary" to the relatively low level of protection described as "multiple use".

Currently there are more than 200 MPAs in Australia, covering 64.8 million hectares. They include marine parks, such as the Great Barrier Reef, fish habitat reserves and sanctuaries, aquatic reserves, conservation areas, and marine and coastal parks.

MPAs may be managed either by federal, state or territory governments. In 1991 the Australian Government initiated the development of a National Representative System of Marine Protected Areas (NRSMPA). The intent is to increase the resilience of MPAs and more comprehensively reflect the biodiversity of Australia's marine ecosystems by developing networks of MPAs that bring together federal, state and territory governments.

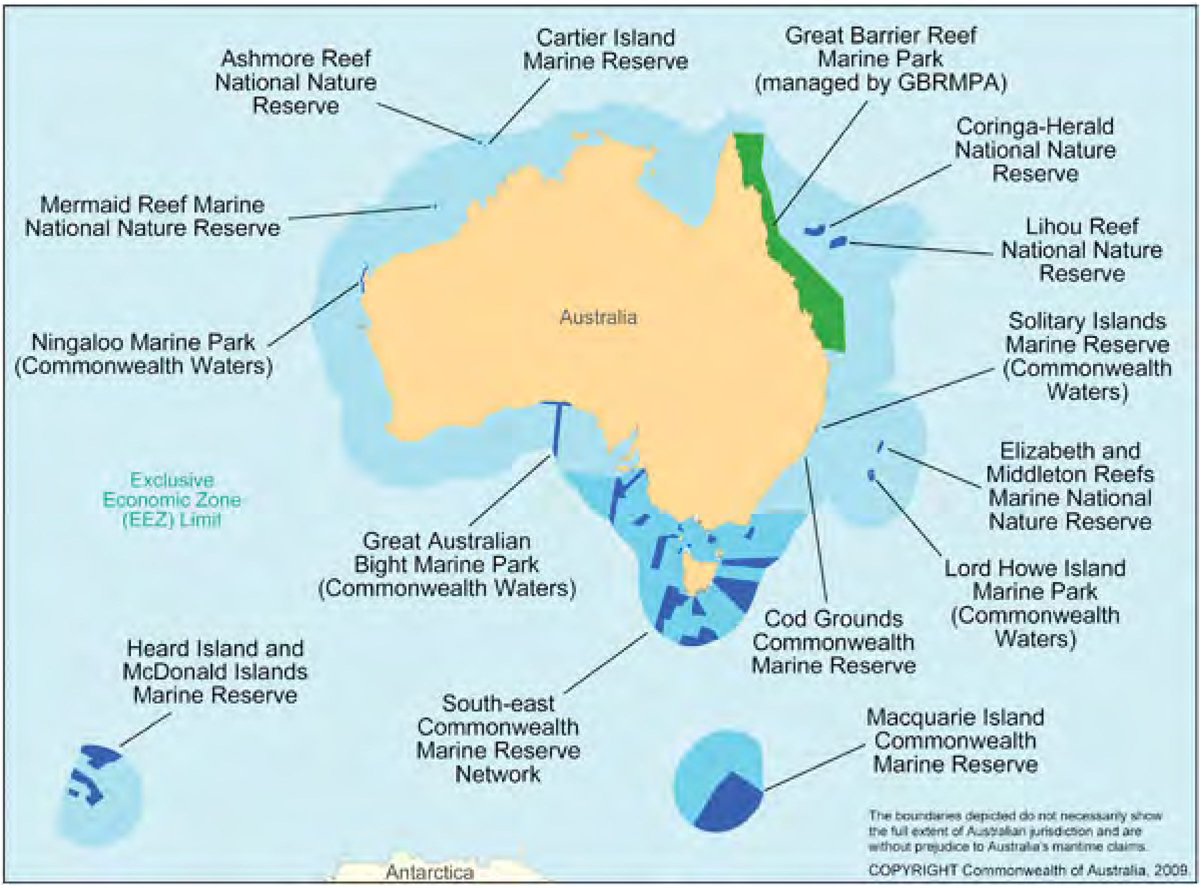


Figure 5-3 Outline of the national network of Federal, State and Territory Marine Protected Areas [84]. © Australian Government (DSEWPaC).

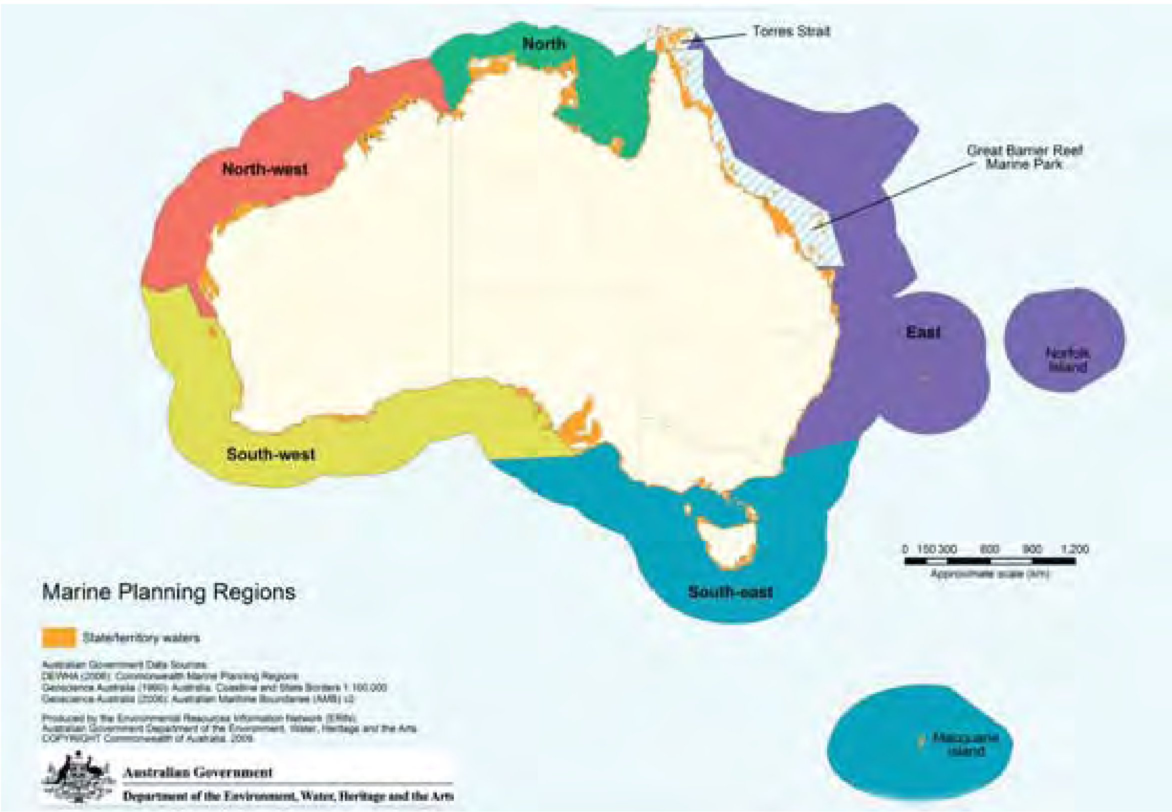


Figure 5-4 Marine Planning Areas [86, 87]. © Australian Government (DSEWPaC).

5.3 Shipping

More than 25000 ships enter Australian ports each year and, because 80 per cent of wave energy transport occurs in the five to 10 metres below the sea surface, it will not be possible for these ships to travel across wave farms. For wave farms to supply 10 per cent of Australia's electricity they could cover a wide range of sizes, with the largest possibly needing up to 40km of coastline and covering areas up to 50 km^2. Clearly it will be necessary to locate wave farms well away from shipping lanes, distribute their sizes; and to ensure that their presence is included on charts and in navigational systems as well as being signalled appropriately. Methods for signalling the presence of a wave farm will require development to ensure they don't interfere with the activities of marine life, whose ability to navigate or seek food may be compromised by large arrays of navigation lights. Government stakeholders in the activities of Australian shipping include:

- Department of Environment and Heritage;
- Department of Infrastructure and Transport;
- Department of Defence;
- Australian Fisheries Management Authority; and
- State Port and Maritime Authorities.

Australian Ports International Only				Australian Ports Domestic and International	
Port	**Weight (MT)**	**Port**	**Value ($bn)**	**Port**	**Weight (MT)**
Port Hedland	104	Melbourne	53.7	Port Hedland	106.3
Damper	103.8	Sydney	45.8	Dampier	104.6
Hay Point	84.8	Brisbane	24.5	Hay Point	84.8
Newcastle	82	Fremantle Perth	18.1	Newcastle	82.3
Port Walcott	58.5	Dampier	12.6	Port Walcott	56.5
Gladstone	47.8	Hay Point	7.4	Gladstone	51.4
Fremantle Perth	20.9	Adelaide	7.0	Fremantle Perth	23.4
Melbourne	20.2	Newcastle	6.6	Melbourne	22.8
Brisbane	20.1	Gladstone	5.0	Brisbane	22.4
Sydney	18.6	Port Hedland	3.9	Sydney	19.3
Other	122.3	Other	30.7	Other	158.9

Table 5-2 Top 10 Australian ports by weight and value 2004–05. Adapted from *Australian transport statistics,* August 2006, Department of Transport and Regional Services.

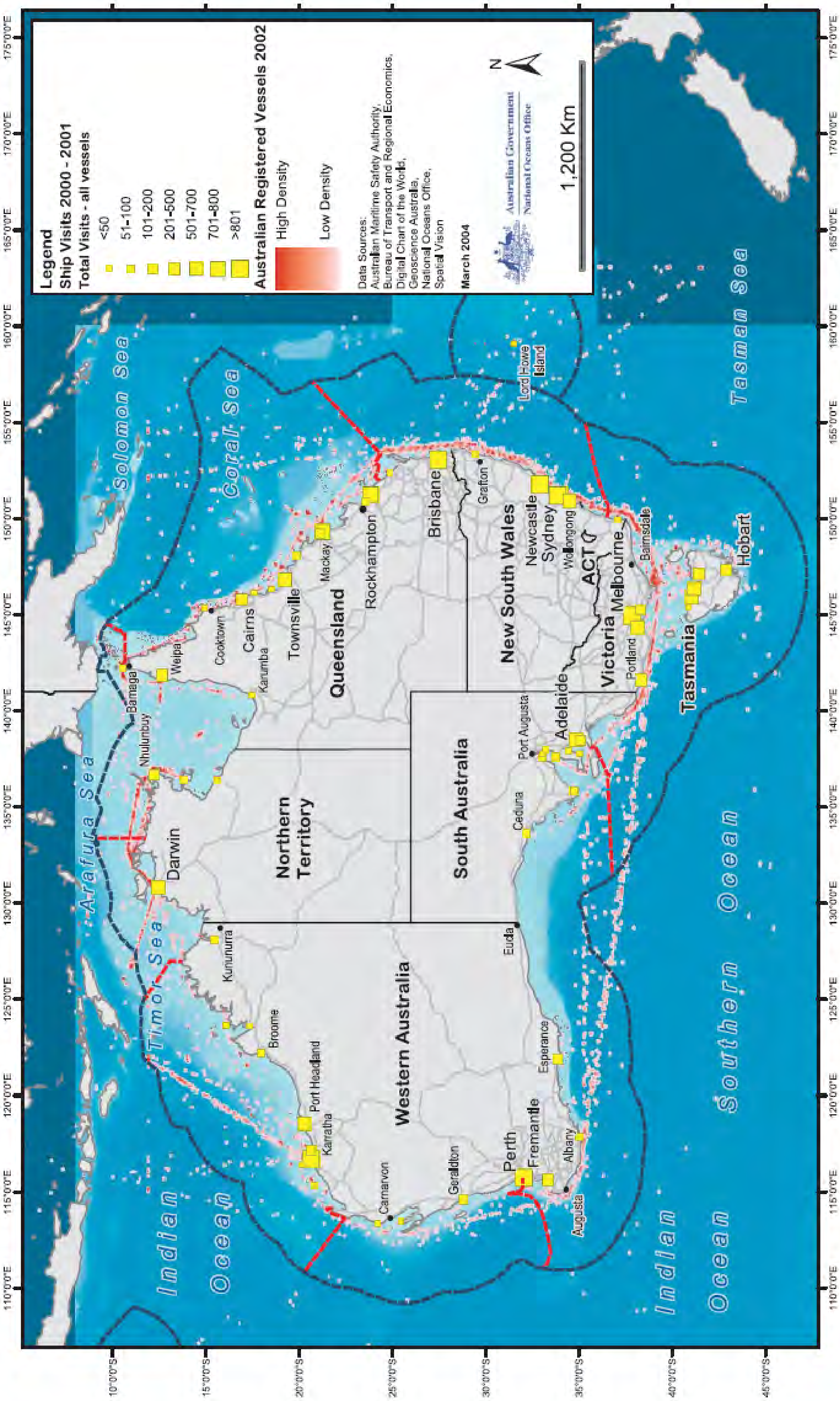


Figure 5-5 First port of call of international shipping into Australia [87]. © Australian Government (DSEWPaC).

5.4 Tourism, Recreation and Real Estate Values

The principal questions regarding the impact of wave farms on tourism, recreation and real estate values might be expected to include: noise, visual amenity, safety, effects on surfing, boating, the environment, recreational fishing and local employment. Wave farms of from 50MW to 250MW located offshore could extend along 5km to 35km of coastline and take up about $5km^2$ to $50km^2$ of area. They would typically be located from 1km to 10km offshore. However, it is unlikely that wave farms greater than 50MW would prove acceptable where these impacts are of concern.

Noise and Visual Amenity

Onshore wave farms would have significant impacts on both noise and visual amenity both in the construction phase and during operation. Furthermore, some forms of wave farm may produce significant levels of underwater noise. However, there is insufficient research to answer the question of what level of subsurface noise is acceptable. With regard to visual amenity and noise above water, most wave farms would not be easily visible from the shore depending on the method of providing navigational hazard warnings. Most of the noise generated would be subsurface.

Safety and Boating

The key issues for safety and boating are likely to be navigation hazards and accidental damage to the farm. It will be necessary to ensure that the presence of a wave farm is included on charts and in navigational systems available to small boat users as well as being appropriately signalled. Broken moorings and electrical cabling may bring the possibility of collision or electrical hazards. It would be expected that such issues could be addressed using inbuilt fault detection and buoy location technology.

Surfing

Whereas for single devices and small scale installations the impact on surfing has been shown to be minimal, the same might not be true for a large scale wave farm. There is an economic imperative to concentrate devices in a confined region, to reduce capital costs and operations and maintenance expenditure. A trade-off exists between the number of farms, their size and the length of coastline they operate in to achieve a competitive wave energy supply with no undesirable impacts on wave height and period. A 500MW farm could be designed to extract as much as 50 per cent of the wave power from coastlines that might be expected to extend along 20km of coast. However, only 10 such farms would be needed to supply 10 per cent of Australia's electricity in 2050. The same energy could be provided by 50MW wave farms each taking up 5km of coastline and extracting 20 per cent of the energy. This would greatly reduce the local impact but require 100 such farms. These are very tentative estimates and it will be essential as wave technology develops to measure and assess the impact of wave energy devices on wave height and period. Projects conducted overseas have benefited in this regard from early engagement with the affected communities.

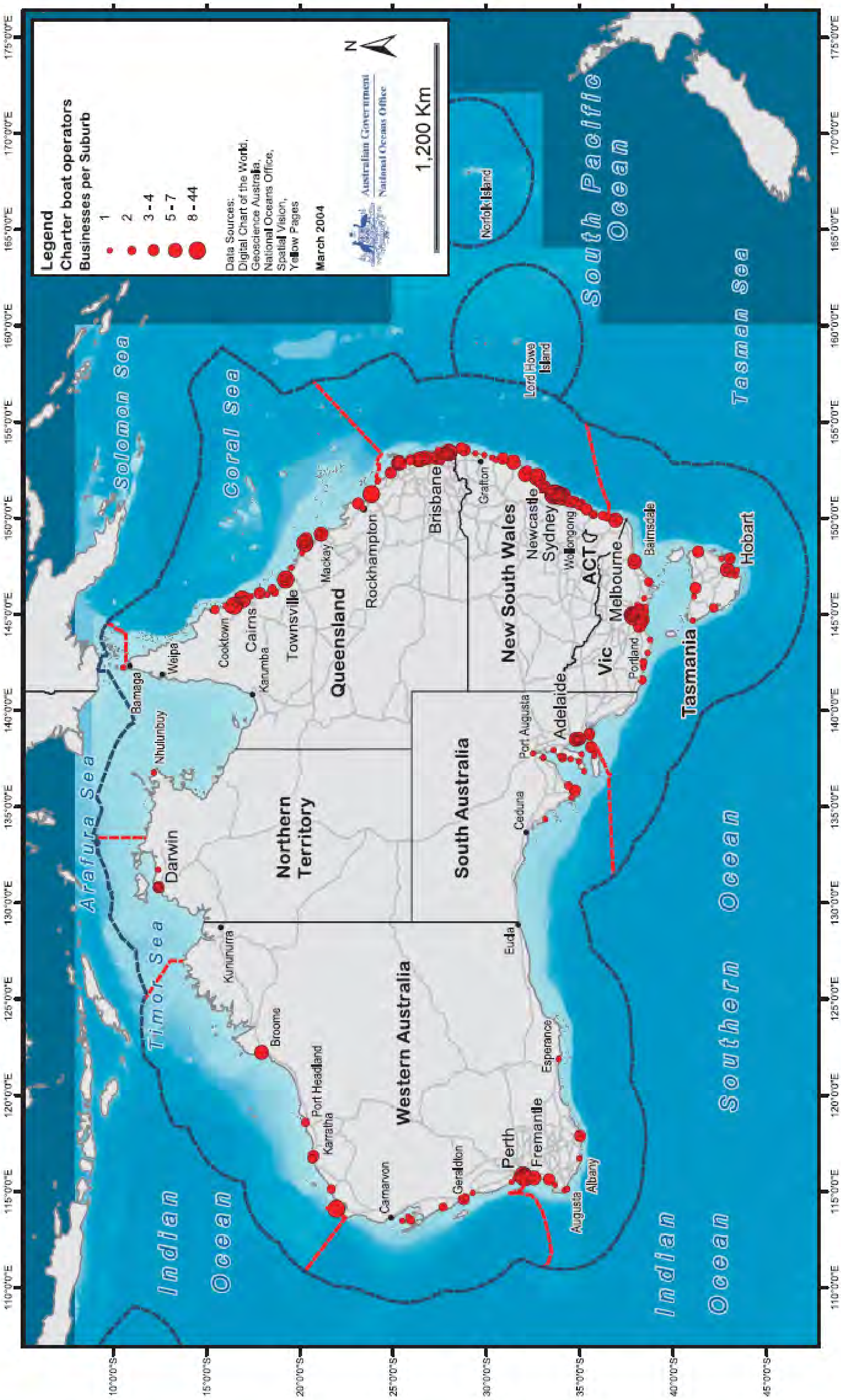


Figure 5-6 Tourist, Recreation, Sport — Chartered Boat Operation [87]. © Australian Government (DSEWPaC).

The Environment, Recreational Fishing and Local Employment

The impact on the environment, as well as the fishing resource, may be intimately linked to local employment and the value of real estate in areas that rely on tourism. We discuss fishing in section 6.5 and the environment in chapter 7.

In areas that rely on fishing, boating and environmental quality to attract tourists it is unlikely that large onshore installations will prove acceptable. Very large offshore installations (500MW) are also problematic. However, medium scale (less than 50MW) offshore wave farms — carefully designed and located — may prove useful and work well in some locations. It is worth emphasising that this is a very preliminary review. The impact of wave farms on tourism will depend on the results of environmental research that has yet to be carried out as well as the mandatory environmental assessment and community consultation.

5.5 Fishing, Aquaculture and Fisheries

The Australian Fishing Zone covers 11 million km^2, extending 200km offshore and with more than 150 fisheries. The fishing industry employs 16,000 people, has 9,000 commercial fishing vessels, and a production value of more than $2bn per year. About 50 per cent of this is for high value exports, particularly abalone, tuna, scallops, prawns and rock lobsters, with tuna, abalone and rock lobsters a particular focus of fishing industries in the southern states. The impact of ORE on the fishing industry can be grouped as: reduction in sea lanes available to fishing boats, alteration of the fishery habitat and prey and interference with fish behaviour (for example movement, catchability, reproduction).

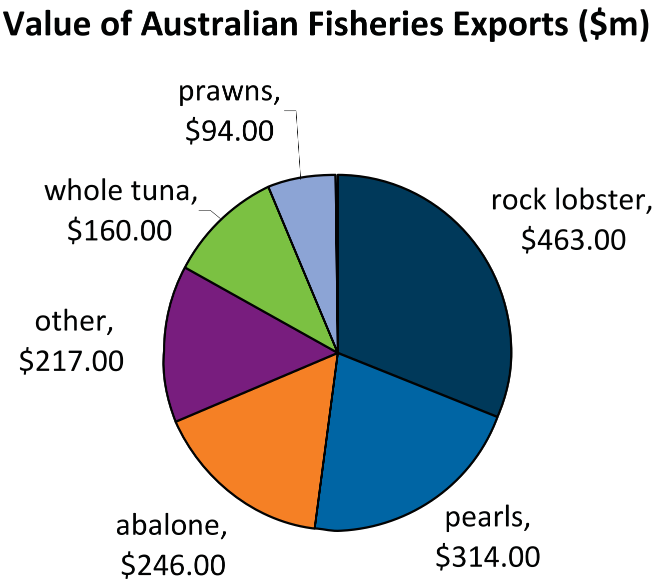


Figure 5-7 Value of Australian Fisheries Exports (*$m) [88].

Reduction in Sea Lanes for Fishing Vessels

This is primarily an issue for offshore wave energy farms. These may be located from 1km to 10km offshore, extend up to 30km along the coast and cover areas up to 50 km^2. Figure 5-7 and Figure 5-8 give an idea of the extent of fishing boat operations and the need for careful assessment of the size and distribution of wave farms in regions with well developed fishing industries.

Alteration of the Fishery Environment

All three of the ORE resources — wave power, tidal power and ocean thermal energy — can alter the habitat in their vicinity in ways that impact significantly on fisheries. Wave farms may alter the distribution of sand along a coast by reducing the energy and changing the distribution of waves. This has the potential to change the sand coverage of rocks and reefs that host lobster and abalone. Tidal barrages and to a much lesser extent tidal fences and tidal current turbines may reduce intertidal areas, alter sediment transport, salinity range and bottom water characteristics, all of which could change the distribution of fish species. Ocean thermal schemes of the open-cycle variety may disrupt ecosystems by bringing cold, nutrient-rich water to the euphotic zone, triggering algal blooms. Large non-tidal ocean current turbines may have a similar impact to some extent.

Interference with Fish Behaviour

Both the wave farms and ocean thermal energy generators may provide an alternative habitat for fish not necessarily the Indigenous species. It is well known that fish will be attracted to structures that provide shelter against predators, surfaces for cleaning and substrates or a more desirable food web. These are the mechanisms that underlie artificial reefs and fish aggregation devices. However, it is not necessarily the case that Indigenous species will prevail; they may be supplanted by more opportunistic sea life.

Some additional factors that may attract repel or disorientate fish and predators are navigation lights, or the sound and electric fields associated with the generator.

The costs or benefits of such environmental changes to the industry are uncertain and require ongoing research as the ORE industry develops.

5.6 Mineral Exploration and Mining

Offshore oil and gas resources and exploration are shown in Figure 5-9 and Figure 5-10. The key issue is to ensure that wave farms don’t remove access to significant prospective regions such as those in the Otway, Bass, Mentelle and Bremer basins. There may also be a synergy between the co-establishment of oil wells with wave farms, with the latter providing wave calming and power and the former potential structures on which to build wave energy conversion devices.

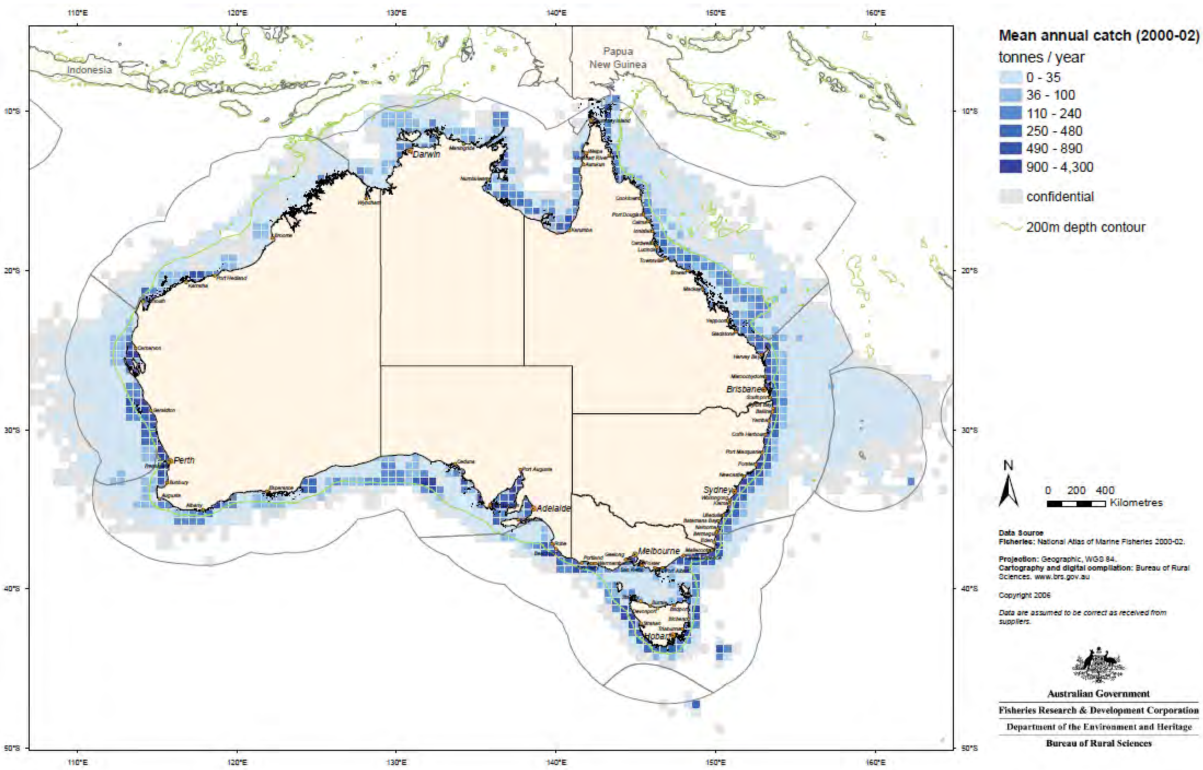


Figure 5-8 Commercial Fishing Catch (2000-02) [89].

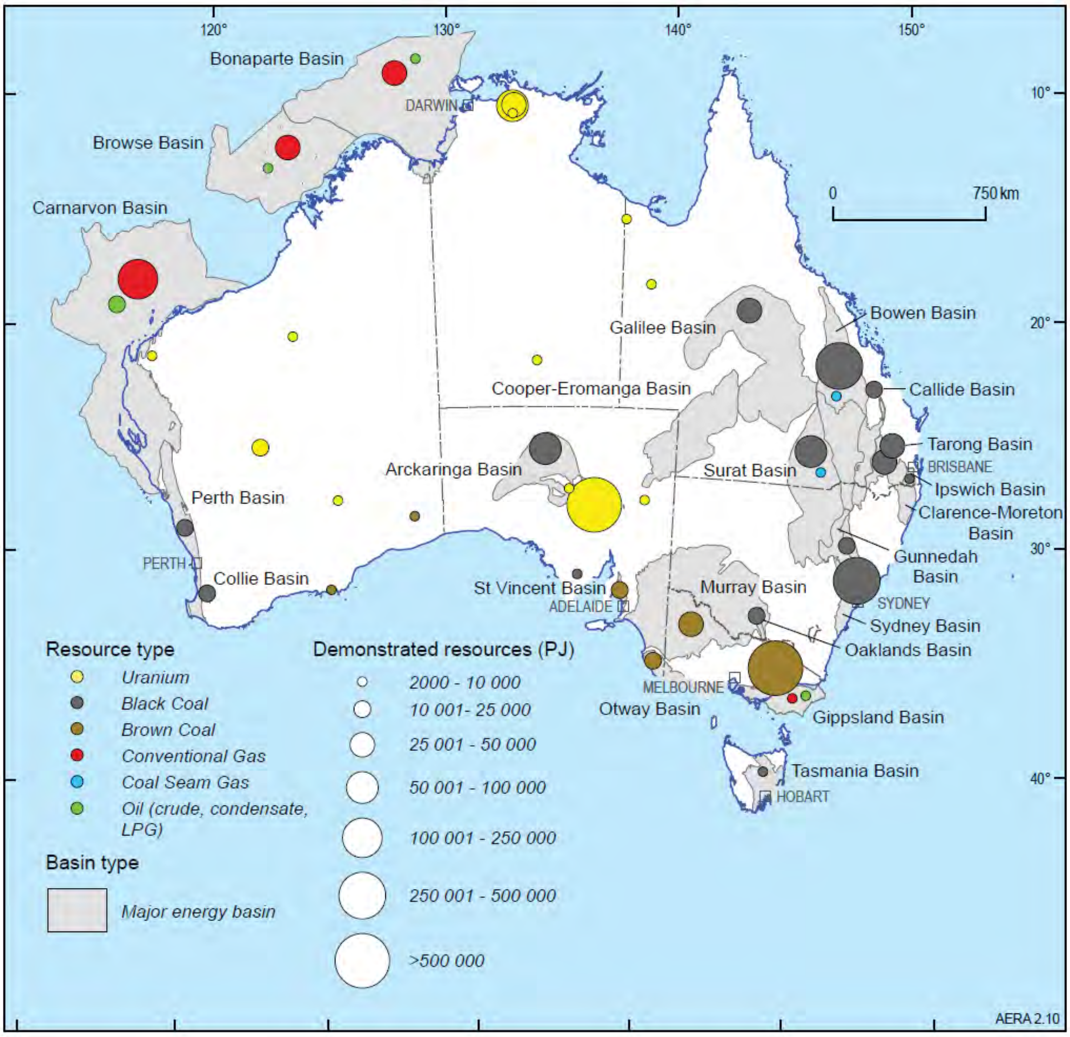


Figure 5-9 Petroleum/Mining — Coastal Mineral Extraction [15].

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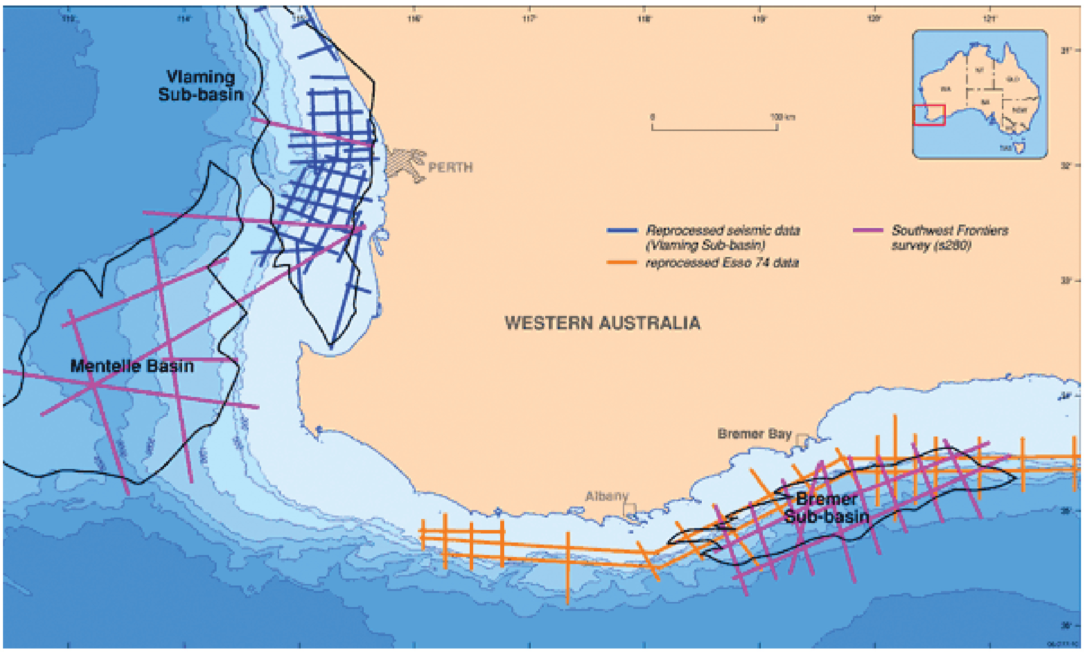

Figure 5-10 The Bremer and Mentelle Basins [90].

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5.7 Defence and Security

The Royal Australian Navy (RAN) is interested in understanding potential applications of wave power technology. Possible future naval applications could include the use of small, off-grid installations to provide power, on a temporary basis, to military operating areas, or to recharge Unmanned Underwater Vehicles in order to increase their mission endurance.

In 2008, the Defence Support Group signed an MOU with Carnegie Wave Energy for an initial feasibility assessment to determine the potential for wave power generation off the west coast of the Garden Island Naval Base in WA. The proposed location of the wave power buoy is in state waters (2km off Garden Island). Although, at this stage, there has been no formal approval from Defence to use Garden Island as the location for a wave power generation facility, the proposal is being assessed by Defence for compliance with relevant policy. If approval is given, Defence will be an "early adopter" of power generation from ORE.

The RAN's attitude to offshore wave energy generation installations is likely to depend on where they are located, and how they are constructed. If they were to be located within any of the Navy's key offshore training areas, or in strategic choke points, the RAN would be concerned about adverse impacts on operational training flexibility and manoeuvre for both surface ships and submarines. These concerns would be greater if parts of the structure protruded into the near surface water column. Acoustic properties may also be a concern to the RAN, since the structures could increase reverberation levels and background noise, as well as providing numerous false targets. In locations away from training areas or choke points, adequately charted installations are unlikely to be of major concern to the RAN.

Shipping and related organisations are likely to advocate that wave energy generation installations do not interfere with commercial shipping operations, and do not present a hazard to navigation. Their concerns in this regard are likely to be the same as the RAN's. Such organisations can be readily engaged through well-established peak bodies, such as Shipping Australia and Ports Australia.

The Australian Defence Organisation has expertise in a number of areas relevant to power generation from ORE. These include corrosion and biofouling of offshore structures, underwater acoustic effects on marine mammals and on naval operations, hydrography and oceanography.

5.8 Conclusion

Offshore farms are not likely to produce visual or auditory impacts on landowners or shore-based businesses. However, subsurface noise may be a problem for divers and for naval operations. The most significant impacts could arise where the size of a wave farm has the potential to interfere with sea lanes, or preclude fishing areas.

Interference with sea lanes can be mitigated by appropriate selection of device types that can alter wave farm size and shape by as much as a factor of x5 to x10. Likewise it may be possible to use subsurface devices to allow smaller boats to pass over the farm.

It is unlikely that fishing would be allowable over a wave farm. On the other hand there is a reasonable prospect that the farms based on larger devices will serve also as shelters for sea life and promote fishery stocks. In terms of fish production, the level of extraction of energy from a wave farm in some areas may need to be researched to ensure there is no migration of sand that might interfere with rock lobster and abalone fisheries.

Wave farms may also be synergistic with other ocean use. They have the potential for sea calming which could be useful if a farm were combined with an offshore oil or gas well, or wind turbine, or to protect a vulnerable section of coast. They also have the potential to provide significant employment to coastal communities.

Detailed research is required prior to the design of a wave farm and ongoing throughout its development and operation. This is to ensure that its benefits can be optimised and the impacts mitigated, for other users in its vicinity.

6. Environmental Impact

The development of ORE is generally perceived as having a minimal risk of environmental degradation and, on occasion, a net positive environmental outcome. An example is the recent construction of a 254MW tidal power station at Sihwa Lake, North Korea that will supply 254MW of power and remediate stagnation caused by the construction of a sea wall in 1994 [91]; or provide shelter and potential for seeding artificial reefs. While such instances show the potential for creative and positive solutions arising from careful planning the slow pace of development of ORE has been matched by an even slower pace of research into its environmental consequences [92, 93]. This deficit will be evident in the following discussion, which suggests a great need for research linked to the development of ORE in Australia.

The potential for environmental impacts, their range and interdependencies can be more readily appreciated by presenting them as classifications in a framework of technologies, stressors, receptors and impacts [93]. Figure 6-1 shows the framework used here to review the environmental risks associated with wave, tidal, current, and ocean thermal sources of renewable energy and to highlight both the known impact and those potential impacts that remain unresearched.

ORE

wave - tidal - ocean current - ocean thermal - salinity gradient

⇩

Stressors

physical presence - dynamic effect - energy removal - chemical - acoustic - electromagnetic - salinity gradient

⇩

Receptors

Physical environment - pelagic* habitat - benthic† habitat - fish - marine birds - mammals ecosystem /food chain

⇩

Duration and Extent of Effect

single effect/short term - single long term - multiple short term - multiple long term

⇩

Direct Impact

population change - community change - biotic process alteration - physical structure/process alteration

⇩

Cumulative impact

SPATIAL - TEMPORAL - HUMAN ACTIVITY

* Pelagic – the ocean water zone distant from the shore
† Benthic – the zone surrounding the sea floor

Figure 6-1 A framework for some considerations of ORE environmental impact. Adapted from G.Boehlert [93].

6.1 Wave Power

Offshore wave devices have the potential for low visibility and noise level from a shore line perspective and minimal construction site impact. However, the impact of offshore ORE devices will depend non-linearly on scale. While small developments are unlikely to have much effect, as the size increases a range of environmental impacts will need research. These include the impacts of i) extracting energy from the sea and ii) the presence of a large distributed structure with some of the characteristics of an artificial reef or fish aggregation device. Both features can have positive and negative impacts:

Sea Calming Effects (taking energy from the sea) [93, 94]

The effects of diffraction and the small size of low power (less than 100MW) installations a kilometre or more offshore could, by design, avoid appreciably reducing the energy flux that reaches the shore, by limiting the extraction of energy. For example a large scale (500MW) wave farm that reduces the energy flux by 20 per cent would extend along 50km of shoreline. Limiting the extraction to 10 per cent would increase the extension proportionately. The trade-off is between the impact of taking up long lengths of shoreline vs. the need to limit the extraction of energy from waves. The balance between detrimental and beneficial effects would need specific research for each location; and ongoing research is essential if wave farm technology develops and expands. Typical effects might include:

- A wave farm might be expected to shelter beaches and prevent erosion. However, it might also encourage the accretion of sand over a sea bed and this in turn could alter the growth of plant life; for example reducing kelp forests and changing the associated fauna; this might critically affect rock lobsters and abalone. Movement of sand towards beaches might also result in some beaches being denuded of sand and excess accumulation in others [94].
- Changes in sediment transport could have an impact on a wide range of species which rely on the presence of a certain distribution or particle sizes in sediments, a distribution which could be affected by the physical presence of structures and/or the removal of some of the wave energy which would naturally be present.
- Alteration of vertical and lateral currents may change the transport of food and larvae from the surface to the seabed or between feeding and spawning grounds.

Artificial Reefs or Fish Aggregation Devices [92, 93]

Floating structures and artificial reefs are thought to attract juvenile and adult fish by providing:

- no take zones and protection against predation;
- the opportunity for new food sources to develop;
- opportunities for spawning; and
- stations for resting or cleaning.

The above effects may improve or detract from a local environment; for instance account should be taken of the potential to:

- divert marine life from their well-established natural habitat;
- favour more opportunistic species that do not reflect the populations of the local natural habitat; and
- interfere with the normal feeding patterns and movement of fish, sea birds and marine mammals by creating obstacles to passage.

Misleading sensory data through the generation of electromagnetic signals, noise and lighting may either repel or attract marine life. For example, the electromagnetic fields associated with power cables may interfere with the ability of sharks and rays to navigate and find prey; while buoy warning lights may interfere with the behaviour of sea birds diverting them from normal activities or causing disorientation and collision [92, 93].

Whether such interfering factors have a net positive or negative effect on marine life and diversity is likely to be locale dependent and to require a strategic program of research associated with the ongoing development of ORE.

6.2 Tidal

The degree to which tidal renewable energy devices have an impact on the environment depends strongly on the class of device employed: barrage, tidal fence, tidal current or dynamic tidal power as described in chapter 4.

Barrages

Barrages are essentially dams with turbines incorporated into their outlets. While each site would need to be assessed on its own merits [95], barrages can have significant environmental impacts, including reducing the intertidal area, slowing down currents, changing sediment transport, reducing the salinity range and changing bottom water characteristics. Each and all of these effects can lead to significant changes in the estuarine flora and fauna [17, 96]. These, together with their high capital cost and their potential impact on shipping, limits the range of suitable sites in Australia and makes them unlikely candidates for renewable energy supply, except, perhaps, for the regions near King Sound in the Kimberley region of WA.

Tidal Fences and Turbines

Tidal fences and turbines are likely to be less damaging to the environment than a barrage as they allow water to flow relatively freely through the caisson support structure. The rotating blades do pose a risk to fish and marine mammals but this can be reduced by gearing turbines to turn slowly (25-50rpm), providing fences or acoustic warnings to direct larger animals away from the turbines and possibly providing detection mechanisms that can slow or stop the turbines in the presence of animals. In the relatively small scale installations constructed to date the timing and amplitude of the tide remains substantially unchanged, reducing the impact on the estuarine tidal area, salinity, and sediment transport. However, for larger scale systems, the effect of changes in tidal velocity on sediment transport will need to be assessed [17, 31].

6.3 Ocean Thermal Energy Conversion

Environmental impacts from Ocean Thermal Energy Conversion (OTEC) include those associated with the construction, maintenance and decommissioning of any large marine structure.

Apart from these, there is a potential impact from transferring nutrient- and chemical-rich cooling water from the sea floor and discharging it as nutrient-rich warmer water near the sea surface. This may alter the food web, changing the quantity, size and species of marine organisms. Larvae or juveniles, small fish, jellyfish, and invertebrates attracted to the nutrient-rich waters could become caught in the OTEC warm water intake. The degree to which this has a positive or negative impact on fisheries and the ecosystem is unknown [62, 97], and would require study at each site, as has been carried out for the Hawai'i OTEC site [98].

In addition, a relatively small amount of CO_2 will be released due to out-gassing from water drawn from the abyss. This has been estimated at about 1 per cent of the CO_2 released from fuel oil combustion for energy production equivalent to the OTEC installation. These issues are thought to be controllable by arranging for the subsurface discharge of cooling water below the ocean surface mixed layers and photic zone, an action that will also improve the efficiency of the plant by reducing the cooling of surface water [17].

The remaining potential impacts are due to possible release of the chemicals ammonia and chlorine. Chlorine if released has been estimated at levels of 0.02ppm. Ammonia would be used in a closed cycle system and would have a significantly toxic impact if released in the event of a catastrophic accident or extreme event [17, 63].

6.4 Conclusion

Wave farms may have both positive and negative environmental and competing use impacts and there is likely to be sufficient flexibility in the design parameters for a farm that the benefits can be optimised and the negative impacts mitigated. However, this will require a detailed level of research specific to each location. This is to avoid environmental damage and damage to the farm and to minimise capital, operations and maintenance costs, by building in a program of assessment considerations at each stage of the wave farm design and development.

7. Economic Projections

7.1 Introduction

The economic viability of wave and ocean current energy has been assessed using two of CSIRO's energy models: the "Global and Local Learning Model" (GALLM) and the "Energy Sector Model" (ESM). GALLM is an international and regional economic model that features endogenous technology learning. GALLM projects the global uptake of electricity generation technologies in a given policy environment [99]. The projected reductions in global and local technology costs as a result of learning-by-doing are provided to ESM for further analysis. ESM repeats the process of projecting technology uptake in Australia but with more detailed constraints on local energy resources and trade between states [100].

7.1.1 Model Overview

In GALLM, most technological development occurs as a result of global technology deployment such that all countries benefit from the spillover effects of other countries investing in new technologies; wind power and photovoltaics (PV) are exceptions. Both wind power and PV were assigned two experience curves: a global curve for wind turbines in the case of wind and a global curve for PV modules for PV and a local curve for both technologies for installation costs and balance of system (BOS) for PV. This reflects the fact that wind turbines and PV modules are sold on an international market while installation is handled locally. This dual approach involves a superior methodology but can only be implemented if the necessary data are available. Unfortunately data on ocean energy local installation costs are not available since it is currently at the early stages of being developed, tested and gradually deployed internationally. A learning rate cannot be found in the literature for any ocean energies since these are emerging technologies. The most similar technology is offshore wind since this is employed in the ocean; its learning rate of 9 per cent was used for both wave and ocean current energy [101].

Before the global financial crisis in 2008, the capital cost of energy technologies was extremely high. In the case of wind energy, the price rise was due to high demand and the resultant increased profit margins and higher materials prices this allowed [102]. These market forces have been included in GALLM as a "penalty" constraint; if demand for one technology exceeds one third of total required new installed capacity, a premium will be placed on the price of that technology. One effect of implementing the penalty constraint in the model is that it creates a disincentive for too rapid an uptake of any single energy technology [99, 103].

ESM is a detailed, state-level model of electricity generation and transport within Australia. This has proven to be particularly useful for wave and ocean current/tidal energy modelling since the wave and current/tidal resources vary widely from state to state (chapters 2, 3 and 4).

Both models were run under three different carbon price scenarios, which varied within regions in GALLM (the developing world has accepted a carbon price by 2025): CPRS-5, CPRS-15 and Garnaut-25[104]. CPRS-5 is consistent with a target of 550ppm CO_2-e concentration; CPRS-15 has a target of 510ppm CO_2-e; while Garnaut-25 has a target of 450ppm CO_2-e. In each of these cases Australia is assumed to take part in a global greenhouse gas reduction effort in which at first only developed countries but eventually all countries contribute to abatement by 2025. The carbon prices associated with each of these scenarios are shown in Figure 7-1 [104]. They were adapted in the light of government announcements about delaying the emissions trading scheme until 2013.

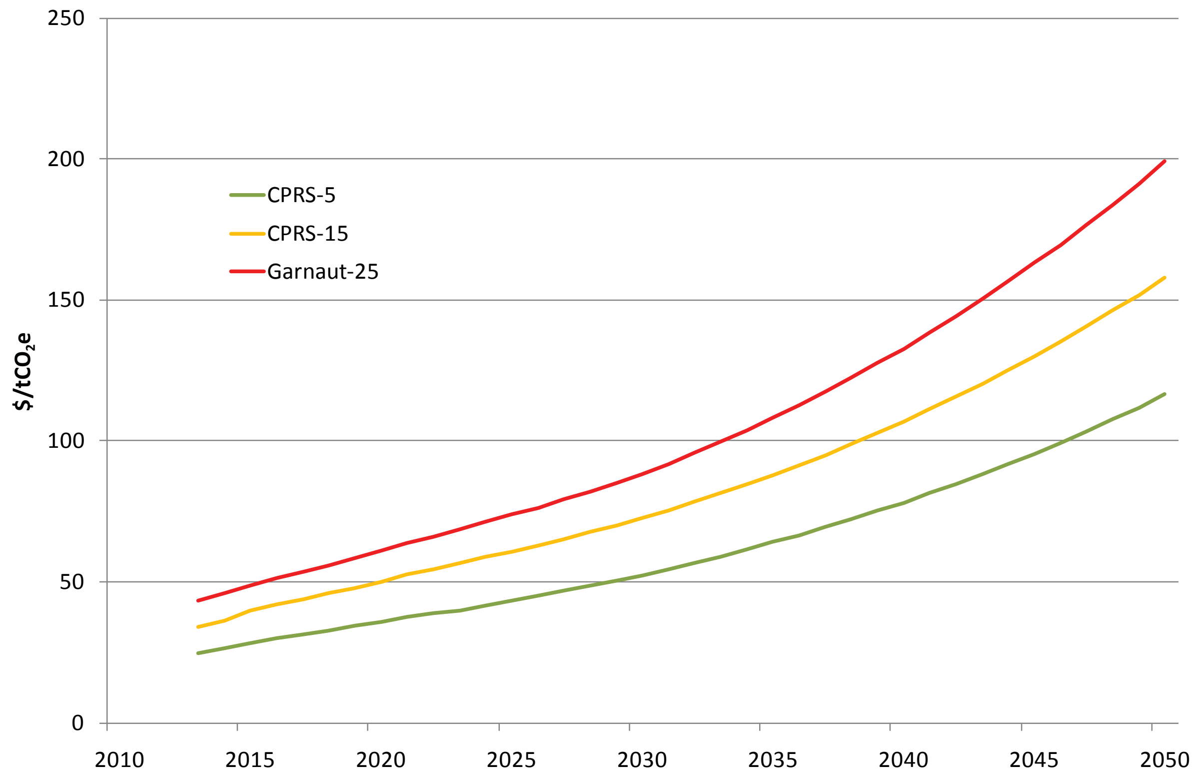

Figure 7-1 Modified carbon price paths [104].

Neither GALLM nor ESM includes any energy storage and the correlation between different technologies — such as synergies between wind and wave energy (discussed in Chapter 1) — cannot be incorporated in either model as they have yearly, not hourly or even daily resolution.

We performed generic runs of both GALLM and ESM, where we did not assume any particular wave energy technology but rather chose parameters that were consistent with the majority of these technologies. We also performed technology-specific runs, where we used actual data for Point Absorber1 and Terminator1 devices [30] and assumed that globally and in Australia only one type of device will be built. The details of the parameters used and the model runs are discussed in the following sections.

7.1.2 Parameters Used in Modelling

Initial Year Capital and Installation Assumptions

An initial (year 2006) capital cost for wave and ocean current/tidal technologies was assumed to be $A7000 and $A5200/kW respectively based on the range provided by the International Energy Agency (IEA) for wave [105]. It is consistent with costs observed in the literature [106] . Experience curves operate on the principle of a rate of cost reduction for each doubling of cumulative capacity of wave farms. This is also based on the rated capacity of the devices, which cancels out in the modelling. For this reason the existing level of capacity can affect the calculations of costs changes. To limit the propensity for this assumption to affect the results, cumulative capacity in the same year was assumed to be 1MW for both wave and ocean current/tidal although, in reality, ocean and tidal current power plants are not yet at this level of deployment. However, tidal current power is currently being deployed on a prototype-scale. A lower limit of $A2000kW was placed on both wave and ocean current/tidal technologies, this being the expected capital cost for ocean energy technologies by 2050 [105]. The capital costs used for wave and ocean current/tidal tend to be higher than other renewable technologies, reflecting the fact that they are at earlier stages of development than, say, wind and solar power.

The rated capacity of different WEC devices can vary depending on the dynamic sea state. In other words, devices need to be rated so they can generate power under a wide range of wave conditions. The rated capacity cancels out in the modelling (see Capacity Factor below and Appendix). However our inital and final capital cost estimates in $A/kW for the generic runs are based on an estimate provided by a consistent source, the IEA, which means these capital costs should be based on the same rated capacity.

Lifetime and Construction Period

The lifetime of the devices affects their economic viability, and lifetimes for ocean energy devices are uncertain because they are both located in and generating power in a hostile environment. We have assumed that the lifetime is the same as other renewable technologies, since the devices are being built to withstand up to an extreme wave event. We have also given wave farms and ocean current/tidal plants a two- and three-year construction period respectively, as with other renewable power plants. Ocean current/tidal plants are assumed to have a greater proportion of their civil works underwater and a concomitantly longer construction time.

Capacity Factor

Capacity factor (average power/rated power) is a commonly used term in energy economic modelling. The use of this term allows our model to compare costs, and average energy production per WEC, across regions or between devices. However, in the marine context, the definition of the rated power component of capacity factor can be too arbitrary for meaningful comparison. This is especially true when devices are at early stages of development without established industry standards. Furthermore, a machine's rated power may depend on the sea state dynamic range, which can be extremely large. For these reasons we ensure the rated power component of capacity factor is cancelled out and not used anywhere in the model to describe or compare the power WEC machines can produce or to compare their cost (see Appendix 4 for a worked example).

However, small variations in average energy production or capacity factor from any energy technology have a large effect on the levelised cost of electricity (LCOE) and consequently on the uptake of that technology [107]. Therefore, in order to examine the effect differences in average energy production can have on the LCOE and uptake of wave energy, we have modelled three scenarios for the trajectories of nominal capacity factors (NCF) over time, which jointly cover current values and future projected values: 0.3 increasing to 0.34 by 2050; 0.4 increasing to 0.43 by 2050; and 0.5 increasing to 0.53 by 2050. Ocean current/tidal devices have been modelled using a nominal capacity factor (NCF) of 0.3 increasing to 0.33 by 2050 [108]. We increase the NCFs over time to take account of likely improvements in the efficiency of extraction of wave energy, providing an increase in average power generated. These improvements are independent of the sea state.

The same NCFs were used for the generic runs in ESM in the states with excellent wave energy resources: i.e. Western Australia, South Australia, Tasmania and Victoria. The remaining states had a NCF of 0.1. Similarly, New South Wales, Queensland and Tasmania are the only currently known states with a suitable ocean current/tidal resource. Therefore, the global NCF was used for those states and the remaining states had negligible values. The Northern Territory has no wave or ocean current resource. It has significant tidal resources (Clarence Strait near Darwin) but these are located at least 50km from transmission lines. As NT has low demand for electricity we restricted possible electricity generation from ocean current/tidal energy to a minimal amount.

Resource Constraints

No wave or ocean current/tidal resource constraints were placed in ESM under the 0.3 and 0.4 NCF scenarios, as the resource was not depleted within the time limits of the model due to the “late start” of these technologies compared with other renewable technologies. Under the 0.5 NCF scenario constraints were placed on ocean current energy to limit it to its natural resource of 300MW in Australia. However, constraints were placed in GALLM for both wave and ocean current/tidal energy as, without them, both wave and ocean current/tidal resources may be used over and above their worldwide technical resource limits (total installed capacity in any year cannot exceed 500 GW). Ocean current/tidal technology was also further constrained to developed countries only, because that is where the resource is located [109]. Here, depletion refers to running out of sites to place the devices rather than to a lack of ocean energy. Other renewable technologies such as hot fractured rocks, conventional geothermal and hydro have similar global resource constraints. However, in the model run, wind and solar power did not exceed their large global resource limits.

Operations and Maintenance Costs

There is also uncertainty surrounding operations and maintenance (O&M) costs for both types of plant as, in particular for wave energy, the different devices have different characteristics and thus different O&M requirements. However, the current high O&M costs are expected to fall as experience with the devices is accumulated. We have therefore made the assumption that the O&M cost starts at a literature value ($US27.87 2009/MWh) [110]. It then decreases from this value by 1.5 per cent per year making it approximately equivalent with the O&M cost of wind energy by 2045.

Dispatchable Power Capability

There have been suggestions that wave energy may be able to supply some energy more reliably (i.e. dispatchable power) while above this the energy output would fluctuate. We have tested, in Australia only, the difference between having wave energy as completely intermittent or with 25 per cent of its output as dispatchable. This is expected to give wave energy a competitive advantage over the intermittent renewable technologies.

Other modelling assumptions and references to those assumptions can be found in Appendix C in Table 9-1 to Table 9-3.

7.2 Generic Case Studies

7.2.1 Global Results

Wave energy was taken up globally under all NCF and carbon price scenarios. The results using the low-range and high-range NCFs are shown in Appendix C Figure 9-4 to Figure 9-9 as they are similar to the results using the mid-range NCF. The results using the mid-range NCF of 0.4-0.43 are shown in this section.

Figure 7-2 shows the projected global electricity generation under the CPRS-5 carbon price scenario. The highest installed capacity of wave energy is 449 GW from 2023 to 2032, after which the capacity gradually reduces as no new wave energy plants are constructed. The vast majority of wave energy installed capacity is in the developing world (maximum of 434 GW), where the electricity demand is greater. Construction begins in earnest in 2014 so some wave energy would be available by 2025 when the carbon price is introduced into the developing world. Wave energy tails off its production by 2050, when the plants constructed earlier are decommissioned and other technologies, such as large scale photovoltaics are cheaper, and displace wave energy.

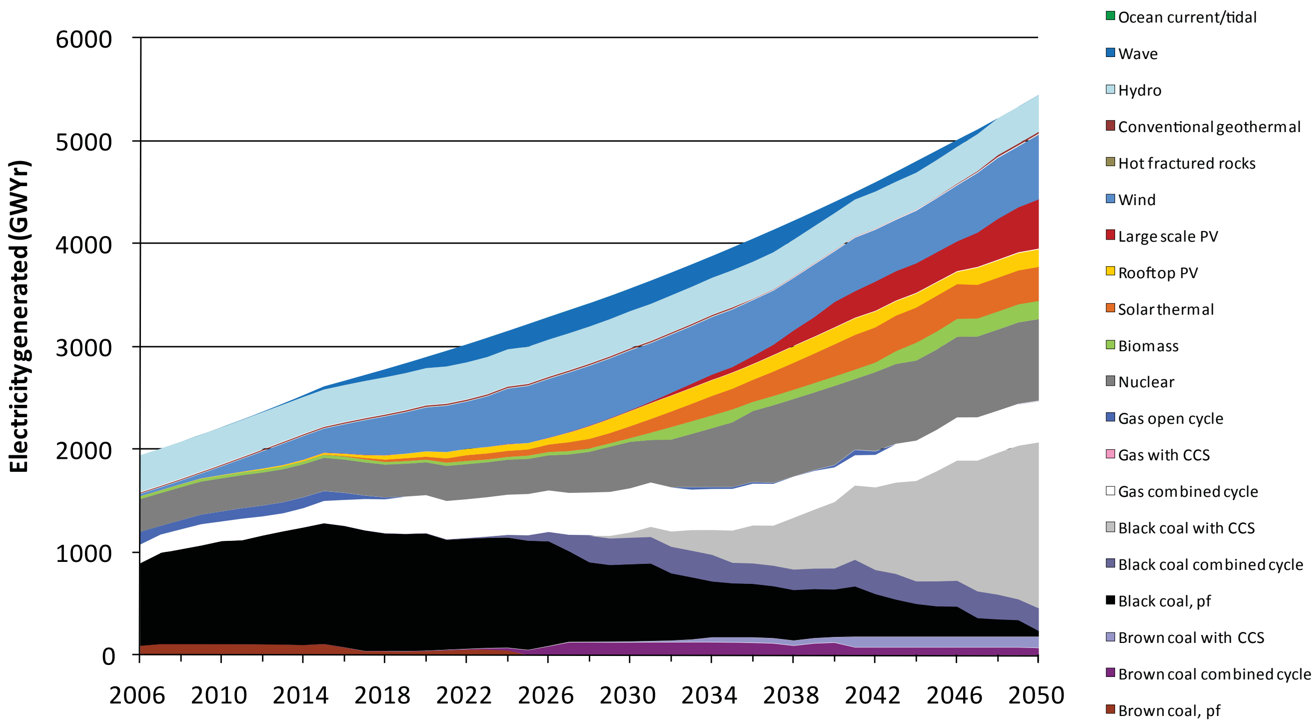

Figure 7-2 Projected global electricity generation under CPRS-5 carbon price scenario with 0.4-0.43 wave energy NCF.

Figure 7-3 shows the projected global electricity generation under the CPRS-15 carbon price scenario. The highest installed capacity of wave energy is 500GW, occuring between the years 2037 and 2045. Once again, the majority of wave energy is installed in the developing world where demand is greater. Construction increases in 2018, in time for the introduction of the carbon price in the developing world.

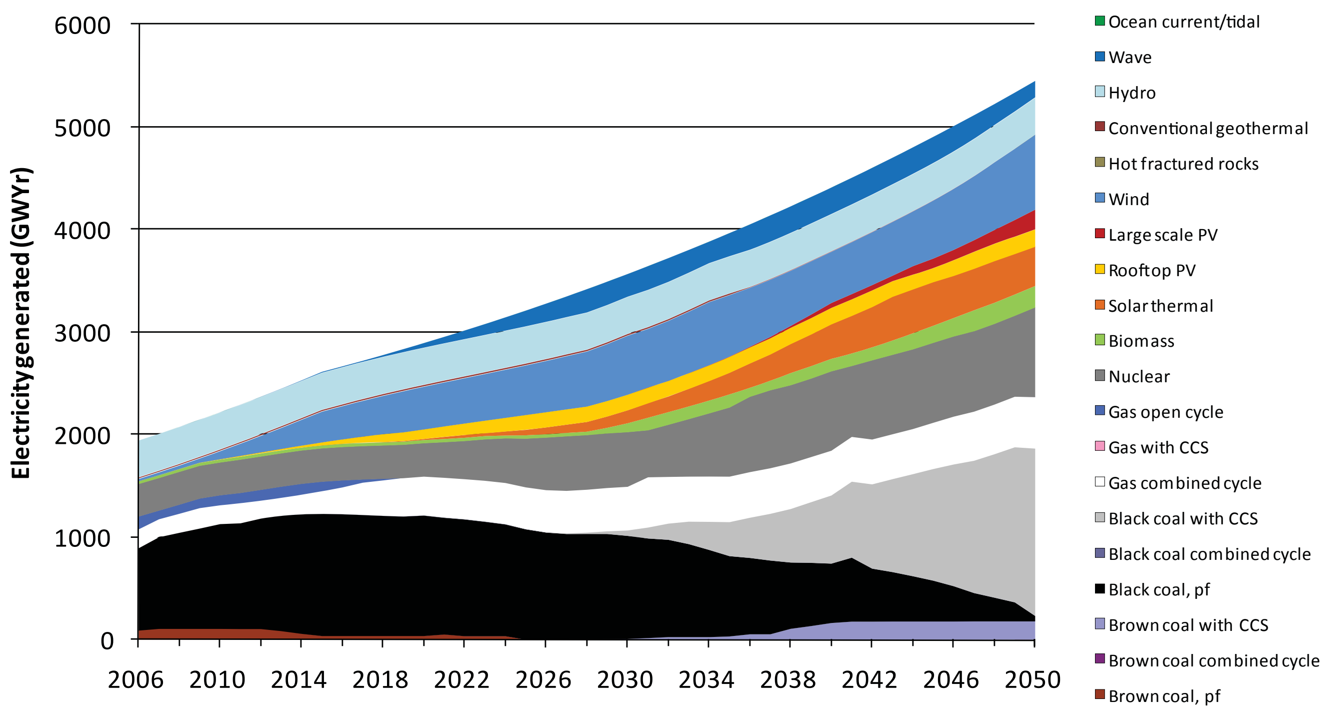

Figure 7-3 Projected global electricity generation under CPRS-15 carbon price scenario with 0.4-0.43 wave energy NCF.

Figure 7-4 shows the projected global electricity generation under the Garnaut-25 carbon price scenario. The outlook is very similar to that of CPRS-15. The maximum allowed amount of wave energy capacity, 500 GW, is installed between 2039 and 2044, and the majority again in the developing world. Construction increases from 2019 onwards.

Large amounts of wave energy are installed later under both higher carbon price scenarios as the higher carbon price means more low emission technologies are needed in the later years when the carbon price is higher; and because of this, more nuclear plants are constructed in the earlier years under these scenarios than under CPRS-5. Nuclear has a very high NCF (0.8), no emissions and a long lifetime, thus replacing the early need for a variety of renewable technologies.

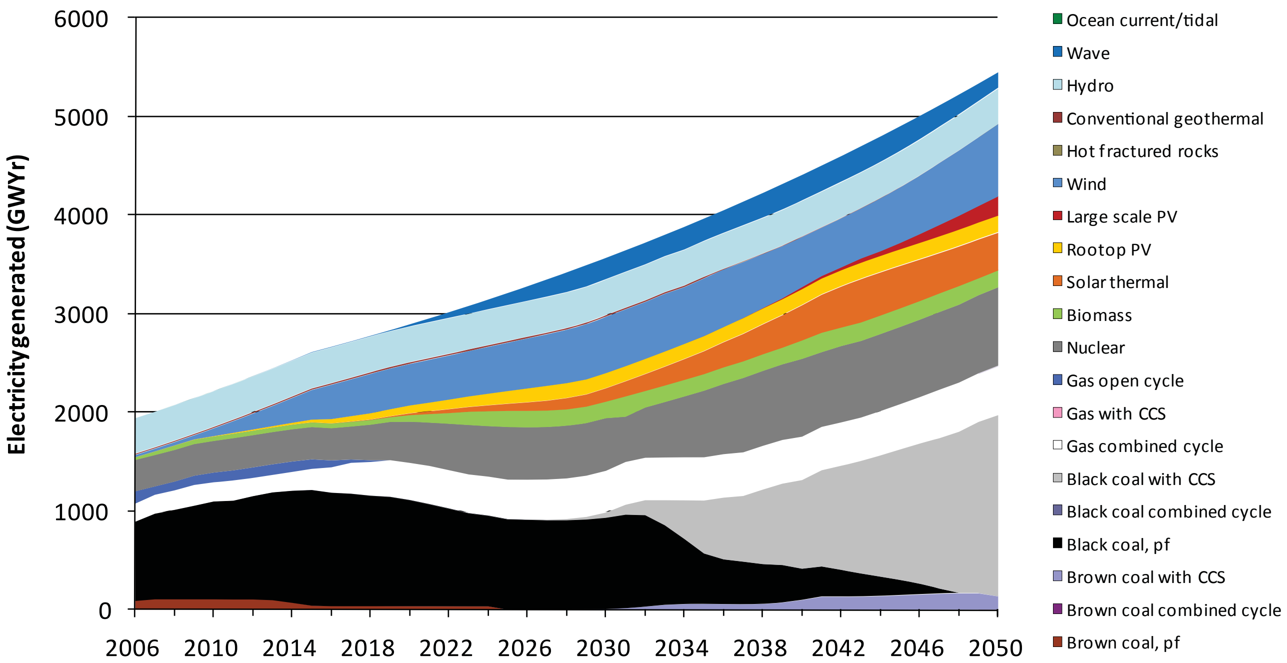

Figure 7-4 Projected global electricity generation under Garnaut-25 carbon price scenario with 0.4-0.43 wave energy NCF.

By comparing the wedge diagrams above with Figure 9-4 to Figure 9-9, it can be seen that the uptake of wave energy is largely invariant to NCF, which normally has the biggest influence on the cost of electricity generation or the levelised cost of electricity (LCOE) for renewable technologies because they are capital-intensive [111]. When the NCF is lower it means the amount of electricity produced is lower and thus the LCOE is higher. In this case, the carbon price is sufficient enough under every scenario to render wave energy a cost-effective zero-emissions source of generation.

The LCOE of electricity for each of the technologies listed in the wedge diagrams under CPRS-5 is shown in Figure 7-5 and Figure 7-6, where the NCF of wave energy is 0.4. It can be seen that wave energy is one of the lower-cost technologies, and on a par with most low-cost coal-fired generation, which explains why it contributes to its maximum limit of electricity generation in the wedge diagrams under this NCF. It has a low cost range compared to, for example, PV large scale, but that is because only one other study published any data on wave energy whereas four studies published PV data.

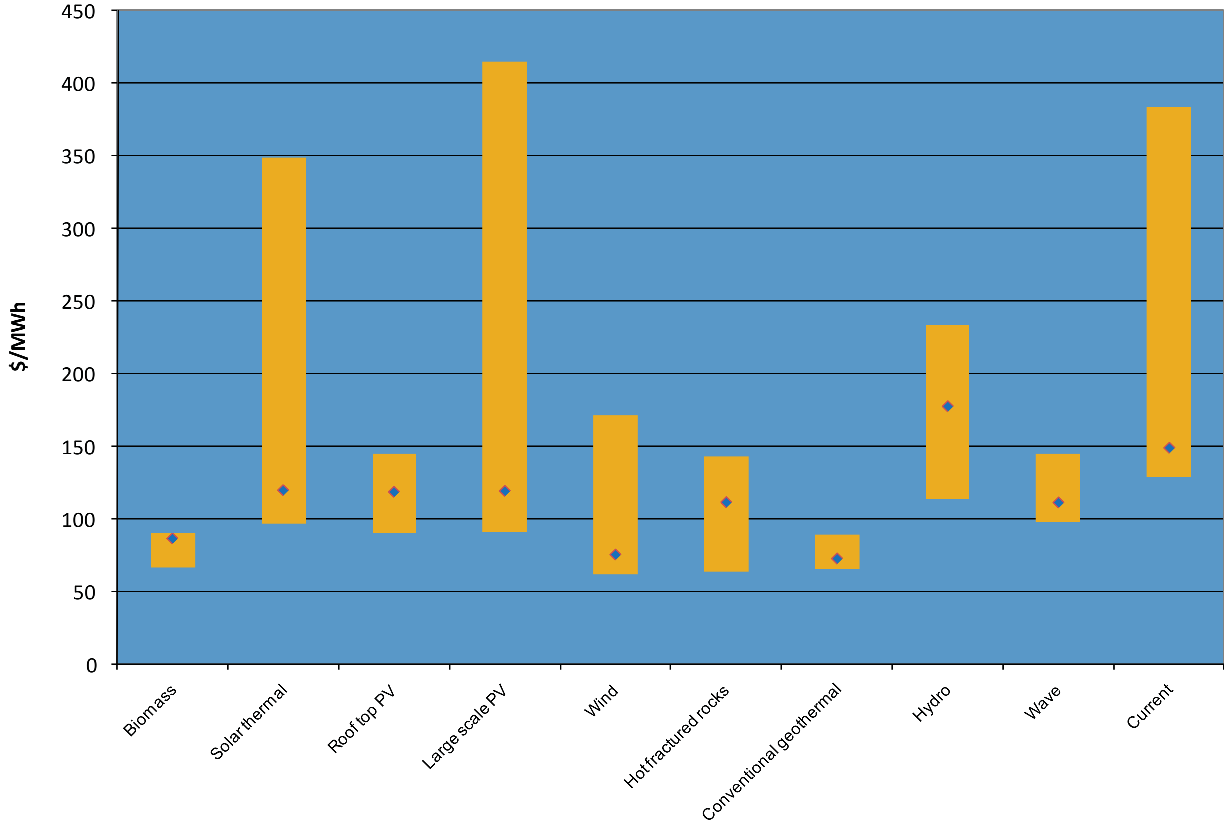

Figure 7-5 Projected LCOE in 2030 for renewable technologies under CPRS-5 carbon price scenario and 0.4 NCF for wave energy. Range represents range of values calculated using variations to the input parameters. The diamond represents the actual value.

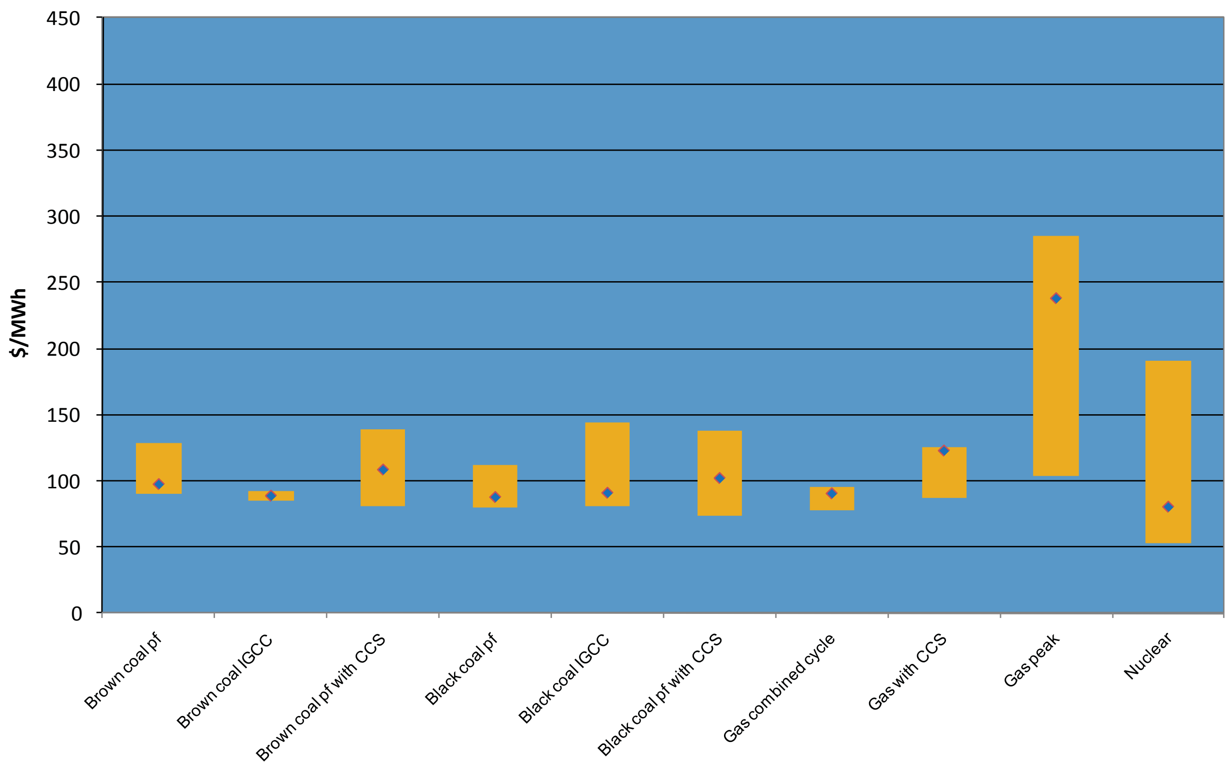

Figure 7-6 Projected LCOE in 2030 for fossil-fuel based technologies under CPRS-5 carbon price scenario and 0.4 NCF for wave energy. Range represents range of values calculated using variations to the input parameters. The diamond represents the actual value.

7.2.2 Australian Results

No wave energy is constructed in Australia under the lowest NCF of 0.3-0.38, even with 25 per cent dispatchable power (results are shown in Appendix C Figure 9-10 to Figure 9-12 and Figure 9-15 to Figure 9-17). Australia has abundant wind and solar thermal resources, with relatively low LCOE. Because these technologies generate intermittently they are limited to — at most — 35 per cent by 2050, and in ESM they force wave energy out of the market. However, under the options with higher NCFs wave energy continues to contribute to electricity generation in Australia. Ocean current/tidal energy makes a relatively small contribution to Australia's generation under any scenario. The results are shown in the following sections.

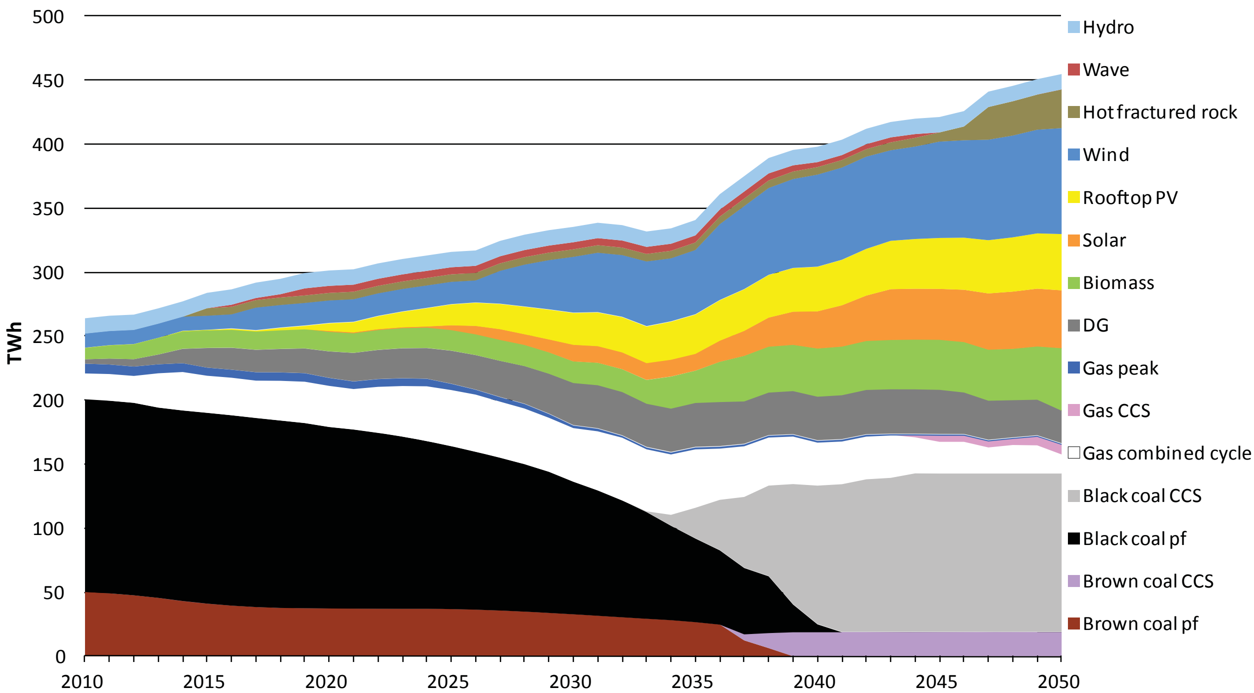

Figure 7-7 Projected Australian electricity generation under CPRS-5 carbon price scenario with 0.4-0.48 NCF for wave energy.

With the NCF set to the mid-range value of 0.4-0.48, wave energy contributes to generation only under the lowest carbon price, CPRS-5, as shown in Figure 7-7. Results under other carbon prices are shown in Appendix C Figure 9-13 and Figure 9-14. Globally, more wave farms are constructed earlier under this carbon price compared with the other carbon price scenarios; hence the capital cost of wave energy is lower earlier relative to other renewable technologies. Wave energy is therefore a more attractive option under this carbon price. Globally, under the higher carbon prices, more nuclear plants are constructed earlier, somewhat delaying the development of wave energy. Because wave energy receives capital cost reductions later under the higher carbon prices its development is delayed compared with the other renewable technologies and thus is too expensive compared to those technologies.

Under the CPRS-5 carbon price scenario from 2019 to 2038 wave energy contributes 5.5 TWh or ~1 per cent of total generation and all of this is generated in Victoria. In fact, wave energy is the third largest provider of renewable electricity in Victoria after wind and biomass. In later years other technologies such as hot fractured rocks and solar become less costly and when the wave farms are decommissioned these other technologies are constructed instead of wave energy.

Under the highest generic NCF range of 0.5-0.58 wave energy contributed to Australian electricity generation under all carbon prices, as shown in Figure 7-8 to Figure 7-10.

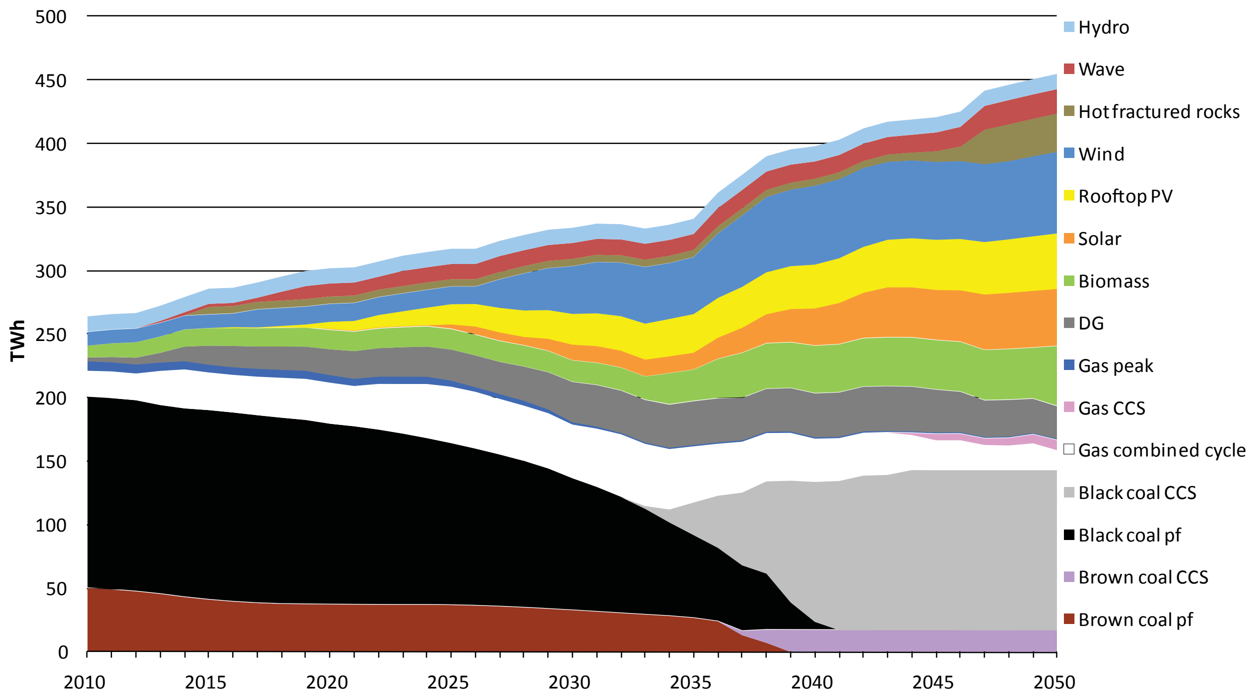

Figure 7-8 Projected Australian electricity generation under CPRS-5 carbon price scenario with 0.5-0.58 NCF for wave energy.

Increasing the NCF has led to more wave energy generation. There are now 10.3 TWh in 2019, increasing to 19.3 TWh by 2050 (4 per cent of total generation); again, all being generated in Victoria. In 2050 it overtakes wind to be the largest source of electricity in the state, closely followed by wind and brown coal with Carbon Capture and Storage (CCS).

The same assumptions under the CPRS-15 carbon price are shown in Figure 7-9. Now the amount of wave energy increases slightly, from 9 TWh in 2019 up to 24.4 TWh by 2050. This represents 5 per cent of total generation in 2050. All of the generation is in Victoria and it is the largest contributor to electricity generation in that state from 2045 onwards.

Under the Garnaut-25 carbon price in Figure 7-10 there is initially less wave energy, 1.6 TWh in 2019 but by 2050 there is more than under the other carbon prices, 25.7 TWh or 6 per cent of total generation. All of this is generated in Victoria and it is the largest source of generation in that state from 2037 onwards, closely followed by hot fractured rocks.

The reason why wave energy is generated in Victoria is that, firstly, it has a high NCF and secondly, it has large demand. The state has a great deal of brown coal pf (pulverised fuel) generation which needs to be replaced when the carbon price forces it out of the market. The installation of wave energy helps make up the shortfall in generation. Additionally, because of its good wave energy resource, Victoria can be a major supplier of renewable energy to New South Wales which has a much poorer resource.

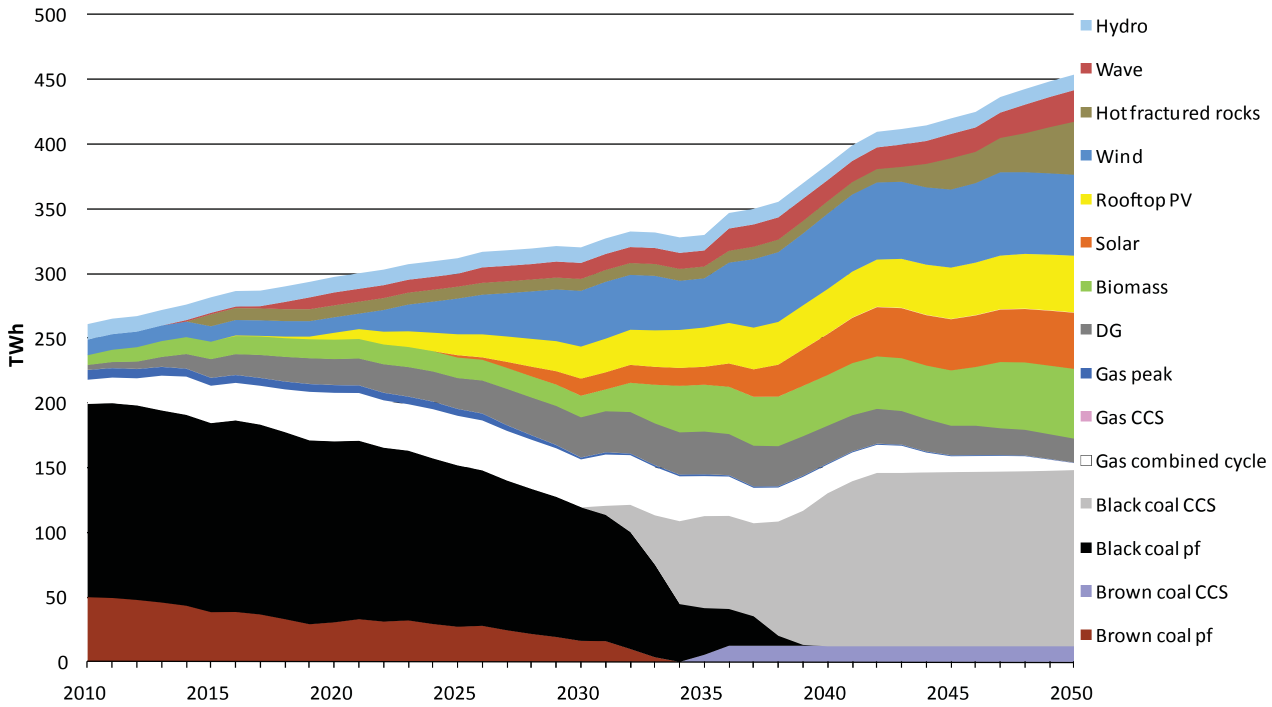

Figure 7-9 Projected Australian electricity generation under CPRS-15 carbon price scenario with 0.5-0.58 NCF for wave energy.

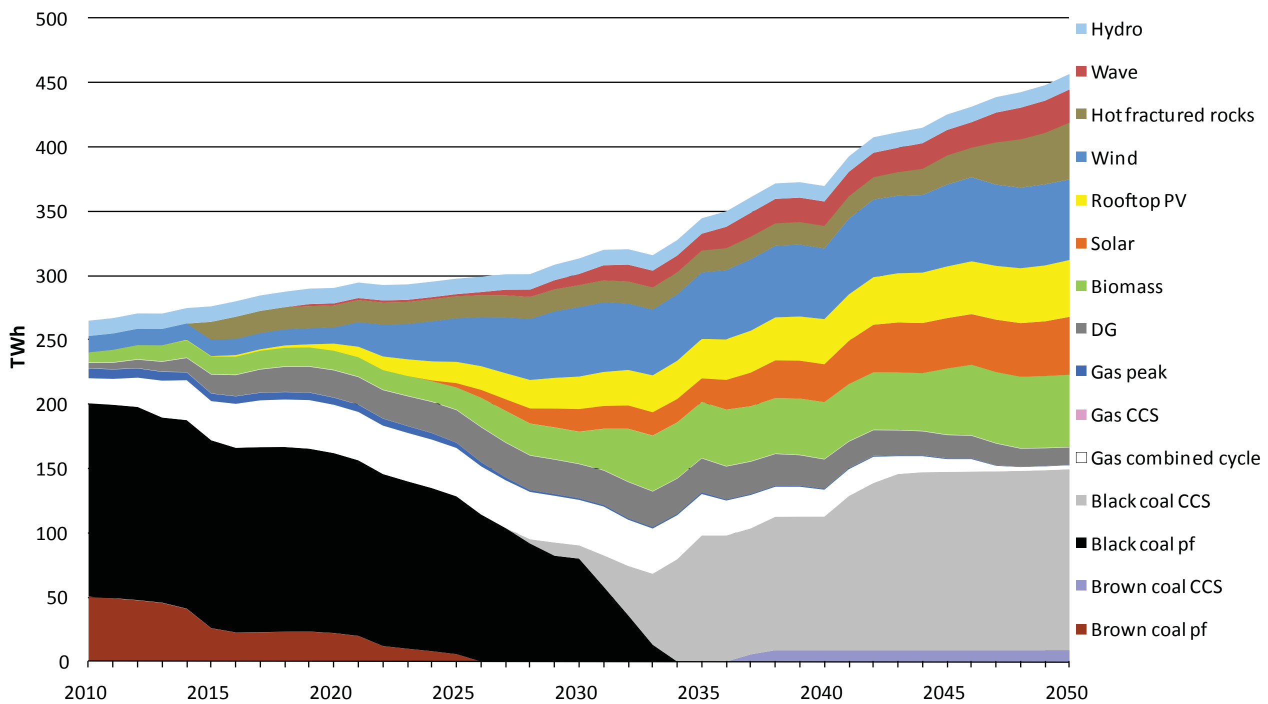

Figure 7-10 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 0.5-0.58 NCF for wave energy.

Except in Victoria, wave energy is not projected to be a major source of electricity generation under these generic scenarios even though it is a zero-emissions technology. Because globally wave energy is a limited resource but has a relatively low cost of electricity, it is being built to its limit under every carbon price. This puts a limit on the amount of learning-by-doing — or capital cost reductions, wave energy can undergo. Wave energy's competitors, namely: wind, solar thermal and PV, do not have these lower resource limits. Therefore, as the carbon price increases, these zero-emission technologies can achieve greater cost reductions than wave energy. As they also have good resources in Australia, they are constructed instead of larger amounts of wave energy.

Dispatchable Power

When 25 per cent of wave energy's output is treated as dispatchable — i.e. as continuous power — there is no change to the results under the 0.4-0.48 NCF and CPRS-5 and CPRS-15 carbon price scenarios without the dispatchable power. Results are shown in Appendix C Figure 9-18 and Figure 9-19. However, under the Garnaut-25 carbon price scenario wave farms are now installed, as shown in Figure 7-11.

In 2036 there are 4.0TWh of wave energy, which increases to 24.8TWh by 2050, or 5 per cent of overall generation. This means a carbon price has an effect on the viability of the dispatchable power potential of this technology. All of the wave energy generation is again in Victoria. It is the greatest source of electricity in that state from 2048 onwards.

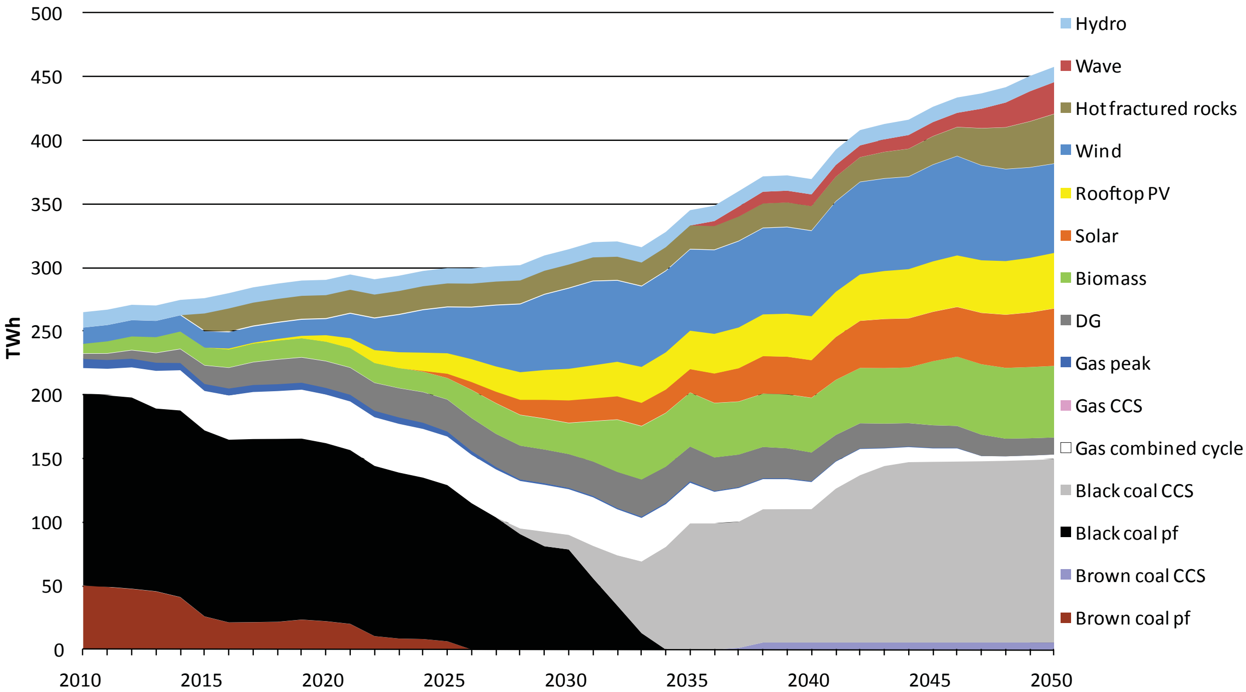

Figure 7-11 Projected Australian electricity generation under Garnaut-25 carbon price scenario and 0.4-0.48 NCF and dispatchable power is allowed.

When the dispatchable power option is added to wave energy when the NCF is 0.5-0.58 there is now an increase in wave energy generation over the normal case, as can be seen in Figure 7-12 for the CPRS-5 carbon price scenario.

The contribution made by wave energy to Australian electricity generation increases from 9.3TWh in 2018 up to 38.5TWh in 2050, which is 8 per cent of total generation. The majority of generation, 31.2TWh in 2050, is from Victoria, but now there is also 1.4TWh in SA and 5.9TWh in WA.

Having just 25 per cent of wave energy as dispatchable power generation has made it a much more attractive choice for some states as it can then replace emissions-intensive fossil fuel technologies. These states all have a good wave resource, which explains why wave energy is built there. Tasmania also has a good wave resource but, because it has relatively lower demand for electricity compared with other states and has existing hydro plants, wave energy is not an important source of zero emissions energy in that state. This result would probably change if the model took Basslink, which allows surplus production to be sold into Victoria, into account.

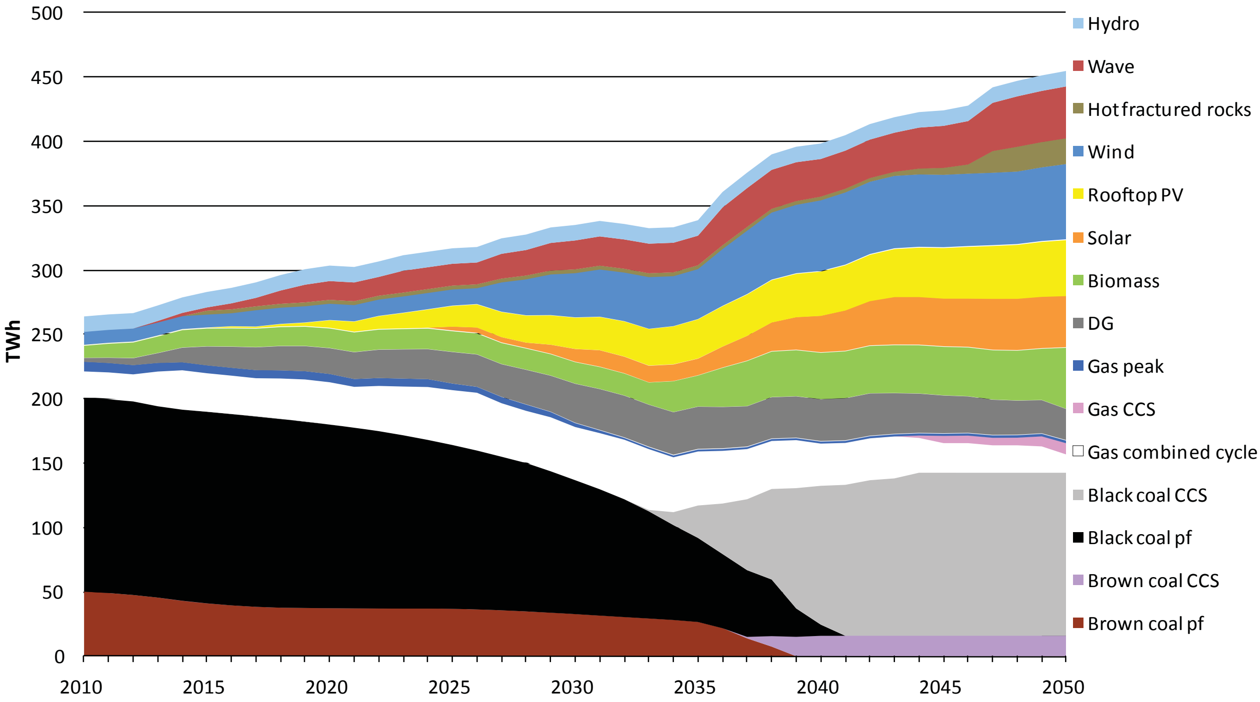

Figure 7-12 Projected Australian electricity generation under CPRS-5 carbon price scenario and 0.5-0.58 NCF and dispatchable power is allowed.

Results under the CPRS-15 carbon price scenario are shown in Figure 7-13. Under the higher carbon price 53.0TWh of wave energy is generated in 2050, representing 12 per cent of total generation, 3 per cent more than under CPRS-5. Again, the majority is in Victoria with 38.9TWh, 3.9TWh in South Australia and 10.1Wh in Western Australia. This is more than double the amount of wave energy under the non-dispatchable power case. Wave energy is being used as dispatchable power, replacing some hot fractured rocks and brown coal with CCS. It is also replacing wind from regions with poorer wind resources.

In Figure 7-14, under Garnaut-25, 50.0TWh of wave energy contributes to Australia's electricity generation in 2050, which is 1 per cent of the total. Again the majority, 40.7TWh, occurs in Victoria, with 3.3TWh in South Australia and 5.9TWh in Western Australia. This is in contrast to the non-dispatchable case which had 25.7TWh of wave energy. Obviously, the dispatchable power capability is important under this carbon price scenario. Wave energy is replacing some wind, hot fractured rocks and brown coal with CCS, as in the CPRS-15 carbon price scenario.

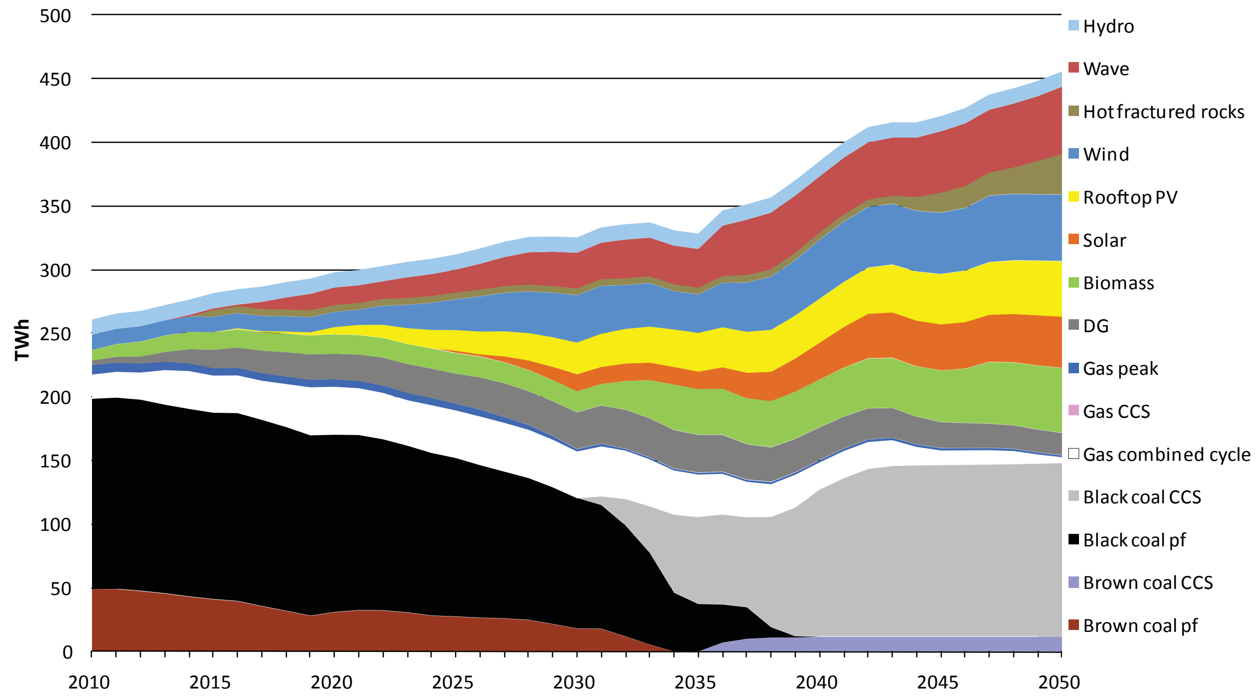

Figure 7-13 Projected Australian electricity generation under CPRS-15 carbon price scenario and 0.5-0.58 NCF and dispatchable power is allowed.

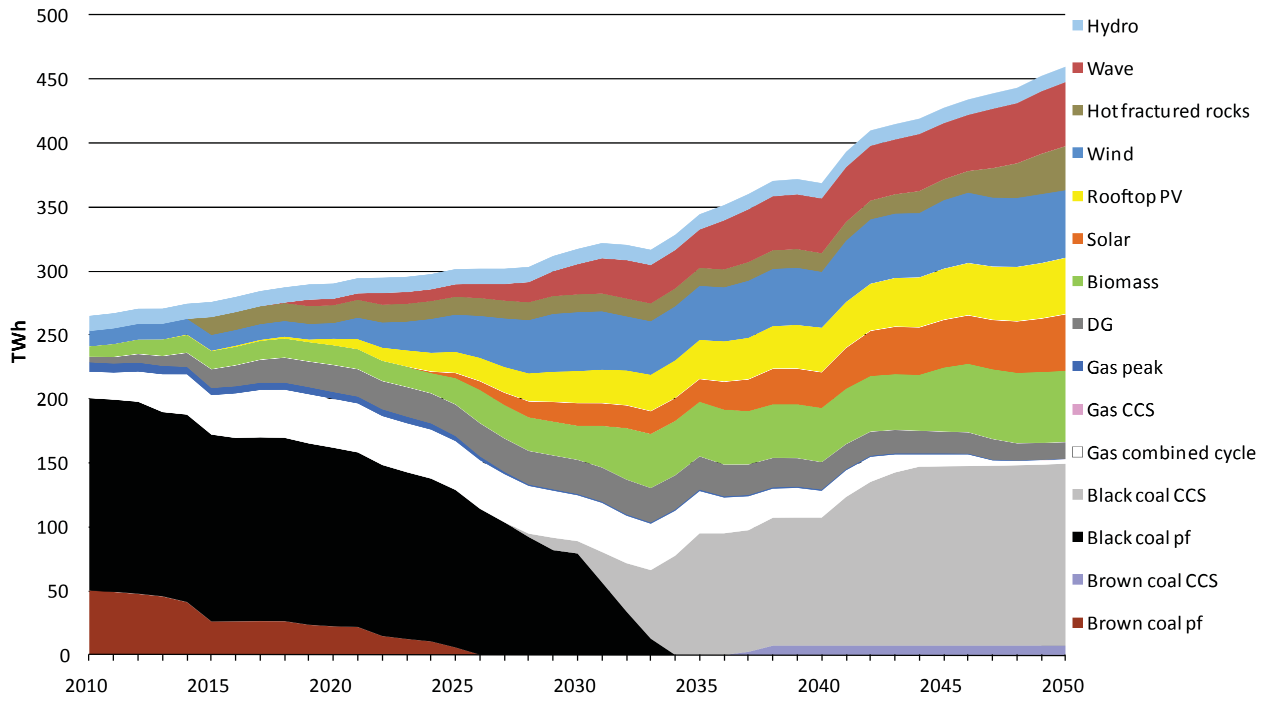

Figure 7-14 Projected Australian electricity generation under Garnaut-25 carbon price scenario and 0.5-0.58 NCF and dispatchable power is allowed.

7.2.3 Summary for Generic Case Studies

Globally, wave energy is installed irrespective of NCF or carbon price. This means it is a relatively low cost source of zero-emissions generation. It is still competitive with wind and solar technologies even though it has limits placed on its availability. In Australia, NCF is the biggest influence on the uptake of wave energy. Under a 0.4 NCF, wave energy is only installed under the lowest CPRS-5 carbon price, as the capital cost reductions achieved under the higher carbon prices occur too late to make wave energy competitive with wind and solar thermal and PV, the other major intermittent technologies. When the NCF is increased to 0.5, wave energy is installed in Australia under every carbon price regime. Under these scenarios, wave energy is installed exclusively in Victoria which needs zero-emission technologies to offset and replace brown coal-based technologies. When wave energy can also provide 25 per cent dispatchable power when the NCF of wave energy is high its contribution to electricity generation increases in Victoria, and SA and WA also have some wave energy generation. However, when the NCF is lower it results in little difference.

Carbon price has a large influence on the uptake of wave energy in Australia, where the amount of wave energy increases as the carbon price increases when the NCF is high. This is expected, given that wave energy is a source of low-emissions electricity and its LCOE is reduced when NCF is increased. However, when the NCF is 0.4-0.48 wave energy is only taken up under the lowest carbon price. This is unexpected, given wave energy is a zero-emissions technology and one would expect it to have greater utility under higher carbon prices. This result is due to the influence of capital costs on uptake. Globally, wave energy is taken up earlier under the lowest carbon price and achieves capital cost reductions from learning-by-doing sooner than it would under the higher carbon prices. Globally, under the higher carbon prices, nuclear is used in the earlier years as a source of zero-emissions generation because it is a lower cost option and nuclear power plants have a long lifetime. Nuclear is not as necessary under the lowest carbon price because the carbon price is lower; counter-intuitvely, this actually helps wave energy. The uptake of nuclear under the higher carbon prices delays the development of wave energy until the carbon price is high enough to ensure that a variety of low emission technologies are employed, including wave energy.

7.3 Technology Case Studies

Examples of three different technologies were evaluated as to their LCOE globally and in Australia. These included examples we have labelled a Point Absorber1, a Linear Attenuator1 and a Terminator1, as data were publically available in a consistent form on their performance [30]. In order to distinguish the technologies in the modelling, capital costs, NCFs and resource limitations were devised for each technology and each was run independently of the others (so there was no competition between technologies in the modelling).

7.3.1 Application of Model Parameters to Specific Technologies

The first step was to calculate the capital cost for a typical wave farm for each technology, which was converted into an $A/kW value for the modelling. We needed to formulate each technology into the same rated capacity (21MW) wave farm configuration to take account of shared mooring and cabling costs between individual units — smaller and lower rated devices (for example the smaller point absorbers) need more units and possibly higher mooring costs for a farm than larger and higher rated units (for example the larger terminators). Cabling and mooring costs vary, depending on a farm's location. Because all of these technologies are designed to perform away from the coast, we have assumed they are located ~5 km from the coastline (and thus require 5km of transmission cabling) and are in seas at a depth of ~50 m (thus need 50 m of mooring per tether on each unit). Dunnett and Wallace [30] provided capital costs perkW for each technology, cabling costs per km and mooring costs per metre in 2006 Canadian Dollars (CDN). We converted these costs to 2006 Australian Dollars using 1 CDN=1.008 $A. For a 21MW wave farm, the Point Absorber1 needed 84 units, the Linear Attenuator1 28 units and the Terminator1 3 units. Based on these assumptions, the capital costs calculated for each technology in a 21MW wave farm configuration are: Point Absorber1 — 1069 (2006) $A/kW, Linear Attenuator1 — 4531 (2006) $A/kW and Terminator1 – 3062.92 (2006) $A/kW.

The Terminator1 and Linear Attenuator1 have been given a learning rate of 9 per cent (the same as in the generic case) but now the starting point of the experience curve in 2006 is their calculated capital costs and a lower limit has been set on the reductions in capital cost, which is equivalent to approximately one third of the starting cost (~1200 $A/kW). This lower limit has been included to take account of basic material and labour costs needed to manufacture and install these technologies. As the Point Absorber1's LCOE is already extremely low compared to the other technologies examined, this technology does not receive learning effects. However, it receives a capital cost reduction of 0.5 per cent per year, in line with other non-learning technologies in GALLM [112].

To test the above capital cost lower limit assumption for the Terminator1, we also tested the case where it has a higher lower limit on its cost reductions, equivalent to approximately two thirds of the starting capital cost (~2000 $A/kW) and performed a global simulation and then an Australian simulation both under the CPRS-5 carbon price scenario. The results are shown in Appendix C Figure 9-58 and Figure 9-59.

The NCFs estimated for each of these wave energy devices are Point Absorber1 – 0.2, Linear Attenuator1 – 0.4 and Terminator1 0.4[5]; these values were used in the global modelling.

The resource data for various regions across Australia discussed in earlier chapters were converted into NCFs and maximum sustainable resource of 20 per cent of extraction of wave energy by region. These data were then used as input into the modelling in ESM. The resource data is given in Table 7-1. NCFs are given in Table 7-2 and Table 7-3 for a Point Absorber1 and Terminator1 respectively. As described in Chapter 4, the Linear Attenuator1 as it currently stands is not optimally tuned to the long wavelengths of the Australian south coast and it was not included in the modelling analysis.

We also prevent the model from constructing any wave farms before 2015. Hot fractured rocks, despite the fact the option is not as advanced as wave energy, also has the same limit.

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	17.9	26.5	15.6	32.6	15.3	19.7	0
2	17.9			43.6	37.7	17.3	
3					66.7	16.3	

Table 7-1 The amount of energy that can be extracted per year in TWh from each region, assuming 20 per cent extraction of wave energy (total for Australia is 197.8 TWh).

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	0.22	0.32	0.21	0.32	0.36	0.39	0.01
2	0.19			0.30	0.32	0.35	
3					0.29	0.33	

Table 7-2 NCFs for a Point Absorber1 in regions with the best resource in each state.

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	0.24	0.51	0.22	0.51	0.57	0.61	0.01
2	0.20			0.49	0.53	0.55	
3					0.48	0.52	

Table 7-3 NCFs for a Terminator1 in regions with the best resource in each state.

As a sensitivity analysis and as we are unsure at this stage of what environmental or otherwise restrictions may be placed on wave farms we have tested two additional scenarios: i) reducing the available resource to 5 per cent of available wave energy; and ii) increasing it to 30 per cent.

7.3.2 Global Results

For brevity, in Figure 9-20 to Figure 9-25, the electricity generation mix as the result of modelling the Point Absorber1 and Terminator1 independently under every carbon price is shown in Appendix C. The key assumption that may affect wave energy's uptake in Australia is, from experience with the generic runs, the carbon price. For these specific technologies,

5 Approximate estimate.

wave energy power plants are constructed under all carbon price scenarios up to their maximum allowable installed capacity of 500 GW. The year that first occurred in is shown in Table 7-4 below.

Point Absorber1			Terminator1		
CPRS-5	CPRS-15	G-25	CPRS-5	CPRS-15	G-25
2031	2028	2027	2038	2026	2027

Table 7-4 Projected installed global wave energy farm capacities in GW for the Point Absorber1 and Terminator1 under all three carbon price scenarios.

The installed capacities do not vary with carbon price or technology, and from the table there is also little difference in the year wave energy reaches its maximum installed capacity. This means that, globally, wave energy is a necessary relatively low-cost source of low emissions electricity. By having this emerging technology, it provides more choices for generators and thus payment of the price premium when too much of one technology is constructed can be avoided.

7.3.3 Australian Results

Results using both the Point Absorber1 and the Terminator1 without and with 25 per cent dispatchable power under the CPRS-5 carbon price scenario will be shown here; the projections under CPRS-15 and G-25 can be found in Appendix C Figure 9-26 to Figure 9-29 and Figure 9-42 to Figure 9-45.

When the resource is limited to 20 per cent of wave extraction, the outlook for electricity generation obtained using the Point Absorber1 technology is shown in Figure 7-15. This scenario results in 44.3TWh of wave energy electricity generation by 2050, or 10 per cent of the total. This means that only 14 per cent of the total sustainably-usable resource (as specified in Table 7-2) or 3 per cent of the total available resource is used. Wave energy is generated in all states that have a good resource: Victoria (26.5TWh), SA (3.6TWh), WA (10.1TWh) and Tasmania (4.2TWh). However, the majority is in Victoria and furthermore, has built up to its 20 per cent resource limit in that state. This is unusual, given that the NCF in Victoria is lower than in WA, Tasmania and SA but the reasons for wave energy generation in Victoria are the same as under the generic studies; the replacement of (emissions-intensive) brown coal, pf and (expensive) brown coal with CCS with a relatively inexpensive renewable source of generation. In fact, wave energy is the largest source of electricity in Victoria by 2050. In WA, SA and Tasmania it is the second largest producer of electricity. The largest producer varies by state: in SA and WA it is black coal with CCS, while in Tasmania it is hydro.

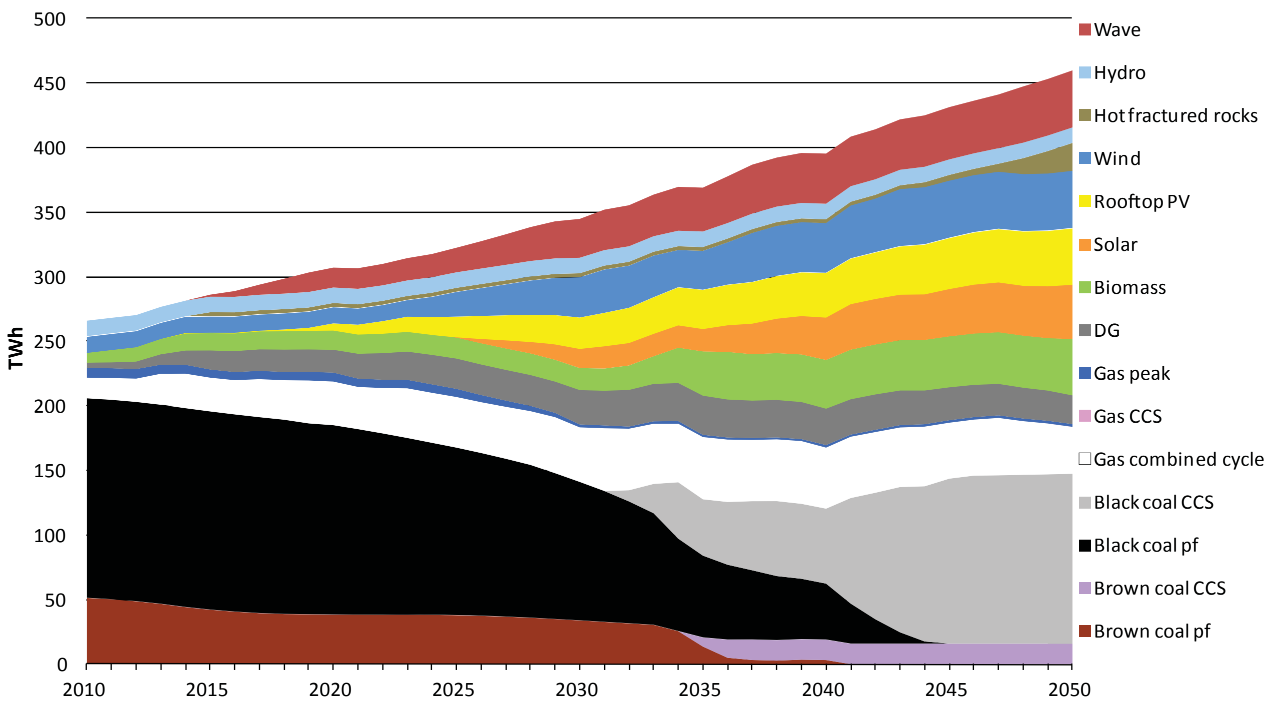

Figure 7-15 Projected electricity generation in Australia using the Point Absorber1 with 20 per cent wave energy extraction.

Results using the Terminator1 wave energy converter are shown in Figure 7-16. Wave energy generates 44.6TWh by 2050, which is 10 per cent of total generation. This is very similar to the results using Point Absorber1. This means that, as with Point Absorber1, 14 per cent of the sustainably-usable resource (as shown in Table 7-3) is used. This constitutes 3 per cent of the total available resource. Wave energy contributes 26.5TWh in Victoria, 10.4TWh in WA, 3.5TWh in SA and 4.2TWh in Tasmania, thus to its resource limit in Victoria as with the Point Absorber1. Again, wave energy is the largest supplier of electricity in Victoria and second largest supplier of electricity in SA, WA and Tasmania.

Comparing the results using the Terminator1, which has a high capital cost but higher NCF and the Point Absorber1, which has a much lower capital cost but lower NCF, allows us to see the effect of capital cost and NCF has on the viability of wave energy. In this case, there is no difference. This means wave energy is always attractive in Victoria. It has some use in other states with good resources, but the resources are not utilised to their full extent. WA, SA and Tasmania have lower demand for electricity and this, combined with the incumbent technologies, limits uptake of wave energy in these states.

Wave energy makes a greater contribution under the Point Absorber1 and Terminator1 scenarios than under the generic case studies (Figure 7-7 to Figure 7-14) because their capital costs are lower and have greater cost reductions than the generic device.

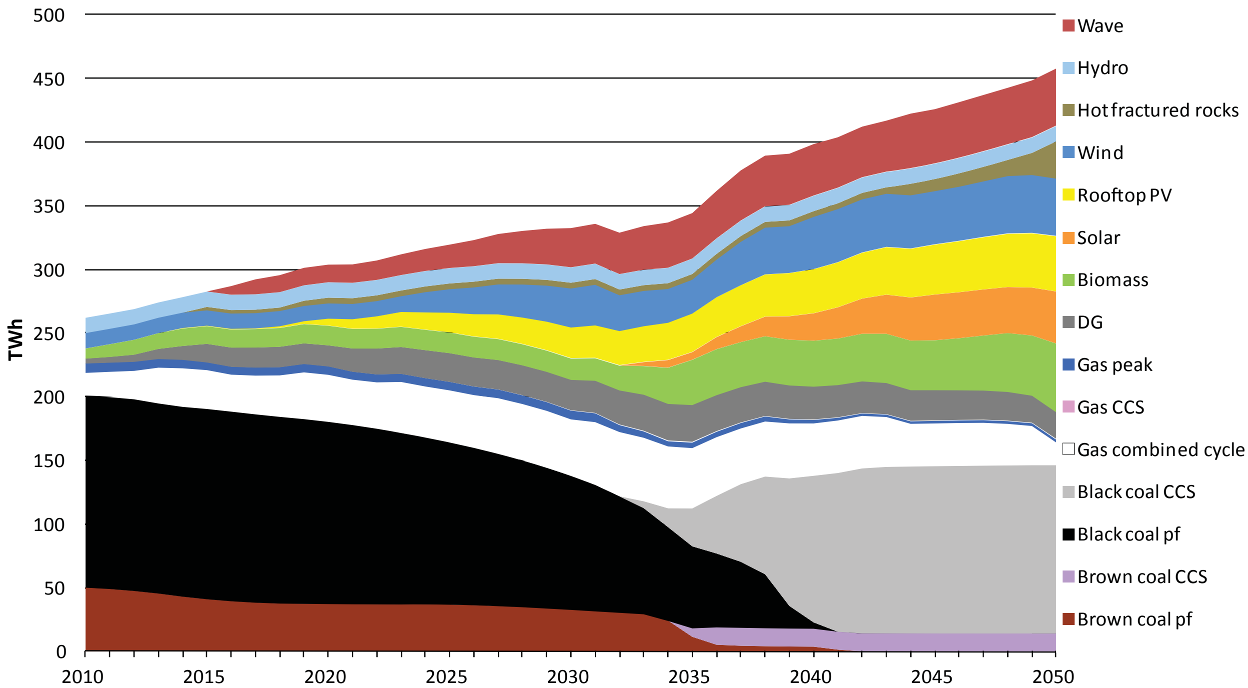

Figure 7-16 Projected electricity generation in Australia using the Terminator1 with 20 per cent wave energy extraction.

When the amount of wave energy extractable in any given site is increased to an upper-limit of 30 per cent, the amount of wave energy generation increases slightly, using the Point Absorber1 to 45.9TWh: Victoria (28.1TWh), SA (3.6TWh), WA (10.1TWh) and Tasmania (4.2TWh). Although all of the increase is in Victoria it doesn't reach the 30 per cent resource limit; it only uses 70 per cent of the available resource (see Appendix C Figure 9-30 to Figure 9-32). When the amount extractable is decreased to 5 per cent, wave energy contributes 21.5TWh to electricity generation in 2050. Most of the decrease is in Victoria, which now has 6.6TWh of wave energy generation. This is again the limit in that state (see Appendix C Figure 9-36 to Figure 9-38). WA also sees a significant decrease to 7.1TWh, which is more than the resource limit for the region with the best resource and it also includes some of the resource from the second-best region. There is no change to generation in Tasmania and SA which do not utilise all of their resource, even when it is reduced to 5 per cent.

We also tested changing the extraction limits to 30 per cent and 5 per cent using the Terminator1 (see Appendix C Figure 9-33 to Figure 9-35 and Figure 9-39 to Figure 9-41). When the limit is 30 per cent, the total amount of wave energy generated is 46.6TWh in 2050. All the increase in generation is in Victoria (28.6TWh), but it doesn't reach its resource limit, using 72 per cent of the sustainable resource or 22 per cent of the total resource. Under 5 per cent, the total amount of wave energy generated is 24.0TWh in 2050. As with the Point Absorber1, most of the decrease is in Victoria which now generates up to its limit of 6.6TWh. WA sees a slight decrease to 9.5TWh and there is no change in Tasmania and SA.

Therefore, in Victoria at least, under this scenario, the wave energy resource is being utilised up to its sustainable limit and could go beyond those bounds, if allowed, to 22 per cent using Terminator1. The other states which actually have better resources also have other good sources of renewable generation, so wave energy is not such a vital source of low-emissions generation.

Dispatchable Power

When 25 per cent dispatchable power capability is added to the scenario with 20 per cent wave energy extraction then the amount of wave energy generation using the Point Absorber1 increases to 51.6TWh by 2050, or 11 per cent of total generation. Victoria again dominates generation with 26.5TWh, followed by WA with 14.1TWh, Tasmania with 6.2TWh and SA with 4.8TWh. Wave energy is now the largest supplier of power in Victoria , WA, Tasmania and SA. This is in contrast to the normal case where wave energy contributed, but was not the major supplier in any state except for Victoria. Therefore, adding dispatchable power capability has given it the upper-edge over its main competitors, wind and solar, at least in those states. However, it only reaches its full resource limit in Victoria.

When the Terminator 1 example is used as the wave energy converter the amount of wave energy generated in 2050 is 52.3 TWh, or 11 per cent of total generation. This is almost the same as the result using the Point Absorber1 and it is higher than the case without dispatchable power; the addition of dispatchable power capability makes a difference to wave energy uptake. The bulk of the increase in wave energy generation is in WA (14.8TWh) and there is an additional 2.3TWh in SA (4.9TWh) and 1.9TWh in Tasmania (6.1TWh). As with the Point Absorber1, wave energy is the major supplier of power in Victoria, WA, SA and Tasmania.

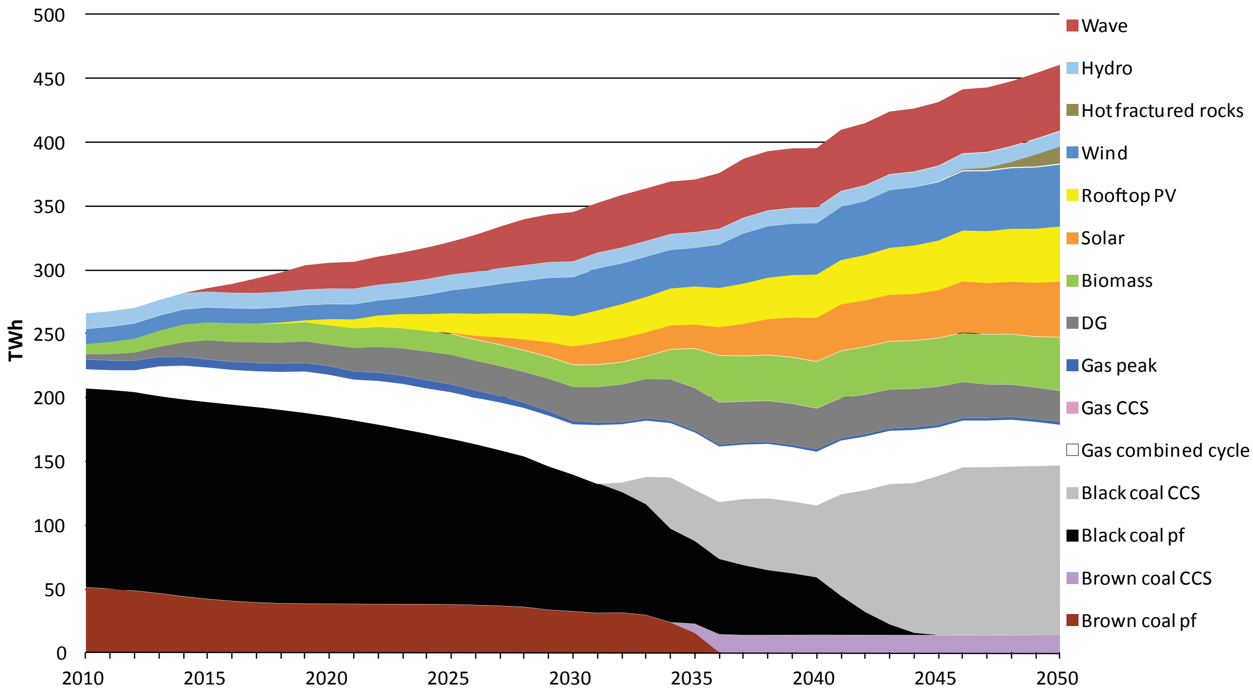

Figure 7-17 Projected Australian electricity generation using the Point Absorber1 with 20 per cent wave energy extraction and dispatchable power.

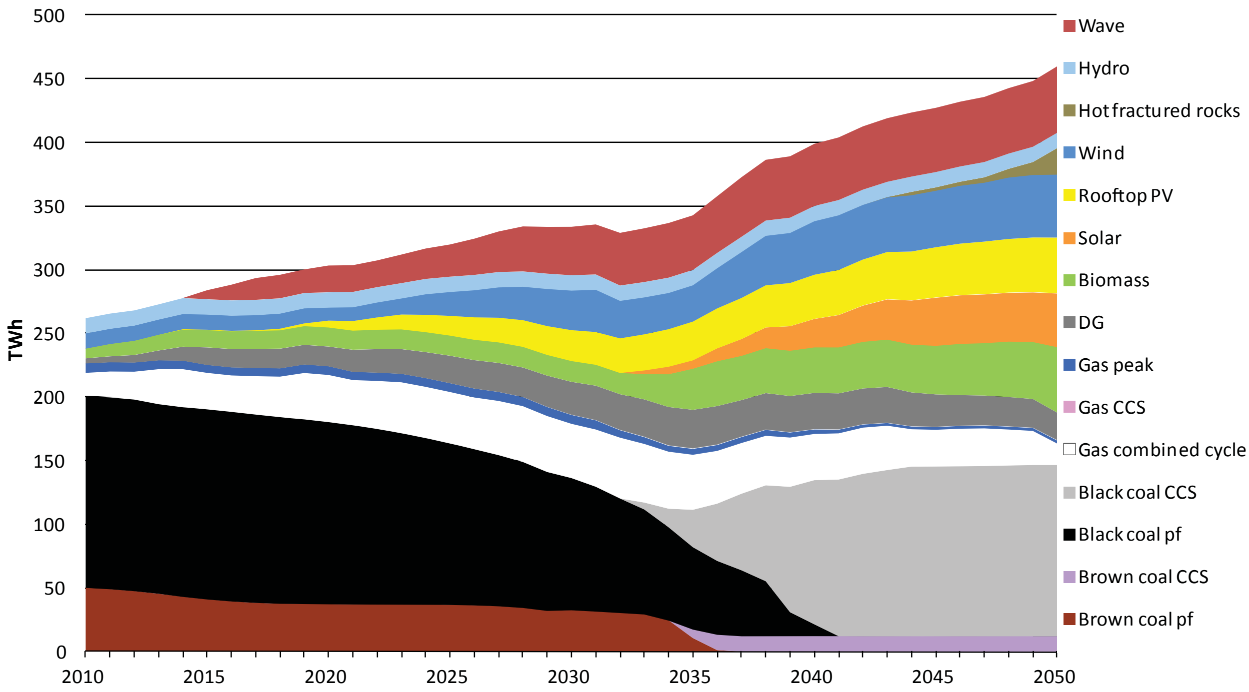

Figure 7-18 Projected Australian electricity generation using the Terminator1 with 20 per cent wave energy extraction and dispatchable power.

The relative advantages and disadvantages of the Point Absorber1 vs. Terminator1 under this scenario have not changed from the normal scenario. The fact that one has a much lower capital cost but lower NCF is no different from the other with a much higher capital cost but also higher NCFs. Adding in dispatchable power capability only increases wave energy generation from both technologies.

When the allowable amount of wave energy extractable from any given site is reduced to 5 per cent this has an effect on uptake of wave energy using the Point Absorber1 and the Terminator1 (see Figure 9-46 to Figure 9-51 in Appendix C). With the Terminator1, the amount of wave energy produced in 2050 is 30.6TWh. Victoria, WA and Tasmania all produce up to their resource limits in the first region. WA uses all of the second region and Tasmania makes partial use of the region with the second-best resource. Using the Point Absorber1, the amount of wave energy produced drops to 30.9TWh in 2050. All the resource in Victoria is used, all of the best region and part of the second-best region in Tasmania are used and the first and second-best regions in WA are used.

Increasing the amount of wave energy extractable to 30 per cent also has an effect on uptake using the Point Absorber1 and the Terminator1. Total generation increases to 63.3TWh and 64.9TWh respectively in 2050. Almost all the increase occurs in Victoria, which generates up to its increased resource limit of 38.9TWh. Tasmania increases its generation to 5.3TWh, but this is not the limit in the first region (see Figure 9-52 to Figure 9-57 in Appendix C).

7.3.4 Summary for Technology Case Studies

The amount of wave energy produced does vary somewhat by technology, but by less than 10 per cent as can be seen from Table 7-5 (the only exception being the Normal cases under the 5 per cent extraction limit where the difference is just over 10 per cent). The capital cost of the Point Absorber1 is almost half that of the Terminator1, giving the Point Absorber1 a huge advantage. The Terminator1 has NCFs equal to and greater than 0.5 in at least one region of each of the states along the southern coastline. From the generic Australian studies we can see that high NCFs are important for the viability of wave energy. However, for these two particular technologies, the effect of capital cost on uptake tends to balance out with that of NCF.

From the modelling we can determine that Victoria consistently has the greatest amount of wave energy. It has high electricity demand and needs to replace its brown coal-dominated power sector with low cost, low emission technologies. Increasing the amount of wave energy extractable from the mid-range of 20 per cent to the upper safe limit of 30 per cent again results in more uptake in Victoria, up to 22 per cent of its total unconstrained resource. Clearly, Victoria is the state where wave energy development will be most needed.

The addition of dispatchable power increases wave energy generation in Victoria up to its resource limit using both technologies. It also increases the amount of generation in WA and Tasmania in particular. These are the states with the best wave resources.

Extraction limit	Point Absorber1		Terminator1	
	Normal case	Dispatchable power	Normal case	Dispatchable power
5 per cent	21.5	30.9	24.0	30.6
20 per cent	44.3	51.6	44.6	52.3
30 per cent	45.9	63.3	46.6	64.9

Table 7-5 Summary of projected wave energy generation in Australia in TWh for the year 2050 for Point Absorber1 and Terminator1 with different extraction limits.

7.3.5 Terminator1 Capital Cost Sensitivity Analysis

Under this scenario, there is 31.9TWh of wave energy by 2050, which is 7 per cent of total generation. Under the normal case, there is 44.6TWh of wave energy by 2050, or 10 per cent of total generation.

The results under this scenario are shown in Appendix C Figure 9-58 and Figure 9-59. It can be seen that, as with the generic studies shown in Figure 7-2 to Figure 7-4, there is significant construction of wave energy globally. In Australia, there is also significant construction of wave energy, but less than under the normal Terminator case, by 12.4TWh. The contribution of wave energy is lower in all states: Victoria (23.1TWh), SA (1.5TWh), WA (4.2TWh) and Tasmania (3.2TWh). Therefore, the higher capital cost has an influence on the uptake of wave energy.

7.4 Conclusion

Wave energy has the potential to make a significant contribution to global and Australian renewable electricity generation. But the extent of its contribution will depend on many factors, which are probably not unique to wave energy. An emissions trading scheme is essential to make most renewable energy technologies, and wave energy in particular, financially viable. Globally, most of the deployment of wave energy has been in the developing world, therefore it is vital for the future of wave energy to have emissions trading schemes in place in those parts of the world.

Wind and solar technologies, the other major intermittent technologies, are already well established, are expanding rapidly world-wide and achieving cost reductions and economies of scale. Because wave energy is only at the prototype/early deployment stage, it lacks the momentum driving the deployment of wind and solar and is thus at a disadvantage. It needs to have a competitive edge over these technologies, which, from the global generic modelling studies, is its initially low capital cost compared with, for example, solar thermal. It has a NCF of at least 0.3.

Australia has abundant solar, wind and wave resources, but wave resources are basically limited to the southern coastline. Because of this, wave faces even greater competition in Australia than globally. For wave energy to be viable in Australia, it needs to have a maximum LCOE of 109 $/MWh under a carbon price regime and, a renewable energy target policy from the Australian government and to achieve significant O&M cost reductions, on a par with wind and solar farms. However, when we add in the advantage of a 25 per cent dispatchable power supply capability to wave energy, generation increases.

On the state level, Victoria is where the majority of wave farms are constructed. It has a good resource and NCF, large population and needs to replace brown coal-fired power stations with a low emission alternative. Wave energy is low cost enough to meet those requirements.

The technology-specific case studies reveal in more detail the effect capital cost, NCF and resource limitations have on the uptake of wave energy. The low capital cost but low NCF technology, Point Absorber1, is as competitive as the expensive but high NCF technology, Terminator1. When the amount of wave energy extractable is limited by environmental or other reasons, electricity generation is also limited, particularly in Victoria, which always reaches its resource limits under the normal case study. When the amount of wave energy extractable is increased to 30 per cent, Victoria increases its generation to use 22 per cent of the available resource. Adding in the dispatchable power generation capability increases wave energy power generation in Victoria, Western Australia and Tasmania, the states with the best wave resources.

There are differences in the results between the generic and technology-specific case studies. On the whole, more wave energy generation is projected under the technology-specific case studies. This is principally because the technology-specific case studies have been selected to optimally match Australian conditions, and only from those technologies that have been proven in sea-trials and/or are in production. The capital cost is therefore lower under all technology-specific case studies; and, for Terminator1 at least, the average energy generated in some regions is greater. These two effects combined result in a lower LCOE under the technology-specific case studies, which means the projected uptake of wave energy will be greater.

It has been suggested that hydro in Tasmania could potentially be used in the future as storage for excess wind and wave power, as is currently the case in Scandinavian countries. This would mean the contribution of hydro would be divided between energy storage and electricity generation, allowing wave energy to make a greater contribution than the model suggests. This additional flexibility would require installation of pumps and catchments at the bottom of dams. To be economic there may need to be another interconnector built between Tasmania and the mainland simply because local demand for electricity in Tasmania is low.

7.5 Summary of all Australian results

Generic			Normal			Dispatchable	
		CPRS-5	CPRS-15	G-25	CPRS-5	CPRS-15	G-25
	0.3	0	0	0	0	0	0
	0.4	5.5	0	0	5.5	0	24.8
	0.5	19.3	24.4	25.7	38.5	53	50
Point Absorber1			**Normal**			**Dispatchable**	
		CPRS-5	CPRS-15	G-25	CPRS-5	CPRS-15	G-25
	5 per cent	21.5	18.3	18.1	30.9	30.5	28.4
	20 per cent	44.3	44.8	41.8	51.6	52.9	52.9
	30 per cent	45.9	47.4	45.7	63.3	66.3	66.2
Terminator1			**Normal**			**Dispatchable**	
		CPRS-5	CPRS-15	G-25	CPRS-5	CPRS-15	G-25
	5 per cent	24	22.2	19	30.6	31	30.2
	20 per cent	44.6	44.9	43.4	52.3	52.9	53.1
	30 per cent	46.6	48.2	47.8	64.9	66.3	66.5
Terminator	**2 per cent**	**Normal**					
		CPRS-5					
	20 per cent	31.9					

Table 7-6 Projected Australian wave energy electricity generation in the year 2050 (TWh).

8. Australian and International Developments

This chapter will first cover developments in Australia largely focussed on quite new technologies specifically designed for Australian conditions. Such projects have the potential advantage of building on the knowledge gained from overseas work and can be designed for optimal performance in Australia.

The second part is an overview of overseas ORE research, development and supporting government policies. While comprehensive lists of the latest technology developments are given, the detailed focus in the international section is on technologies that have made the greatest impact and provide valuable information for those entering the field.

8.1 ORE – Australian Developments

There is increasing R&D and commercial ORE activity in Australia. This is in response particularly to the government-mandated target of 20 per cent of Australia's domestic energy (mainly electricity) to be produced from renewable sources by 2020. The federal government is also in the progress of developing a model for the pricing of carbon dioxide emissions, although at the time of writing this is still very much undecided as it does not have bi-partisan agreement. Both measures strongly favour the increased development and integration of low emission energy technologies into the nation's electricity supply.

There are a number of ocean energy companies developing and applying a range of Indigenous and overseas technologies in Australia. These range from small scale testing to pilot demonstrations and the beginning of commercial developments.

The following lists the significant ORE companies operating in Australia. These are companies that have received government and/or private funding, announced plans and/or are actively developing ORE process and activities in Australia.

8.1.1 Wave Energy Companies Active in Australia

Company: Carnegie Wave Energy Limited

http://www.carnegiecorp.com.au/

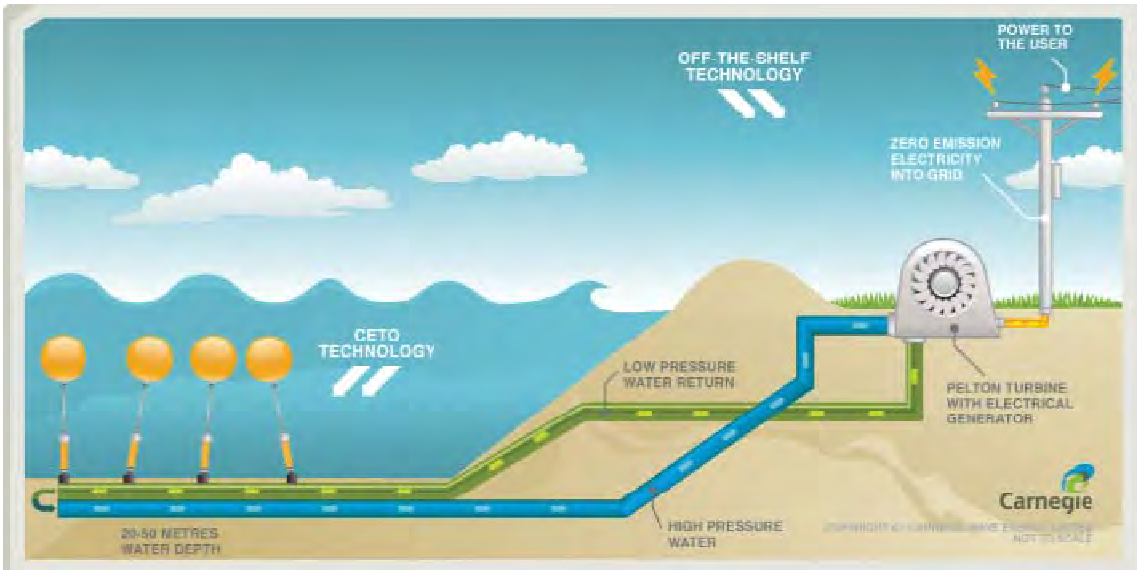

Figure 8-1 Carnegie Wave Energy – CETO: schematic of operation [113]. Image courtesy of Carnegie Wave Energy Ltd.

Technology

Carnegie is developing CETO wave energy technology. Arrays of submerged buoys are tethered to seabed pump units. The pumps are driven by the buoys as they move up and down under the influence of passing waves. The resulting pressurised water (currently freshwater) is pumped onshore to generate electricity, or can be used to pressurise seawater for reverse osmosis desalination units to produce potable water. The system has been tested to produce high pressure (140bar) sea water directly. The CETO design incorporates an energy relief system that limits loads in high sea states.

State of Development

Carnegie has announced its first commercial demonstration project will be at Garden Island off the coast of Perth, WA. The Australian Navy Defence Support Group signed an MOU with Carnegie Wave Energy in 2008 to support an initial feasibility assessment of the potential for wave power generation off the west coast of Garden Island. In April 2011 a single unit was deployed off Garden Island. Stage 1 will collect operating information for up to 12 months from a single stand-alone commercial 200kW CETO unit. Stage 2 will consist of a 5MW array (up to 30 commercial units) and associated onshore generation facilities. The operational target date is the end ofDecember, 2012 [114]. Carnegie won a $12.5 million grant from the WA state Government for the project [115] and has actively sought funds from other sources. On 25 July, it was announced [116] that Carnegie had won $500,000 from the National Centre of Excellence in Desalination (NCED).

A large scale power and/or desalination project in Australia has not yet been announced, although the desalination pilot project is planned for the 2011-2012 period, with first revenue from desalination planned in 2013. After the company failed to secure a large application to the Renewable Energy Development Fund (REDP), the company placed a proposed $400 million project at Port MacDonnell in South Australia “on ice” [117]. It is likely any such project will be located in the Northern Hemisphere [103]; an MOU has been signed with EDF EN and French marine defence contractor DCNS for a 15MW installation on Reunion Island [106]. In September 2010, Carnegie announced to the Australian Stock Exchange that it had signed a Collaboration Agreement with Sustainable Energy Authority Ireland’s (SEAI) Ocean Energy Development Unit (OEDU) to jointly develop a wave energy project at the Belmullet Wave Energy Test Site and “other locations in Ireland” [117]. However, long term Australian commercial projects are still in Carnegie’s project pipeline. For example, the company has been awarded an investigation licence and option to leases from the Victorian Government for three potential wave energy sites off Victoria at Portland, Warrnambool and Phillip Island [107]. The desktop evaluation of the Port MacDonnell project is continuing.

Company: Ocean Power Technologies Australasia (OPTA)

http://www.oceanpowertechnologies.com/index.htm

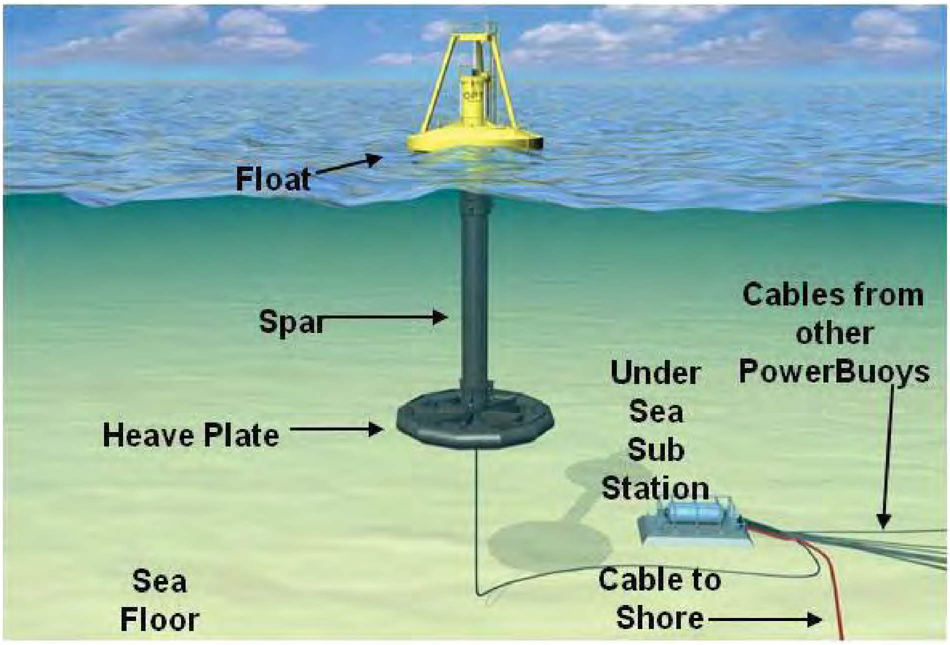

Figure 8-2 Ocean Power Technologies — Power Buoy [118]. Image courtesy of OPTA.

Technology

OPTA uses the PowerBuoy wave generation system. The rise and fall of passing waves causes a surface floating buoy, tethered to the seabed, to move up and down. The oscillating action is converted to electricity via a mechanical generator. The power is transmitted onshore by underwater cable. The PB150, and its moorings, have an operational wave range of 1.2 to 7m and are certified to survive a 100-year, 24m wave. OPTA estimate that the cost of power with production at 400 units per year will be around 10c/kWhr, and less for the larger PB500 unit.

State of Development

The USA-based Ocean Power Technologies company was founded by an Australian inventor, George Taylor, in 1994 and began ocean trials off New Jersey in 1997. The company is listed on the London stock exchange and the NASDAQ in the USA. The company is building a 10-unit wave farm off the north coast of Spain in conjunction with the Spanish company Iberdola and French company, Total. If successful, Iberdola has plans to roll out wave farms generating “hundreds of megawatts in the Bay of Biscay” [119]. OTP has other international projects in advanced planning and construction stages [120].

In 2010 Victorian Wave Partners, a joint venture between Leighton Contractors Pty Ltd and Ocean Power Technologies Pty Ltd, received a $66.7 million grant from the federal government (through the REDF) to construct a 19MW wave power project off the coast of Victoria, near Portland [121]. The project will proceed in three stages and be delivered by a special purpose company, Victorian Wave Partners, formed in December 2008 to pursue wave power opportunities off the south and east coasts of Australia.

Company: Oceanlinx Limited

http://www.oceanlinx.com/

State of Development

The Oceanlinx technology was developed in Australia. The first full scale prototype, Mk1, was initially deployed in 2005 and decommissioned in 2009. This 500-tonne device used a parabolic wall to direct wave energy into a 100 square metre oscillating water chamber. The Mk2 1/3 scale device was commissioned in late 2007 to obtain detailed floating device technical data. The Mk3 pre-commercial WEC, designed specifically for operation in the Port Kembla, NSW, coastal area, was installed in February 2010. The device, rated at 2.5MW, was connected to the grid and provided electricity to customers of the local retailer Integral Energy from March to May, operating successfully as one of the world's first grid-connected ocean energy devices [48].

On 14 May 2010, several weeks before its planned decommissioning, the Mk3 unit broke free of its moorings in high seas and ended the, hitherto highly successful trial. Future plans for the technology have not been revealed at the time of writing, although international groups have expressed interest in the technology. For example, on 15 September 2009, Oceanlinx Hawai'i LLC filed an application to study the feasibility of the Oceanlinx Maui Wave Energy Project 0.6 miles north of Pauwela Point, Hawai'i. The proposed project would consist of a floating pontoon, 30m wide by 100m long by 10m high, moored to the sea floor. The pontoon would contain eight oscillating water column units with a combined capacity of 2.7MW [122]. Oceanlinx technology is well-advanced with a number of key milestones met. The company has functionally deployed three operational units, is one of a very small number of companies to have sold electricity to the grid, and in 2006 was the first company to produce desalinated water on board a wave energy device.

More recent information from Oceanlinx details two designs; the greenWAVE, shallow water device, and a blueWAVE deep water device.

greenWAVE

(Personal communication — Tom Denniss, Oceanlinx Ltd)

Oceanlinx has a developed a specific shallow water oscillating water column (OWC) application, termed greenWAVE (see figure below). This OWC is located in about ten metres of water depth, and is mounted on the seabed. While the structure can technically be fabricated from any material, it is generally made from concrete or steel.

Besides the ten metres of the unit below the waterline, the structure also extends several metres above sea level. The above sea level component of the structure is where the airWAVE turbine and electrical control systems are housed. The airWAVE turbine is the only moving part of the technology, and is located well above the waterline.

The Oceanlinx greenWAVE technology differs from the floating blueWAVE in several key areas. Besides being fixed to the seabed, it is smaller and in shallower water. It is also typically constructed from concrete, as opposed to blueWAVE's steel. The biggest differentiator, however, is that greenWAVE involves a single OWC, whereas blueWAVE is a cluster of six OWCs.

The electrical output of a greenWAVE unit is dependent on the local wave climate. In a very good climate, a single 20 metre wide greenWAVE device would be rated at 1MW or more. The unit can be dedicated to the production of electricity, desalinated seawater, or both.

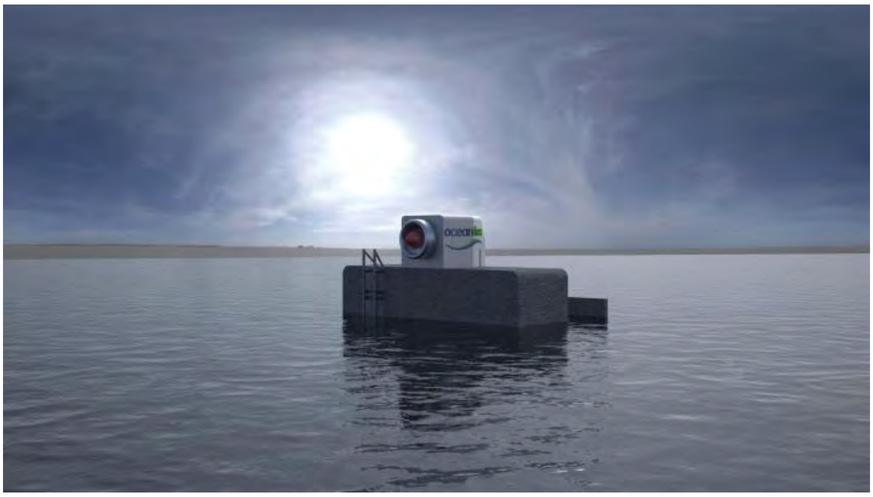

Figure 8-3 greenWAVE, Oceanlinx Ltd. Image courtesy of OceanLinx Ltd.

blueWAVE

(Personal communication — Tom Denniss, Oceanlinx Ltd)

Oceanlinx has also a developed a specific deep water OWC, termed blueWAVE. This structure consists of a cluster of six floating OWCs, joined together via a space-frame. The blueWAVE is located in 40-80 metres of water depth, and is an anchored floating device. While the structure can technically be fabricated from any material, it is generally made from steel.

The method of anchoring the floating structure to the bottom of the ocean depends on the geotechnical nature of the seabed. Gravity, drag, and suction anchors are typical candidates for this task.

Each blueWAVE is floated to its deployment site, where the task of securing the anchoring system takes place. The distance from shore will depend on the seabed slope, and how rapidly the nominal 40 – 80 metres of water depth is achieved.

The Oceanlinx blueWAVE technology differs from greenWAVE in several key respects. Besides being a floating structure in deeper water, its six OWC chambers means it is bigger than greenWAVE. It is also typically constructed from steel, as opposed to greenWAVE's concrete.

The electrical output of a blueWAVE unit depends on the local wave climate. In a good climate, a single blueWAVE device would be rated at 2.5MW or more. The unit can be dedicated to the production of electricity, desalinated seawater, or both.

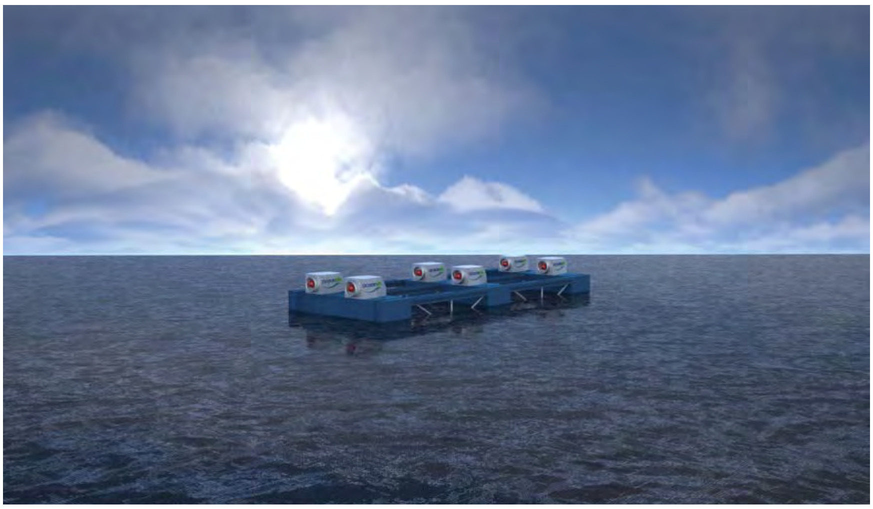

Figure 8-4 blueWAVE, Oceanlinx Ltd. Image courtesy of OceanLinx Ltd.

Company: BioPower Systems

http://www.biopowersystems.com/

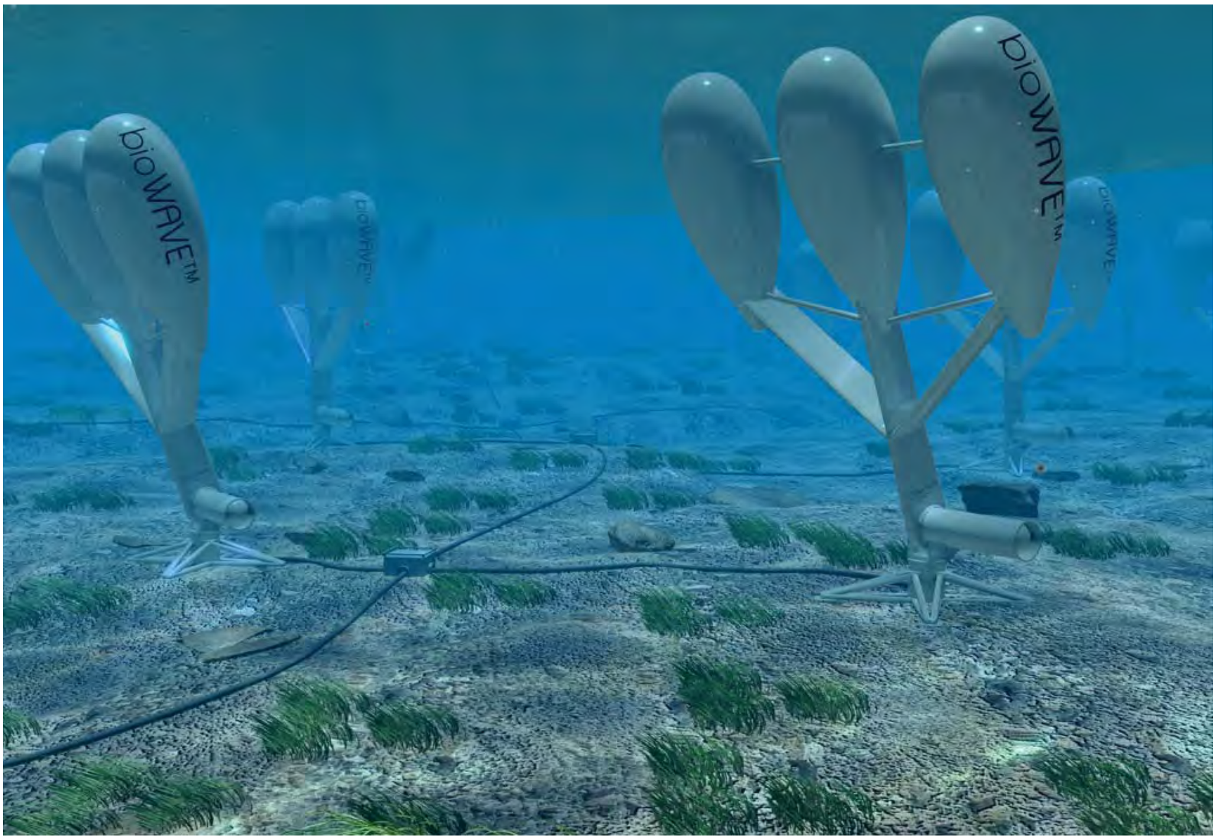

Figure 8-5 BioWAVE: schematic of operation. Copyright: BioPower Systems Pty Ltd [123].

Technology

BioWAVE is a device in which the converter is attached to the seabed and can be fully submerged at all times. The units consist of large, rounded blades or connected football-shaped buoyant devices which rock back and forwards with the passing waves. They are designed to mimic the swaying motion of sea plants in the presence of ocean waves. The motion is used to drive an on-board hydraulic generator to produce electric power which is taken onshore by cables with an AC-DC-AC conversion system. The company claims that by adjusting the quantity of water allowed into the swaying modules, they can be "tuned" to maximise the rocking motion. At times of extreme conditions, the modules can be filled with water and parked on the sea floor.

State of Development

In February 2008, the company was awarded a $5 million grant under the Australian government's AusIndustry Renewable Energy Development Initiative (REDI). The grant was matched by BioPower to fund a $10.3 million, two-year project to deploy and ocean test the company's wave (and tidal-current) energy converters [124]. BioPower has also received cornerstone funding from CVC REEF Limited, the Federal Government's Renewable Energy Equity Fund.

The company has conducted preliminary site investigations at King Island and Port Fairy as locations for testing of the bioWAVE system. A 250kW installation supplying power into Hydro Tasmania's distribution system on the local islands and into the Victorian power grid are in the planning stage. Development is now on hold pending further capital raising.

Company: Advanced Wave Power (AWP)

http://www.advancedwavepower.com/

Technology

The basic design of the Nautilus Prototype is an array of oscillating water columns. Several units are linked together and connected to a single air turbine. Each unit contains a high pressure outflow valve and a low pressure inflow valve that open and close independently, depending on the position of the unit within the wave cycle. It is claimed the uni-directional air flow has cost and efficiency advantages over more complex multi-directional air turbine systems.

State of Development

The company has been building and testing laboratory prototypes at the University of Queensland's wave laboratories for some years. The Queensland Government has invested $160,000 in the technology. In June 2009, the Queensland Minister for Natural Resources, Mines and Energy launched a 3kW prototype, the Nautilus. When it is scaled up the company hopes to uses the small waves in Morton Bay to generate "up to 100kWh per hour"[125]. It was the developer's intention to commence commercial development in the 2009-10 financial year and "hopes investors and power corporations will rally to surf the eco wave into the future"[126].

Another company, which appears to use the same or a similar technology, is IVEC [3]. Both have connections with the University of Queensland, although there is no cross-referencing between the companies.

Company: AquaGen Technologies

http://www.aquagen.com.au/

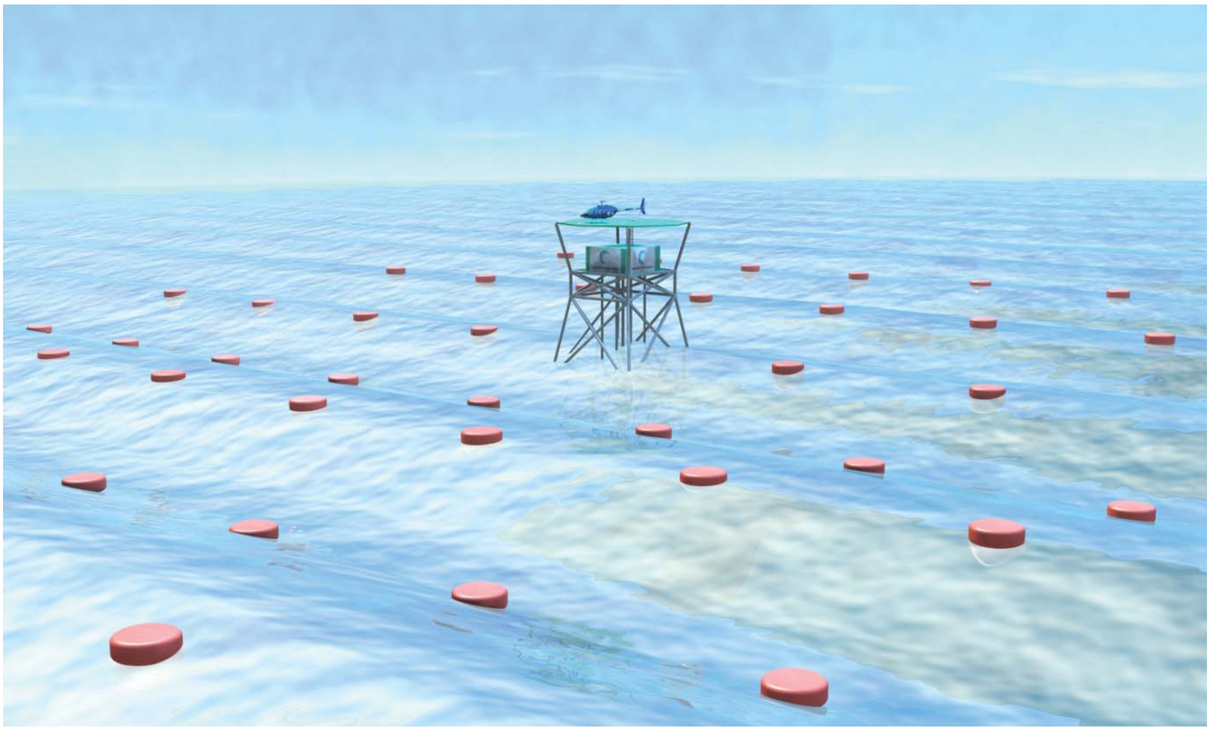

Figure 8-6 AquaGen Technologies: SurgeDrive. Copyright: AquaGen Technologies Pty Ltd [127].

Technology

AquaGen technologies is developing SurgeDrive®. This is a point energy-style wave energy system which harnesses the energy of ocean waves to produce electricity or desalinated water. Passing waves move elements of the wave farm, and this movement is transferred, via tension transfer components, to generation equipment located out of the water. The location of the critical and costly elements out of the water leads to lower cost deployments. The critical design elements of corrosion resistant materials, access to components for maintenance and foul weather survivability are enhanced. This leads to reduced generation or desalination costs. The system is readily scalable by the addition of more buoyancy elements and the technology is applicable to a number of applications, including vessel mooring systems [128]. The forces are then turned into either electricity or desalinated water by an above-water conversion unit.

State of Development

AquaGen Technologies installed its first open water demonstration on Lorne pier in Victoria in November 2010. The company is working on logging operational data from the unit to enable it to scale up to the next stage and commercialise the technology. Dependent on the results, the next prototype is planned to comprise a minimum of two full size 8m buoyancy units with an output of 150kW. This will later be scaled up to a full-size wave farm of 5MW with proposed delivery in 2013.

Company: Proteus Wave Power P/L

Technology

Units consist of long, curved floating pontoon structures. The designers are aiming for an eventual power production of 2MW per unit. Scale models (1:80 and 1:20) were built and deployed between 2007 and 2010. The current unit being constructed is a 1:6 scale model. This unit is 35m in length, while the full-size unit is approximately 190m in length and has a mass of 3200 tonnes.

State of Development

The company secured a $200k grant from the Queensland Government via the Queensland Sustainable Energy Innovation Fund (QSEIF) to assist with further development. Construction of the 1:6 scale unit was expected to be completed in late 2011. The full-scale prototype is slated for completion in 2012 depending on further grants [129].

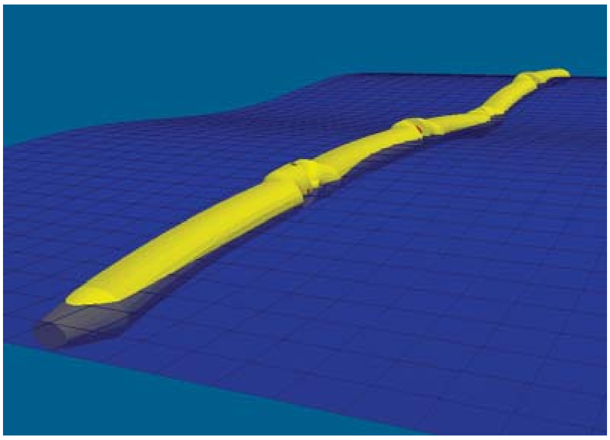

Figure 8-7 Design layout of the Proteus wave energy harvester (left) and the deployed 1:20 scale unit. Copyright: Proteus Wave Power Pty Ltd.

Company: Wave Rider Energy

http://www.waveriderenergy.com.au/

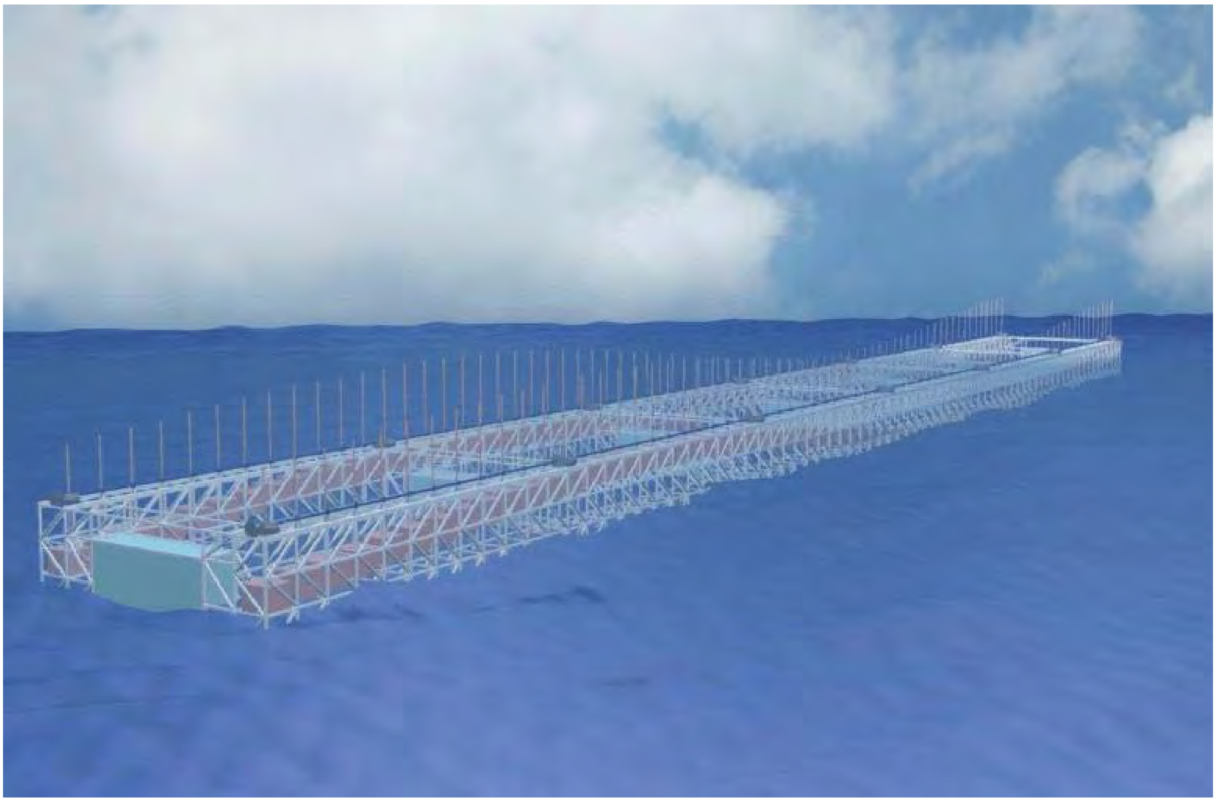

Figure 8-8 Concept drawing of the Wave Rider wave energy harvester. Copyright: Wave Rider Energy.

Technology

The Wave Rider device consists of an open steel truss with buoyancy pontoons that keep the structure afloat. A series of below surface buoys are fitted along the length of the structure. The buoys move up and down with passing waves. This movement causes the rotation of an axle, connected by a chain drive on top of the structure that drives generators to produce an electrical output which will be taken to shore via undersea cables [130].

State of Development

The company has approval from the state and federal governments to build and deploy a $5 million, 200 tonne, 110 metre wide steel structure to be located 800 metres offshore (in 30 metre water depth) between Locks Well Beach and Elliston on South Australia's Eyre Peninsula [131]. The device is on schedule to be completed in mid-2011, with deployment in the water by October 2011.

Company: PerpetuWave Power

http://www.perpetuwavepower.com/

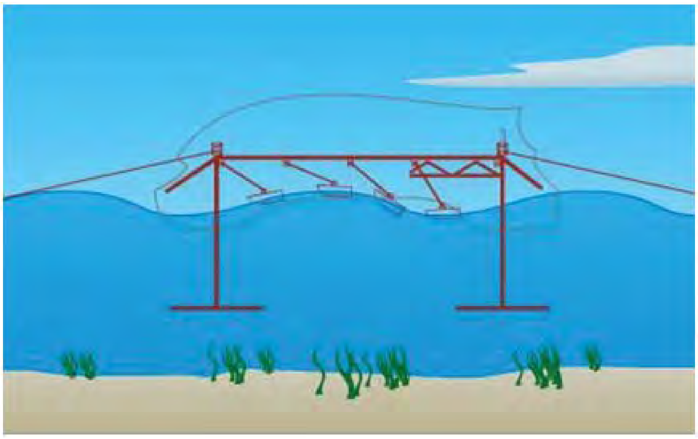

Figure 8-9 The Perpetuwave Power wave energy harvester. Copyright: Perpetuwave Power.

Technology

The PerpetuWave technology is a line attenuator harvester, where multiple floats on a trailing arm heave and translate to generate power. The use of multiple floats effectively smooths the output energy between wave crests. The power generation machinery is located above the water, offering benefits for corrosion control and serviceability. The vessel housing the float system is modelled on floating oil platforms with damping plates to minimise movement of the platform [132].

State of Development

In February 2010 the company announced improved output from its 500W test unit, and the following May received a $70k Australian Government grant to assist in the development and marketing of their wave harvester. Further independent testing in a wave tank at the University of Queensland has improved output with unit efficiency noted at 30-40 per cent energy extraction (waves-to-watts). In October 2010, the company announced design of a 20kW unit. This unit is 18m long and 11m wide, and has a planned delivery date of early 2012.

8.1.2 Tidal/Ocean Current Energy Companies Active in Australia

Company: Tenax Energy

http://www.tenaxenergy.com.au/

Technology

Power is directly generated from ocean flows via turbines sitting on the seafloor. The preferred tidal energy generator technology proposed for installation by Tenax Energy at Clarence Strait is similar to that designed by OpenHydro, Ireland and Clean Current Power Systems, Canada. OpenHydro installed the first grid-connected facility based on this technology at the European Marine Energy Centre (EMEC) in Orkney, in northern Scotland, in 2006, while Clean Current installed their tidal energy generator in the Race Rocks Ecological Reserve, British Columbia, during 2006, replacing the traditional power generation systems on the island. Both open centre turbine designs were among the first tidal technologies in the world to reach the stage of permanent deployment at sea. The global licence to the Clean Current device has been purchased by the global turbine manufacturer Alstom. The turbines consist of an open core 15m in diameter, surrounded by axial turbine blades, and are held in place with a heavy mass, which mitigates the need to excavate footings. The required depth of the operating turbine means there is no disruption to shipping in the area.

State of Development

Tenax Energy proposes the use of OpenHydro turbines to develop an off-shore tidal energy facility in Port Phillip Bay [133]. The facility will comprise up to 45 seabed turbines, producing 80.6 TWh of electricity, with a power cable connection to the grid. The company has submitted an EES Referral and application to lease Crown land to the Victorian Government [128]. The company recently announced plans to establish a 200MW tidal energy project off the coast near Darwin, which will see "at least two hundred 1MW tidal energy turbines installed in the Clarence Strait" [133]. It was announced in September 2010 that the Northern Territory Government has given the site licence allowing Tenax to undertake a range of studies on site to complete an environmental impact statement. The company is also investigating tidal energy potential in Banks Strait, Tasmania.

Company: Atlantis Resources Corporation

http://www.atlantisresourcescorporation.com/

Figure 8-10 Atlantis Resources Corporation: The AR1000 tidal turbine installation. Copyright: Atlantis Resources [134].

Technology

Atlantis has developed a number of technologies. These include the now superseded Nereus tidal turbine, a shallow water turbine that uses "Aquafoils" to capture momentum from the flow of water to drive a chain perpendicular to the flow direction. The newest commercial "flagship" products are the 1MW AK1000 and AR1000 turbines rated at 2.65m/s. The AK (Atlantis Kong) is a twin-rotor non-rotating turbine. The AS (Atlantis Solon), is a shrouded turbine that has been tested in Tasmanian waters [135]. The AR (Atlantis Rotate) is a single-rotor turbine with full nacelle rotation capability.

State of Development

Atlantis has been developing water flow turbine systems and testing them at San Remo, Victoria for the past decade. The Company established operations in Singapore in 2006. The first tow test took place in Victoria in December 2007. In July 2008, the Nereus II tidal current turbine was tested successfully in an open ocean environment. In mid 2008, the company unveiled its Solon (AS) series turbines [128]. The turbine was successfully tested in Singapore and verified as the world's largest horizontal axis turbine ever tow-tested. It was claimed to be the world's most efficient tidal current turbine. Atlantis has now announced the development of the world's largest undersea turbine (1MW). The AK1000 is due to be installed at a dedicated berth at the European Marine Energy Centre in the Orkneys.

The company is pursuing overseas applications of its turbine technology and was looking forward to permit approvals in 2009, enabling the development of commercial facilities at Port Phillip Heads in Victoria and around Broome and Derby in Western Australia [128]. The company aspires to have over 200MW of tidal power installed in Australia within five years and 500MW within a decade. No update on these plans was available at the time of writing.

Company: Tidal Energy Pty Ltd

http://www.tidalenergy.net.au/

Technology

The Davidson-Hill Venturi turbine is the key component of the Davidson-Hill design. The venturi creates a vortex of low pressure behind the turbine — drawing the flow across the turbine. This increased flow allows the turbine to operate at higher efficiencies, claimed to be as much as 3.84 times compared with the same turbine without the shroud [137].

State of Development

Tidal Energy is the operator of a stalled $400 million tidal river energy project in the Kimberly region. Woodside Petroleum has undertaken informal discussions with the company over the possibility of using their technology to provide power for Woodside's James Point LNG project [138].

Company: Cetus Energy

http://www.cetusenergy.com.au/

Technology

Cetus Energy is a Melbourne-based renewable energy technology company that claims to have developed the world's only omni-directional impeller capable of extracting energy from chaotic flows [139]. The structurally-flexible impeller design can use both lift and drag to extract energy from flowing water environments ranging from shallow rivers and beaches to deep-sea marine currents.

State of Development

On 24 February 2010, Cetus Energy and AGL Energy Limited jointly announced [139] they had signed an agreement to scope the installation of a demonstration project at AGL's Rubicon Valley Mountain Stream Hydro facility in Central Victoria. The project is aimed at gathering sufficient data to provide the partners with confidence that the Cetus turbine technology can "optimise" the use of waters in rivers, streams and channels for renewable energy generation. Although there are limited references to the use of the technology in marine/ocean environments, a series of videos on the Cetus website show small demonstrations of the technology in shoreline waves and in a wave tank.

Other Companies

Other companies developing ocean flow technologies in Australia include HydroGen Power Industries Pty Ltd [140] , Elemental Energy Technologies Ltd (SeaUrchin) [141] and Sundermann Water Power [142]. These have not been listed in any detail as they are either less developed, have not announced firm demonstration plans and/or have not received significant funding body support.

8.1.3 Research in Australia

This section is a brief survey of ocean energy research in Australia, not including resource estimation/distribution which was included in chapters 2 and 3.

Australia does not have a coordinated research approach to ocean energy. What little is done comes mainly from the universities, with some contributions by companies and a few research institutions, including CSIRO. However, with the growing interest in ocean energy, prompted by start-up company push and recent government funding for demonstrations, this is likely to change. An encouraging development is that Australia, via the company Oceanlinx, joined the International Energy Agency's Implementing Agreement on Ocean Energy Systems in 2009 [143].

Australian academic institutions active in ocean energy research include the University of Tasmania's Australian Maritime College, the University of Wollongong, the University of New South Wales Water Research Laboratory, and the University of Sydney [144]. Other universities have various levels of activity in the field. A keyword search of Australian contributions to ocean energy research in Australia returned around 20 relevant hits for the period 2006-2010.

The most numerous contributions are from the University of Sydney, with five publications describing experimental and theoretical analyses of bottom-pivoted devices similar to, and leading to, the development of the BioPower wave energy extraction system. Similarly, the University of Western Australia has published a theoretical paper on wave forces on a horizontal cylinder close to the sea bed [145] and verified the model with reference to literature experimental results dating from 1995.

The University of Western Australia also recently published two papers on the efficiency of the extraction of energy from oscillating water columns [146, 147]. These papers appear very similar and come to the same conclusion: that there is a broad band of efficiency centred on the natural frequency of oscillating water columns. Stappenbelt and Cooper [148] and Zhu and Mitchell [148] from the University of Wollongong have published papers on the coupled dynamics of the water column and the diffraction and radiation of ocean waves around floating structures. They allude to the complexity associated with using oscillating water columns to extract wave energy and the need to do more fundamental research to maximise energy extraction. A contribution from the University of Technology, Sydney [149] describes a small segmented oscillating water column with three sections together with modelling techniques that can be used to simulate its performance. The senior author of this work, DG Dorrell, has also published the design of a direct-drive permanent-magnet generator for use in a novel "sea-wave electrical generator" [150].

While CSIRO has published widely on Australia's ocean energy resources base, the development of ocean energy extraction devices has not been a priority for the organisation. However, a recent paper by Fowler and Behrens [151] investigates the feasibility of a multidimensional wave energy harvester that generates electrical energy from multiple transitional and rotational motions available from waves. A computer-based model has been developed and the simulations have compared favourably to real-world wave data captured from a data logging buoy. Other recent CSIRO work builds on expertise in fluid dynamics, particularly the energetics of breaking ocean waves [152, 153]. This expertise has been used particularly to assist Cetus Energy to study the performance of their WaveBlade technology (mentioned above).

Though the University of New South Wales does not appear prominently in ocean energy research, its Faculty of Law has produced a useful contribution on the current state of ocean energy regulations [154]. The authors conclude that one of the major challenges for the development of ocean energy extraction in Australia ensuring that appropriate regulatory systems are in place and that these will need to be developed over time as the industry develops. In a not-unrelated approach, an offering from the University of Adelaide develops a Geographical Information System (GIS) to guide the connection of wave farms to the electricity network, taking into account a range of exclusion zones, such as native vegetation [155]. The GIS methods may be of assistance to governments in setting appropriate marine renewable energy policy and identifying existing policy that may require amending to support the growth of wave (ocean) energy.

Apart from the universities, a number of Australian private companies have contributed to the international literature on ocean energy. These include OEMG Global, providing specialist skills in oceanographic and environmental management services, and AMOG, the Australian marine and offshore group. OEMG has contributed recently to policy issues [156] and AMOG to engineering aspects of ocean energy, such as the design of mooring and foundation systems [157] and wave load effects for various ocean energy device designs [158].

This section is not an exhaustive review of research in Australia; however, it gives a flavour of recent activities. Given the rather random and uncoordinated nature of the Australian research effort, there is a good case developing a more organised approach, perhaps by the formation of an Australian ocean energy association, Co-operative Research Centre or Institute. As interest grows in ocean energy in Australia, it is likely that the various industry players would find it in their collective interest to support ocean energy research, targeted at Australian applications into the future.

8.2 World Developments

8.2.1 Overview

The world's most productive wave energy is more available in countries with unsheltered coastlines, facing oceans where wind is converted to wave energy over fetch distances of hundreds to thousands of kilometres. This includes the Americas, Australia, Ireland, Portugal, parts of Scandinavia, South Africa and the United Kingdom.

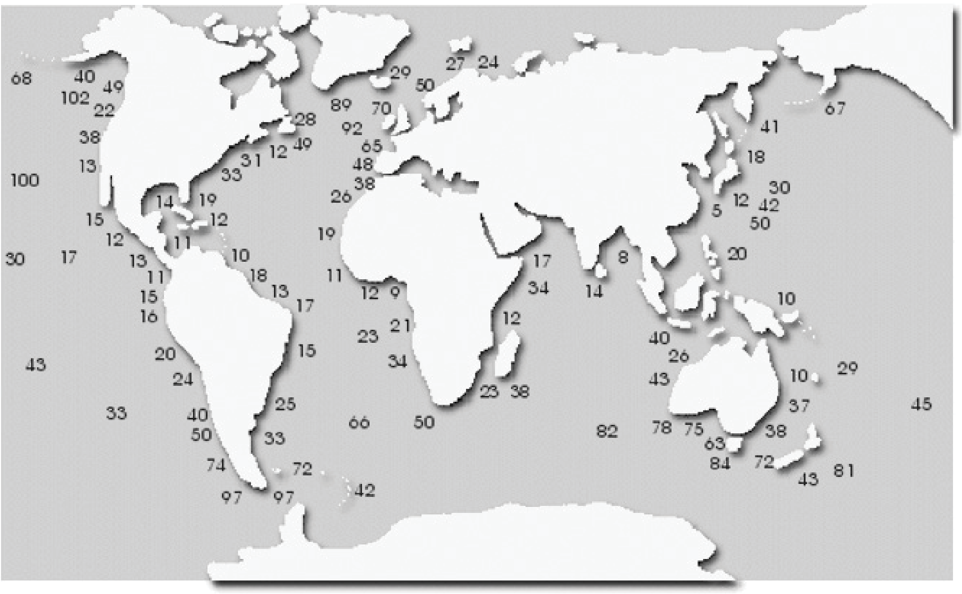

Figure 8-11 Global Wave Power per metre wave crest (kW/m) [29].

Tidal energy potential is comparatively low compared with wave energy, although resources are widespread, with significant resources in the Americas, Canada, China, France, India, Ireland, Russia and the United Kingdom.

Ocean thermal energy is most available in tropical and sub-tropical regions in locations with a relatively narrow continental shelf, typically associated with islands near China, Japan, India and Pacific Islands.

Salt gradient energy is restricted to the few countries with large fresh water supplies adjacent to the sea, such as Norway and Denmark.

ORE Resource [7, 17, 92, 159-161]

Electricity demand	2006: 15,665TWh	2030: 28,000TWh
Extractable wave energy 15	140TWh/yr to 750TWh/yr (present)	
	2000 TWh/yr (future)	
Extractable tidal energy	570TWh/yr	
Theoretical ocean thermal energy	2,000,000TWh/yr	
Theoretical salt gradient energy	23,000TWh/yr	

ORE Development

There are many countries working on wave and tidal energy but the prime focus for wave energy and tidal device development is Europe.

Ireland, Portugal and the United Kingdom all have substantial wave energy resources and have developed very significant strengths in the provision of device testing facilities, and policy for ORE development as well as device development.

Denmark and Sweden are world leaders in wave energy device development despite not having a particularly large wave energy resource. Denmark has a strong track record in developing wind turbines and is applying its experience to the development of low-head turbines for its wave power generator project Wave Dragon and its energy storage Green Island program. Sweden is driven by its policy of becoming an oil-free society and has two wave energy projects in its renewable energy development program.

Norway has a long history of wave energy device development but is focussing on tidal energy. It currently has two commercial wave energy developers and a commercial/university collaboration investigating salt gradient power.

Examples of the international coordinating societies, mechanisms and reviews that facilitate this development include:

- Renewable Energy Policy Network for the 21st Century (REN21). Available at http://www.ren21.net/
- International Energy Agency — Ocean Energy Systems (IEA-OES). Available at http://www.iea-oceans.org/
- Marine Renewable Energy — Research Challenges and Opportunities for a new Energy Era in Europe. Available at http://www.esf.org/index.php?id=1437

8.2.2 Canada

Canada generates about 370TWh of hydroelectricity a year, making it the second largest producer of hydroelectricity in the world [101]. In 2003 Canada joined the IEA's Implementing Agreement on Ocean Energy Systems. Its interest in ocean energy resources is primarily focussed on tidal resources in the Bay of Fundy, which has some of the largest tidal ranges in the world. To develop this resource and in response to a strategic Environmental Assessment for offshore renewable energy, the Government of Nova Scotia has set up the Fundy Tidal Institute to work with three local companies in developing the Bay of Fundy tidal resource. Canada's interest in wave energy is also starting to grow, with a comparatively large number of companies developing prototypes for sea testing. Canada has a sustained interest in renewable energy with the Canadian Government setting up the $A1.45 billion ecoENERGY for Renewable Energy Power in September 2010. Canada's National Energy Board forecasts that about 20GW of their marine energy capacity will come from wave and tidal current energy resources.

ORE Resource [101, 161-163]

The east coast of Canada has an estimated average wave power of 146.5GW and the west coast has 37GW. This wave power is four to seven times as great in winter as in summer time. The most significant resource for tidal power is in the Bay of Fundy, passing 100 billion tonnes of water during each tidal period.

Total Electricity generating capacity	2007: 124GW
Electricity demand	2007: 598TWh
Theoretical wave energy	1600TWhr/yr
Extractable wave energy	no formal estimates found
Theoretical tidal energy	255TWh
Extractable tidal resource	no formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 163]

The Bay of Fundy has had a barrage tidal generator, Annapolis Royal, since 1984. It incorporates a 20MW Straflo rim generator turbine producing more than 20GWh per year.

The Government of Nova Scotia has committed to develop the tidal resource of the Cumberland and the Minas basins in the Bay of Fundy, which together have a potential to produce 17TWh per year. Three companies are working together with the Fundy Tidal Institute, sharing some of the costs and infrastructure for the development.

Nova Scotia Power will be testing the largest in-stream tidal turbine in the world, a unit supplied by Open Hydro of Ireland. Subject to the success of this project, Nova Scotia Power plans to construct a number of tidal farms in the Bay of Fundy. Clean Current Power systems will be trialling the Clean Current Mark III Turbine and Minas Basin Pulp and Paper will be using a SeaGen turbine supplied by Marine Current Technology. Infrastructure includes connections to both the local and the national grid.

University and Institutional ORE Research [164-166]
College of the North Atlantic
Dalhousie University
Memorial University
University of Toronto
University of Victoria
NRC Institute for Ocean Technology (NRC-IOT)
NRC Canadian Hydraulics Centre (NRC-CHC) (commercial arm of NRC-IOT)
Offshore Energy Environmental Research Association (OEER)
The Ocean Renewable Energy Group (OREG)
University of British Columbia

Table 8-1 Canadian Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Blue Energy	Vertical axis unit based on Davis Turbine.	20kW to 100kW production units installed.
Clean Current	Horizontal ducted tidal turbine with a permanent magnet generator.	Prototype commercial scale unit under construction.
Coastal Hydropower	Very low head turbine.	Commercialisation under way.
Finavera AquaEnergy (AquaBuOY)	Point absorber.	Full scale prototype, sea tests, based on Swedish technology sea tested but data not in public domain.
New Energy	Vertical axis turbine 5W to 250kW.	Commercial products.
Nova Scotia Power	20MW tidal barrage plant producing 50GWh (5.7MW).	The plant generates on the ebb tide and fills the reservoir on the flood tide. It uses a 20MW rim-generation-type Straflo turbine, the largest in the world.
Seawood Designs Surf Power	Prototype.	Wave tank testing
Sieber	SieWAVE.	Prototype — lab tests.
SyncWave energy	Point absorber.	Prototype — lab tests.
Water wall	Vertical axis turbines.	Prototype information not to be published.
Wave Energy Technologies	WET EnGen; point absorber.	Prototype — sea tests.
Waveberg Development	Prototype.	Sea tests.
Wavemill Energy Corp	Solar thermal desalination.	Prototype.

Table 8-2 Canadian ORE developers.

Government Strategy and Support [166, 168]

The Canadian Government has made a commitment that Canada's total GHG emissions will be reduced by 17 per cent from 2005 levels by 2020. This will involve a range of measures including the further development of renewable energy resources through the funding of pilot projects within Canada.

The Canadian Federal Government's responsibility for ORE lies with the Marine Energy R&D group in the Department of Natural Resources (DNR). A researcher from the group is currently chairman of the International Electrotechnical Committee on Marine Energy, and Canada is a participating member of the International Energy Agency Implementing Agreement on Ocean Energy Systems and Wave, Tidal and Other Water Currents.

DNR works closely with the ORE Group (OREG) a Canadian industry association DNR and is also responsible for administering Canada's Clean Energy Fund program, investing $795 million over five years in clean energy technologies. Projects include three major initiatives in ORE:

- A project valued somewhere between $2.5M and $5m to evaluate a SyncWave Systems pre-commercial 100kW WEC in seas off British Columbia's open coast.
- A project valued somewhere between $10M and $20m in the Minas Passage of the Bay of Fundy to evaluate the first Canadian deployment of commercial-scale tidal turbines.
- A project valued somewhere between $10M and $20m to demonstrate three in-stream hydro technologies including fish-friendly, low-head hydro turbines along the Mississippi River System, Ontario.

8.2.3 China

China's coastline, including more than 6500 islands, is longer than 14000km, with the greater part of the ocean energy resource lying along the more developed eastern coast and mainly located in the seas around Guangdong, Fujian, Zhejiang, Hainan and Taiwan. About 40 per cent of the tidal resource is located in Fujian and 50 per cent in Zheijiang. One-third of the wave energy resource is located in Taiwan and most of the ocean thermal resource is around the Xisha islands and offshore east of Taiwan. China has eight operational tidal power stations with three in continuous operation. Jiangxia is the largest in Asia and the third largest in the world.

ORE resource [101, 169-171]

Total electricity generating capacity	2007: 716GW
Electricity demand	2007: 3000TWh/yr
Theoretical wave energy	600TWhr/yr
Extractable wave energy	113TWh/yr
Theoretical tidal energy	960TWh/yr
Extractable tidal resource	62 TWh/yr
Ocean thermal energy	12000TWh/yr
Extractable ocean thermal energy	No estimates found
Salinity gradient	960TWh/yr
Extractable salinity	Gradient: no formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 169-171]

China has been active in Marine Energy Research since the 1980s, constructing a number of research wave power generating stations ranging in power from 3kW to 100kW, as well as a program starting in 1958 for the development of tidal power stations. This involved the construction of 40 small scale tidal power stations, typically with a capacity of 12kW. From 1980 there was a program to scale up tidal power stations, many of which have now been decommissioned. Seven tidal power stations (plus one tide flood station) remain with a total capacity of 11MW. China has also focussed on the development of beacons powered by wave energy producing and deploying about 650 60W units, including some that have been exported to Japan. Research areas include:

Tidal research:

- Jiangxia tidal barrage plant, 3MWp, mean 1.3MW of power, 11GWh/yr.
- Baishakou tidal barrage plant 640kW.
- Haishan tidal barrage plants 150kW.

Wave power research into oscillating water columns:

- Since 1985 a series of oscillating water column have been constructed by the Guangzhou Institute of Energy Conversion (GIOC). Early units had unstable power output and during operation produced on average a fewkW. More recently a 400kW rated unit has been producing sustained power of 50kW or 4.2L/s of desalinated water.

Other ORE research includes:

- Vertical axis turbine development in Wanxiang.
- A method of ocean thermal energy utilisation named "Mist Lift Cycle".
- 100kW tilting wave power station at Daguan Island at Qingdao, Shandong Province.

University and Institutional ORE Research [165, 169-171]
Harbin Engineering University
Chinese Academy of Sciences Guangzhou Institute of Energy Conversion
Ocean University of China, Qingdao
National Ocean Technology Center, State Oceanic Administration (SOA)
The Second Institute of Oceanography (SOA)
Ocean Energy Committee, Chinese Renewable Energy Society

Table 8-3 Chinese Universities and Institutions researching ORE.

ORE Developers

There are no commercial developers of ORE in China at present.

Government Strategy and Support [168-172]

In January 2006 China enacted a "Renewable Energy Law" to provide a legal and policy framework for planning and funding the development and use of hydroelectricity, wind power, solar energy, biomass energy, geothermal energy and marine energy. The objective is for renewable energy capacity to make up 15 per cent of the electricity supply by 2020 and the law includes a commitment to invest $180 billion to achieve this. In addition it provides for the encouragement of public and vocational educational programs and offers a range of financial incentives. The latter include "tax relief, encouragement of grid connection, online discount price, discounted loans, financial subsidies and other incentive policies". The grid connection requirement dates back to 2001 but is now further supported by regulation of the grid price through the National Development and Reform Commission.

The Ministry of Finance in China has included in the goals of the associated funding and financial management policy support to be given to key projects involving the development of alternatives to oil, such as solar energy, geothermal energy, wind energy and ocean energy.

8.2.4 Denmark

Denmark pioneered the use of wind energy during the 1970s, and despite having relatively poor wind resources, has positioned itself to supply half of the world's wind turbines. Denmark likewise has relatively modest wave resources; nevertheless in 1998 it commenced supporting wave energy technology and is currently a world leader, with Wave Dragon being one of the few commercially available wave converters to have been extensively sea trialled. A search through the government-sponsored research projects listed under government strategy reveals some of the most advanced ocean research programs under way in the world.

ORE Resource [101, 173]

Denmark's wave energy resource is located in the north western regions of its North Sea coastline with an annual mean wave power between 7 and 24kW/m.

Total electricity generating capacity	2007: 13GW
Electricity demand	2007: 36TWh/yr
Theoretical wave energy	30TWhr/yr
Extractable wave energy	No formal estimates found
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	No formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 167, 173-175]

The Danish Energy Agency (DEA) ran the Danish Wave Energy Programme from 1997 to 2006. It had an initial budget of $A7.5M and funded research into 40 wave energy projects, taking nine of them from concept through to detailed designs. The Wave Dragon is a leading example of cost-effective design arising out of this program and it has subsequently undergone assessment by EPRI. It is closely followed by Wave Star, which is currently undergoing sea trial at a number of sites around the world as listed in the government's funding strategy below. Additional resources for the development of both Wave Dragon and Wave Star were made available by the privately-funded Public Service Obligation (PSO).

The Danish Maritime Institute (DMI) and the Danish Hydraulic Institute (DHI) at the University of Aalborg provided test facilities and an ocean test site was later set up at Nissum Bredning located at Limfjord and funded by the Danish Energy Agency. The Danish Wave Energy Association was formed in 1997 to promote interest in wave energy as a renewable resource, and has established an Advisory Panel of experts focusing on wave energy testing and research. Members of this Association are from the DHI, the DMI, the Folkecenter for Renewable Energy, the University of Aalborg and the Technical University of Denmark.

Ongoing projects [175]

Wave Star WEC

The Wave Star is a multipoint absorber WEC, consisting of a long platform set perpendicular to the wavefront. A row of floats is mounted on each side of the platform. Each float is connected by a lever to the platform and the movement of the floats operates the lever to create a hydraulic pressure and electricity in a hydraulic system and generator mounted on the platform. A grid-connected 1/10th scale 6kW system has been tested at Nissum Bredning in 1/10th North Sea conditions since 2006. In 2009, a 50kW section of a 500kW unit was installed and is currently under test prior to installation of a 500kW commercial generator. The design is expected to be scaled up to 6MW.

Wave Dragon WEC

The Wave Dragon is an overtopping WEC. It has two floating arms that focus waves towards a ramp and into a floating reservoir. The reservoir supplies water flow to a set of low-head Kaplan turbines to generate electricity. A 237-tonne, grid connected prototype was tested at Nissum Bredning between 2003 and 2005. The unit was rated at 20kW and typically produced two to three kilowatts in the relatively low wave energy environment of Nissum Bredning. In January 2005 the Wave Dragon successfully withstood storm conditions unprecedented for the Nissum Bredning area. Full scale units are planned for installation in Wales and Portugal.

Wave Plane WEC

The Wave plane is an overtopping WEC designed to capture as much as possible of the wave energy before the wave breaks. It does this by directing the wave through a series of curved channels converting the linear motion of the wave to rotational motion prior to entering the turbine. A scale model has been tested in Japan and full scale sea testing is about to take place in Denmark.

Nissum Bredning test station

To date more than 30 devices have been tested. Prior to testing, devices are required to be tested at a university wave tank. The wave environment is relatively sheltered and devices may therefore be tested down to ¼ scale. Testing may be carried out for periods ranging from a few days to several years. Facilities include lifting equipment, anchorage at 8m water depth, assistance with device launches, wind speed and wave height monitors and access to a range of local contractors for mechanical handling and lifting, electrical power and data management.

University and Institutional ORE Research [165]
University of Aalborg, Hydraulics and Coastal Engineering Laboratory,
Danish Maritime Institute (DMI)
Danish Hydraulic Institute (DHI)
Danish Technological Institute
Danish Wave Energy Society

Table 8-4 Danish Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Floating Power Plant	Poseidon 37	Prototype, sea tests
Leancon Wave Energy	MAWEC	Prototype, wave tank tests
Wave Star Energy A/S	Wave Star	Prototype, sea tests
WavePiston	WavePiston	Prototype, wave "tank" tests, public data
WavePlane A/S	Waveplane	Prototype, sea tests
Wave Dragon	Wave Dragon	Prototype, sea tests, public data Commercial scale units available

Table 8-5 Danish ORE developers.

Government Strategy and Support [168, 175, 176]

By 2020, Denmark aims to reduce its greenhouse gas emissions by 20 per cent relative to their 2005 level. Increasing the use of renewable energy towards independence from fossil fuels is a core policy requirement and steps towards this goal have been set as a 20 per cent renewable share of the energy mix by 2011 and a 30 per cent share by 2020. To achieve these targets the Danish Government has doubled its public expenditure for R&D to $A200 million per year. Denmark is keenly interested in wave energy, having tested about 40 wave energy concepts, taken nine to an advanced design stage and three to sea testing. Two are currently moving towards commercialisation. Denmark is also a member of the IEA's Implementing Agreement. The principal funding program for wave energy is ForskVE under the Law on the Deployment of Renewable Energy. Energinet.dk focuses on photovoltaics, wave-power units and other RE technologies such as bio-gasification and Stirling engines. Ocean energy projects currently running under this program include:

- advanced WECs 1 & 2 — LEANCON Wave Energy;
- energy production from marine biomass 1 & 2 (Ulva lactuca) — Danish Technological Institute;
- Integrated Wind and Wave Platform — Floating Power Plant;
- Green Power Island projects (not wave power but perhaps related through need for scale up to town level, wave calming, energy storage and international cooperation);
- grid connection of the Horns Rev 500kW system (Wave Star);
- grid connection of the Roshage test section of Wave Star;
- optimisation ofkWh production and reliability of Wave Star unit;
- optimisation of energy production on a Wave Star converter;
- determination of the osmotic power potential in Denmark;
- the world's first offshore electricity grid — Kriegers Flak;
- Wave Star Energy, C5, 500kW demonstrator for the North Sea; and
- wave wing.

8.2.5 India

With a 7,500 kilometre coastline and an average wave potential of 5 to 10kW/m, India is in the position of having a significant but low grade wave energy resource and has successfully demonstrated a small number of prototype OWC WECs producing from 6kW to 75kW. Significant OTEC resources are also available and India has made one unsuccessful attempt to access this resource. Perhaps the most widely-discussed resource is the tidal barrage for the Gulfs of Kutch and Khambat in Kalpasar. CSIRO's International Development group was involved some years ago in very early assessments of the Kalpasar resource. It has the theoretical potential to provide 16TWh of energy and also to act as a freshwater reservoir. The project has elicited significant levels of discussion over several decades on the environmental impact of creating this barrage and the resulting water quality.

ORE Resource [101, 177, 178]

Total electricity generating capacity	2007: 160GW
Electricity demand	2007: 570TWh
Theoretical wave energy	175TWhr/yr
Extractable wave energy	No formal estimates found
Theoretical tidal energy	88TWh/yr
Extractable tidal resource	No formal estimates found
Ocean thermal energy	440TWh/yr
Extractable tidal resource	No formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 59, 177, 178]

Wave energy

Initially wave energy projects were managed by the Indian Institute of Technology and the Department of Ocean Development. The focus was on Oscillating Wave Converters, and a number were built and operated — notably a 150kW wave energy system at Kerala in 1983 which had an average output that varied between 25kW and 75kW. The National Institute of Ocean Technology currently has an OWC plant operating at 6kW and producing 700 to 8000 litres of desalinated water per day. Wave energy is not yet considered to be commercially viable in India.

Tidal energy

Tidal power is being considered at length for the Gulfs of Kutch with a tidal range of five metres and potential resource of 1.6TWh (7GW) and Khambat in Kalpasar with a tidal range of six metres and a potential resource of 16.4TWh (9GW). India's first tidal power plant is being installed in Durgaduani creek in the Sunderbans delta by the West Bengal Renewable Energy Development Agency. The tidal range in this area is three metres and the plant will have an output of 3.5MW.

Ocean Thermal Energy Conversion

The National Institute of Ocean Technology (NIOT) have made an attempt to set up the world's first floating Ocean Thermal Energy Conversion (OTEC) plant for electricity generation (500kW). It is a Rankine Cycle-based power plant located on a barge, the Sagar Shakthi, 60 km off the Tuticorin coast, Tamil Nadu. The project has not yet been completed because of problems with the kilometre-long high density polyethylene pipeline and may instead be adapted for desalination applications.

University and Institutional ORE Research [165]
The National Institute of Ocean Technology
Indian Institute of Technology
Ministry of Earth Science (formerly Department of Ocean Development)
The West Bengal Renewable Energy Development Agency

Table 8-6 Indian Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Indian Wave Energy	IWAVE	Concept, information sparse

Table 8-7 Indian ORE developers.

Government Strategy and Support [168, 172, 177, 178]

The Ministry for New and Renewable Energy (MNRE) is actively engaged in the development of tidal energy resources and the Ministry of Earth Science, through its National Institute of Ocean Technology, is actively engaged with wave energy and OTEC. MNRE is responsible for taking the Indian Government's policy on renewable energy forward and this is described in their policy summaries:

- Policy Support for Grid Interactive Renewable Power.
- Renewable Power Policies.
- The National Mission For Enhanced Energy Efficiency.

8.2.6 Ireland

Ireland is notable for its significant wave resource. The west coast of Ireland has the highest level of wave energy in Europe. The Irish government has developed a structured policy for using ORE. This is supported by a high level of research activity and the development of test sites and protocols for trialling WEC technologies.

ORE Resource [101, 173, 179]

Total electricity generating capacity	2007: 7GW
Electricity demand	2007: 25TWh
Theoretical wave energy	190TWhr/yr
Extractable wave energy	21TWh/yr
Theoretical tidal energy	230TWh/yr
Extractable tidal resource	2.6TWh/yr
Economically extractable tidal energy	0.9TWh/yr

Wave Farms, ORE Projects and Test Facilities [7, 167, 173, 180]

Hydraulics and Maritime Research Centre

Based at University College, Cork, research at the Hydraulics and Maritime Research Centre (HMRC) includes investigations into wave climate analysis, wave energy devices and the use of a wave flume and an ocean wave basin. The Centre has also developed a quarter-scale test facility in Galway Bay and a test protocol for wave energy device development which is now in use throughout Ireland and has been promoted by the UK government.

Smart Bay

This is an environmental test and demonstration platform being set up by the Marine Institute in Galway Bay. Steps taken so far include the deployment of an array of buoys, each of which collect and deliver real time information on ocean conditions for dissemination via web-based services. One of the capabilities is expected to be a reduction in the time delay in acquiring data used for testing WEC prototypes.

Projects supported before 2009:

- Wavebob.
- Ocean Energy Buoy.
- Open Hydro.
- AquaBuOY.
- McCabe Wave Pump.

University and Institutional ORE Research [165]
Electricity Research Centre (ERC)
Department of Communication Energy and Natural Resources
Marine Institute
Sustainable Energy Ireland (the national energy agency)
University of Limerick
University College Cork

Table 8-8 Irish Universities and Institutions researching ORE.

Figure 8-12 Open Water Testing at the Ocean Energy test site [181].

ORE Developers [167]	Device	Status
Hydam Technology	McCabe Wave Pump	Scale prototype sea test
Jospa Ltd	Irish Tube Compressor	Lab tests
Joules Energy Efficiency Services	TETRON	Information sparse
Ocean Energy Ltd	Ocean Energy OWC Buoy	Sea tested
Wavebob Limited	Wavebob	Sea tested

Table 8-9 Irish ORE developers.

Government Strategy and Support [168, 179, 182]

The Irish Government has set a target to achieve a 50 per cent share of renewables in gross electricity consumption by 2025. It has made a policy decision to accelerate the development of Ocean Energy (Wave and Tidal) with the twin objectives:

- To have a centre of excellence in ocean energy technology and to encourage a world-class industry cluster.
- For 500MW of ocean energy to be connected by 2020.

Financial support is through an Ocean Energy Development fund expenditure estimated as $A37M from 2008 to 2009 and $A6.5M proposed for 2010. A feed-in tariff of $A0.30k/Wh for ORE was also introduced in 2008.

In response to this the Sustainable Energy Authority Ireland (SEAI), Ireland's national energy authority, has formed an Ocean Energy Development Unit to follow through a four phase strategic programme:

- Phase 1 Development: (2006 – 2008).
- Phase 2 Pre-Commercial Single Device: (2008 – 2012).
- Phase 3 Pre-Commercial 10MW Array.
- Phase 4 Commercial Deployment.

A major component of this plan will be the development of a National Wave Energy Test Site, proposed to be located off Annagh Head, in County Mayo. SEAI are currently assisting the Department of Communications, Energy and Natural Resources to prepare the Offshore Renewable Energy Development Plan. This will "describe the policy context for development of offshore wind, wave and tidal current energy in Irish waters for the period to 2030".

Prototype Development Fund Projects

Company	Project
Key Engineering Services Ltd	Industry led feasibility study of wave energy device
Cyan Technologies Ltd	Concept Testing of the CyanWave – Novel WEC
Technology from Ideas Ltd	TFI Wave Protector
Waveberg Ireland	Extended Tank Testing of the Waveberg 1:32 scale model
Ocean Energy Ltd	OE Buoy Research Project, Phase 3b, Finalisation of Research and Testing of Current Prototype (Quarter Scale)
OpenHydro Group Ltd	Design & Development of 16m Open-Centre Turbine System
Martin Houston and Sons Ltd	Houston WEC Proof of Concept Study
Wavebob Ltd	Wavebob ADM3 and ADM4 staged and combined wave-to-wire wave energy conversion demonstrated with linear generation power take-off (PTO)
Sea Power Ltd	Development of C pump
Marine Renewables Industry Association Ltd	Provision of a policy framework for Marine Renewables/ Ocean Energy (Wave and Tide)
Jospa Ltd	Phase 1 – Validation Model and Concept Testing

Table 8-10 Projects in Ireland about to be supported through the Prototype Development Fund

8.2.7 Japan

Japan has a relatively poor wave and tidal energy resource.

ORE resource [101]

Total electricity generating capacity	2007: 279GW
Electricity demand	2007: 1000TWh
Theoretical wave energy	36GW
Extractable wave energy	No formal estimates found
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	No formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 167, 168, 183]

Oscillating Water Columns (OWCs)

A number of OWCs have been trialled in Japan; these have been onshore or near shore units and include the following:

- From 1983 a number of near-shore or onshore OWC generators have been developed and tested at Sanze and Sakata by Saga University, sponsored by the Ministry of Transport. These have generally been rated from about 50kW to 100kW and have produced typically of the order of ten kilowatts, representative of the performance of such generators worldwide.
- The "Mighty Whale" was an offshore OWC project developed for the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). It was based on a ship and deployed in Gokasho Bay. The device had vertical columns in the front of the ship, which fed into Wells Turbines. The OWC was rated at 110kW with an average output of 6kW from wave heights of typically half a metre. It operated from 1987 to 2002 when it was decommissioned. During this period it produced 136MWh.

Saga University in Japan and institutes in Ireland and China are collaborating with the ongoing development of an OWC "backward bent" buoy installed in 1987, The Pendulor.

Inverted Pendulum

- An inverted pendulum device, developed by the Muroran Institute of Technology at the Harbor Research Centre, uses wave energy to swing a hinged plate driving hydraulic pistons which provide pressurised fluid to an electrical generator. The device can produce up to 5kW of power with efficiencies as high as 55 per cent. This device operated from 1994 to 1999.

Ocean Thermal Energy Conversion (OTEC)

- In 2003, the Japanese Government provided over $US40 million to The Institute of Ocean Energy at Saga University for research on OTEC. In 2006 the University demonstrated a small scale 30kW plant based on a mixed water/ammonia working fluid. Saga and NIOT of India have recently been collaborating on the development of a closed cycle OTEC system with ammonia as the working fluid.

University and institutional ORE research [165, 167, 168]
Ministry of Transport, Japan, Sakata
The Institute of Ocean Energy (IOES), Saga University
The Matsue National College of Technology, Saga University
Muroran Institute of Technology — Pendulor
Japan Marine Science and Technology Center in Yokohama — Mighty Whale

Table 8-11 Japanese Universities and Institutions researching ORE.

ORE Developers

ORE development is university and government-based.

Government Strategy and Support [168]

The Japanese Government has set a target for 2030 of 70 per cent for zero emission power. Its ORE research focus is on OTEC.

8.2.8 New Zealand

ORE Resource [101, 184]

Total electricity generating capacity	2008: 42GW
Electricity demand	2008: 39TWh/yr
Theoretical wave energy	Unknown
Extractable wave energy	61TWh (caution — early estimate)
Theoretical tidal energy	Unknown
Extractable tidal resource	4.5TWh/yr (caution — early estimate)

University and Institutional ORE Research

The National Institute of Water and Atmospheric Research (NIWA) is the Crown Research Institute with expertise in marine sciences, including resource assessments, hydrodynamics and mooring. Its National Centre for Energy Solutions is researching the extraction of energy from tidal systems with a focus on impacts and assessing the actual tidal flows and the variability in those flows [165, 185].

Wave Energy Technology-New Zealand (WET-NZ), in collaboration with Power Projects Limited and the Crown Research Institute, Industrial Research Limited (IRL), has developed a quarter scale, 2kW, WEC. This has undergone periodic sea testing off the coast of Christchurch since 2006. The consortium is currently developing a half-scale version funded by the New Zealand Government's Marine Energy Deployment Fund. It is expected to be commissioned in 2011 [165, 186].

The Aotearoa Wave and Tidal Energy Association (AWATEA) has 56 corporate, professional, non-profit and individual members [165].

University and Institutional ORE Research
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Table 8-12 New Zealand Universities and Institutions researching ORE.

There are an estimated 18 developers of ORE in New Zealand working at stages ranging from university research to sea testing scaled prototypes. Of these only seven have publicised their work. The WetNZ has achieved significant periods of deployment [184, 187].

ORE Developers [184, 187]	Device	Status
Crest Energy	Open Hydro Location — Kaipara Harbour	Resource consent hearing 29/05/08
Neptune Power	TiDEL device Location — Cook Strait	Resource consent granted 10/04/08
Power Generation Projects	Pelamis	On hold
WET-NZ	Proprietary device Location — Pegasus Bay & Wellington	Foundation for Research, Science and Technology (FRST) and Marine Energy Development Fund (MEDF) Government funding Device deployed periodically since December 2006
Tidal Flow Seamills	Vertical axis turbine Location — Karori Rip	On hold
Natural Systems Limited	HydroVenturi Location — Canterbury irrigation canals	Pending results of UK trials
Chatham Islands Marine Energy Ltd	Oscillating Water Column South-west coast of Chatham Island	MEDF Pending resource consent

Table 8-13 New Zealand ORE developers.

Government Strategy and Support

Policy [168]

The New Zealand Government announced its intention to prepare a national policy statement for renewable electricity generation in 2007. A policy draft note has been proposed. It describes the need for, and value of, marine energy. It makes note of approaches to the identification of adverse effects, and potential new opportunities. The draft note is not part of the national policy statement but is intended to indicate its general effect.

Funding [187]

The Energy Efficiency and Conservation Authority (EECA) manages the Marine Energy Deployment Fund, which helps support the development of marine energy in New Zealand. It was established in 2007 with a fund of $NZ8M. To date three grants have been allocated:

- $NZ1.85 million to Crest Energy for a tidal stream generator project at Kaipara Harbour.
- $NZ760,000 to WET-NZ for a WEC of the coast near Christchurch.
- $NZ2.16 million to Chatham Islands Marine Energy Ltd for two 110kW oscillating water columns wave converters on the south-west coast of Chatham Island.

The Foundation for Research, Science and Technology is another resource available for ORE funding, having in the past funded WET-NZ.

8.2.9 Norway

Norway has a large potential wave energy resource (400TWh/year) with wave power levels between 50kW/m in the north and 23kW/m in the south. Despite the potential for wave energy it is likely that Norway's work will remain focused on tidal energy because of its track record in hydroelectric projects, which produces 98 per cent of its electricity, and the relative uncertainties and early stage of development of wave energy technology.

ORE Resource [101, 173, 188]

Total electricity generating capacity	2007: 30GW
Electricity demand	2007: 114TWh/yr
Theoretical wave energy	400TWhr/yr
Extractable wave energy	No formal estimates found
Theoretical tidal energy	17TWh/yr
Extractable tidal resource	1TWh/yr — outdated, underestimated
Salinity gradient	25 TWh/yr

Wave Farms, ORE Projects and Test Facilities [7, 64, 173, 188]

Tidal

The Hammerfest tidal turbine is a 3-blade horizontal axis turbine. It is anchored to the seabed facing the tidal stream. The first tidal stream turbine is running at 50 metres depth in Kvalsundet near Hammerfest and has been supplying electricity to the grid for four years. Hammerfest plan to install a prototype in Scotland, eventually scaling up to 1MW commercial devices.

Wave

In the 1980s two onshore WECs were developed with government support following an extended period of research on WECs at the Norwegian University of Science and Technology. These were Kværner Brug's oscillating water column device and the Norwave A.S., Overtopping Water Turbine. Both were installed on the cliffs at Toftesfallen near Bergen. The Kvaerner Brug OWC sank in 1988 during a storm when the anchoring failed. The TAPCHAN overtopping device was damaged during an attempted upgrade. There have been several moves to commercialise the TAPCHAN. However, it is limited in application by its site requirements and there has been little news on the technology in recent years.

The FO3 device

FO3 is a multi point absorber developed by Fred Olsen Ltd with pressurised hydraulics. The point absorber floats oscillate in response to the waves, operating a hydraulic piston/motor system to generate pressurised fluid for use in an electrical generator. A 1:20 prototype was built and tested at the Marintek/Sintef laboratories in Trondheim and a 1:3 scale prototype, "Buldra", was installed outside Jomfruland, near the entrance to the Oslo fjord. The full-scale device is expected to produce 1.5MW.

Salinity gradient

Statkraft in collaboration with the Norwegian University of Science and Technology have set up the first laboratory to test the effectiveness of extracting the Gibbs free energy contained in the dipolar, electrostatic and hydrogen bonds between ions and water. They have set up prototypes at Tofte and intend to scale up this process in the next few years. The method they are using is the salinity gradient using pressure-retarded osmosis. It operates by using the osmotic flow of fresh water through an ion-selective membrane selecting solutions containing different concentrations of salt. This flow is used to turn a turbine. While large quantities of fresh water and a quite expensive membrane system are required, this process does have the advantage of having the highest energy density of all ORE resources. The theoretical potential has been confirmed by the Foundation for Scientific and Industrial Research (SINTEF).

University and Institutional ORE Research [165]
Research Council of Norway
Norwegian University of Science and Technology
University of Tromsø
Ghent University

Table 8-14 Norwegian Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Euro wave energy	Floating absorber	Concepts
Fred Olsen & Co and SEEWEC consortium	SEEWEC FO3	Sea tested
Ing Arvid Nesheim	Oscillating Device	Concepts
Langlee Wave Power	Langlee System	Prototype – preparing for sea tests
Ocean Wave and Wind Energy	Wave Pump Rig	Concept
Pelagic Power AS	Pelagic Power	Scale prototype, sea test
Pontoon Power	Pontoon Power Converter	Concept
Statkraft	Salinity gradient	Laboratory prototype
Straumekraft AS	Winch operated buoy	Sea trials
Wave Energy AS	Seawave Slot-Cone	Prototype, sea test

Table 8-15 Norwegian ORE developers.

Government Strategy and Support [168]

In 2006 the Norwegian Government set a goal for 2016 of 30TWh renewable energy sources over its 2001 level. This applies to heat and electricity. The agency for funding the research and development to support this goal is RENERGI, whose primary research areas are the renewables: hydro, bioenergy, wind, photovoltaics, thermal solar and ocean energy as well as energy usage and energy systems (including distribution and transmission), biofuels and hydrogen.

8.2.10 Portugal

Portugal has a significant wave energy resource with an annual wave power flux of 30 to 40kW/m. The most powerful waves are found on the north western coast and in the Azores. Portugal's scientists have been engaged in ORE research for three decades. The focus for wave energy development has been the design and testing of WEC devices, particularly OWC devices, both individually and in wave farms.

ORE Resource [101, 173]

Total electricity generating capacity	2007: 15GW
Electricity demand	2007: 49TWh/yr
Theoretical wave energy	88TWhr/yr
Extractable wave energy	44TWh/yr
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	No formal estimates found

Wave Farms, ORE projects and test facilities [7, 165, 173, 189-191]

While Portugal has specialised in the development of OWC technology it also has a very active international program for testing new technologies at its offshore facilities.

The Pico onshore OWC Pilot Plant

This was first set up in the Azores in 1999 under the coordination of the Instituto Superior Tecnico. Between 2003 and 2006 the Wave Energy Center and Instituto Superior Tecnico coordinated a refurbishment and testing program. The type of turbine and its environment produce a wide dynamic range of output varying from 1MWh between 2005 and 2006 and almost 1MWh in a period of 48 hours in May 2009. In recent years the installation has been used in a program of maintenance, measurement, training and public demonstrations.

Pelamis Wave Farm

This was a group of three P1-A Pelamis machines with a total rated capacity of 2.25MW installed at Aguçadoura, five km off the coast of northern Portugal. They operated for several months supplying power to the electricity grid at a feed-in tariff valued at approximately €0.23/kWh [29].

Wave Energy Centre

This is a non-profit organisation based in Portugal which conducts a range of national and international projects related to the management, monitoring and impact of ORE technologies. This includes a 700kW rated OWC installed in the Foz do Douro breakwater WEC technology, and which the Centre managed from 2004 to 2007.

The Archimedes Wave Swing (AWS)

The AWS point absorber converter is fully submerged 43m below the sea surface. It consists of an air-filled cylindrical chamber fixed to the sea bed and a floating movable upper cylinder. As a wave passes the associated water pressure moves the floater downwards, compressing the air inside the AWS to operate an electrical generator. This WEC was tested five km offshore at Leixoes, in 2004 delivering electrical power to the grid. Power levels of the order 10skW to 100skW were obtained [192].

The WaveRoller

This device is a system of plates anchored to the sea floor that can rock back and forward in response to wave surges. The movement is converted to hydraulic pressure via a set of piston pumps and then converted to electricity. The system was deployed for testing in April 2007 in Peniche.

University and Institutional ORE Research [165]
Instituto Superior Técnico
LNEG – Laboratório Nacional de Energia e Geologia (former INETI)
Wave Energy Centre

Table 8-16 Portuguese Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Martifer Energy Systems	FLOW	Prototype sparse information

Table 8-17 Portuguese ORE developers.

Government Strategy and Support [168]

The Portuguese gGvernment set a target in 2001 for 9680 MW of additional renewable energy capacity by 2010, with 50MW of this was intended to come from ORE. In addition Portugal is committed to a reduction of 8 per cent from 1990 levels by 2012 under Kyoto and this is in an environment of energy consumption growth of 14 per cent between 2001 and 2010. To this end the Ministry of Science and Technology provides funding for energy R&D projects, while funding for demonstration projects is provided by the Ministry of Economy using national and European funding sources. Additional incentives include:

- The creation of a Maritime Pilot Zone to facilitate licensing and permitting; the establishment of offshore corridors and the construction and maintenance of surrounding infrastructure.
- Feed-in tariffs for renewable energy which are set according to the type of resource/technology and the associated level of CO_2 emissions; wave energy has one of the highest feed-in tariffs (between $A201/MWh and $A388/MWh).

8.2.11 Sweden

Sweden has been carrying out research into WECs since 1976 and has provided the impetus for three commercial devices. This is despite the relatively low level of wave energy resource and the fact that its electricity supply is almost free of fossil fuel emissions. Exploitable wave energy can be found to the north of the coast facing the North Sea and Baltic Sea.

ORE Resource [101, 173]

Total electricity generating capacity	2007: 34GW
Electricity demand	2007: 135TWh/yr
Theoretical wave energy	No formal estimates found
Extractable wave energy	10TWhr/yr
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	No formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 43, 44, 173, 174]

Wave energy research in Sweden commenced at Chalmers University of Technology in 1976 and included a collaboration with the Technocean company. In 1980 Interproject Service AB developed a half-scale WEC, a point absorber buoy device invented by Sven A. Noren, that was sea tested off the coast near Goteborg. Between 1983 and 1986 a large number of WECs were developed as part of a National Wave Energy Programme. This included a hose-pump converter which has been incorporated into the AquaBuOY technology.

Floating Wave Power Vessel

The Floating Wave Power Vessel (FWPV) is an offshore slack-moored overtopping water turbine developed by Seapower International AB. It uses a tapered channel to focus and direct waves into a reservoir that drains through a set of low-head hydro turbines. A prototype was constructed and tested in waves of up to 12 metres. Model test were carried out at Chalmers University of Technology followed by sea testing for eight months off the west coast of Sweden in seas of up to 12 metres. Scottish & Southern Energy have let a contract for a full-scale plant to be installed off the coast of the Shetland Islands; this is projected to produce 5.2GWh per year.

EXIM (Tidal Vertical Axis Turbine)

Sea Power have also developed the EXIM Tidal Turbine Sea Power Sweden Vertical Axis Turbine, which has been tested at the Ship and Research Centre in Gdansk, Poland and in tidal currents near the Shetland Islands.

The Wave Farm at Lysekil

The Wave Power Project is focused on a linear generator technology directly converting wave power into electricity. The project has been running since 2001 through the Swedish Centre for Renewable Electric Energy Conversion at the Angstrom Laboratory, Uppsala University. It aims to install 10 generators at Lysekil, on the country's west coast, about one nautical mile west of the Islandsberg peninsula. The generators have a capacity of 10kW and are together capable of producing about 300MWh/yr. In addition. about 30 dummy buoys will be installed as part of the environmental testing. The project has three objectives:

- to verify the basic technology;
- to test the technology under realistic conditions; and
- to measure the impact on the local environment.

Uppsala University has described its research in some detail, covering design, construction, sea testing, and environmental impacts. The prototype technology is now well developed and a local company, Seabased, is in the process of installing the wave farm in Lysekil. By 2009 WECs and a number of environmental test buoys had been installed together with the underwater substation that collects and transforms the energy into a form suitable for connection to the grid. This research is principally funded by: Swedish utility Vattenfall, the Swedish Energy Agency, the Ångpanneföreningen research foundation, Gothenburg Energy and the Dutch cable manufacturer Draka Holding N.V.

University and Institutional ORE Research [165]
Uppsala University
Chalmers University of Technology

Table 8-18 Swedish Universities and Institutions researching ORE.

Figure 8-13 Biology buoys for environmental research at Lysekil prior to establishing the wave farm [45].

ORE Developers [167]	Device	Status
Interproject Service (IPS) AB	IPS OWEC Buoy	Full scale sea tests
Ocean Harvesting Technologies	Ocean Harvester	Concept
Sea Power International AB	Streamturbine	Commercial unit under construction, sea tests
Sea Power International	Floating Wave Power Vessel	Commercial unit under construction, sea tests
Seabased AB	Linear generator	Prototype sea tests with public data
Vigor Wave Energy AB	Vigor WEC	Concept

Table 8-19 Swedish ORE developers

Government Strategy and Support [168, 193-195]

More than a third of Sweden's energy supply depends on oil imports, with electricity in Sweden being largely supplied locally from hydropower and nuclear power production. Since 1970 the use of oil has reduced from 70 per cent to 30 per cent with renewable energy increasing to 22 per cent of Sweden's energy supply, particularly biomass and to a lesser extent wind energy. The Commission on Oil Independence is responsible to the Swedish Government for presenting proposals to reduce Sweden's dependence on oil. Its report "Making Sweden an Oil Free Society" proposes supporting the use of wave power and the Swedish Energy Agency has awarded the company Seabased $A21M to develop a full-scale wave power plant for large-scale electricity production with an output of 10 megawatts.

8.2.12 United Kingdom (UK)

The northern and west coasts of the UK receive wave energy absorbed from wind across thousands of kilometres of fetch over the Atlantic Ocean. This is about 35 per cent of Europe's total wave energy resource and potentially 12 per cent of UK electricity production. This combined with the oil crisis of 1973 has led to a long-standing research program for WEC device development and the provision of testing facilities to trial technologies from around the world.

ORE Resource [101, 173, 196, 197]

Electricity generating capacity	2007: 84GW
Electricity demand	2007: 346TWh/yr
Theoretical wave energy	260TWhr/yr
Extractable wave energy	60TWh/yr
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	17TWh/yr

Wave Farms, ORE Projects and Test Facilities [7, 198]

Land Installed Marine Powered Energy Transformer (LIMPET)

The Limpet OWC WEC was a research unit evaluated for several years on the Isle of Islay and a significant project in the UK's DTI Sustainable Energy Programme. The converter was not located in a region with sufficiently strong waves to function at full power, or a grid system rated to take its full power output. Nevertheless it reached its rated capacity on at least one occasion during a storm, remaining operational with minimal damage. The machine was compromised on two occasions by debris build up in the water intake. The machine typically operated at 10 per cent of its capacity. Nevertheless the device produced sufficient data for subsequent small-scale designs to be developed for commercialisation by Voith Hydro Wavegen Limited.

European Marine Energy Centre (EMEC)

The European Marine Energy Centre was set up in Scotland to provide open sea test facilities for wave and tidal current technology. It was established in 2004 at the recommendation of a House of Commons Science & Technology Select Committee. There are two sea test sites: one at Orkney for WECs and the other at the Isle of Eday for tidal stream generators. The sites provide an opportunity for research into tidal and wave energy devices as well as facilities for energy conversion assessment, life testing, and accreditation for Renewables Obligation certification — along with access to nearby harbours and engineering capabilities. One of the first devices to be successfully tested at EMEC was the Pelamis in 1994. This was the first commercial scale machine to deliver electricity to the national grid.

Peninsula Research Institute for Marine Renewable Energy

Exeter and Plymouth universities have formed the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE). This aims to carry out research projects on marine renewable energy using the nearby Wave Hub facility and a facility at Falmouth Bay for testing mooring dynamics and design. Research focuses on the significant challenges faced by marine renewable energy including:

- resource characterisation;
- marine renewable energy systems;
- environmental and biodiversity impacts;
- safe operations and navigational risk;
- underwater and surface electrical systems; and
- socio-economic factors.

New and Renewable Energy Centre (NaREC)

NaREC is a Marine Test Facility set up as a "Centre of Excellence" by the regional development agency One NorthEast. The facility provides design simulation testing, and wave testing of scaled (typically 1/10) devices. It has three seawater docks, a wave maker, and pumps to simulate a tidal race.

Wave Hub

Construction of the Wave Hub was competed in 2010. It allows developers to take their WECs from a single device test facility such as EMEC and set them up for testing in an offshore wave farm configuration. It provides a sea floor grid connection weighing 11 tonnes, costing £42M and rated at 11kV, 16MW, with a limit of 4 to 5MW per development. Up to four developments can be accommodated for five years at a time with each in an area up to 2km^2.

Pelamis

There are numerous examples of WEC devices being developed in the UK or imported for trial in the UK. One of the most advanced devices of UK origin is the Pelamis, an "articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure fluid through hydraulic motors". The pressurised fluid is then used to drive a generator within the structure and power is fed to a junction box on the seabed. The Pelamis is rated at 750kW and will usually produce between 25 per cent and 40 per cent of its rated output. It has been sea trialled in the North Sea, at the EMEC test centre, Orkney, and in a wave farm configuration at Agucadoura, Portugal. A second generation version has undergone sea testing in the Firth of Forth and has recently been installed for tests at EMEC. Pelamis Wave Power is planning to set up four wave farms in: the Shetland Isles, Portugal and the north and west coasts of Scotland.

University and institutional ORE research [165, 198]
Queen's University Belfast
Exeter University
Plymouth University
Supergen (Consortium of Universities of Edinburgh, Robert Gordon, Lancaster, Heriot-Watt and Strathclyde)
Carbon Trust
Edinburgh University Sloped IBS Buoy, Wave Power Group – Salter Duck

Table 8-20 UK Universities and Institutions researching ORE.

ORE Developers [167]	Device	Status
Aquamarine Power	Oyster	Concept & lab tests
AWS Ocean Energy	AWS 1,2	Prototypes, sea tests, public data
	AWS 3	Concept & lab tests
Caley Ocean Systems	Wave Plane	Prototype
Checkmate Sea energy UK Ltd	Anaconda	Concept & lab tests
C-Wave	C-wave	Prototype
Embley Energy	Sperboy	Prototype
Green Ocean Energy Ltd	Ocean Treader wind/wave	Prototype
Greencat Renewables	Wave Turbine	Prototype
Manchester Bobber	Manchester Bobber	Prototype
Neptune Renewable Energy Ltd	Triton	Prototype 1/10 scale
Ocean Navitas	Aegir Dynamo	Prototype full scale
Ocean Wavemaster Ltd	Wave Master	No recent information
Offshore Wave Energy Ltd	OWEL Energy Converter	Concept and lab tests
Pelamis Wave Power	Pelamis	Sea tested full scale public data
Renewable Energy Holdings	CETO	Prototype
Trident Energy Ltd	The Linear Generator	Prototype
Voith Hydro Wavegen	Limpet	Sea tests, public data

Table 8-21 UK ORE developers.

Government Strategy and Support [168, 199, 200]

The UK government has recognised the potential of the UK's wave and tidal energy to supply 15 to 20 per cent of its current electricity demand and for its advanced test facilities to act as a "global focal point" for development of wave and tidal energy. Through the Department of Energy and Climate Change (DECC) it has also developed a Marine Action Plan with the following themes:

- The need to prove the technology, particularly to stimulate long-term investor confidence.
- Providing the appropriate regulatory frameworks.
- Ensuring appropriate funding is in place for the sector (public and private).
- Co-operation and engagement across the sector and supply chain; and the importance of interdependency of all these themes.

In developing ORE technology the DECC encourages the use of test facilities and industry best practice through protocols such as the:

- Preliminary Wave Energy Device Performance Protocol: a set of guidelines aimed at producing clear, consistent and meaningful assessments of the performance of wave devices.
- The Ocean Energy Development & Evaluation Protocol: a schedule of trials from concept assessment, through wave tank testing towards testing in the open sea. This follows a protocol similar to those used by NASA and many engineering research establishments.

The DECC Marine Action Plan makes the following recommendations for funding and oversight of expenditure:

- Set up a strategic coordination group that encompasses Government and Devolved Administrations, Regional Development Agencies, Carbon Trust, Technology Strategy Board, Energy Technology Institute, and the EPSRC Supergen Marine Research Consortium, to ensure that a strategic overview for Government funding exists and that value from government expenditure is maximised.
- Retain the Marine Renewables Deployment Fund (budget $A80M over a maximum of seven years) or similar instrument and extend its operation to cover new devices reaching demonstration stage in the period 2011–2014.
- Highlight wave or tidal energy as one of the three project applications for funding under the European Commission in the New Entrants Reserve. This Reserve is valued at $A424M and is available until 31 December 2015 to help stimulate the construction and operation of up to 12 commercial demonstration projects — though aimed at carbon capture and storage projects — apply also to innovative wave and tidal stream demonstration projects.

Most importantly, the Marine Action Plan sets out a time frame to 2030 for development of wave and tidal energy. This is of crucial importance to Australian considerations as our economic projections suggest that timing and foresight would be essential for expansion of an ORE market in Australia, and this plan is a reasonable indication of how the technology is expected to develop amongst the key nations developing the ORE resource. In examining this plan it is worth bearing in mind that the economic projections we have made assume a rapid start up of wave farm installation in Australia commencing in 2015.

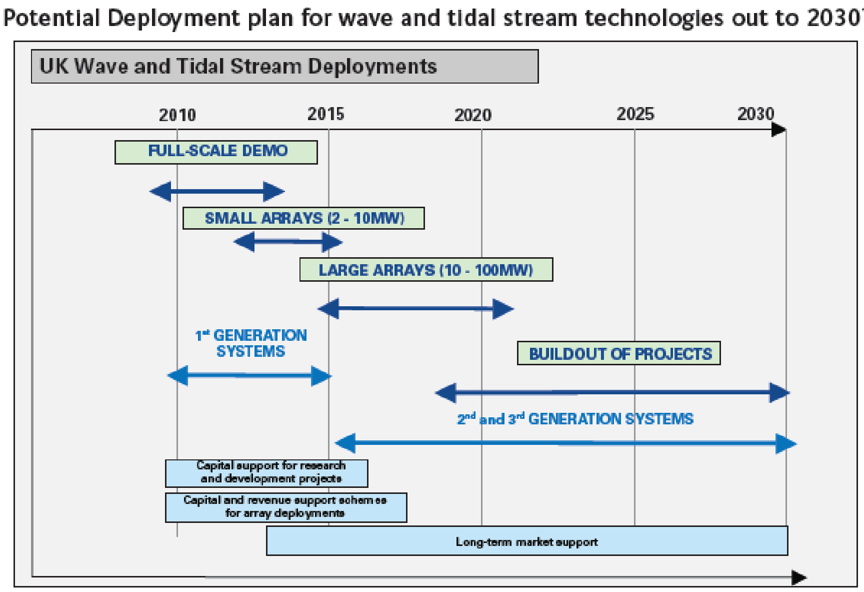

Figure 8-14 Potential deployment for wave and tidal stream technologies to 2030 [200].

8.2.13 United States of America (USA)

In 2005 The Electrical Power Research Institute carried out a preliminary survey identifying a total US resource of 2100TWH/yr with potential sites in Northern California, Hawai'i, Oregon, Washington State and Massachusetts. This has helped to stimulate interest in the US, which now has an active program of ORE development. In September 2010 after a lengthy programme of sea testing in the Atlantic and Pacific Oceans, a WEC was connected to the grid for the first time in the United States.

ORE Resource [101, 201]

Total electricity generating capacity	2007: 995GW
Electricity demand	2007: 4000TWh
Theoretical wave energy	2100TWhr/yr
Extractable wave energy	No formal estimates found
Theoretical tidal energy	No formal estimates found
Extractable tidal resource	No formal estimates found

Wave Farms, ORE Projects and Test Facilities [7, 198]

Northwest National Marine Renewable Energy Center (NNMREC)

This centre is a partnership between Oregon State University and Washington University with collaborative linkages also to the University of Hawai'i and Florida Atlantic University. The NNMREC has proposed developing a test centre for developers of wave and tidal energy. At present the principal focus is on tidal energy. Field studies are carried out at Admiralty Inlet Puget Sound and research foci include:

- "Modelling of environmental effects of extraction for both near-field and far-field."
- "Instrumentation for cost-effective characterisation of sites and devices."
- "Optimisation of arrays with respect to device orientation and placement."
- "Improved reliability and survivability of devices through use of advanced composites."

Hawai'i National Marine Renewable Energy Center

The Hawai'i National Marine Renewable Energy Center (HINMREC) is funded by the USDOE and managed by the Hawai'i Natural Energy Institute (HNEI) at the University of Hawai'i. It has set itself two goals:

- "at least one utility intertie [6] Wave Energy Conversion (WEC) device operating under a power–purchase-agreement (PPA) in Hawai'i."
- "the final (engineering) design, with licensing and permits, of a pre-commercial Ocean Thermal Energy Conversion (OTEC) plant sized at about 5MW."

HINMREC currently has four sites with research focusing on:

- Commercial wave power systems test site (under development at Maui and Kaneohe Oahu).
- Corrosion and biofouling research (Makapu'u Oahu).
- Ocean thermal energy research (Hawai'i).

New England Marine Renewable Energy Center

The New England Marine Renewable Energy Center (NEMREC) is a large consortium of universities and industry partners that became active in 2008 and has set itself the following goals:

- "A world class university research consortium to encourage collaboration, cooperation and education for marine renewable research."
- "Permanent ocean test sites to facilitate research and demonstration of ocean based renewable technologies."
- "An industry user group to elicit research needs, and to assist in advocating for public and private development support."
- "Involvement of regulatory and environmental public interest groups to ensure ocean development standards minimise impact to the ocean ecosystem."
- "Education and training to support the marine renewable energy industry."

The centre has coordinated four conferences over the last two years and is promoting the concept of the test centres.

Florida Atlantic University's Center for Ocean Energy Technology

The Center for Ocean Energy Technology (COET) was set up in 2007 at Florida Atlantic University (FAU), with a $US5 million grant from the State of Florida. In August 2010 the US Department of Energy designated the COET as a national centre for ocean energy research and development. Funding will be made available from the Department of Energy (DOE) for the centre to work on ocean current and ocean thermal energy technologies. While FAU is located in Boca Raton, it has campuses located in the Florida cities of Dania Beach, near the US Navy South Florida Testing Facility, and in Fort Pierce at the Harbor Branch Oceanographic Institution. Marine and oceanographic research has been carried out at these institutions for 40 to 50 years. It is possibly the only institution worldwide with a focus on exploiting non-tidal (Gulf Stream) ocean current power.

Oregon State University

Oregon State University is carrying out research on linear direct-drive WECs and in 2008, in collaboration with Columbia Power Technologies demonstrated power generation in a 10kW rated device installed for five days off Newport Oregon. It continues to carry out research towards a full scale WEC at the Northwest National Marine Renewable Energy Center.

Ocean Power Technology

Ocean Power Technology have been developing their Power Buoy WEC since 1994 and have accumulated 4,400 operational hours of testing. In September 2010 OPT were the first in the United States to connect a WEC to the grid. They estimate that a 10MW rated Power Buoy station would take up 0.125 square km.

6 "Intertie" – connection from wave energy converter to electricity grid.

University and Institutional ORE Research [165, 198]
The Ocean Renewable Energy Coalition (OREC)
Electric Power Research Institute (EPRI)
National Renewable Energy Laboratory (NREL)
Northwest National Marine Renewable Energy Center (NNMREC), a partnership between: > Oregon State University (wave energy research) > University of Washington (tidal energy research)
Florida Atlantic University's Center for Ocean Energy Technology
New England Marine Renewable Energy Center > UMass Dartmouth — School for Marine Science and Technology > UMass Amherst — The Wind Energy Center > UMass Boston — Urban Harbors Institute (UHI) > MIT — School Wide Modular Program for Fluid Mechanics > University of New Hampshire — Center for Ocean Renewable Energy (CORE) > University of Rhode Island Ocean Renewable Energy Colloquium > University of Edinburgh, Science and Engineering Department, Institute of Energy Systems (link to UK Super Gen consortium)
Hawai'i National Marine Renewable Energy Center

Table 8-22 USA Universities and Institutions researching ORE.

Figure 8-15 Oregon State University Wave Research Lab used to develop the Linear Direct-Drive Wave Energy Generator [202].

ORE Developers [167]	Device	Status
Able Technologies L.L.C.	Electric Generating Wave Pipe	Concept
Atmocean	Combined CSS/electricity	Sea tested
Aerovironment (AV)	Sub Surface Wave Buoy	Prototype sea tested
Bourne Energy	OceanStar	Limited information
Columbia Power Technologies	Linear Generator Buoy	Sea tested
Delbuoy	Wave Powered Desal	Sea tested
DEXA Wave UK Ltd	DEXA WEC	prototype
ELGEN Wave	Horizon Platform	Limited information
Finevara Renewables	Aqua Buoy	Sea tested some public data
GyroWaveGen	GyroWaveGen	Prototype
Independent Natural Resources	SEADOG	Sea tested
Ocean Energy Industries, Inc	WaveSurfer	Sea tests some public data
Ocean Motion International		Prototype
Ocean Power Technologies	Power Buoy	Sea tested full scale
Ocean Wave Energy Company	OWEC	Limited information
Offshore Islands Limited	Wave Catcher	Limited information
Renewable Energy Pumps	Wave Water Pump	Concepts
Resolute Marine Energy, Inc	Resolute WEC	Prototype
Rothman Energy Systems	Rothman Energy Systems	Limited information
Sara Ltd	MHD WEC	Prototype
SeaVolt Technologies	Wave Rider	Australian project
SRI International	Electroactive Polymer	Sea tested prototype
Swell Fuel	Lever Operated Pivoting Float Swell Fuel	Limited information
WindWavesAndSun	WaveBlanket	Limited information

Table 8-23 USA ORE developers.

Government Strategy and Support [168, 203, 204]

The United States does not have a national renewable energy standard. However, 28 states have set Renewable Portfolio Standards aimed at encouraging increased investment in research and development.

Federal permits for ORE development

The Federal Energy Regulatory Commission (FERC) has responsibility for preliminary permits to assess wave energy resources, device performance and environmental impact. These preliminary permits are required for locations within 3NM of shore prior to applying for either a pilot project license (short term), or a full license, both of which will allow on site construction and grid connection. On the outer continental shelf the licensing responsibility is shared with the Department of Interior (DOI) through the Minerals Management Service. At the end of 2009, 13 FERC preliminary licenses had been issued.

Federal incentives for wave power development include:

- corporate tax credits (e.g. Renewable Energy Production Tax Credit);
- grants (DOE, Treasury);
- loans for local governments, utilities, or rural electric cooperatives;
- Production Incentives (for example Renewable Energy Production Incentive); and
- Green Power Purchasing and Aggregation Incentives (for federal government energy purchases).

The US Federal government also provides significant support for renewable energy with Treasury issuing $US 2.2 billion Clean Renewable Energy Bonds and DOE providing about $US850 million in 2009. However, the proportion that goes to wave energy is relatively small at about $US30 million of DOE grants for all forms of water power including hydropower [205].

Wave Energy – FERC Preliminary Permits

Project Name	Licensee	Authorised Power Capacity
Reedsport OPT Wave Park	Reedsport OPT Wave Park, LLC	50MW
Coos Bay OPT Wave Park	Oregon Wave Energy Park Partners	100MW
Douglas County Wave& Tidal Energy	Douglas County, Oregon	1-3MW
PG&E Humboldt Waveconnect	Pacific Gas & Electric	40MW
Oregon Coastal Wave Energy	Tillamook Intergovernmental Development Entity	180MW
Grays Harbor Ocean Energy	Grays Harbor Ocean Energy Co., LLC	6MW
Green Wave San Luis Obispo	Green Wave Energy Solutions, LLC	100MW
Green Wave Mendocino	Green Wave Energy Solutions, LLC	100MW
Del Mar Landing	Sonoma County (CA) Water Agency	5MW
Fort Ross (South)	Sonoma County (CA) Water Agency	5MW
Fort Ross (North)	Sonoma County (CA) Water Agency	5MW
SWAVE Catalina Green Wave	Sara, Inc.	6MW
Oceanlinx Maui	Oceanlinx Hawai'i, LLC	2.7MW

Table 8-24 USA FERC permits.

8.3 Summary

While research into ORE is evident in all continents of the word, the hub for this research is centred in Europe with Denmark, Norway Sweden and the UK, leading device research and Ireland, Portugal and the UK having placed a significant investment into the development of "WaveHubs", sea-based test centres that serve the dual purpose of allowing device developers to test their WECs and local utilities to gain experience in bringing the power from such devices to the grid. The United States and Canada are developing a diverse range of technologies and have significant expertise along with Ireland in the generation of publicly available device assessment data notably through EPRI.

In Australia, research has been ongoing for a decade or more into OWC converters and tidal power. It has accelerated in recent years to include several developed or nearly developed technologies notably CETO and OPT. There is, however, a significant lack of experience in public device evaluation and in costing, valuing and managing the power that may be generated by such devices.

9. Conclusion

A comprehensive study, on behalf of the Wealth from Oceans (WfO) and the Energy Transformed (ETF) Flagship Programs, of the potential role of Ocean Renewable Energy (ORE) in Australia has been completed. The study covered the inferred energy resource, in terms of wave, tidal and ocean flows, the availability of the resource, conversion devices and their operation, economic projections and Australian and international developments. The study also touched on potential environmental impacts and competing use issues associated with prospective ORE sites.

The study concluded that there is likely to be a significant role for wave energy in Australia's energy future, provided there is a price on carbon dioxide emissions as proposed by the Federal Government and that the various technologies remain within appropriate capital and operating cost thresholds. Prospects for large scale deployment of tidal and ocean energy devices and systems were less likely to penetrate the market in the timeframe considered.

Sixteen ORE companies that have significant activities in Australia were identified. These vary from the beginnings of the construction of commercial "farms" of devices, to demonstration and piloting of individual devices to small scale/laboratory testing of devices and concepts. In a number of cases, significant grant support (e.g. $A66 million to OPTA) has been given to the more advanced of the Australian activities.

Given the current activity, and the outputs of the modelling showing that ORE could be a significant contributor to Australia's future energy supply, the study recommends CSIRO commence a structured approach to the development of an ORE program. Recommendations are made and presented in stages to ensure that the impact, funding and scientific requirements of the WfO and ETF Flagships Programs can be monitored and satisfied.

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Appendix A: Supplementary Information for Chapter 7

Additional modelling assumptions

The capital costs in the starting year of the models (2006) in 2006 $A are shown as sent-out figures in $A/kW. For the technologies with experience curves the starting cost may vary slightly from this value because of the segmentation of the experience curve. This is particularly the case for PV and wind, where there was already a price bubble in 2006. The experience curves are at a lower cost in the model but the penalty constraint ensures that the price in the objective function reflects the actual price paid. The efficiency of fossil fuel, biomass and nuclear technologies in 2006 is also given, as is the capacity factor of each technology in 2006.

For wind, PV, solar thermal, wave and ocean current, the capacity factor includes the availability factor. During the model run the efficiency and capacity factors are assumed to improve by incremental amounts in addition to continuing technological development captured in the experience curves.

The physical lifetime of the technology varies between technologies. For coal-based, hydro and nuclear it is 50 years. For biomass, conventional geothermal and hot fractured rocks it is 30 years and for all others 25 years. The assumed amortisation periods for capital cost calculation purposes are assumed to be shorter — between 20 to 30 years. The inverter used in PV is a special case. The inverter is replaced at half the lifetime of the rest of the PV plant (at 12.5 years). The construction times for the plant are assumed to be less than one year for PV and all forms of DG, one year for wind and gas peaking plant, two years for wave farms, solar thermal and biomass plants, five years for nuclear and three years for all other plants. The fuel costs and fixed and variable operations and maintenance costs are from the ESM database. The discount rate is 7 per cent and the cost of CO_2 transport and storage is fixed at $A20/tonne for all CCS plants [206-208].

The values used for the fixed and variable O&M cost are constant over time for fossil fuel plants, nuclear, hydro, conventional geothermal and hot fractured rocks but vary for all of the other plants, where they tend to decrease over time. There is no fixed O&M cost for rooftop PV. The transmission and distribution (T&D) cost is fixed over time but it varies by technology depending on the location of the resource (because of the requirement for new transmission infrastructure) [209].

The costs of all fossil fuels are assumed to increase over time. Global reserves of natural gas are more constrained than coal and the price of gas has tended to follow the oil price globally [210]. Therefore, natural gas is treated differently in GALLM. The supply vs. price is segmented into an upward-sloping step function so that high gas consumption increases the price. Uranium and biomass also have segmented supply vs. price curves because they are a limited resource, biomass in particular for Australia. There are five different segments in the model for each supply-constrained fuel.

Technology	Capital cost ($/kW sent out)	Efficiency (per cent)	Capacity factor (%)	Variable O&M ($/MWh)	Fixed O&M ($/MWh)	References
Black coal, pf	1948	35.1	80	1.2	4.28	[206, 211-214]
Black coal, IGCC	3004	41.0	80	1.5	6.28	[206, 213-216]
Black coal with CCS	4348	25.2	80	2.7	7.13	[206, 211-214, 217]
Brown coal, pf	2895	28.0	80	1.2	6.14	[206, 211-214]
Brown coal, IGCC	3320	41.0	80	1.5	6.99	[206, 213-216]
Brown coal with CCS	7380	17.0	80	2.7	7.85	[206, 211-214, 217]
Gas open cycle	449	20.0	20	7.5	12.47	[206, 213-216]
Gas combined cycle	892	49.0	80	4.85	2.85	[206, 213-216]
Gas with CCS	2900	40.0	80	14.96	10.73	[206, 213-215, 217-220]
Nuclear	3971	34.0	80	2.0	4.99	[206, 213-215]

Table 9-1 Modelling assumptions and references for fossil fuel technologies.

Technology	Capital cost ($/kW sent out)	Efficiency (per cent)	Capacity factor (%)	Variable O&M ($/MWh)	Fixed O&M ($/MWh)	References
Hydro	3246	NA	20	2.0	19.98	[206, 213, 214]
Biomass	2924	26.0	45	3.0	12.54	[206, 213, 214]
Solar thermal	5898	NA	25	1.5	22.73	[206, 213, 214, 221-239]
Hot fractured rocks	4633	NA	80	2.0	9.99	[206, 213, 214, 235, 240-248]
Conv. geothermal	2878	NA	80	2.0	9.99	[235, 239, 248-251]
Wave	7000	NA	50	17.0	15.13	[106, 235, 252-259]
Ocean current	5200	NA	35	17.0	21.61	[106, 235]
Wind	1518 (DV); 1742 (AU); 1389 (UN)	NA	29	1.6	13.73	[101, 106, 206, 213-216, 260-265]
PV rooftop	10529 (DV); 9960 (AU); 11858 (UN)	NA	20	2.14	0	[106, 220, 235, 252, 266-275]
PV large scale	6969 (DV); 6615 (AU); 7867 (UN)	NA	20	1.5	11.33	As above

Table 9-2 Modelling assumptions and references for renewable technologies.

Fuel type	Cost of fuel ($/GJ)	Emissions (kgCO_2/GJ)
Brown Coal	0.5	93.6
Black Coal	1.0	95.29
Natural gas	0.9	62.9
Biomass fuel	0.6	0
Uranium	0.7	0

Table 9-3 Modelling fuel cost and emission assumptions.

Capacity factor and rated power cancelling worked examples

Shown in Table 9-4 below is a hypothetical example where we use a generic WEC which has a fixed cost (in $A) and it produces a given average amount of electricity (inkWyr) in a generic location. In both cases shown below the same WEC is assigned a different rated power. This leads to a different capital cost (in $A/kW) and a different capacity factor (unitless). However, the LCOE (in $A/kWh) is the same. This means the rated power and the capacity factor have cancelled out. In the economic models, the technologies with the lowest LCOE (subject to constraints) are the ones that contribute to electricity generation.

	Low rated power example	High rated power example
Cost of one unit of WEC	$A1000	$A1000
Rated power	1kW	10kW
Capital cost	1000/1 = 1000 $A/kW	1000/10 = 100 $A/kW
Avg electricity prodn in same region	0.5kWyr	0.5kWyr
Capacity factor	0.5/1 = 0.5	0.5/10 = 0.05
LCOE	(1000*constant)/0.5 = 2000*constant $/kWh	(100*constant)/0.05 = 2000*constant $/kWh

Table 9-4 Worked example of capacity factor and rated power cancelling.

To further stress the point, we have performed simulations in ESM where the WEC in the model is taken from the example shown above. Thus, in the first simulation we have used a capital cost of 1000 $A/kW with a capacity factor of 0.5. In the second simulation, we have used a capital cost of 100 $A/kW and a capacity factor of 0.05. These are the only differences in the simulations. The results are shown below: they are exactly the same. For ease of exposition, these calculations use simplified assumptions as shown in order to focus on the effect of capacity factor. They should not be used as projections.

Capacity factor check results

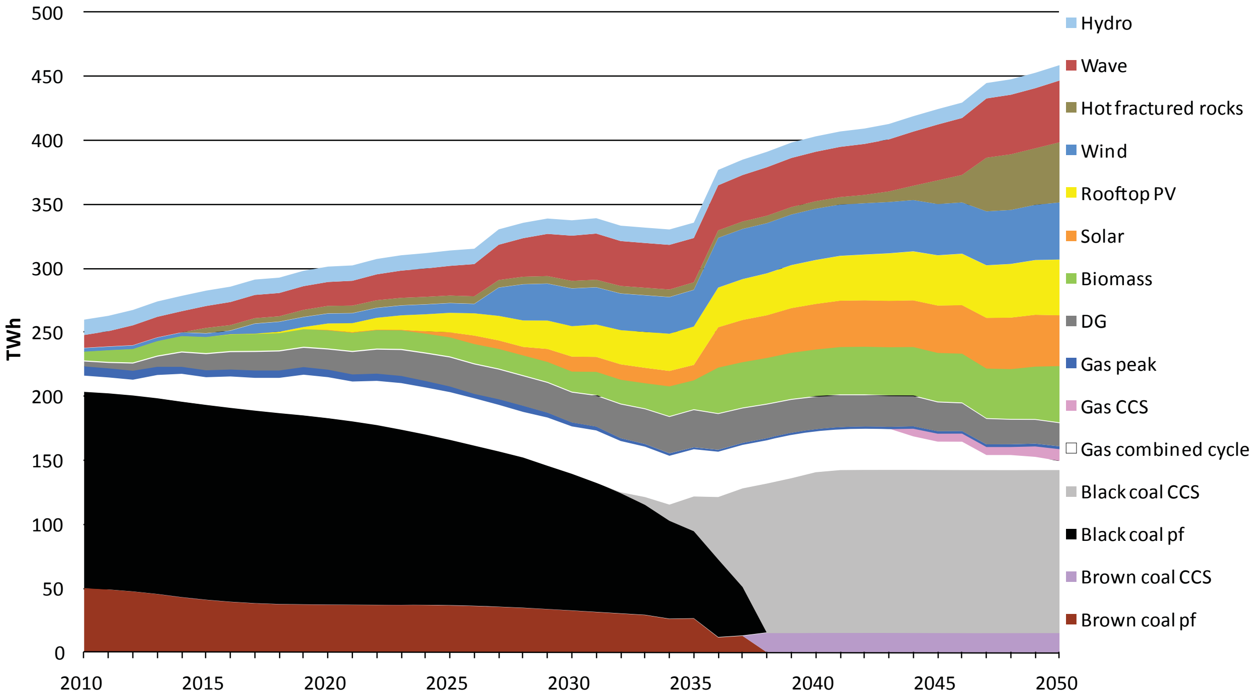

Figure 9-1 Low rated power example.

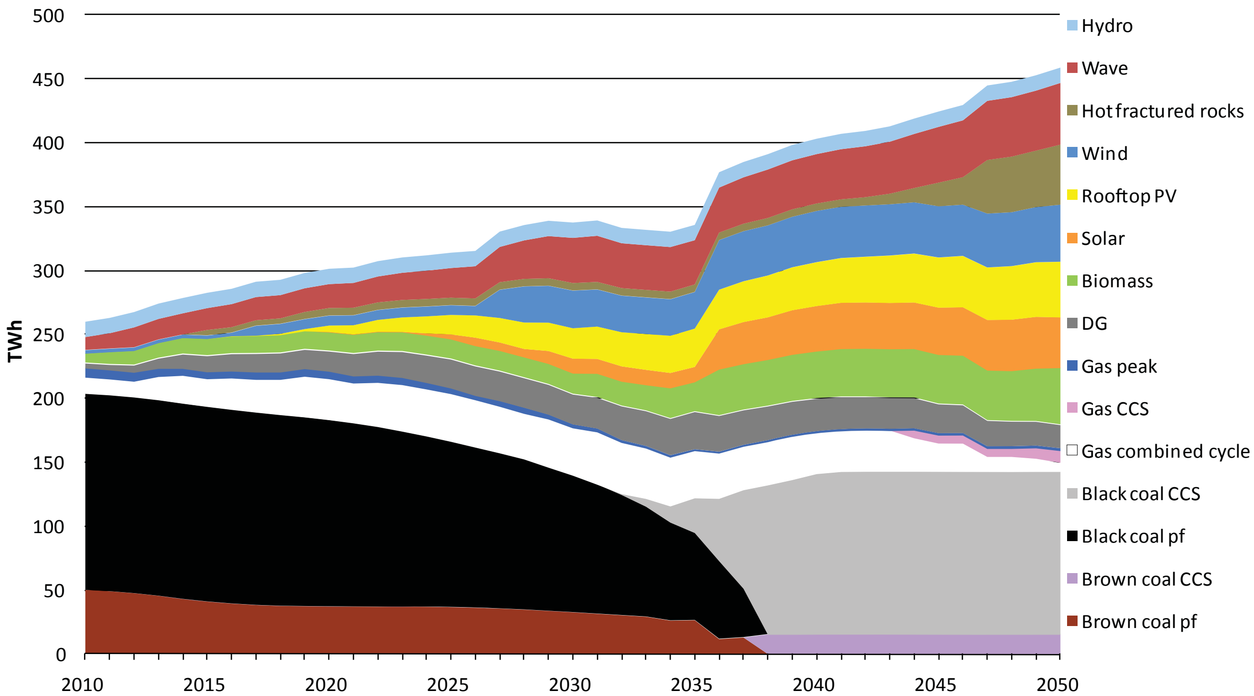

Figure 9-2 High rated power example.

Summary of Assumptions

All costs are in 2006 AUD.

Capital costs

Initial costs in 2006 are:

- Point absorber: 1069 $/kW
- Linear attenuator: 4531 $/kW
- Terminator: 3063 $/kW

These costs were taken from Dunnett and Wallace (2006).

These costs are based on a 21MW wave farm configuration. Because each device type has a different rated capacity, this means there are different numbers of devices in a 21MW wave farm.

- Point absorber: 84 units
- Linear attenuator: 28 units
- Terminator: 3 units

Based on the number of units, we were able to determine the amount of mooring required to tether each unit. The cost of mooring to a depth of less than 50 metres was taken from Dunnett and Wallace (2006).

The amount of cabling required to connect the farm to the grid was the same for each wave farm configuration. This was assumed to be 5 Km of cabling. The cost of cabling was taken from Dunnett and Wallace (2006).

Final capital costs in 2050 are:

- Point absorber: 858 $/kW
- Terminator: 1026 $/kW or 2228 $/kW

We did not model the linear attenuator as its levelised cost of electricity (LCOE) was too high in the earlier analysis we performed (Behrens *et al.* 2011).

The terminator has been tested with two lower limits on its capital cost, in order to test the sensitivity of the results to capital cost. The first results in a reduction in the capital cost of approximately one-third. This lower limit has been included to take account of basic material and labour costs needed to manufacture and install these technologies. The second, higher lower limit results in a reduction in the capital cost of approximately two-thirds of the starting capital cost.

Learning rate

9 per cent — the same as offshore wind. This is conservative — photovoltaics have a LR of 20 per cent.

O&M costs

Initial costs in 2006 are:

10 $/GJ (wind is 5.8 $/GJ in VIC)

Final costs in 2050 are:

5.1 $/GJ (wind is 5.0 $/GJ in VIC)

The cost is decreased by 1.5 per cent per year to reflect LBD improvements.

Construction time

2 years (same as solar thermal).

Amortisation period

25 years (same as all renewables).

Starting point

2015 for technology cases. This is based on an assumption of when investment may occur (same as hot fractured rocks).

Resource

20 per cent extraction of available wave energy. This is based on WFO information that this would be the sustainable limit.

Variations: 5 per cent and 30 per cent.

Based on calculations by team.

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	17.9	26.5	15.6	32.6	15.3	19.7	0
2	17.9			43.6	37.7	17.3	
3					66.7	16.3	

Table 9-5 Resource extractable in every region in TWh.

Capacity factor

Based on calculations by team.

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	0.22	0.32	0.21	0.32	0.36	0.39	0.01
2	0.19			0.30	0.32	0.35	
3					0.29	0.33	

Table 9-6 Capacity factors for point absorber1.

Region	NSW	VIC	QLD	SA	WA	TAS	NT
1	0.24	0.51	0.22	0.51	0.57	0.61	0.01
2	0.20			0.49	0.53	0.55	
3					0.48	0.52	

Table 9-7 Capacity factors for terminator 1.

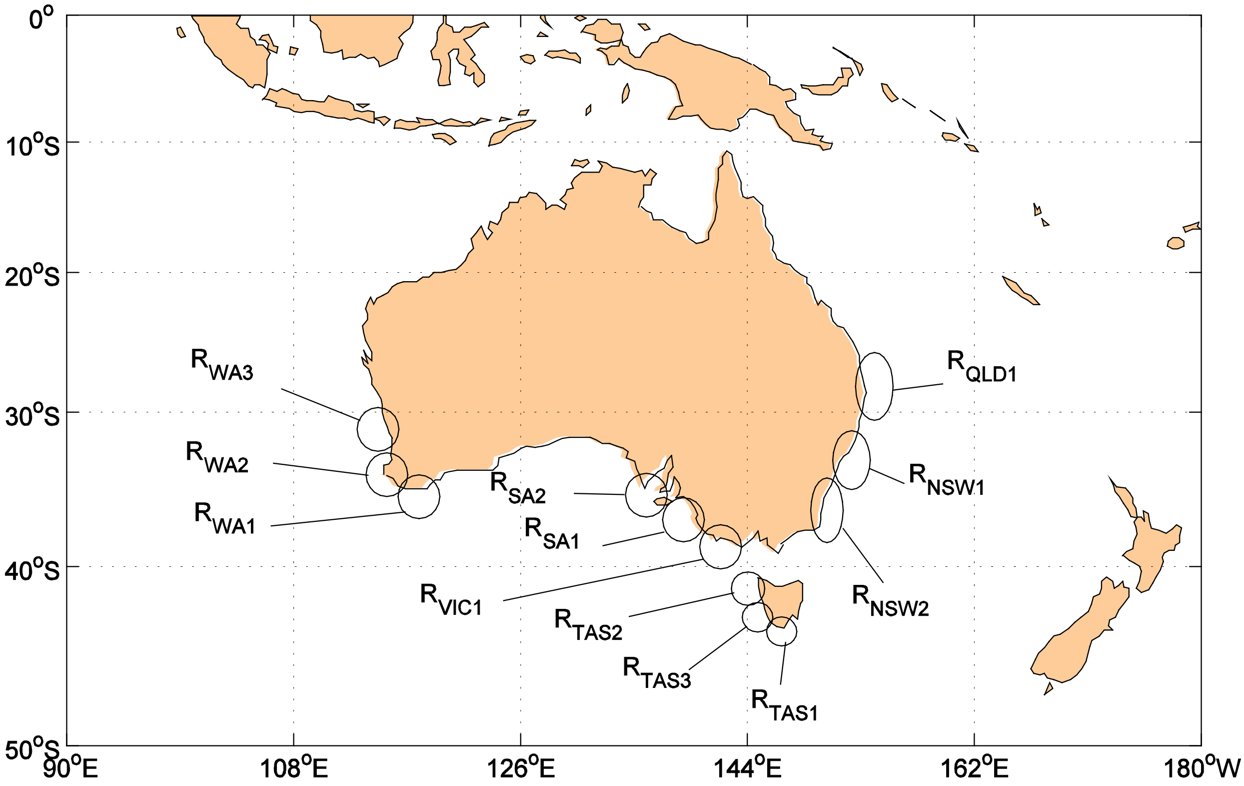

Figure 9-3 Regions used in modelling.

Transmission costs

We assume the transmission infrastructure is in place. Therefore, there is no additional cost.

Global generic results

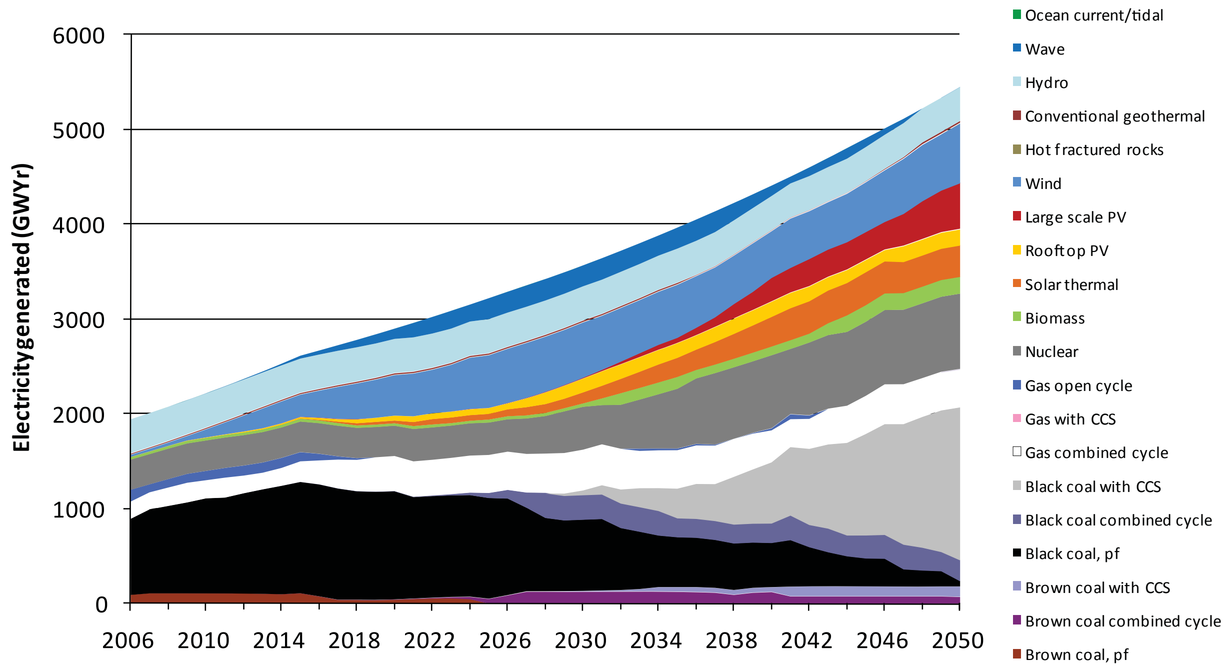

Figure 9-4 Projected global electricity generation under CPRS-5 carbon price scenario and 0.3-0.34 wave energy capacity factor.

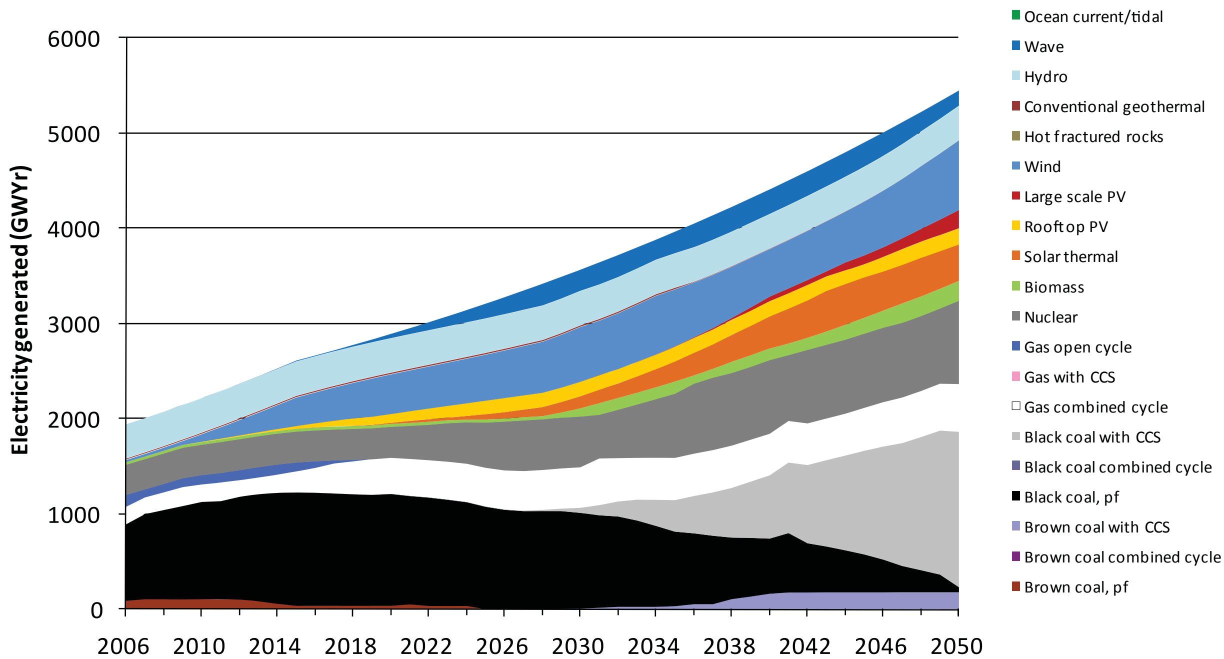

Figure 9-5 Projected global electricity generation under CPRS-15 carbon price scenario and 0.3-0.34 wave energy capacity factor.

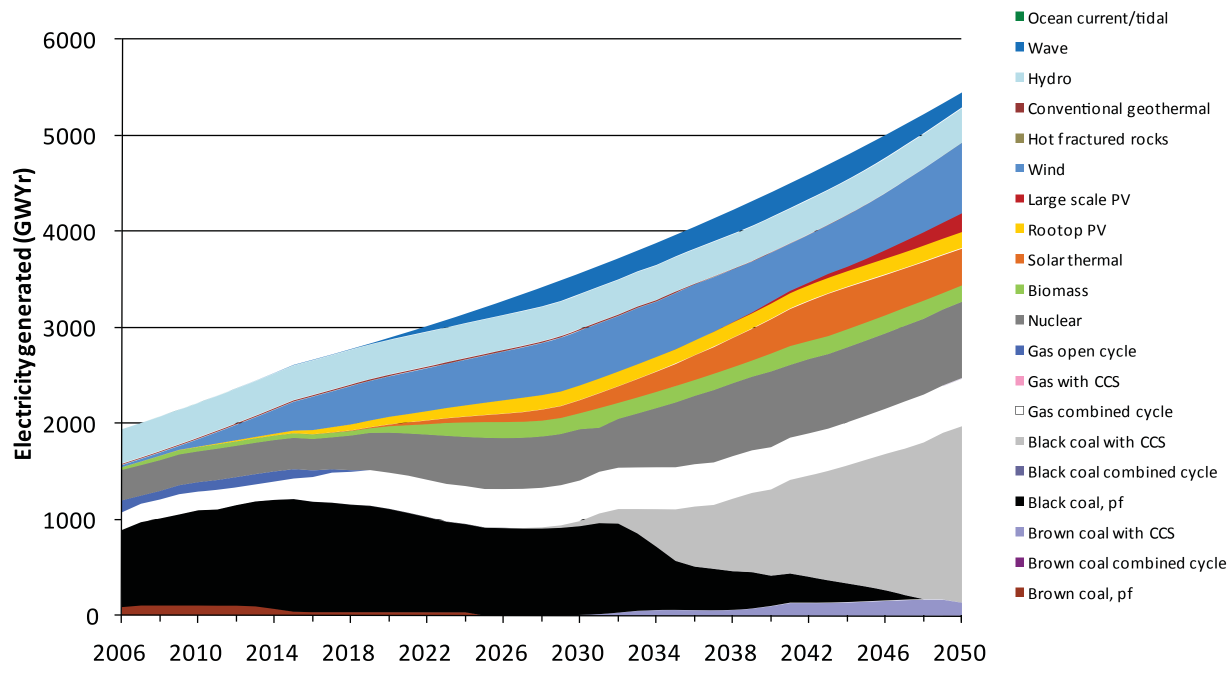

Figure 9-6 Projected global electricity generation under Garnaut-25 carbon price scenario and 0.3-0.34 wave energy capacity factor.

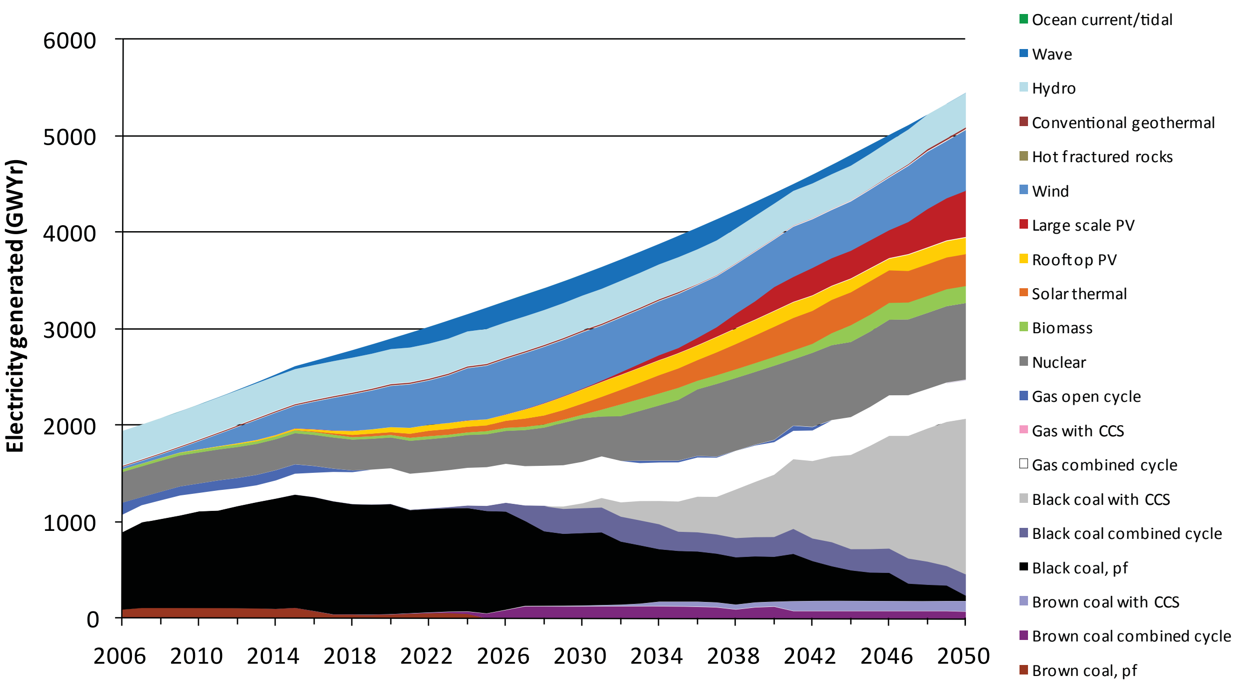

Figure 9-7 Projected global electricity generation under CPRS-5 carbon price scenario and 0.5-0.54 wave energy capacity factor.

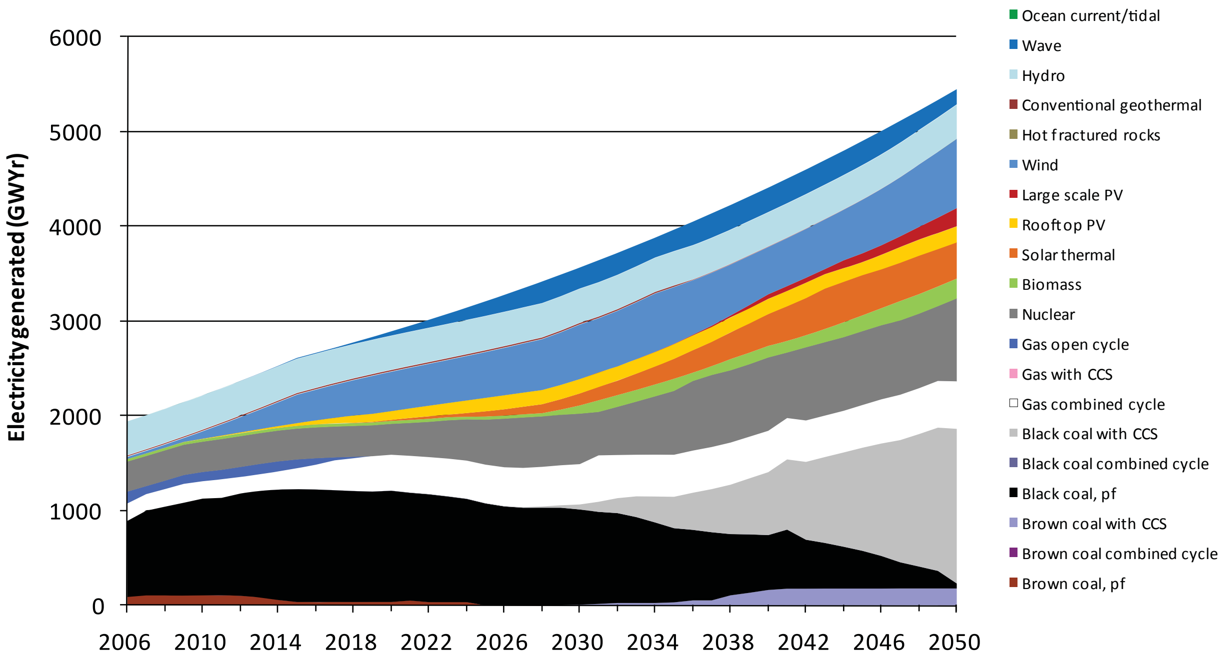

Figure 9-8 Projected global electricity generation under CPRS-15 carbon price scenario and 0.5-0.54 wave energy capacity factor.

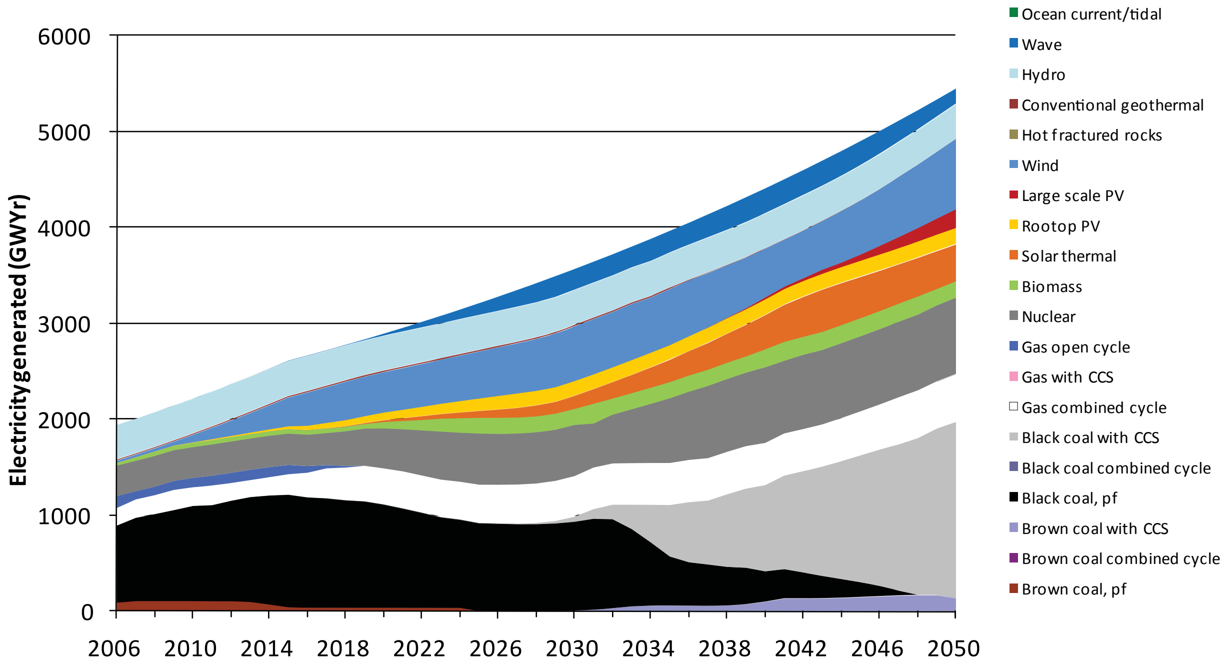

Figure 9-9 Projected global electricity generation under Garnaut-25 carbon price scenario and 0.5-0.54 wave energy capacity factor.

Australian generic results without dispatchable power capability

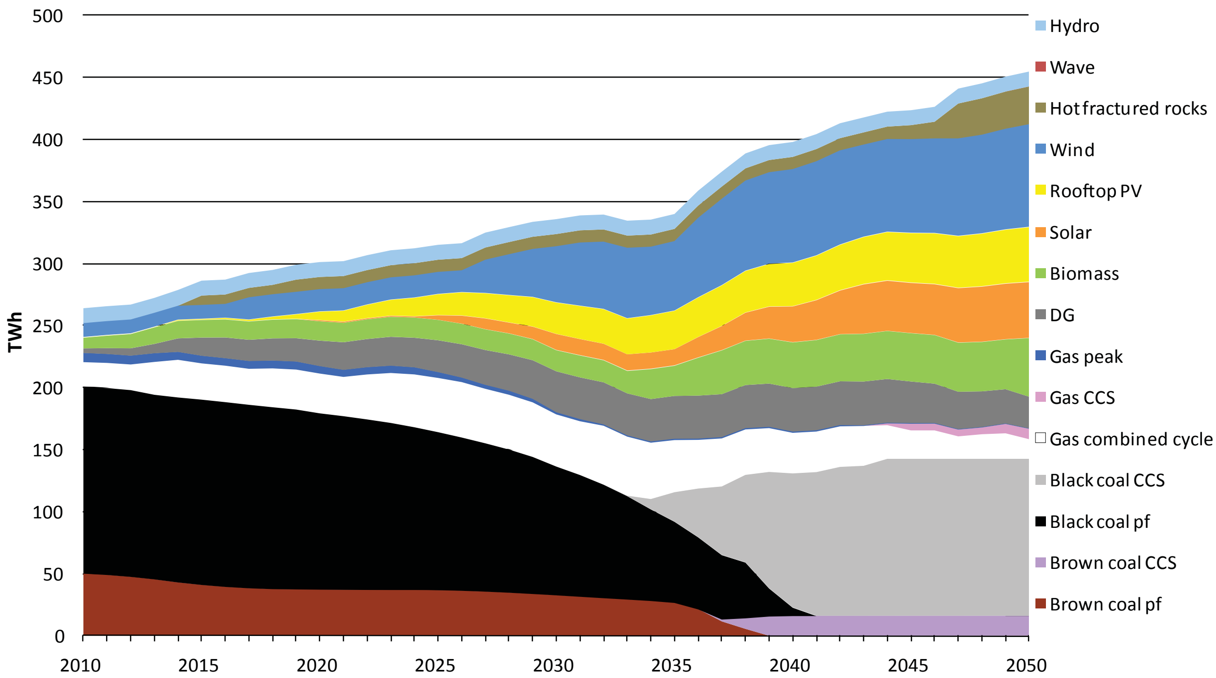

Figure 9-10 Projected Australian electricity generation under CPRS-5 carbon price scenario with 0.3-0.38 wave energy capacity factor.

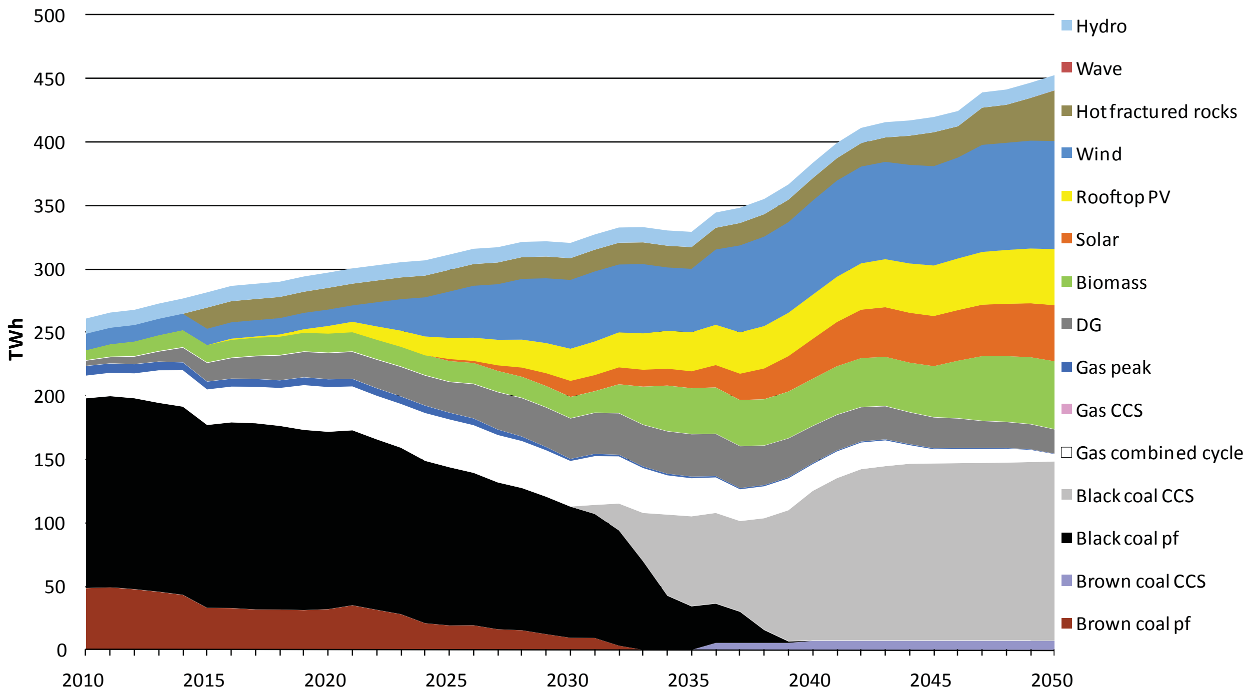

Figure 9-11 Projected Australian electricity generation under CPRS-15 carbon price scenario with 0.3-0.38 wave energy capacity factor.

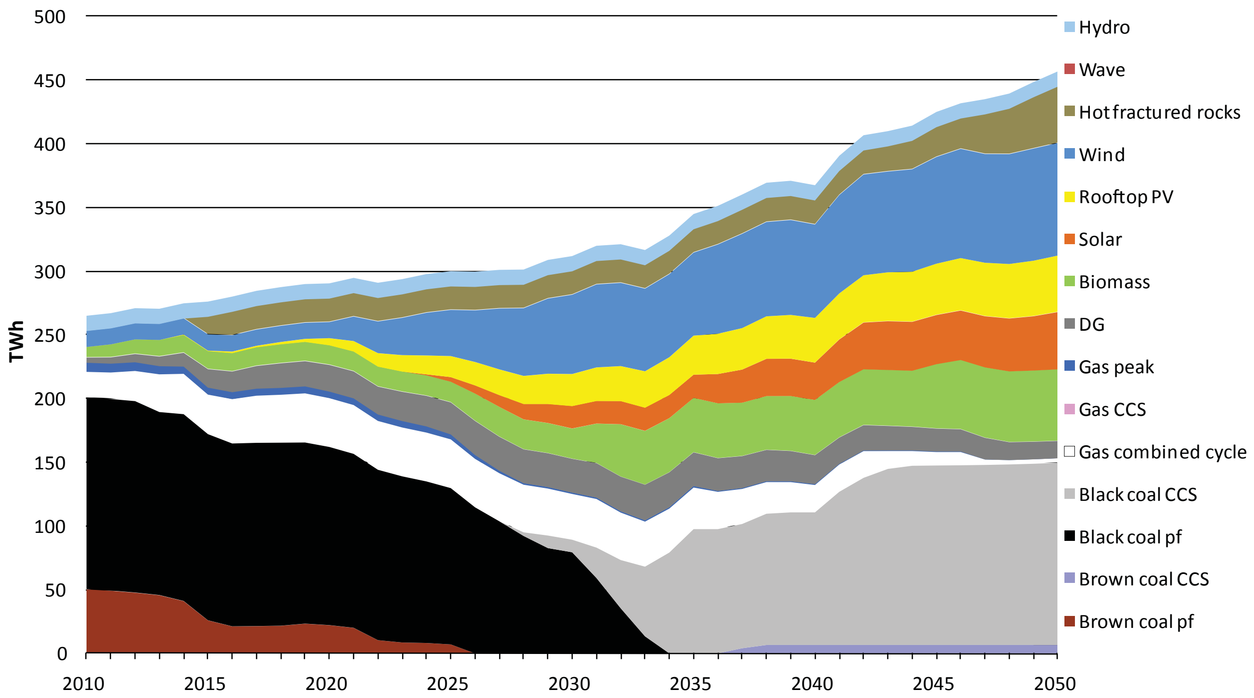

Figure 9-12 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 0.3-0.38 wave energy capacity factor.

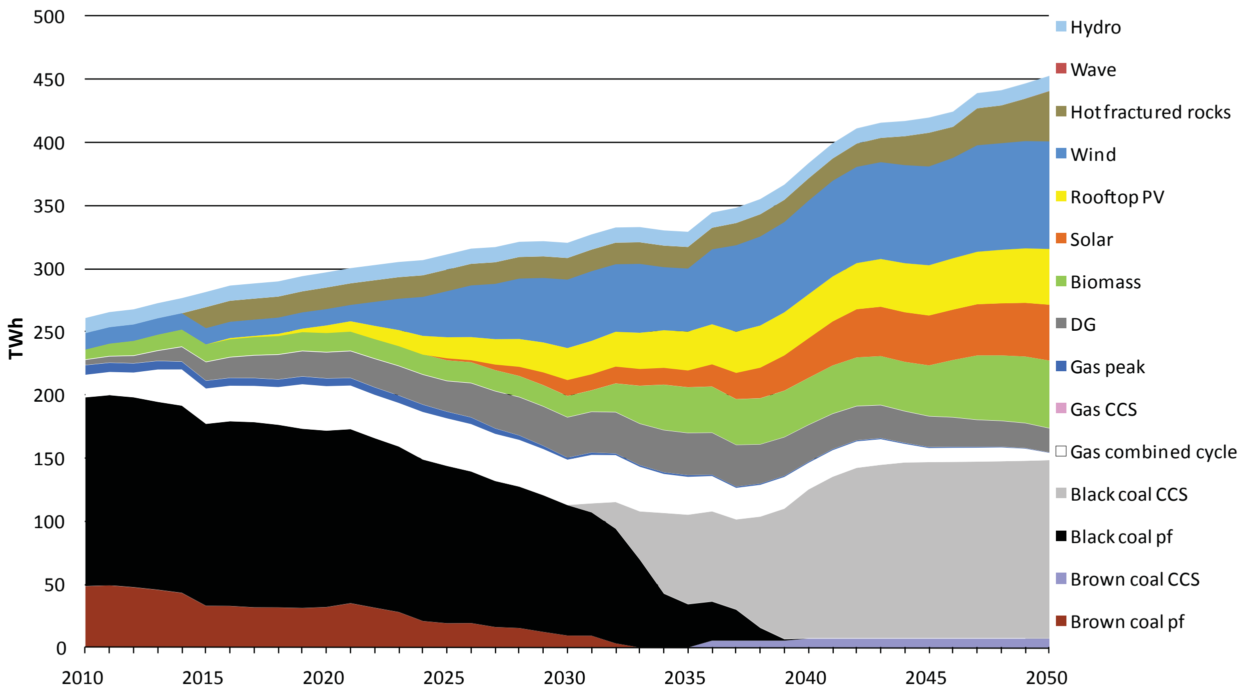

Figure 9-13 Projected Australian electricity generation under CPRS-15 carbon price scenario with 0.4-0.48 wave energy capacity factor.

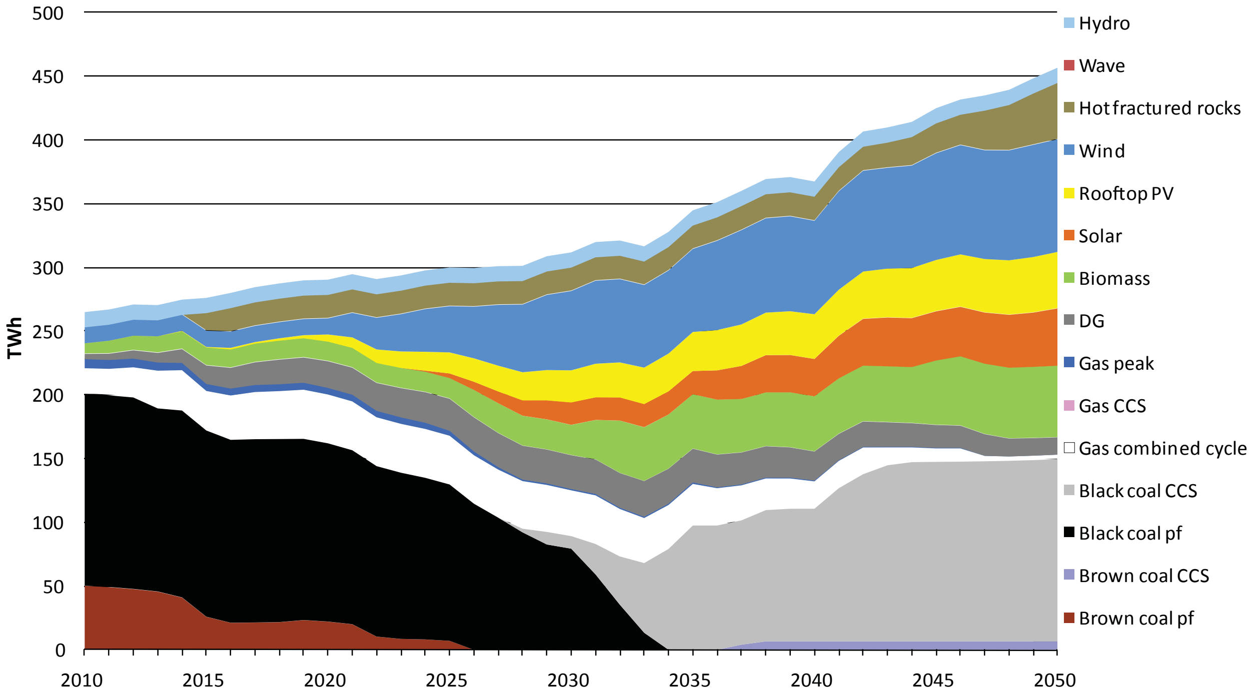

Figure 9-14 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 0.4-0.48 wave energy capacity factor.

Australian generic results with dispatchable power capability

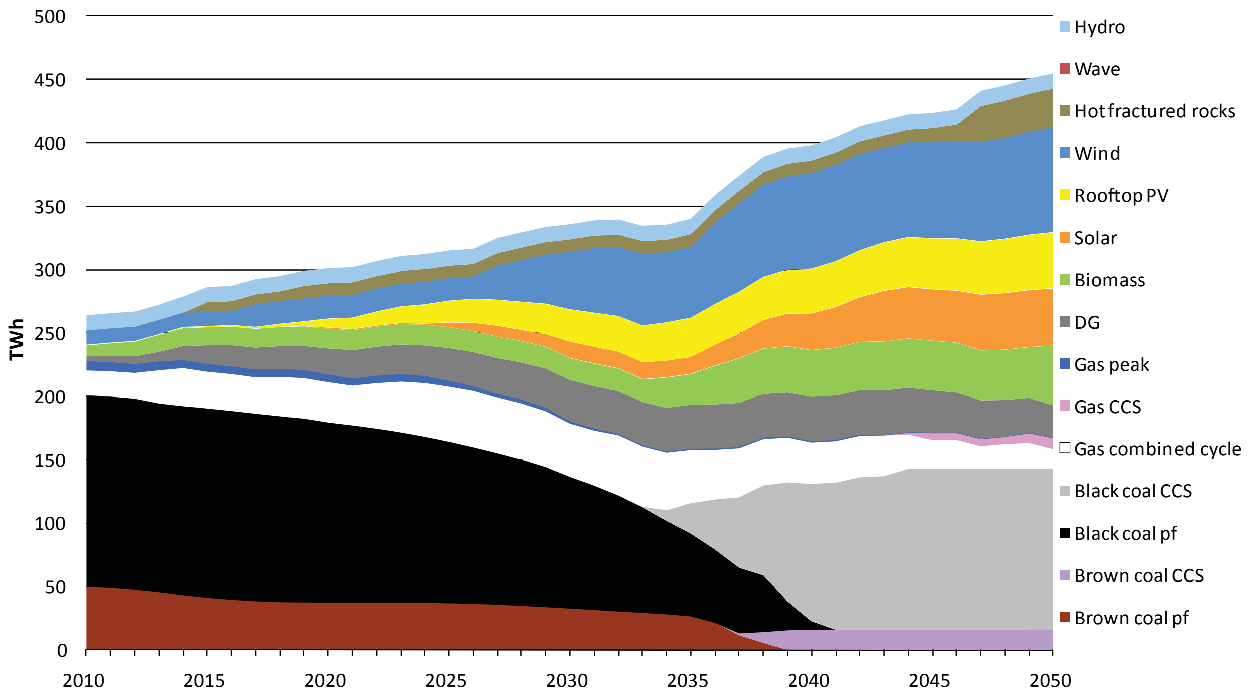

Figure 9-15 Projected Australian electricity generation under CPRS-5 carbon price scenario with 0.3-0.38 wave energy capacity factor and dispatchable power.

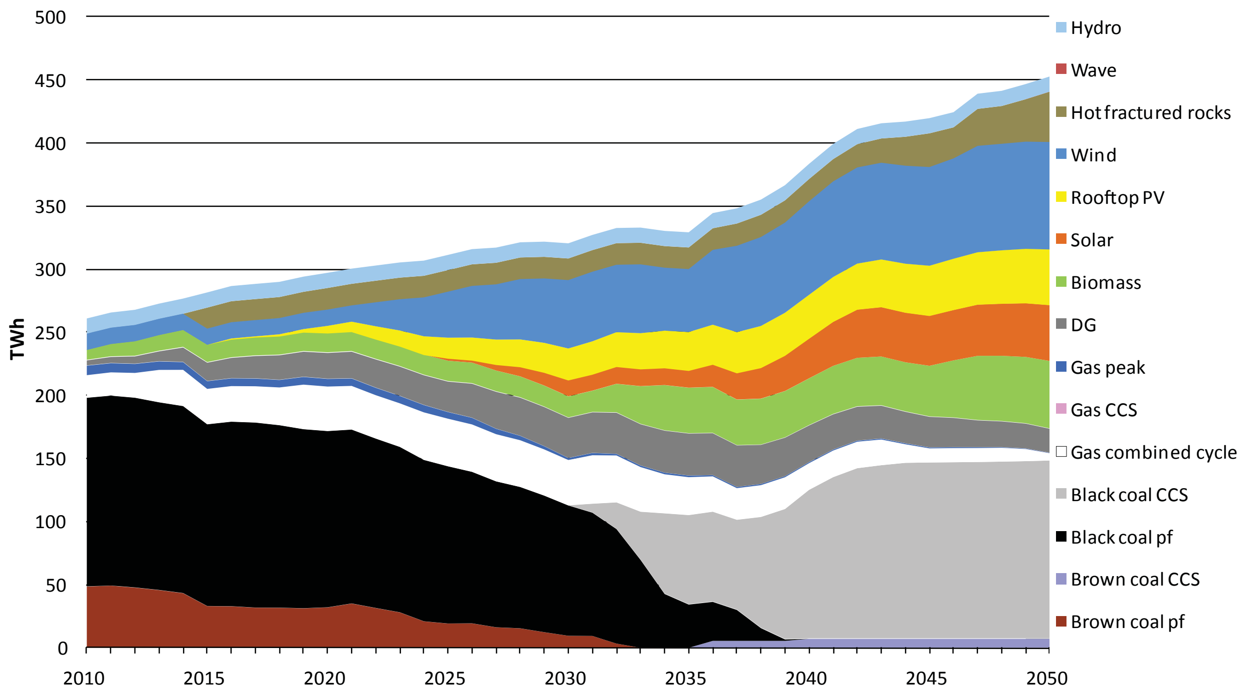

Figure 9-16 Projected Australian electricity generation under CPRS-15 carbon price scenario with 0.3-0.38 wave energy capacity factor and dispatchable power.

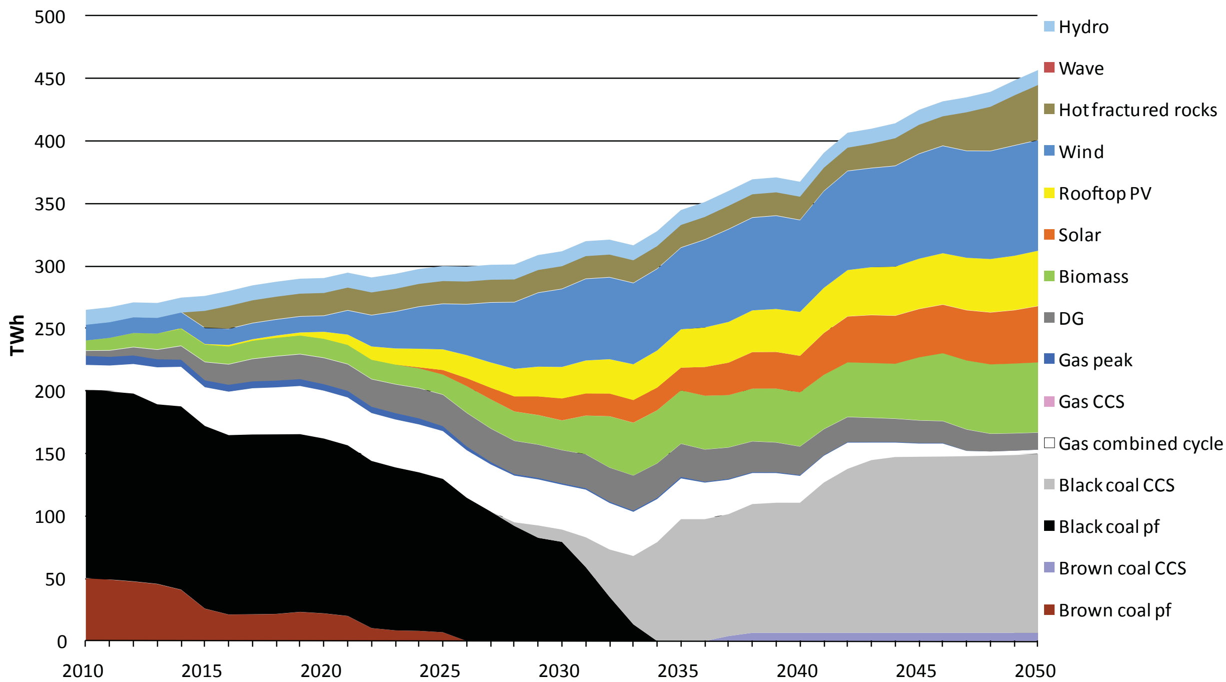

Figure 9-17 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 0.3-0.38 wave energy capacity factor and dispatchable power.

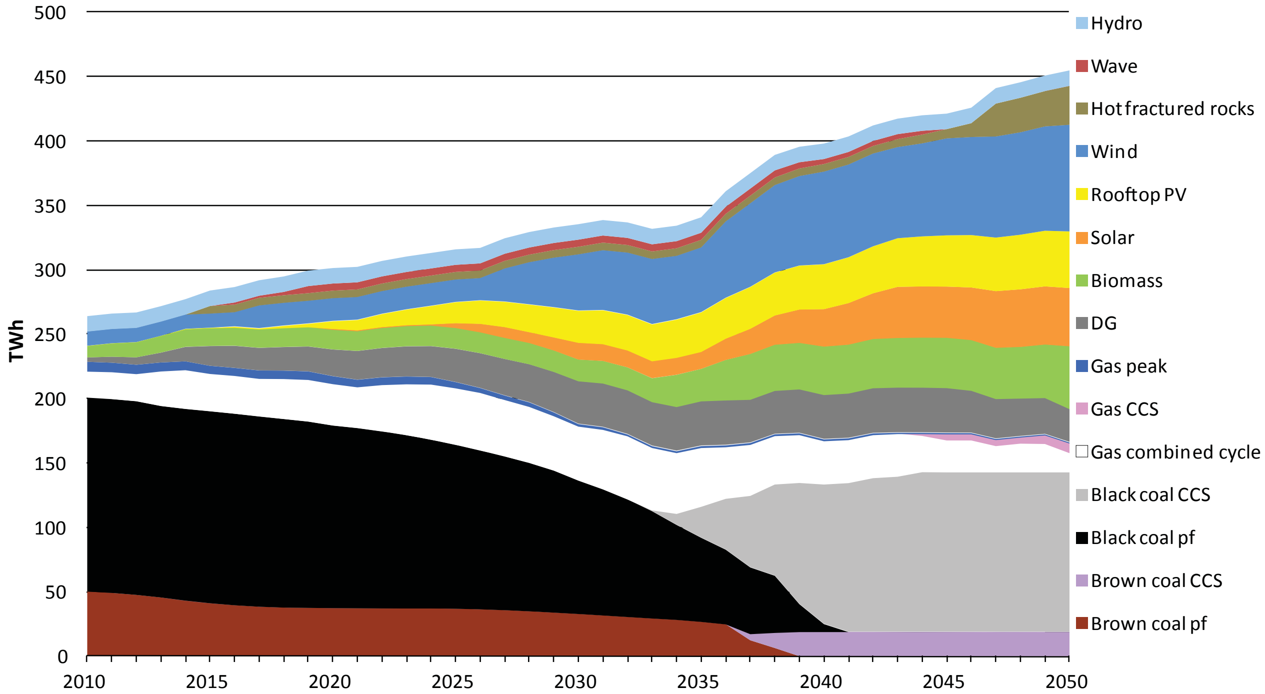

Figure 9-18 Projected Australian electricity generation under CPRS-5 carbon price scenario with 0.4-0.48 wave energy capacity factor and dispatchable power.

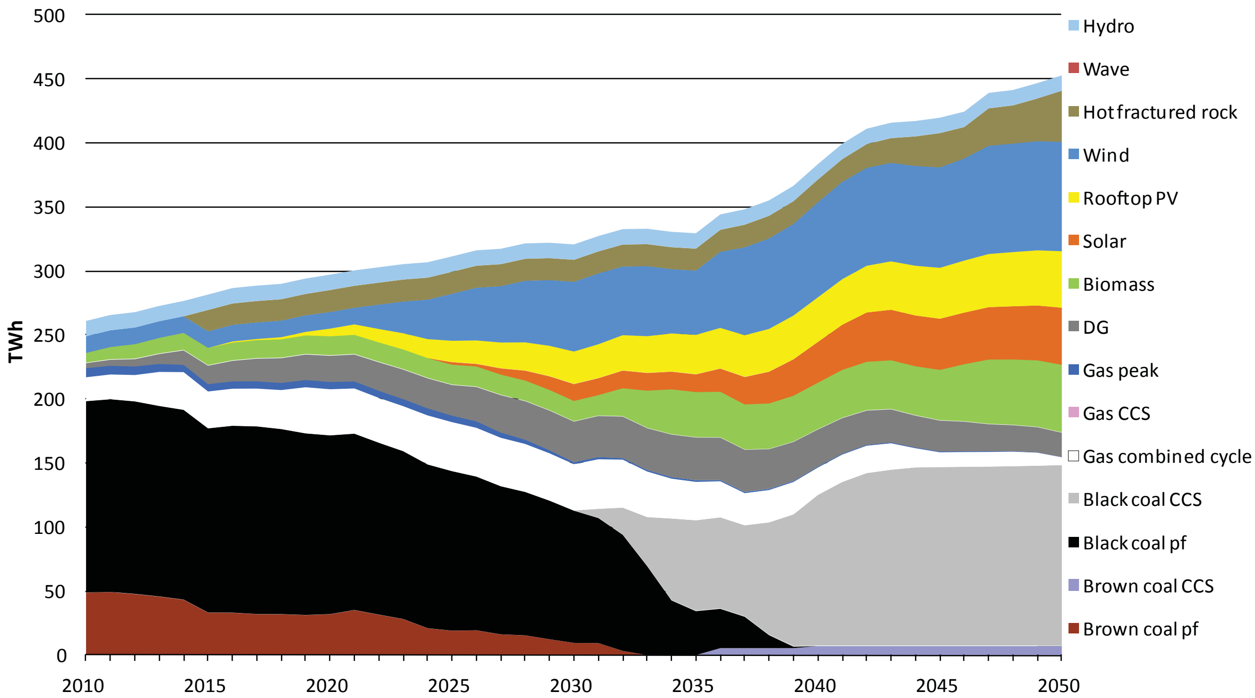

Figure 9-19 Projected Australian electricity generation under CPRS-15 carbon price scenario with 0.4-0.48 wave energy capacity factor and dispatchable power.

Global technology specific results

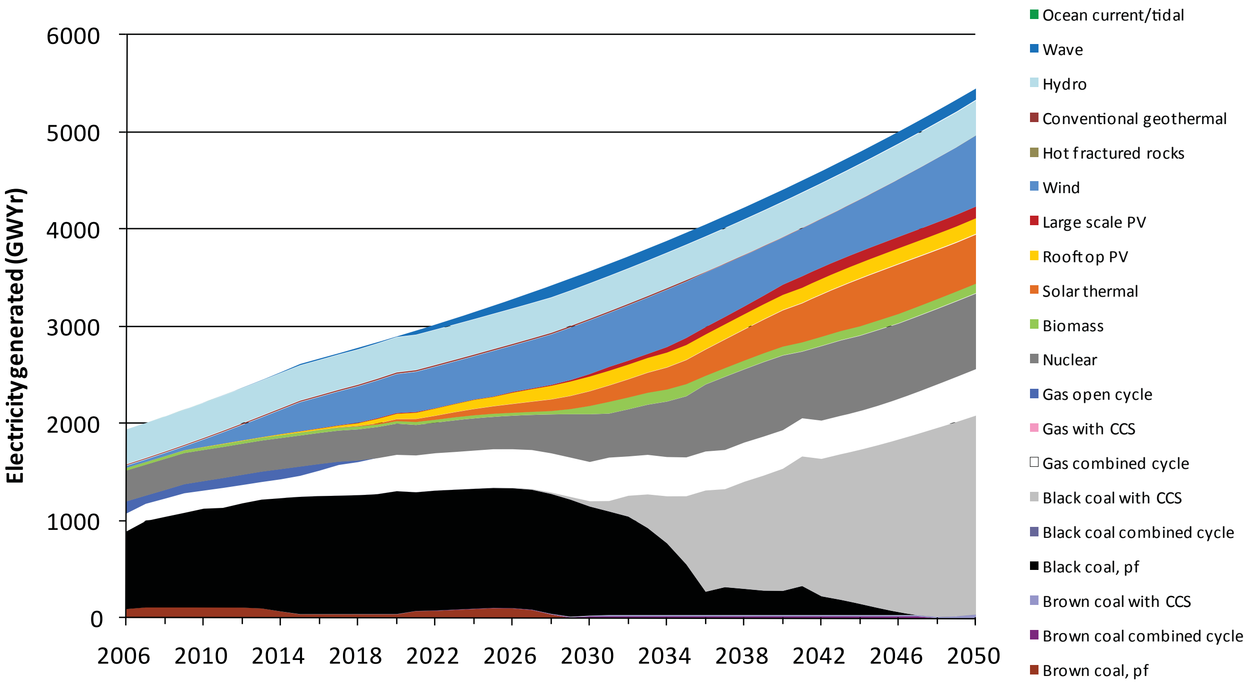

Figure 9-20 Projected global electricity generation under CPRS-5 carbon price scenario with a Point Absorber1 wave energy convertor.

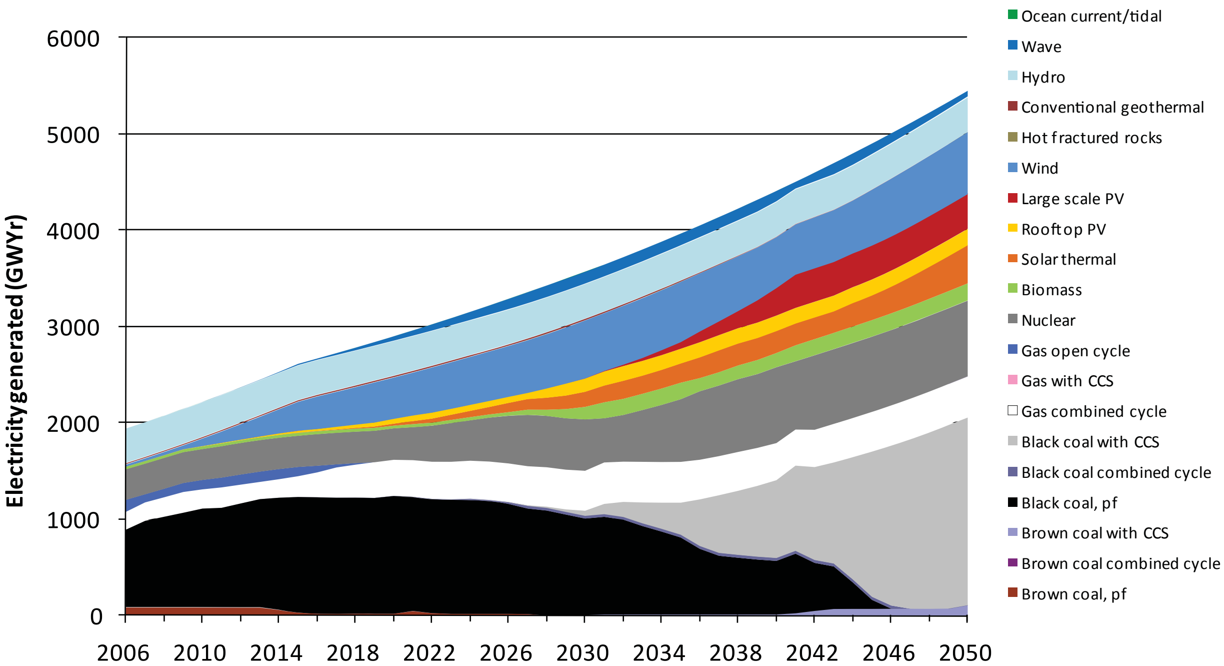

Figure 9-21 Projected global electricity generation under CPRS-15 carbon price scenario with a Point Absorber1 wave energy convertor.

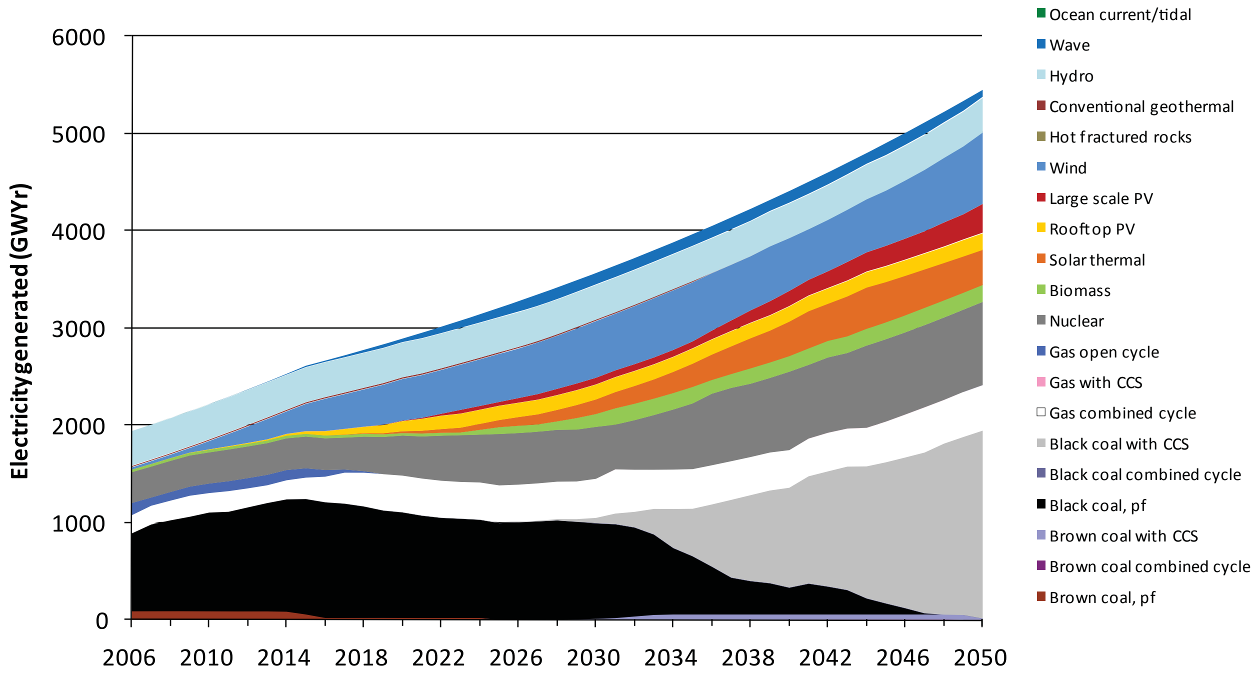

Figure 9-22 Projected global electricity generation under Garnaut-25 carbon price scenario with a Point Absorber1 wave energy convertor.

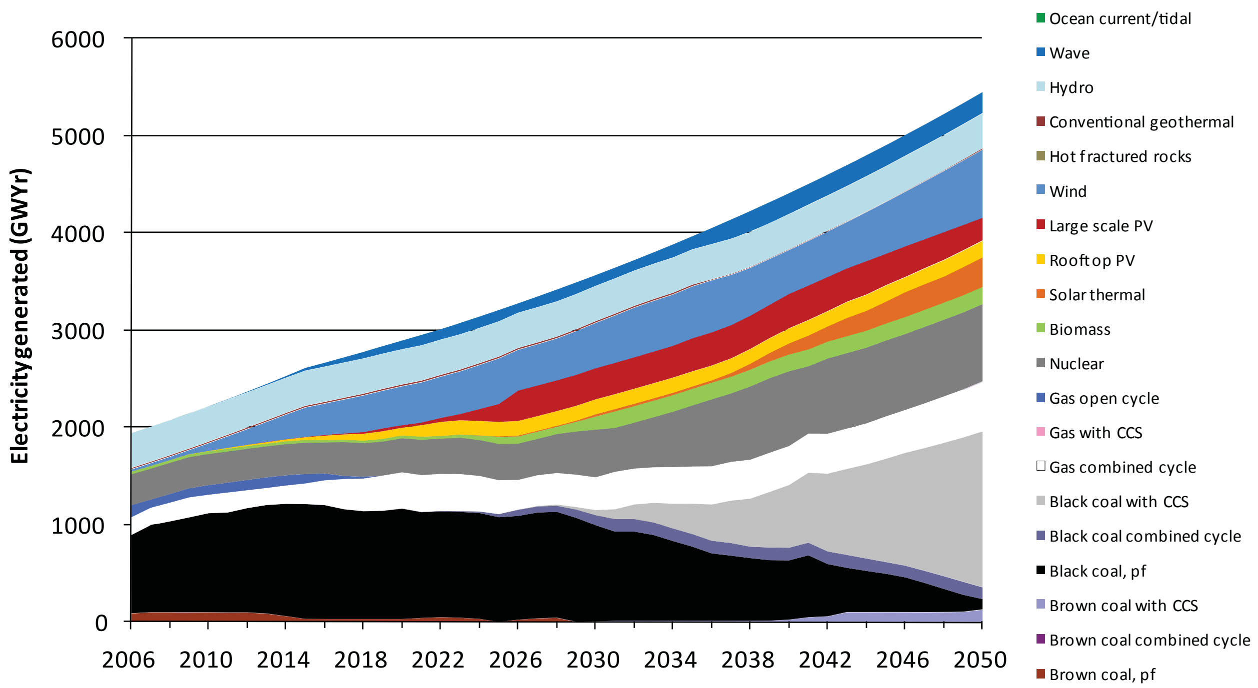

Figure 9-23 Projected global electricity generation under CPRS-5 carbon price scenario with a Terminator1 wave energy convertor.

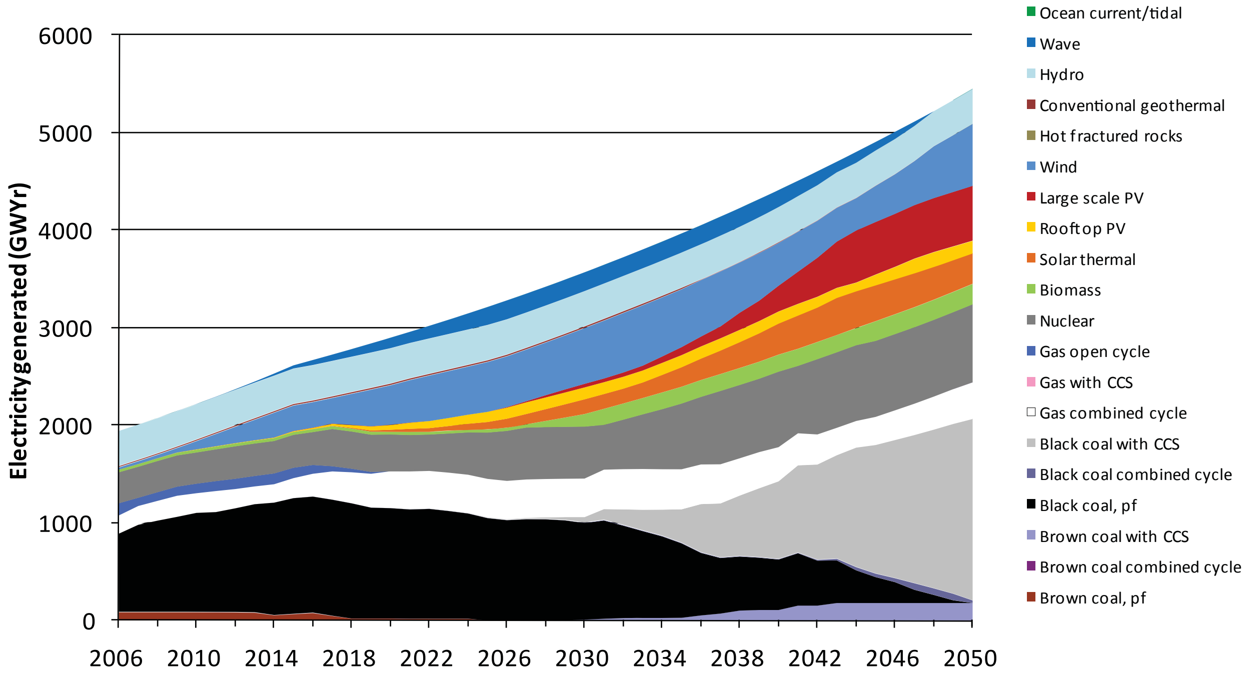

Figure 9-24 Projected global electricity generation under CPRS-15 carbon price scenario with a Terminator1 wave energy convertor.

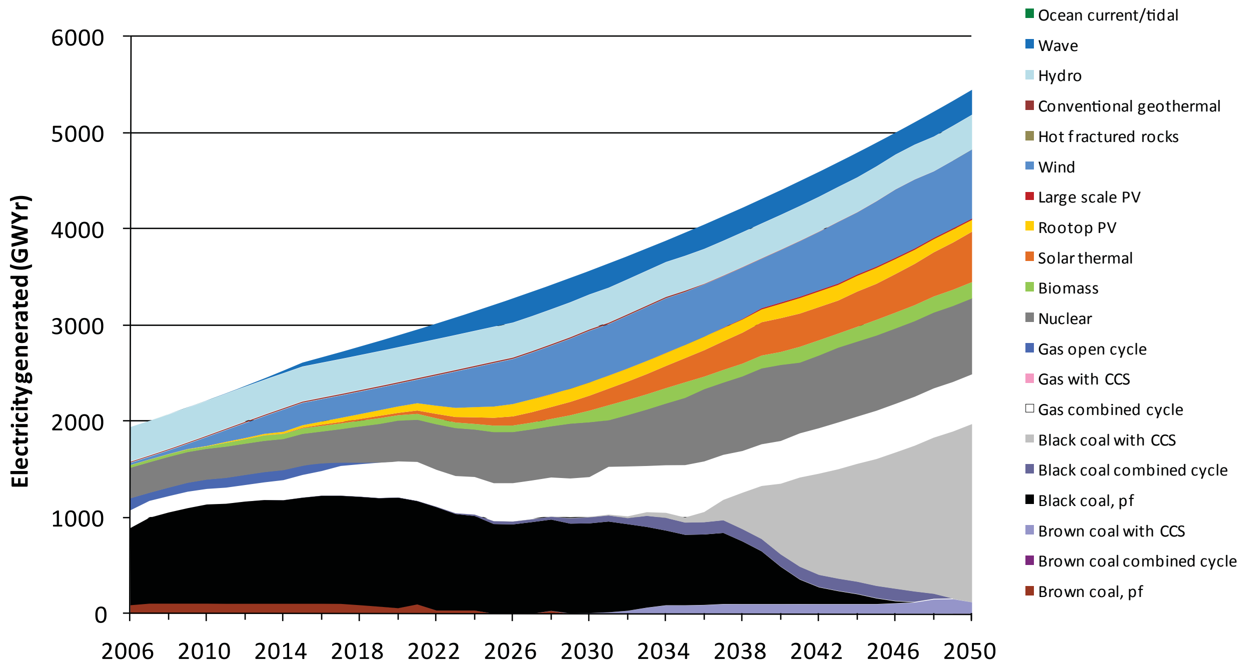

Figure 9-25 Projected global electricity generation under Garnaut-25 carbon price scenario with a Terminator1 wave energy convertor.

Australian technology specific results without dispatchable power capability

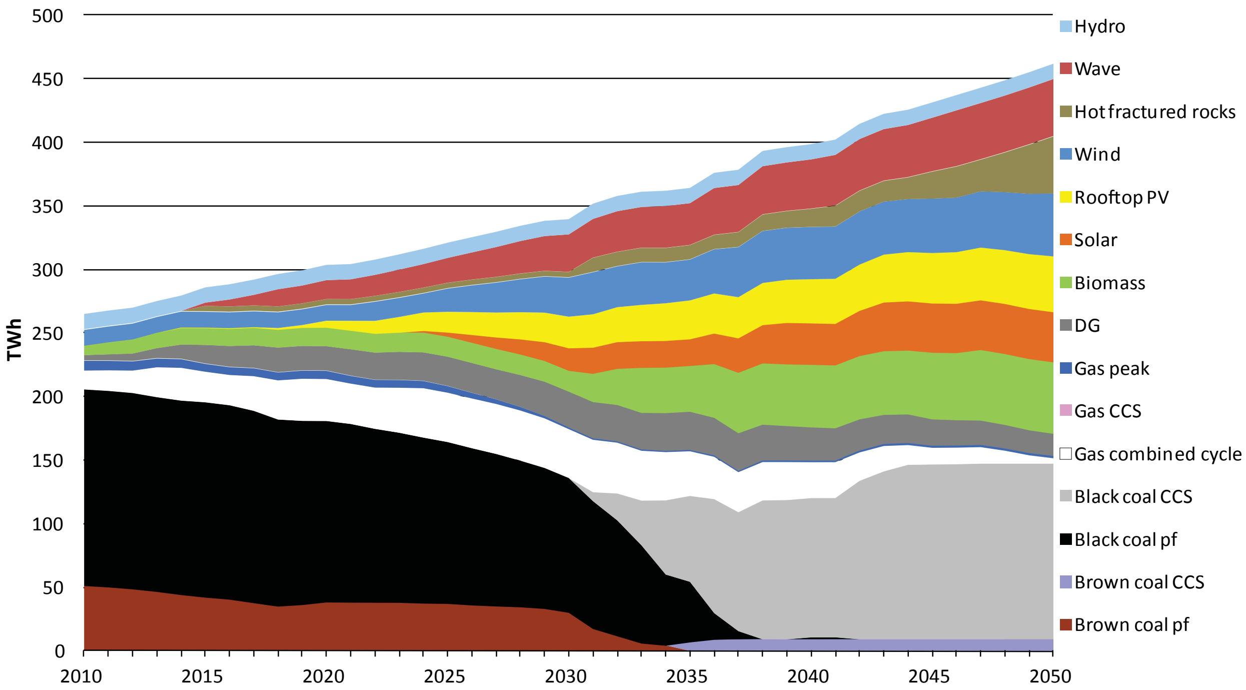

Figure 9-26 Projected Australian electricity generation under CPRS-15 carbon price scenario with 20 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

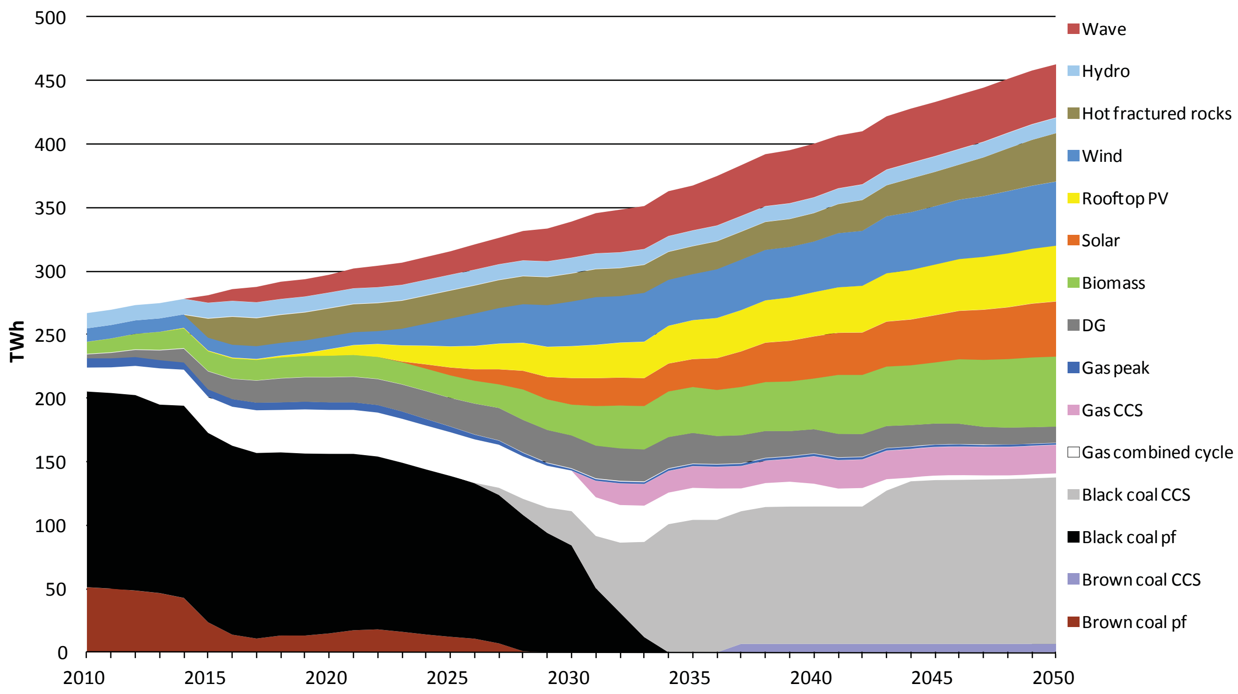

Figure 9-27 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 20 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

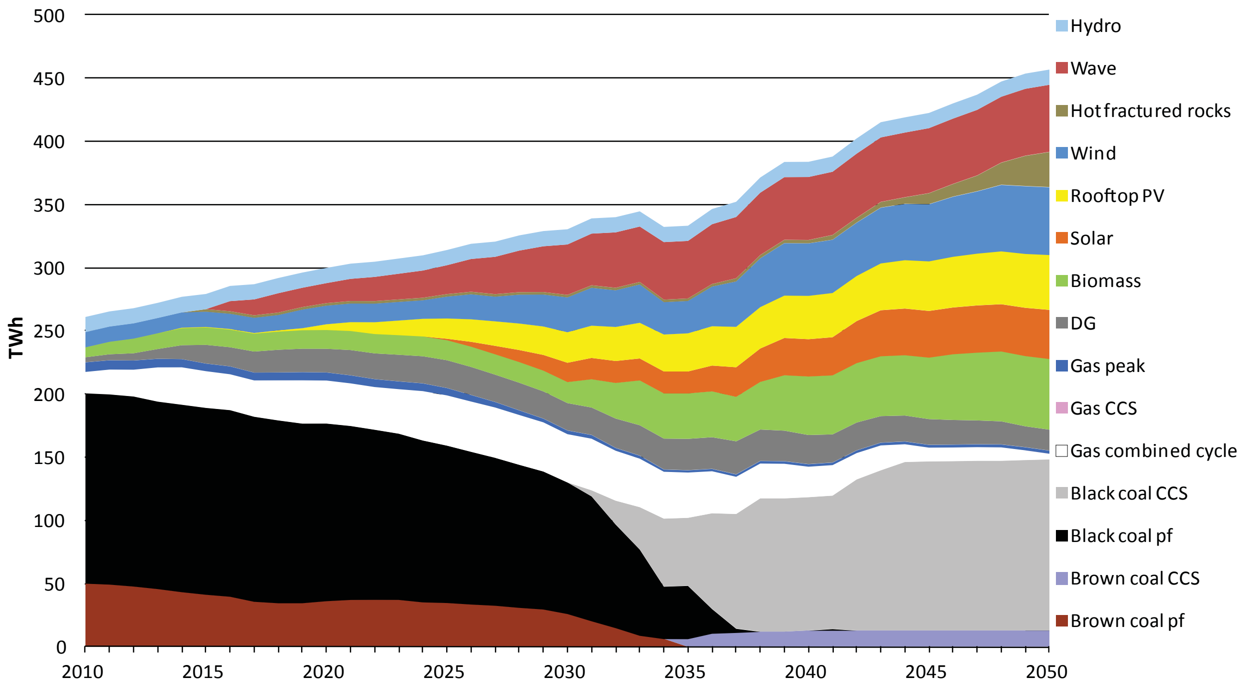

Figure 9-28 Projected Australian electricity generation under CPRS-15 carbon price scenario with 20 per cent wave energy extraction using a Terminator1 wave energy convertor.

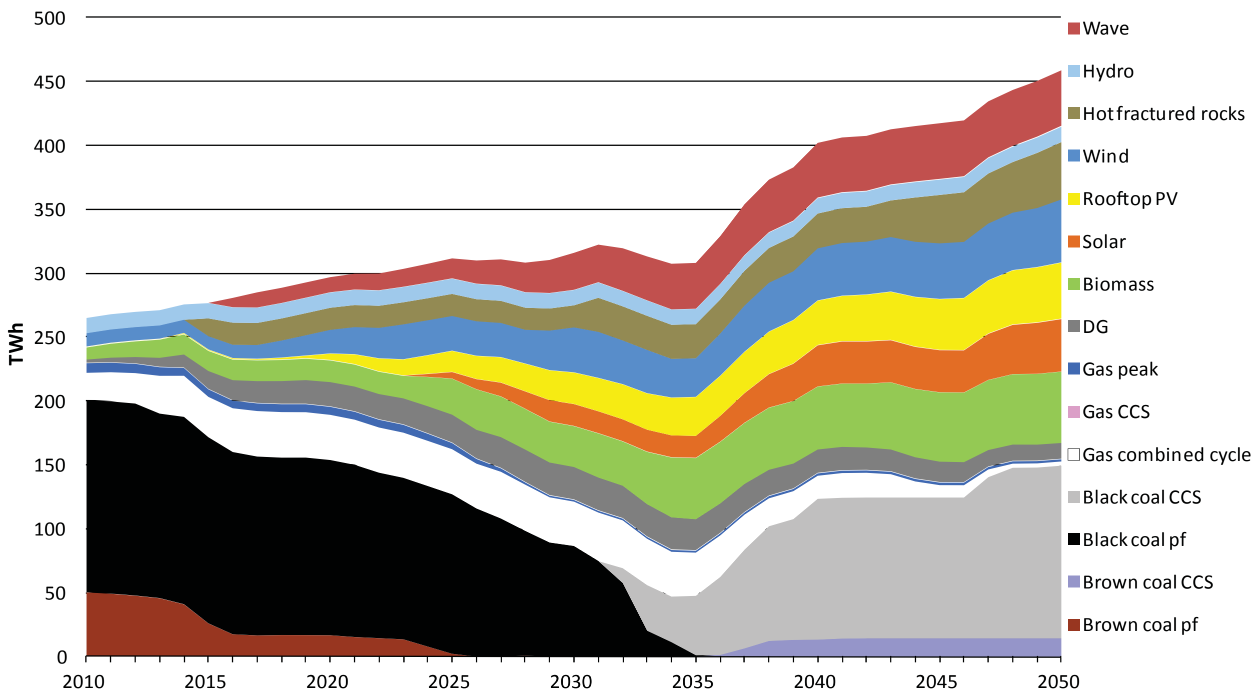

Figure 9-29 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 20 per cent wave energy extraction using a Terminator1 wave energy convertor.

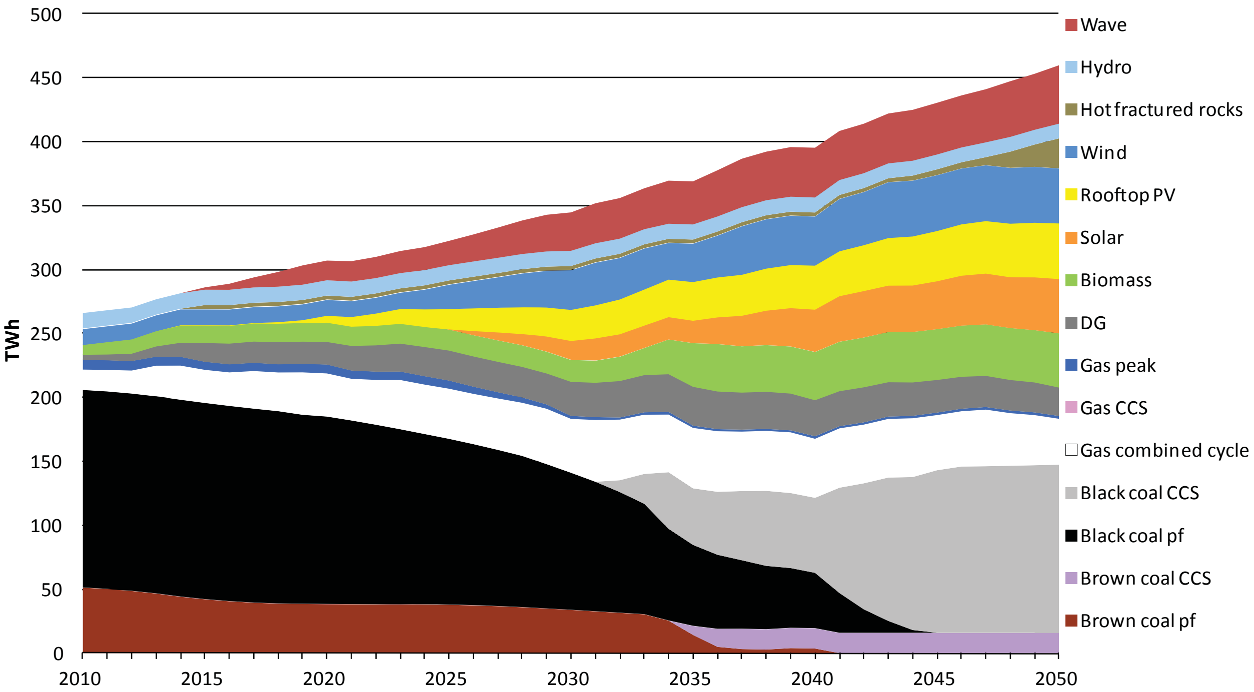

Figure 9-30 Projected Australian electricity generation under CPRS-5 carbon price scenario with 30 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

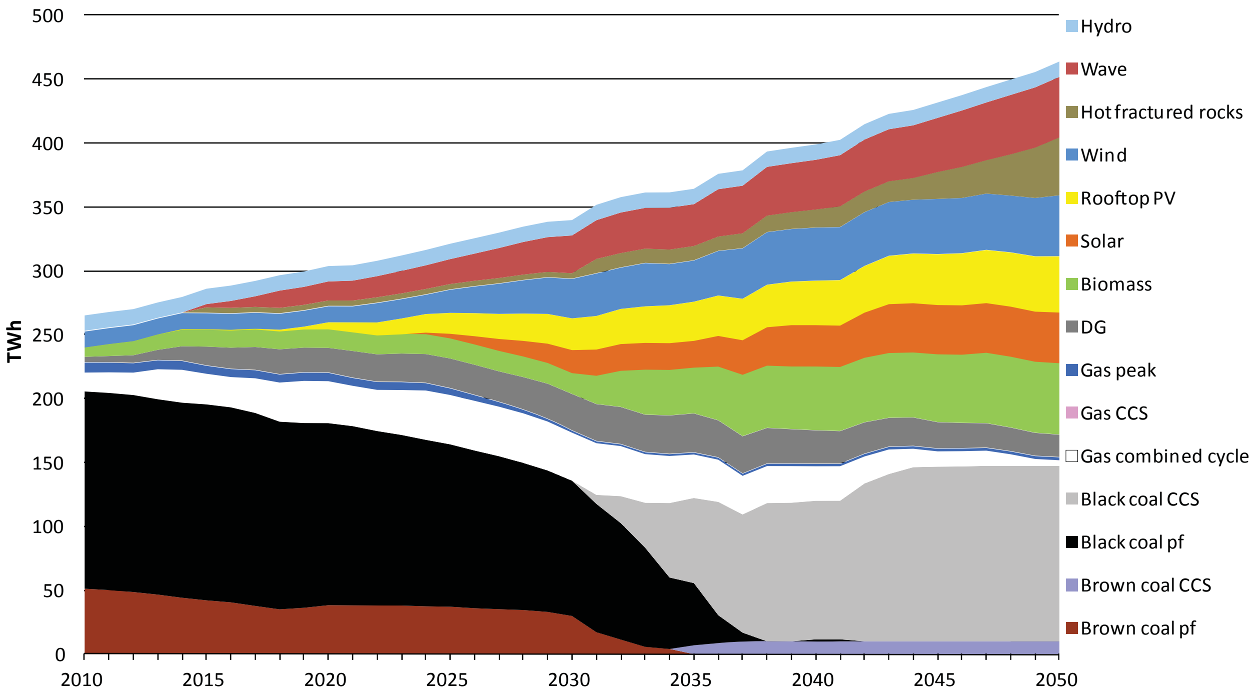

Figure 9-31 Projected Australian electricity generation under CPRS-15 carbon price scenario with 30 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

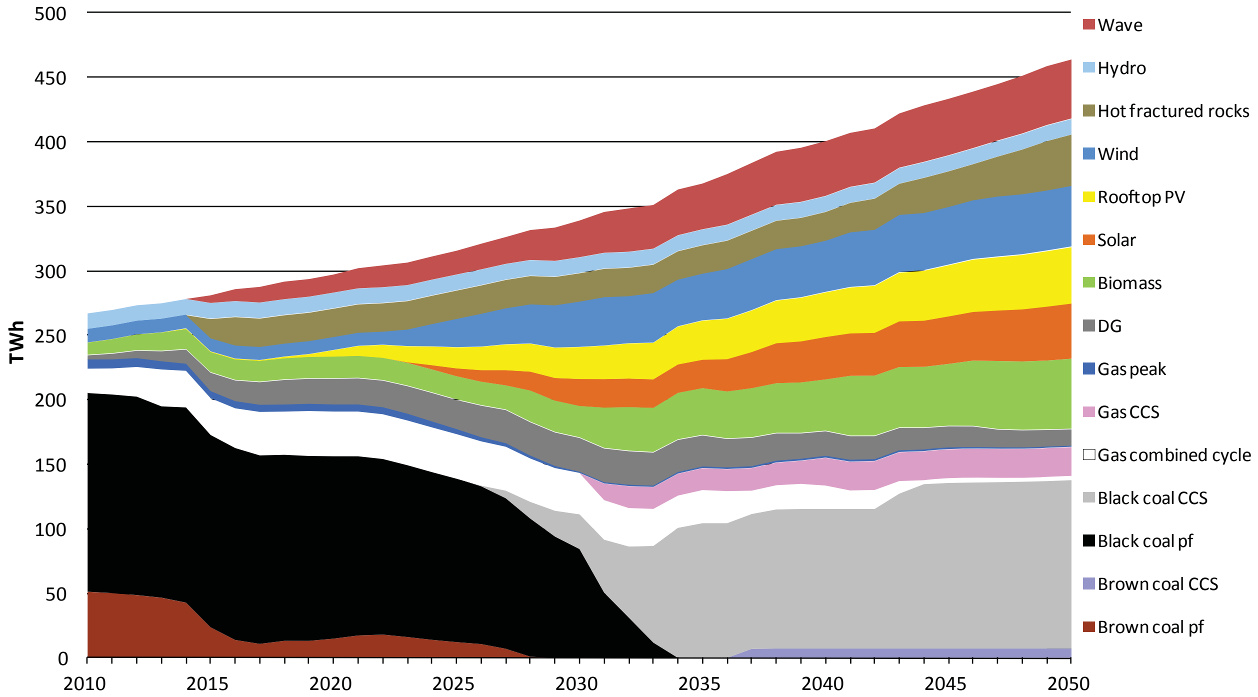

Figure 9-32 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 30 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

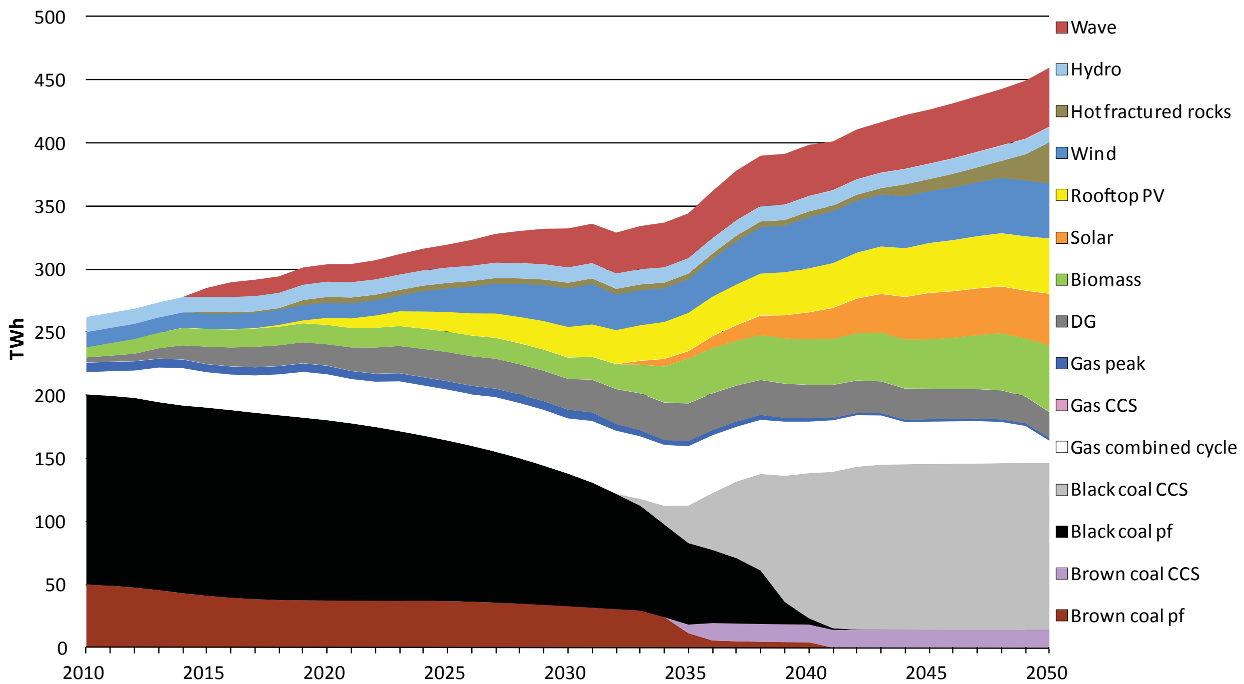

Figure 9-33 Projected Australian electricity generation under CPRS-5 carbon price scenario with 30 per cent wave energy extraction using a Terminator1 wave energy convertor.

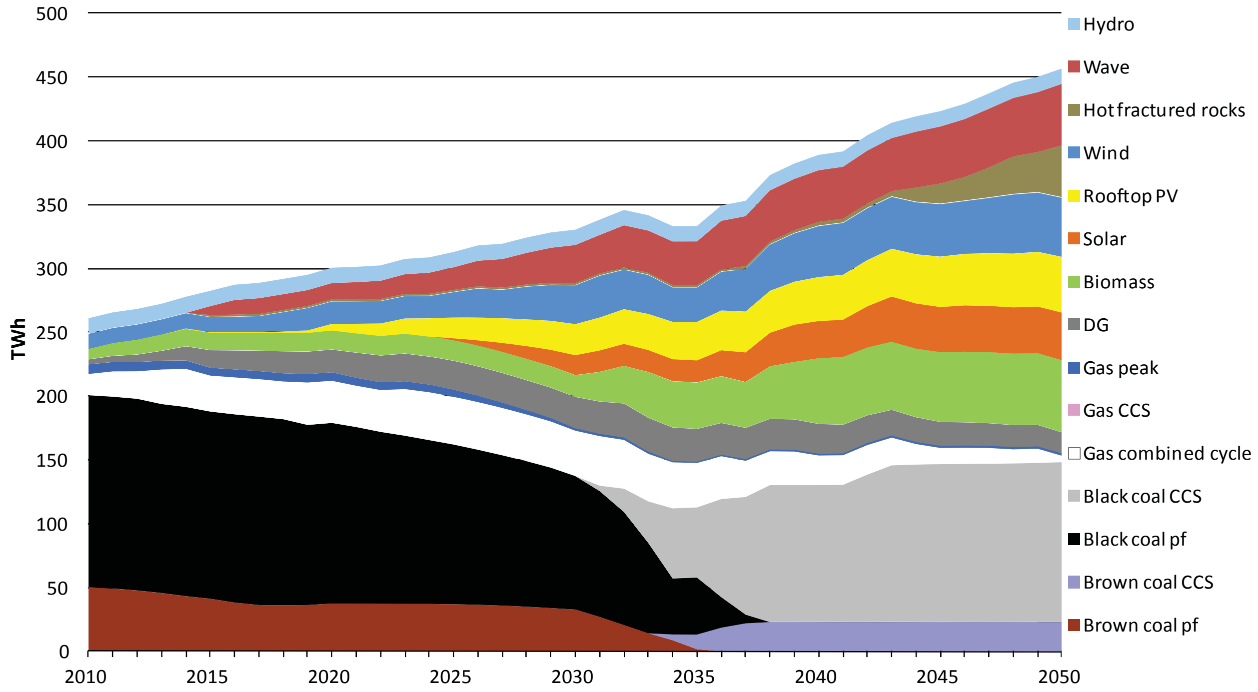

Figure 9-34 Projected Australian electricity generation under CPRS-15 carbon price scenario with 30 per cent wave energy extraction using a Terminator1 wave energy convertor.

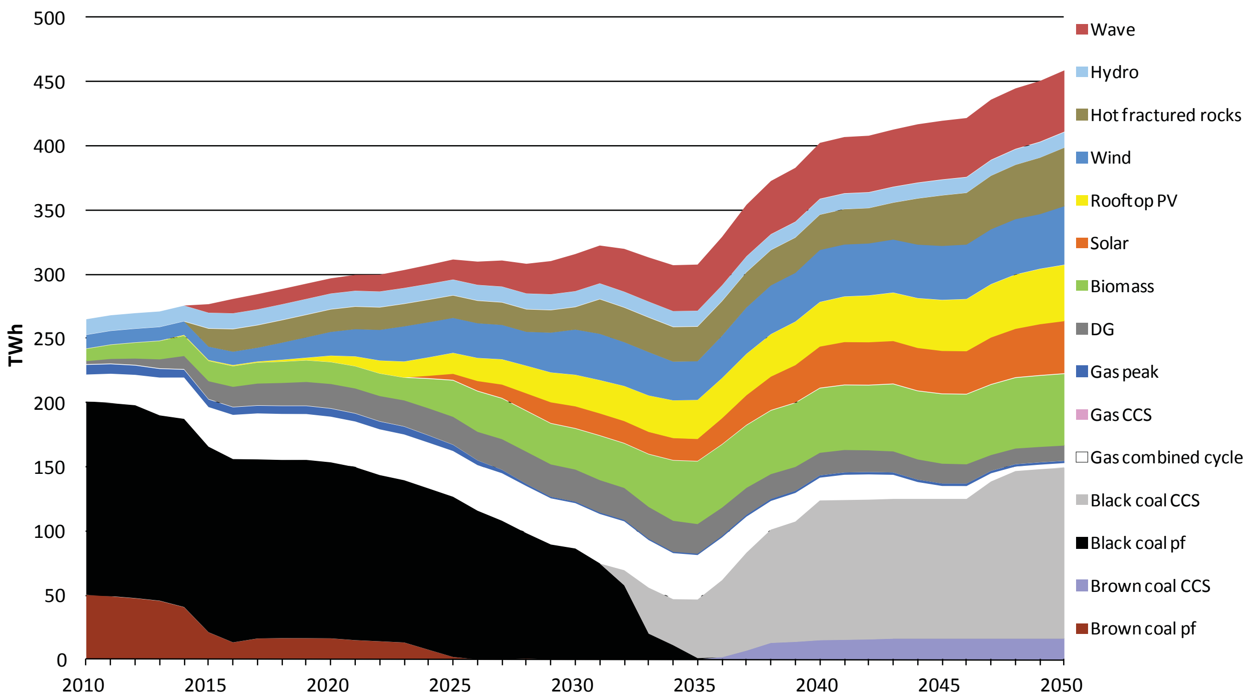

Figure 9-35 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 30 per cent wave energy extraction using a Terminator1 wave energy convertor.

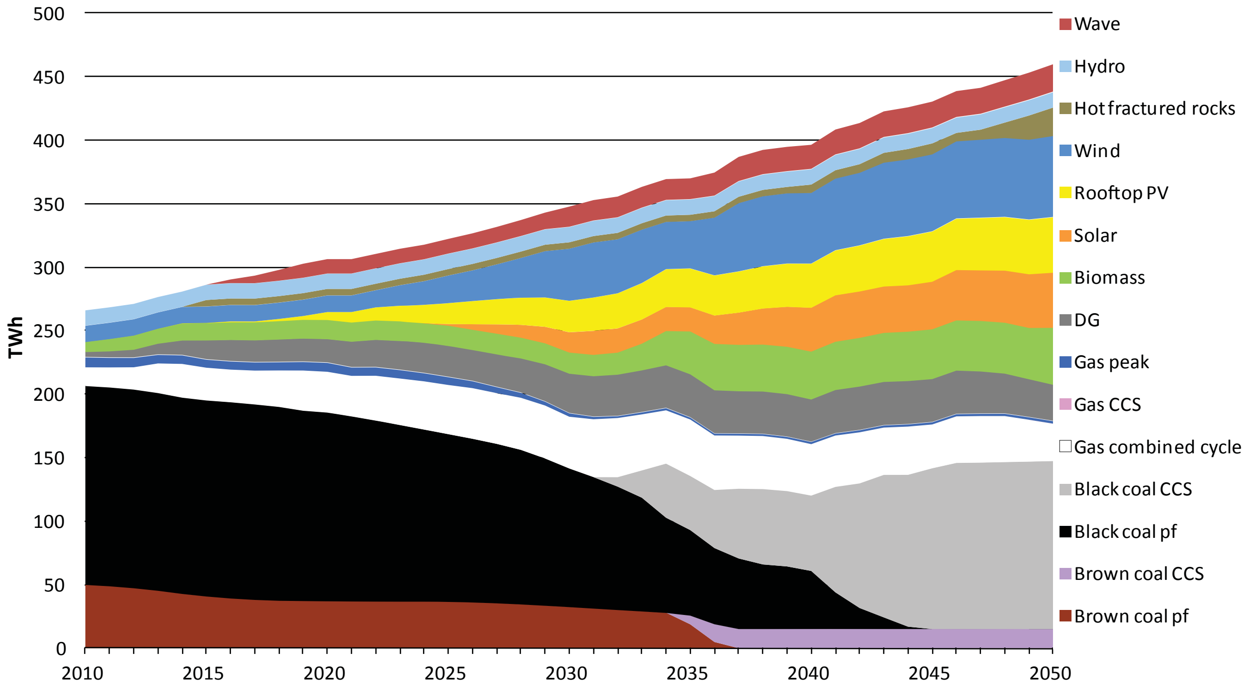

Figure 9-36 Projected Australian electricity generation under CPRS-5 carbon price scenario with 5 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

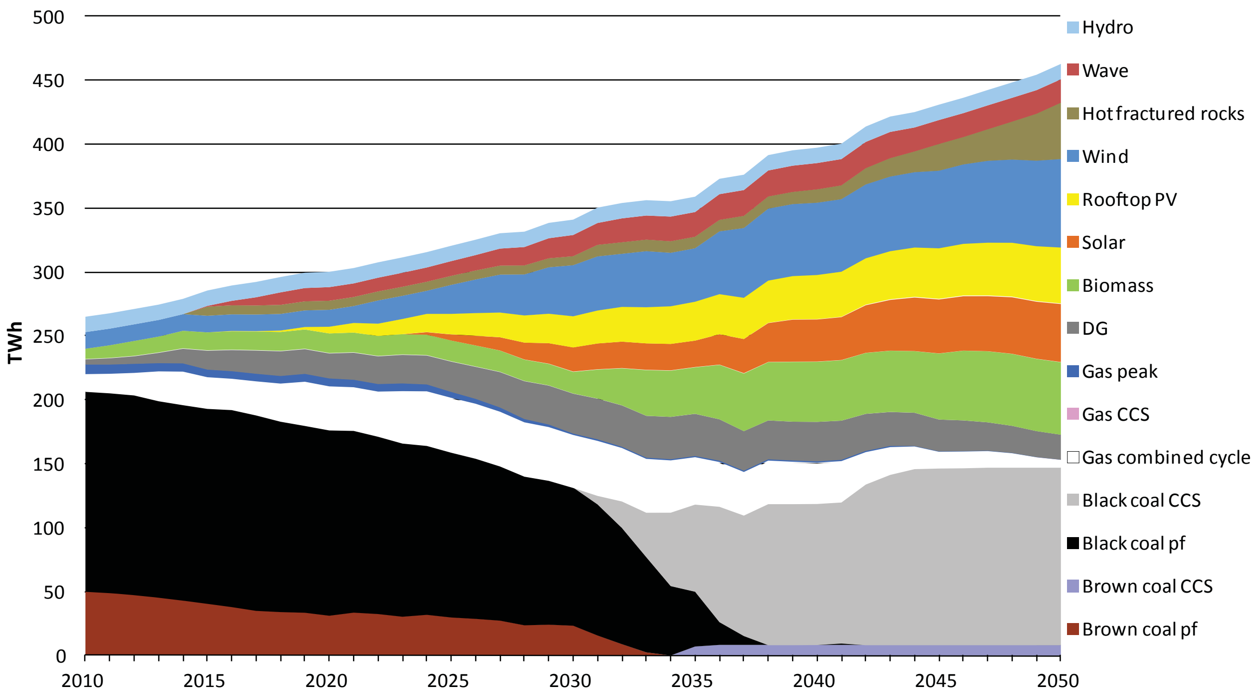

Figure 9-37 Projected Australian electricity generation under CPRS-15 carbon price scenario with 5 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

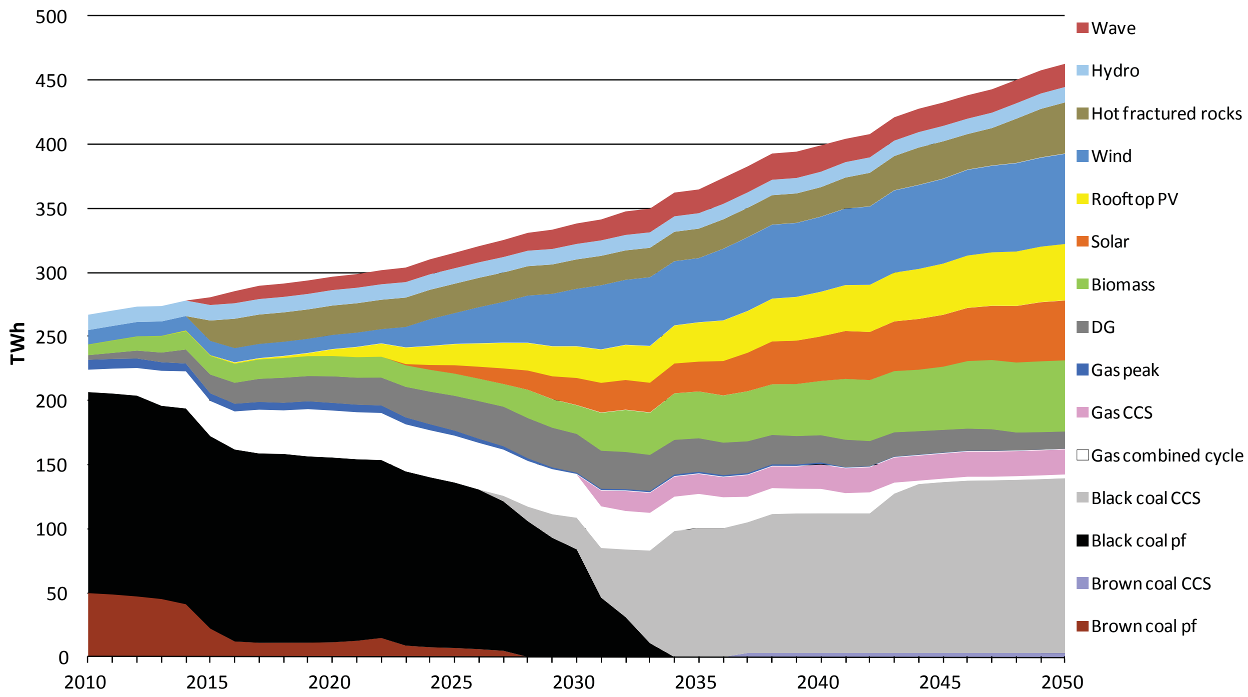

Figure 9-38 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 5 per cent wave energy extraction using a Point Absorber1 wave energy convertor.

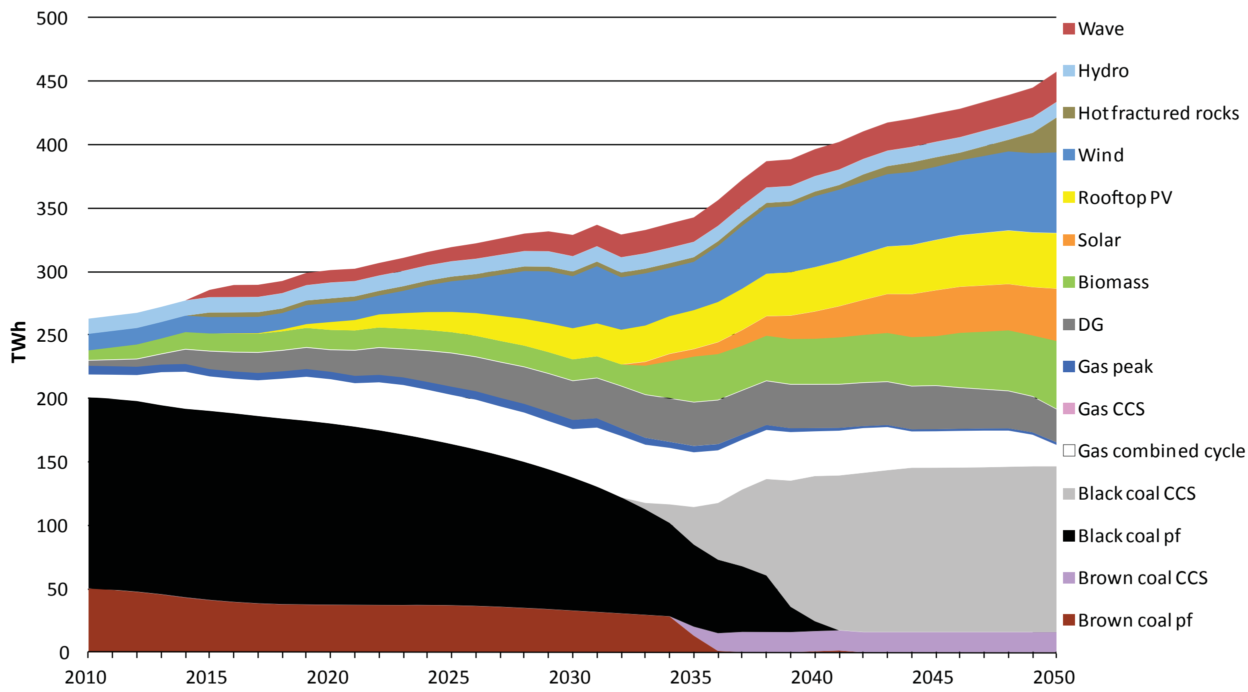

Figure 9-39 Projected Australian electricity generation under CPRS-5 carbon price scenario with 5 per cent wave energy extraction using a Terminator1 wave energy convertor.

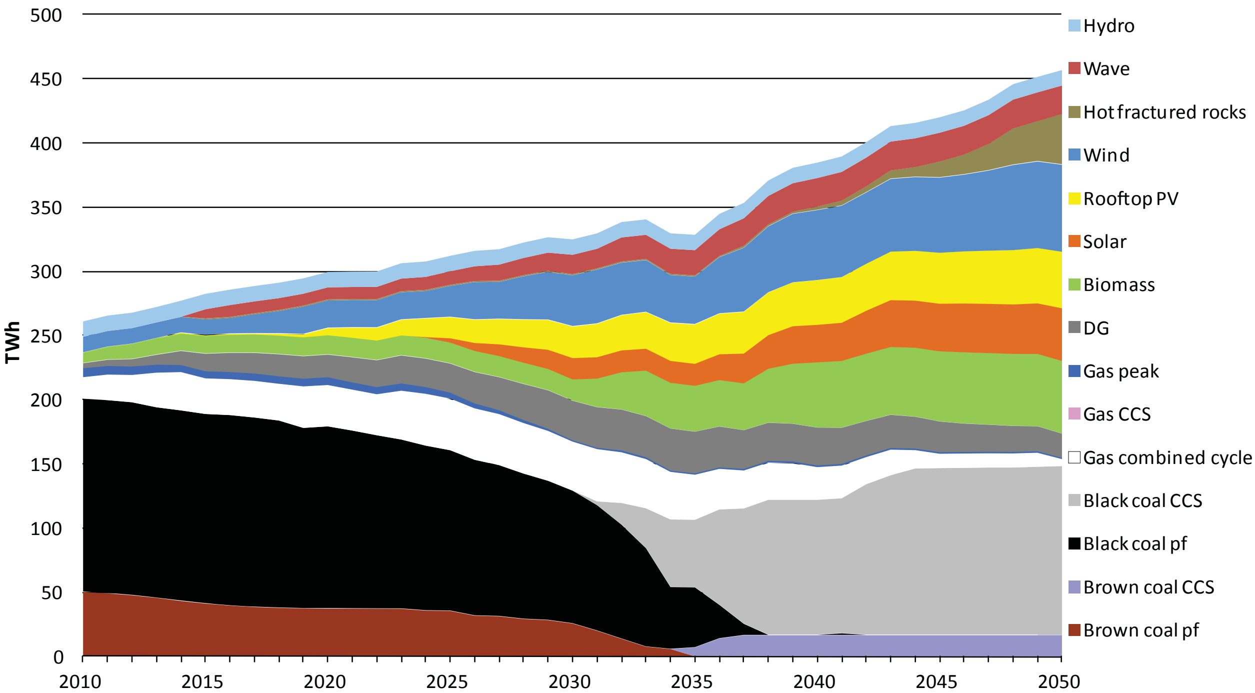

Figure 9-40 Projected Australian electricity generation under CPRS-15 carbon price scenario with 5 per cent wave energy extraction using a Terminator1 wave energy convertor.

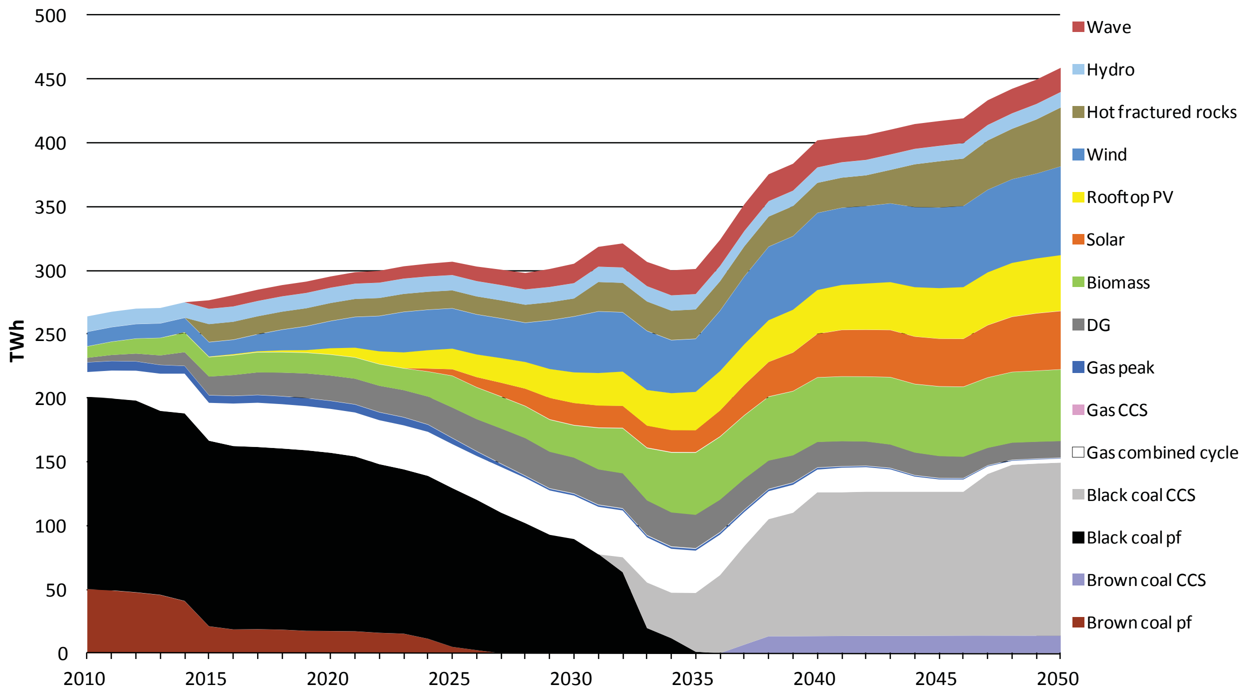

Figure 9-41 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 5 per cent wave energy extraction using a Terminator1 wave energy convertor.

Australian technology specific results with dispatchable power capability

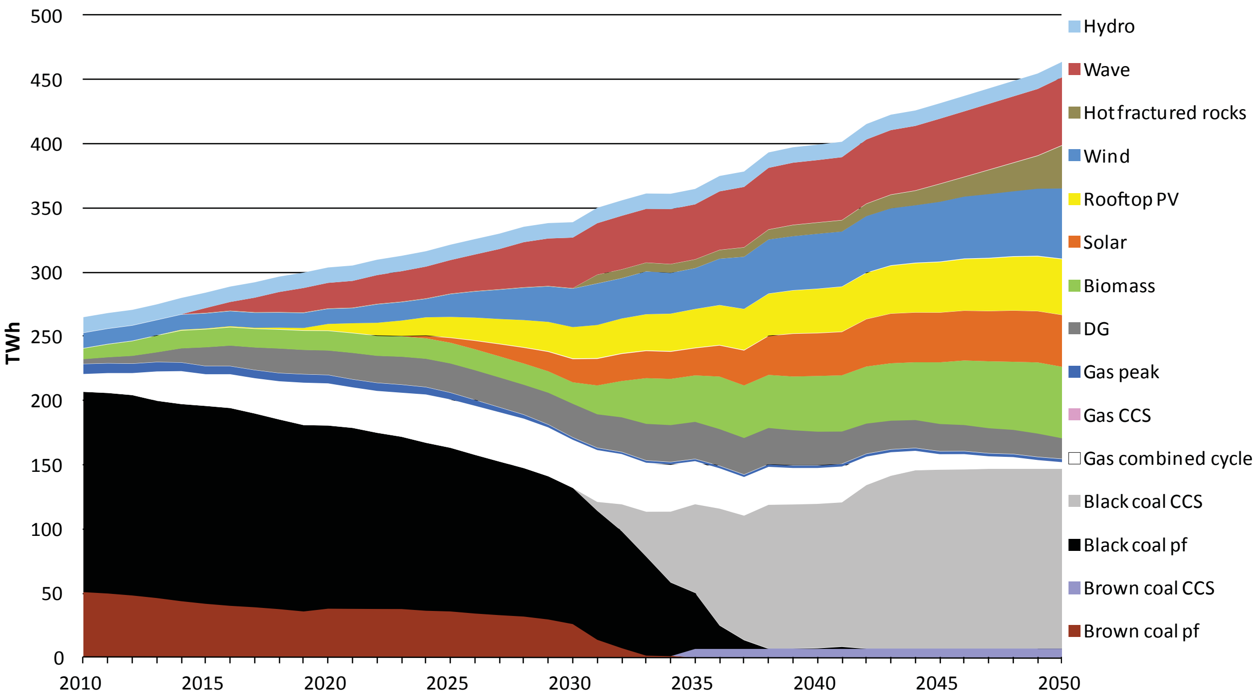

Figure 9-42 Projected Australian electricity generation under CPRS-15 carbon price scenario with 20 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

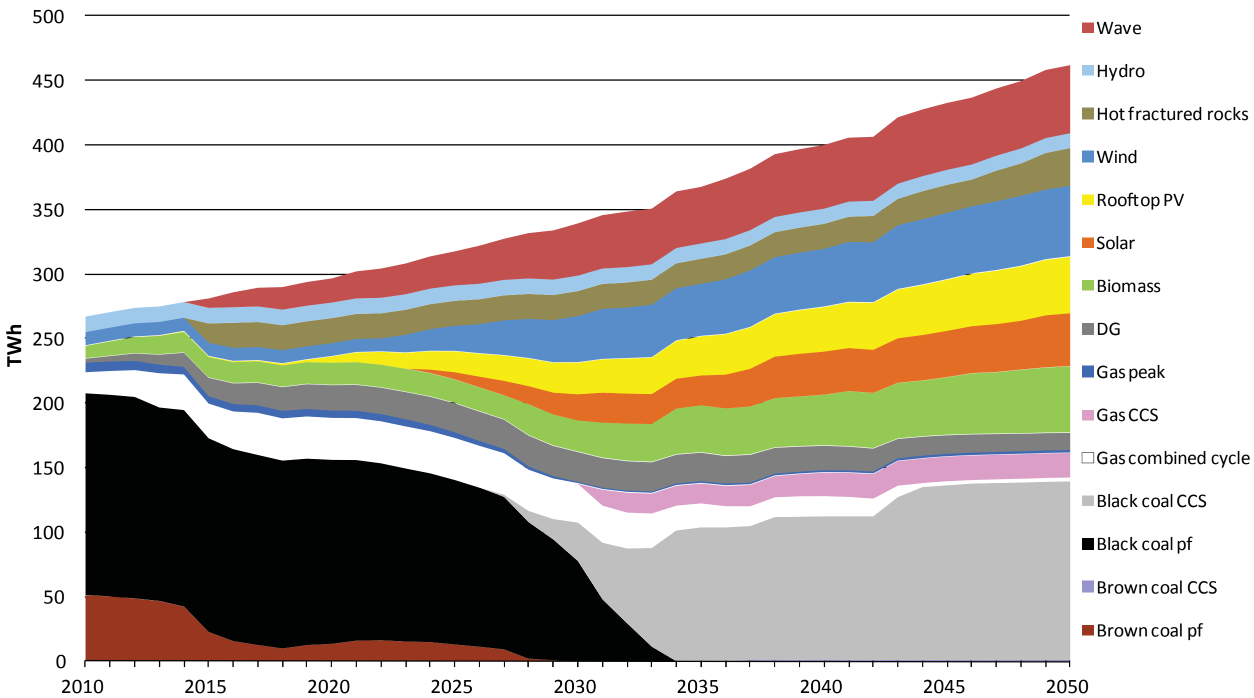

Figure 9-43 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 20 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

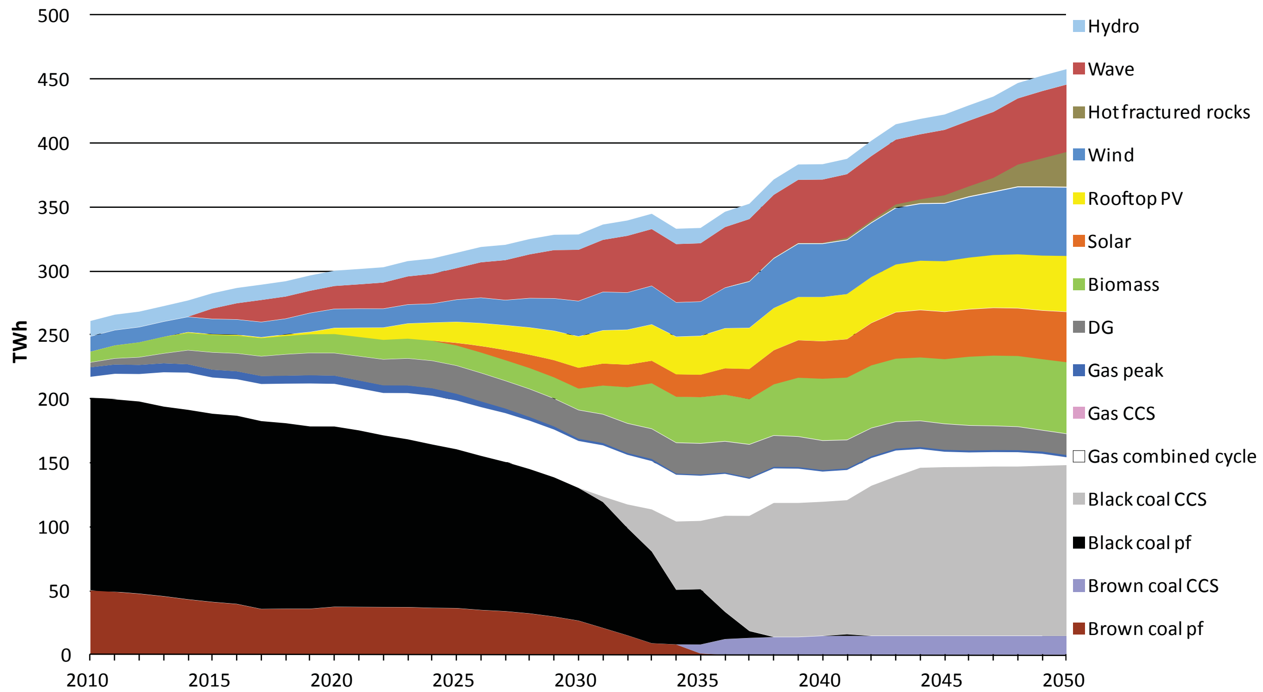

Figure 9-44 Projected Australian electricity generation under CPRS-15 carbon price scenario with 20 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

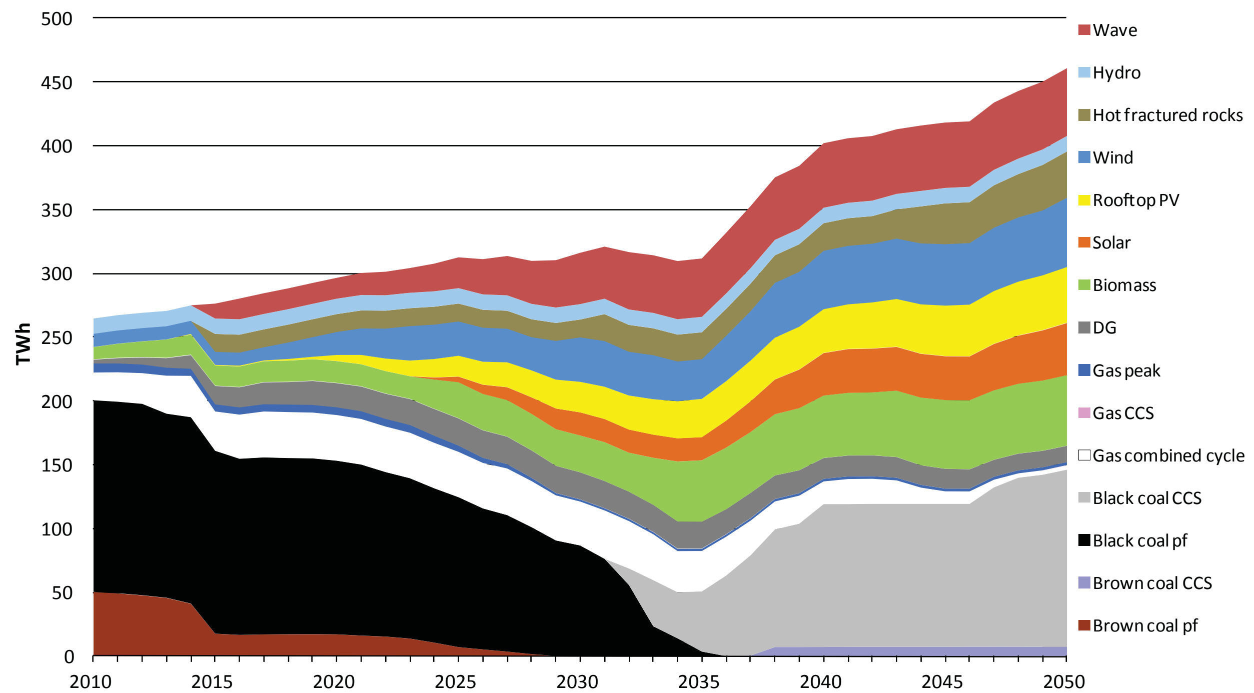

Figure 9-45 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 20 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

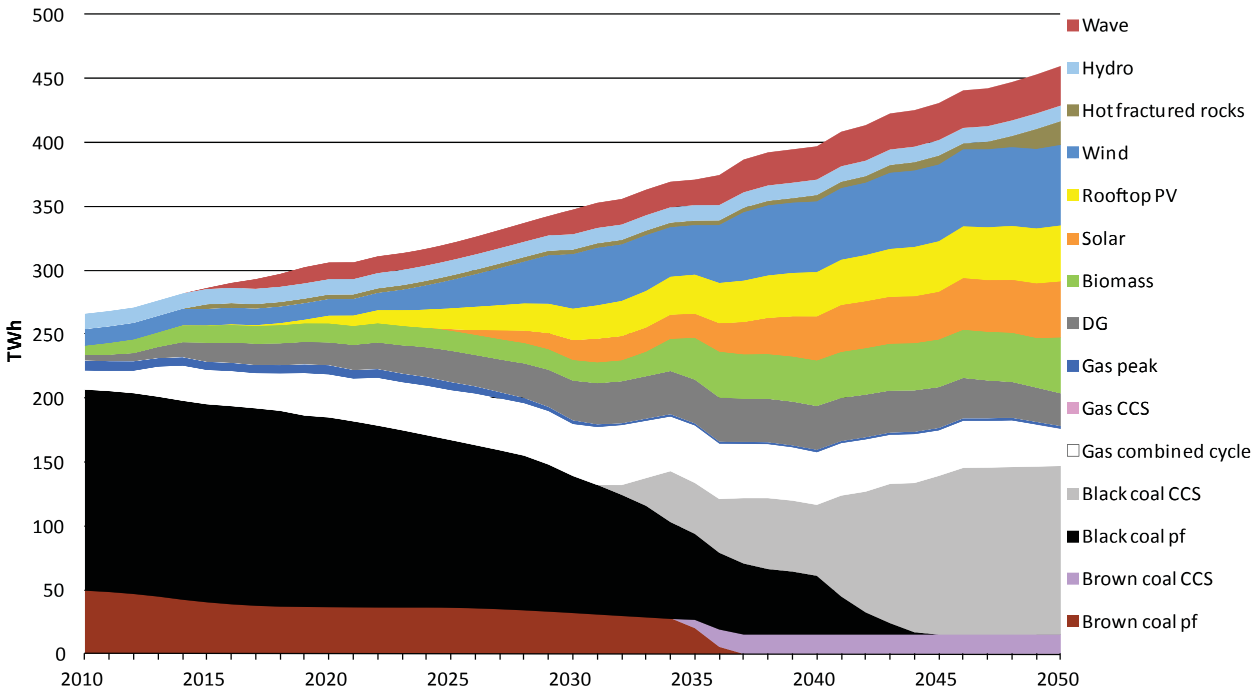

Figure 9-46 Projected Australian electricity generation under CPRS-5 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

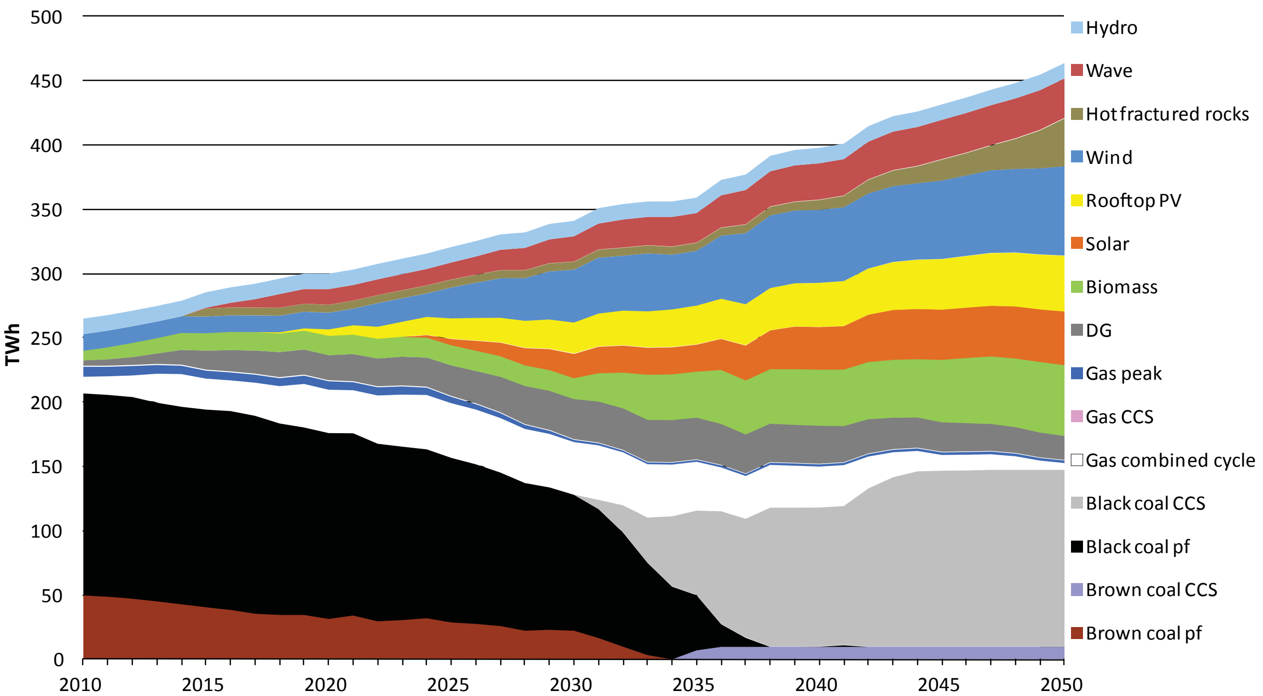

Figure 9-47 Projected Australian electricity generation under CPRS-15 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

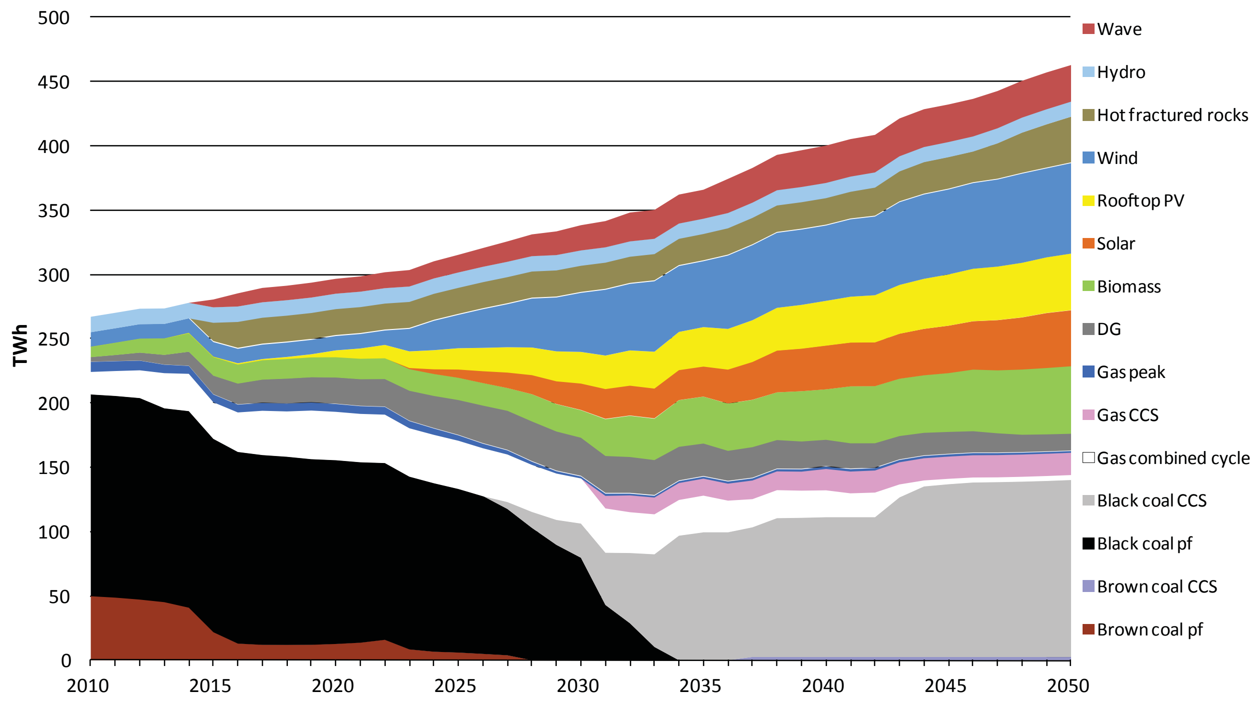

Figure 9-48 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

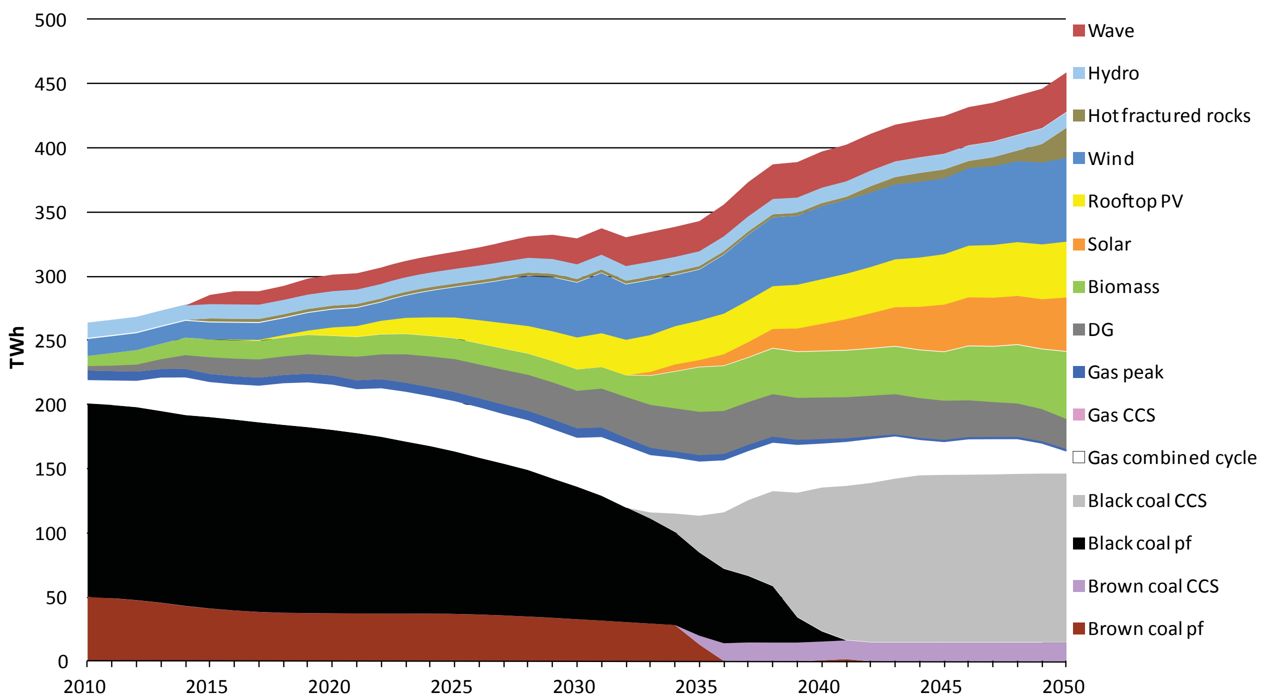

Figure 9-49 Projected Australian electricity generation under CPRS-5 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

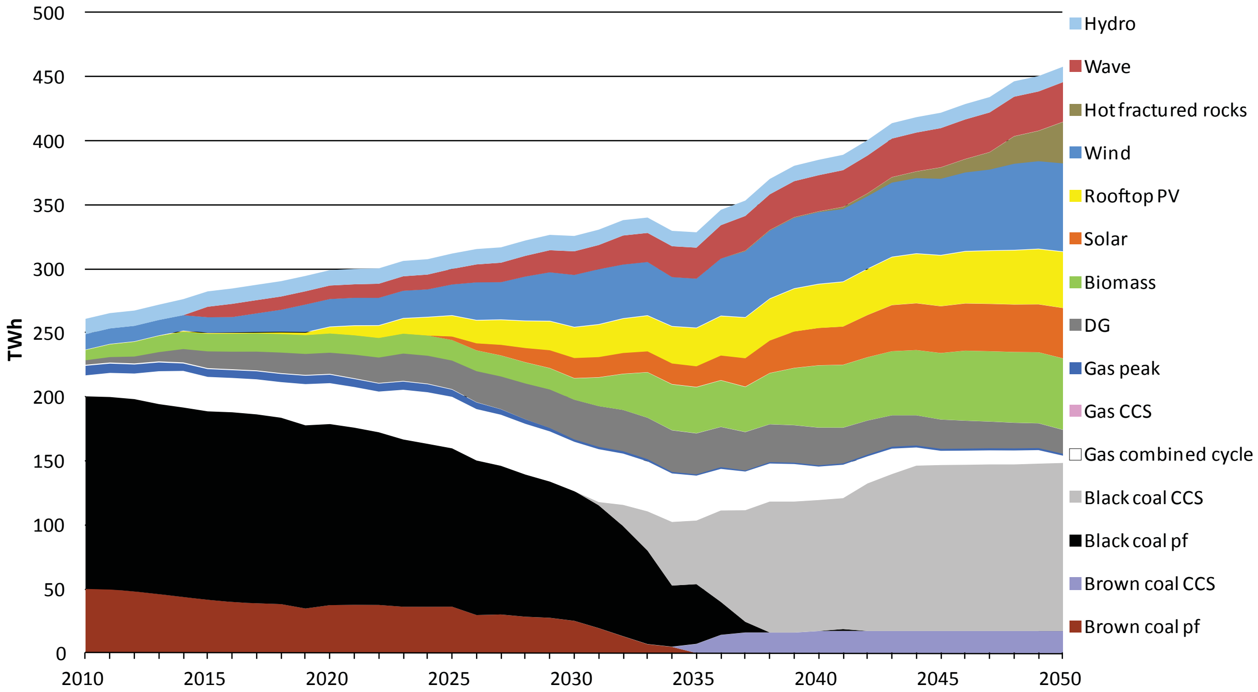

Figure 9-50 Projected Australian electricity generation under CPRS-15 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

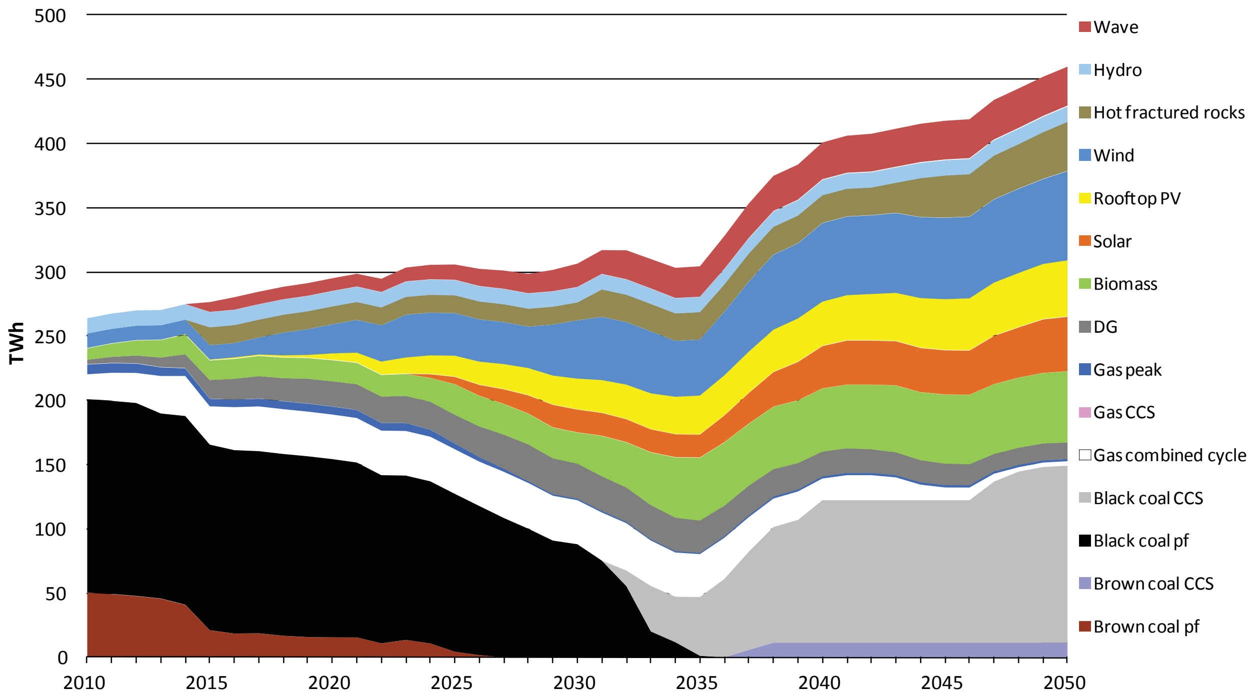

Figure 9-51 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 5 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

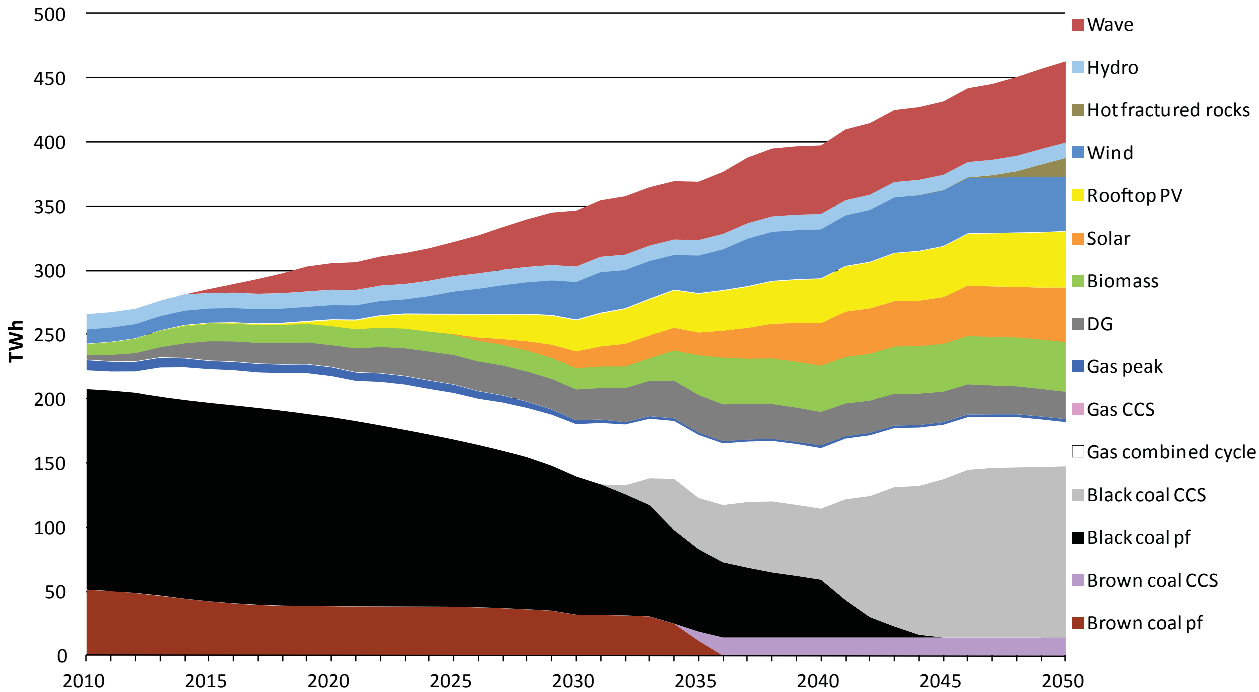

Figure 9-52 Projected Australian electricity generation under CPRS-5 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

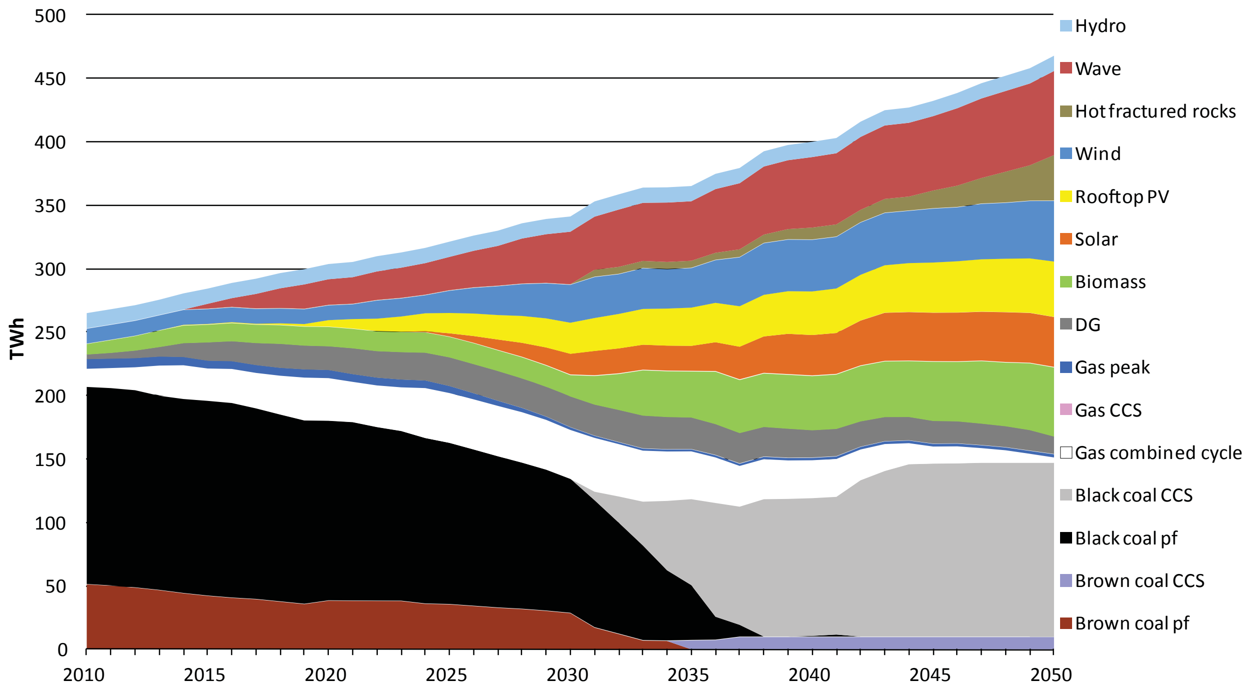

Figure 9-53 Projected Australian electricity generation under CPRS-15 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

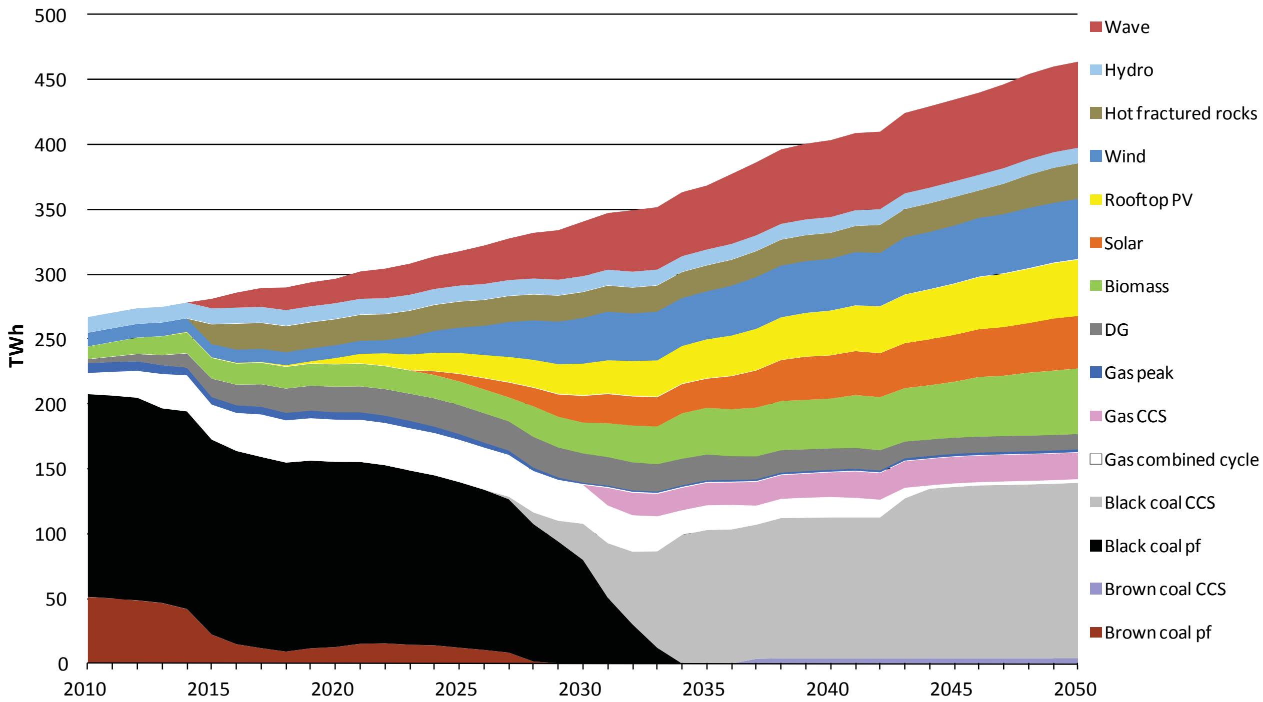

Figure 9-54 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Point Absorber1 wave energy convertor.

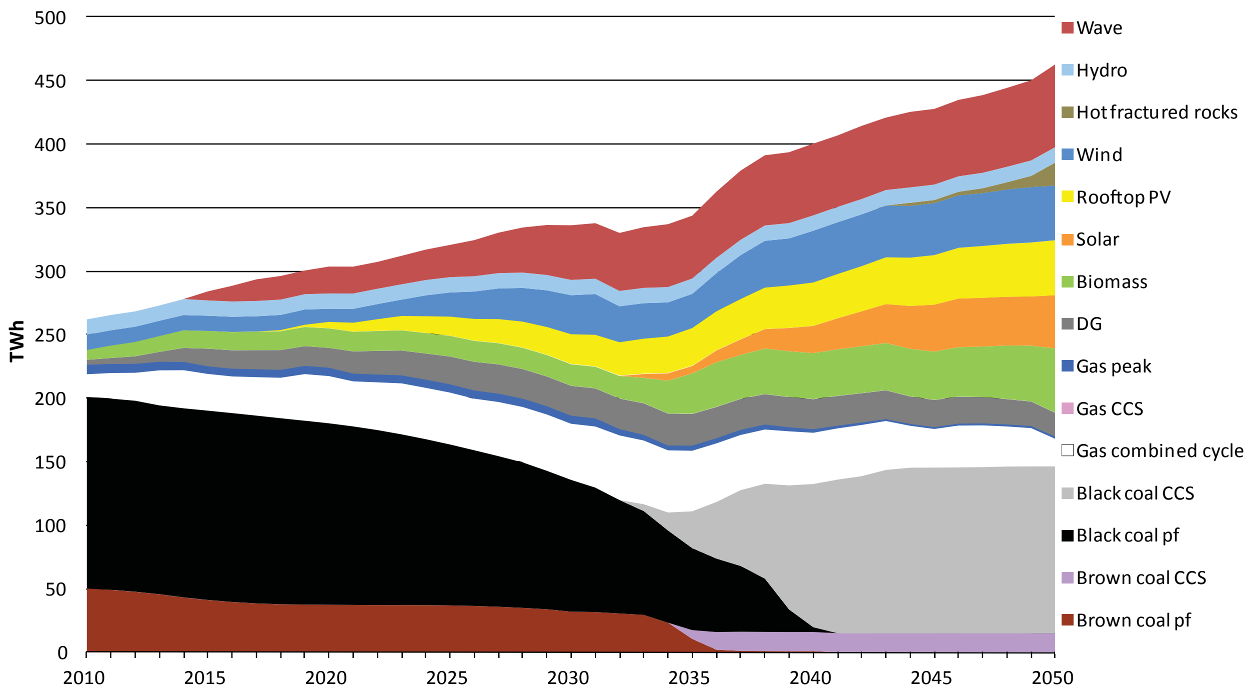

Figure 9-55 Projected Australian electricity generation under CPRS-5 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

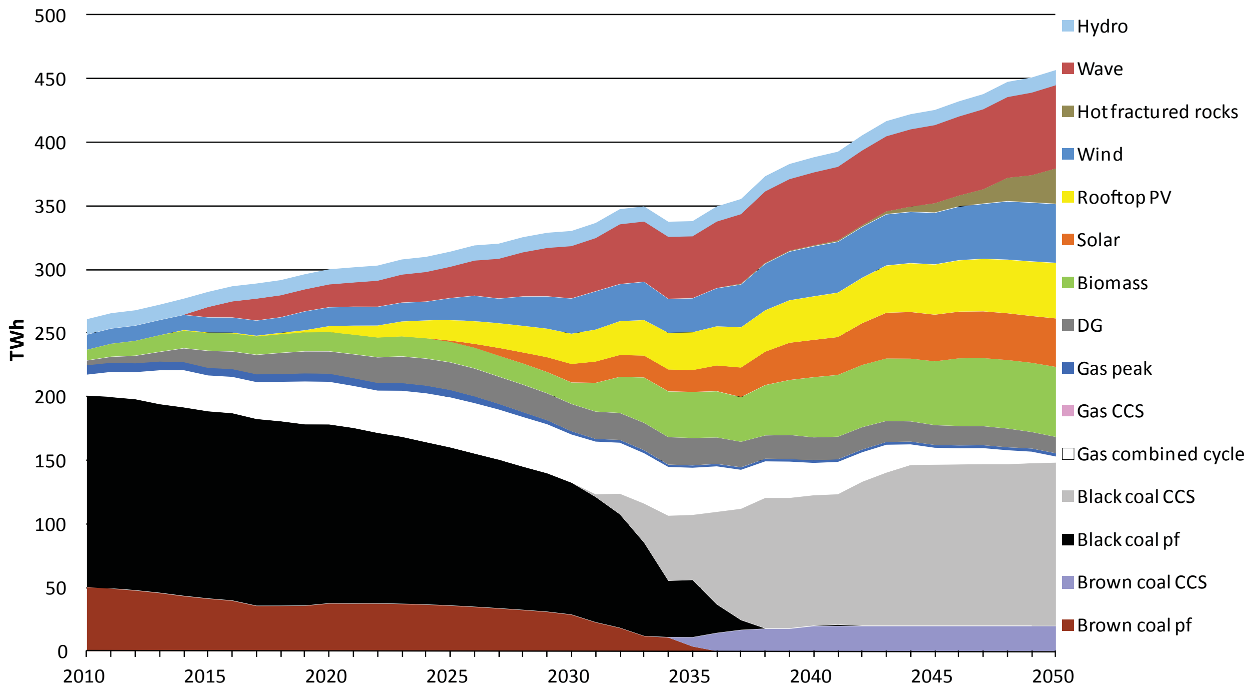

Figure 9-56 Projected Australian electricity generation under CPRS-15 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

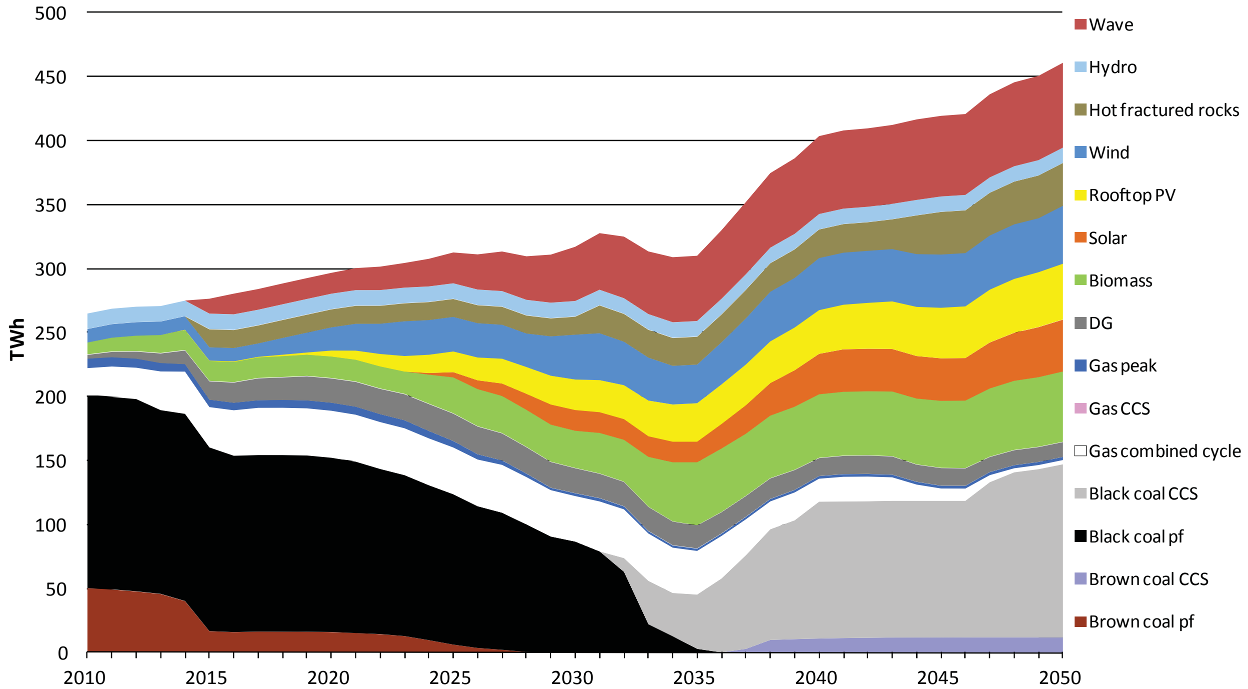

Figure 9-57 Projected Australian electricity generation under Garnaut-25 carbon price scenario with 30 per cent wave energy extraction and dispatchable power using a Terminator1 wave energy convertor.

Terminator capital cost sensitivity analysis

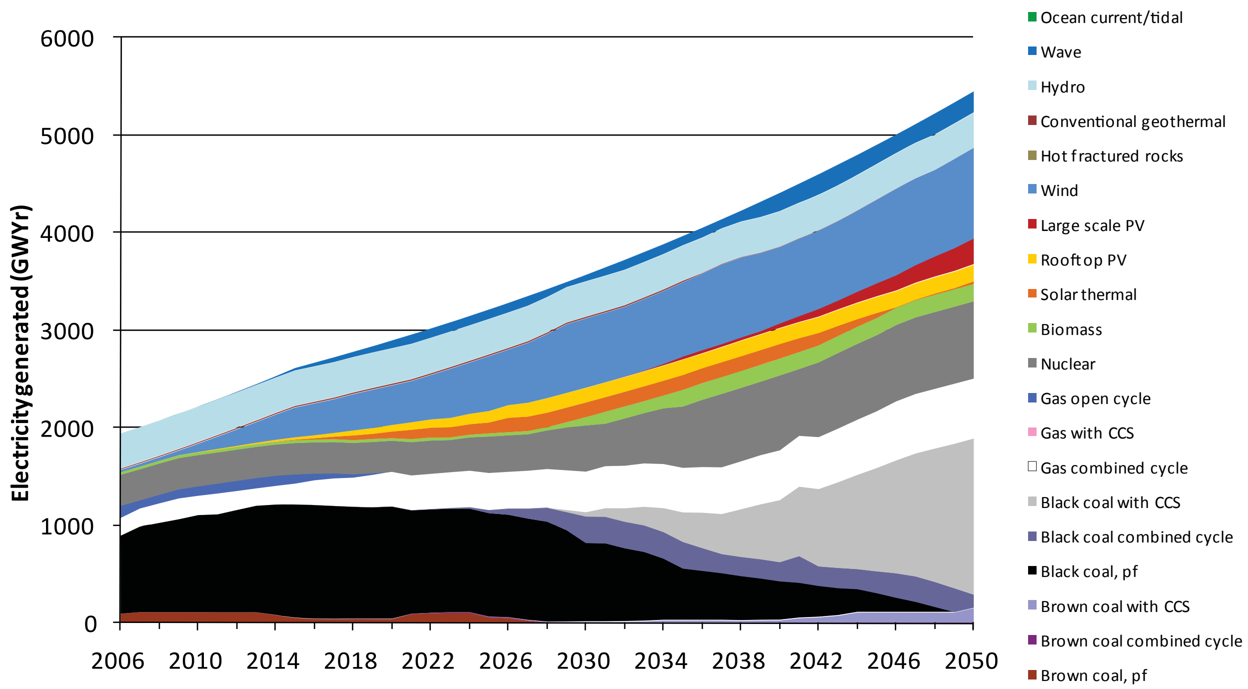

Figure 9-58 Projected global electricity generation under CPRS-5 carbon price scenario and Terminator1 wave energy convertor sensitivity case.

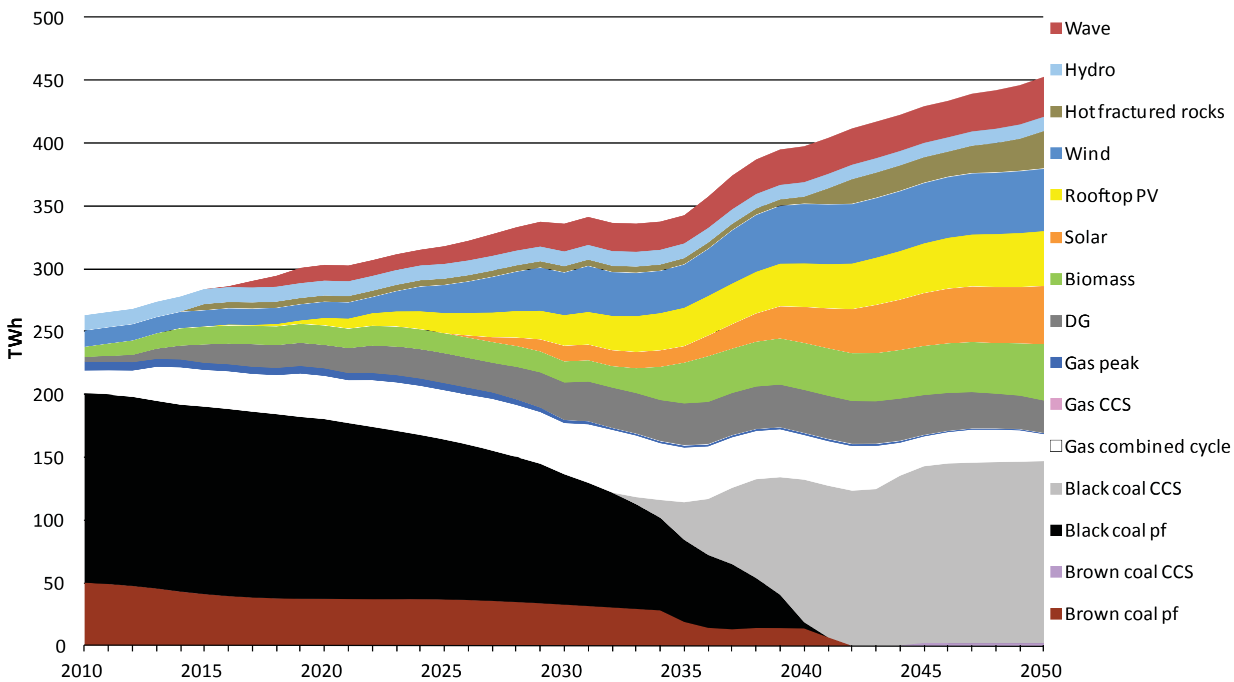

Figure 9-59 Projected Australian electricity generation under CPRS-5 carbon price scenario and Terminator1 wave energy convertor sensitivity case.

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