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Deep ocean currents energy resources–A case study of Australia*

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Abstract. The paper discusses the relevance of renewable energy in the global energy mix worldwide and for the specific of Australia. As Australia is the world top net sequestering country for carbon dioxide, the major short term goal should be modernization of the obsolete coal fired power stations still covering more than 90% of the energy mix plus valorization of the huge biomass resources presently mostly neglected. Instead of investing more resources in wind and solar technologies, which have proved expensive and ineffective, attention should be paid to the development of novel technologies. The paper provides a first assessment of the deep ocean currents energy resources around Australia. The most relevant areas where to focus further research are determined on the basis of the maps for non-tidal ocean current speeds, at 30-40 m and 10-20 m off the bottom, based on the CSIRO Blue Link ocean circulation model. Recoverable power densities are subsequently computed by considering likely efficiencies of free stream ocean turbines.

Keywords: wodeep ocean currents, ocean circulation, marine energy, free stream turbines, modelling

1 Introduction

The paper examines first the role of renewable energy in the energy mix worldwide and for the particular of Australia, the present energy mix contributions and the future trends. This introductory section is needed to put the harvesting of deep ocean currents along the Australian coastline subsequently explored in more details in the right perspective. After proposing other sections on ocean energy in general, tidal and deep currents, and turbines for deep currents, the potentials of deep current energy harvesting around Australia are finally assessed. As the harvesting of deep ocean currents is a new born science, there is not too much literature to consider about the former achievements and what is the research direction. The novelty of the paper is the assessment of the recoverable specific power densities around the Australian coastline by using oceanic turbines calculated for efficiency potentials by using a computational fluid dynamic tool and the maps for non-tidal ocean current speeds based on the CSIRO Blue Link ocean circulation model.

1.1 Present energy mix contributions

The worldwide production of electricity via renewable energies such as wind, solar and geothermal, is still deemed to be unsatisfactory. According to [1], the production of electricity worldwide during 2010 had a minimal solar/wind component (2.82% OECD, 0.71% Non-OECD, 1.78% World, 2.10% Australia), that was almost entirely wind, and basically no geothermal, as reported in Tab. 1. Other renewable energy sources contributed much more than wind/solar, as the hydroelectric component was much larger (12.99% OECD, 19.81% Non-OECD, 16.34% World, 5.18% Australia) and biofuels & waste contributed only slightly less (2.41% OECD, 0.64% Non-OECD, 1.54% World, 1.62% Australia). Fossil fuels were the largest contributor, while nuclear contributed significantly for OECD countries at 20.95% but did not contribute at all for

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Australia, where despite the huge reserves of uranium and the leading position of exporter of nuclear fuels the nuclear energy is banned. The fossil fuel contribution was 60.43% OECD, 74.18% non-OECD, 67.20% World and 91.10% Australia.

Regardless of the huge biomass resources, Australia[2–4] is not supporting too much the use of biomass, and it is not considering upgrading of the mostly obsolete fossil fuels power plants much less efficient and polluting than the OECD average[4], the most part of the investments have been allocated for wind and solar similarly to other OECD countries [5–7]. While wind is certainly performing much better than solar in terms of production per $ invested, aim of the paper is to assess the potentials of Ocean energy harvesting to compete with wind and solar.

Table 1: World gross electricity production, by country, by source, 2010 (from [1]).

	Nuclear	Hydro	Geo Thermal	Solar/ Wind	Fossil Fuels	Biofuels & Waste	Total
OECD	2288.37	1418.68	43.45	308.17	6599.56	263.54	10921.8
	20.95%	12.99%	0.40%	2.82%	60.43%	2.41%	100.00%
Non-OECD	467.92	2097.28	24.7	74.87	7855.1	67.5	10589.3
	4.42%	19.81%	0.23%	0.71%	74.18%	0.64%	100.00%
World	2756.29	3515.97	68.15	383.04	14454.66	331.04	21511.1
	12.81%	16.34%	0.32%	1.78%	67.20%	1.54%	100.00%
Australia	0	12.52	0	5.08	220.08	3.91	241.58
	0.00%	5.18%	0.00%	2.10%	91.10%	1.62%	100.00%

1.2 Latest global energy outlook

According to the recent International Energy Outlook 2013 of the US Energy Information Administration (EIA)[8], the world energy consumption will grow by 56% between 2010 and 2040. Much of this growth will occur in countries outside the Organization for Economic Cooperation and Development (OECD), where demand is driven by strong, long-term economic growth. While the energy use in non-OECD countries will increase by 90%, in OECD countries, the increase will be only 17%.

Renewable energy is the world's fastest-growing energy source, increasing by 2.5% per year. Nevertheless, fossil fuels will continue to supply the vast majority of the world energy use through 2040, with natural gas consumption increasing by 1.7% per year, but coal use supposed to grow faster than petroleum and other liquid fuel use until after 2030. This reference case does not incorporate prospective legislation or policies that might affect energy markets. However, these numbers have clear implications on the best strategies to adopt in pursuing higher shares of renewable energy in the global world energy mix.

The small percentages of renewable energy contribution to the global energy mix is a result of the high costs sustained so far to support mostly wind and solar. Though solar energy systems are considered a mature technology able to deliver electricity production targets as wind, it is certainly not the case yet, as evidenced by the large difference in between solar installed power capacity and electric energy eventually delivered to the grid[9].

Considering only the US, over the period 2009 to 2012 about $14 billion have been invested into solar, wind and other renewable energy project developers. This includes $9.2 billion to 748 small and large wind projects and $2.7 billion to more than 44,000 small solar projects to add only 48 terawatt hours of renewable electricity almost entirely from wind. According to EIA figures, wind accounted for 3.4 % of electricity in 2012, while solar accounted for a negligible 0.11 %. While investment and government incentive for wind and solar have been substantial, small results have been obtained for wind, and practically no appreciable result have been achieved with solar[9].

Renewable energy roadmaps to 2050 include a significant wind energy contribution[1], with a projected growth according to the ETP 2008 BLUE MAP scenario from the 700 TWh/yr in 2010 to the 2700 TWh/yr in 2050, or from 3% to 12% of the global electricity production. This share may increase to the 5800 TWh/yr in 2050 or the 24% of the global electricity production in the ETP 2010 BLUE High Renewable scenario. Ocean energy is not even considered as a future contributor at the present time.

1.3 Renewable energy for Australia

Australia is presently a world top net sequestering nation for carbon dioxide[10]. The most significant transient objective is modernization of the out of date coal fired power stations covering more than 90% of the energy supply[4]. Valorization of the enormous biomass assets is also a priority[4]. As opposed to putting more assets in established wind and solar technologies, consideration ought to be paid to the improvement of novel technologies likewise considering so far disregarded other novel renewable energy sources. The harvesting of ocean energy is one neglected renewable energy source that certainly needs further studies, especially for Australia, an island continent and the world's sixth largest country (7,682,300 km^2) lying between the Indian and Pacific oceans, with a coastline 36,735 km long.

2 Ocean energy status

Ocean energy[11, 12] includes the energy carried by ocean tides, waves, currents, salinity, and ocean temperature difference. Tidal energy has been so far the most developed technology of this pool of energy harvesting opportunities[11]. Nevertheless, the worldwide production of tidal energy electricity is still minimal and the very few installations realized so far had huge environmental and economic costs.

The movement of water in the oceans creates a large amount of energy that in principle can be harnessed to generate electricity. Exploitation of ocean energy has been so far very limited, with efforts mostly focused on tidal motion of large bodies of water, and surface wave powers. The theoretical global ocean energy resources are listed in Tab. 2. While these values may certainly be regarded as optimistic, the marine currents potential is certainly not negligible.

Table 2: Theoretical global ocean energy resources (from [13, 14]).

Capacity (GW)	Annual gen. (TWh)	Form
5,000	50,000	Marine current
20	2,000	Osmotic salinity gradient energy
1,000	10,000	Ocean thermal energy
90	800	Tidal
1,000ł9,000	8,000ł80,000	Wave

Difference in between tides and currents is that tides go up and down while currents move left and right[12]. Tides are driven by the gravitational force of the moon and sun. Oceanic currents are driven by several factors including the rise and fall of the tides, wind and thermo-haline circulation driven by density differences in water due to temperature (thermo) and salinity (haline).

2.1 Tidal energy

There is only a very small share of the world energy mix produced by ocean energy, and this small amount is entirely from tidal energy, with only demonstration plants or tests developed so far for wave (the Aguçadoura Wave Park opened in 2008 in Portugal[11]) and ocean thermal energy (the Kume Island test started in 2013 in Japan[12]).

Presently, tide power is the only commercial technology of the five proposed in Tab. 2. Tides are long period waves that result in the cyclical rise and fall of the ocean's surface. Tides produce different sea levels from one place on the continental shelf to the next at any one time, and this causes the water column to flow horizontally back and forth over the shelf[13].

Tides contain both potential energy, related to the vertical fluctuations in sea level, and kinetic energy, related to the horizontal motion of the water column[13] that can both be harvested with different technologies. Tidal power can be harvested by using tidal stream generators that make use of the kinetic energy of moving water to power turbines in a similar way to wind turbines that use wind to power turbines. Alternatively, tidal barrages make use of the potential energy in the difference in head between high and low tides.

Tide mills have been used since long times ago, with the earliest occurrences from the Roman times, and the world's first large-scale tidal power plant became operational in 1966. However, only two tidal power plants have at the present time a capacity exceeding 25 MW. La Rance Tidal Power Station in France has a capacity of 240 MW and an annual output of 540 GWh while the Sihwa Lake Tidal Power Station in South Korea has a capacity of 254 MW and an annual energy production of 550 GWh.

Tidal barrages are dams across the full width of a tidal estuary. Water enters the basin through channel gates in the barrage and is released through low-head turbines to generate electricity. Tidal stream generators are free-standing structures built in channels, straits or on the shelf and are designed to harness the kinetic energy of the tide. The tidal stream generators are turbines generating electricity from horizontally flowing tidal currents analogously to wind turbines. La Rance Tidal Power Station in France and the Sihwa Lake Tidal Power Station in South Korea are both tidal barrages.

Tidal power has traditionally suffered from relatively high economic and environmental cost and limited availability of sites with sufficiently high tidal ranges or flow velocities. Recent technology developments indicate that the total availability of tidal power is much higher than previously assumed. Even if the economic and environmental costs may be reduced, the competitiveness of this contribution to the global energy mix remains questionable.

2.2 Oceanic currents

Oceanic currents may be harvested with standalone stream turbines similarly to the tidal currents. Due to the larger amount of energy available with approximately constant velocity in many sites of potential interest, this ocean energy harvesting has the potentials to become the most relevant ocean energy source in the near future and a sizable contributor to the world energy mix, similarly to what is being done for wind turbines, providing the issues of the off-coast operation in harsh environments are successfully addressed.

The energy from the Sun doesn't fall equally all over the Earth. The most part of the Sun's energy enters at the equator and this leads to large temperature gradients between the equator and the Poles generating a movement of both the air and the oceans[14]. Seawater continuously circulates around the globe moving from the surface to the deep waters and back. The movement of water around the oceans is density or wind driven.

Fig. 1 shows a schematic view of the ocean circulation (same picture proposed in [14] and [15]). The main currents at the surface are shown in red, the main currents in the deeper layers in blue. Violet is the Antarctic bottom water. Deep water formation is taking place at the yellow spots in the Northern Atlantic and near Antarctica due to sea ice production. Fig. 2 (from [16]) presents the regional and global ocean currents in the Australasian region.

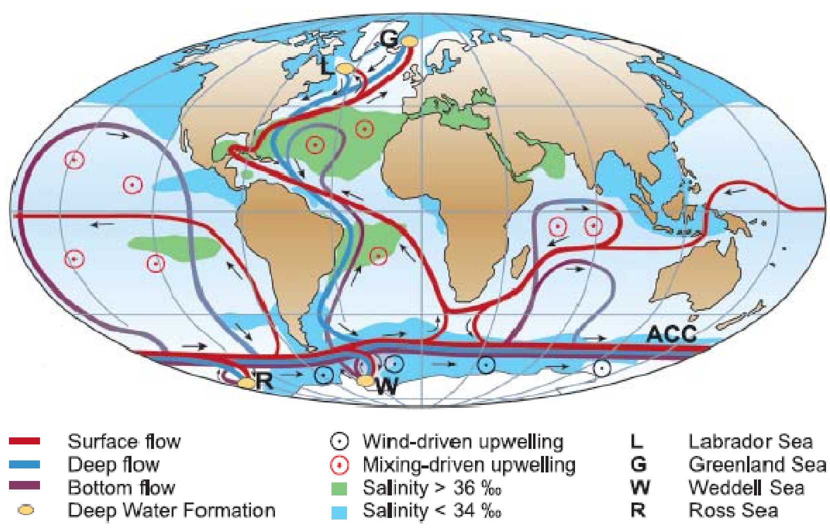


Fig. 1: Schematic view of the ocean circulation (picture proposed in references [18] and [19])

Fig. 2: Regional and global ocean currents in the Australasian region (image from [20])

The Antarctic Circumpolar Current connects the Atlantic, Pacific and Indian Oceans in an eastward flow[16]. It comprises a series of merging and separating jets acting as a buffer between different masses of water either side of the sub-tropical front and the sub-Antarctic front. The Leeuwin Current forms near the North West Shelf on Australia's west coast[16].

As it travels south the current breaks into a series of southward and eastward flowing eddies and eventually dissipates in the Tasman Sea and Southern Ocean. The Indonesian through-flow is a system of currents that carries water westward from the Pacific to the Indian Ocean through the deep passages and straits of the Indonesian Archipelago[16].

The East Australian Current flows south along the east coast of Australia from near Queensland's Fraser Island to Tasmania[16]. It is an important feature of the Tasman Sea between Australia and New Zealand. The Indonesian through-flow, the system of currents linking the Pacific and Indian Ocean, is evident and very strong in the North. Apart from this region, where potentials of ocean currents exploitation are larger, close to the Australian coasts, significant currents are also recorded along the south western, the south and the eastern coasts.

3 Turbines for deep ocean currents

Marine current energy is now receiving a growing attention, as demonstrated by the many recent works on the subject and the growing number of start-up companies dealing with the harvesting of the energy of oceanic currents. However, the harvesting techniques are still far from being consolidated technologies, and of the many different options that have been proposed, very likely only few will progress.

Up to date, the only activity of relevance has been the one conducted by the researchers at Florida Atlantic University (FAU)[17–19]. The team is studying the ocean currents along Florida's southeast coast and has determined practical turbine operating areas that maximize energy extraction. The project aim is to help understand the limits and the potentials of the technology for energy developers and others interested in creating pilot projects.

In principle, open-flow devices as those of [17–19] are preferable to ducted versions, as it is the case of wind energy. Common sense also suggests that ocean current turbines may certainly also work better if placed on the ocean floor rather than adopting floating arrangements. Deep current turbines in the free-standing versions are more likely to deliver the best all-inclusive cost-to-benefit ratio.

The relatively constant flow of ocean currents carries large amounts of water across the earth's oceans. Technologies are being developed so that energy can be converted to electricity. While ocean currents move slowly compared to typical wind speeds, they carry a great deal of energy because of the density of water. Deep ocean currents run at a constant speed of about 3 to 5 knots or 5.5 to 9 kilometres per hour. Strong currents can be found within a few kilometres from shore also at relatively easy-to-reach depths of 30 to 150 meters.

Ocean currents are relatively constant and flow in one direction, in contrast to tidal currents along the shore. Ocean current energy is at an early stage of development[20]. Relative to wind, wave, and tidal resources, ocean current power technology is certainly the least mature[20]. Only a small number of prototypes and demonstration units have been tested, and prototype horizontal axis turbines, similar to wind turbines, have been the solution more widely built and tested.

The fundamental laws that apply to wind turbines[21] also apply in principle to stream turbines designed to harvest the ocean currents. However, for ocean current energy to be utilized successfully at a commercial scale, a number of engineering and technical challenges need to be addressed including very high hydrostatic pressures, salt water, avoidance of cavitation, prevention of marine growth build up, system reliability and corrosion resistance[20] and more generally all the issues linked to the operation in harsh environments.

The power that may be harvested by an axial flow wind turbine is proportional to the wind power

$$P = \frac{1}{2} \times \rho \times A \times v^3,$$

where P is the power, ρ the air density, A the swept area of the turbine and v the wind speed. Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor (Betz Limit). Therefore

$$P = C_P \times \frac{1}{2} \times \rho \times A \times v^3$$

with C_p of a wind turbine is 0.593.

Wind turbines cannot operate at the Betz limit and various engineering requirements as for example strength and durability limit the operating C_p well below this limit. Deep oceans turbines may certainly deliver much less than wind turbines in terms of C_p due to the operation in a particularly harsh environment and the much closer proximity of the rotor to the ocean floor. The best tidal energy turbine is claimed to have a peak C_p of about 0.48 for both rotors on both tides[22] very close to the best wind energy turbines claimed to have peak C_p of about 0.5. However, the overall system efficiency, including all losses in the generator, gearbox and power electronics, is claimed to be in the range 40 to 45%; that is the proportion of energy in the flow of water that can get delivered as electrical energy into the grid[22]. Marine turbines are designed by using the same principles as wind turbines, with the significant difference of the much higher density of the water versus the density of the air and the much higher surrounding pressure, the smaller diameter of rotor and the closer proximity to the ocean floor.

Results of preliminary Computational Fluid Dynamic (CFD) simulations by using Star-CCM[23] of the operation of the ocean turbine of [24], Fig. 3 indicates the opportunity to achieve C_p values of around 0.30-0.40 over the expected range of speeds operating in deep waters with 300 bar of pressure at the axis of the nacelle. The rotor has a diameter of 5.65 m. The distance of the axis of the nacelle from the ocean floor is not enough to cancel the effects of the boundary layer on the energy harvesting of the turbine. These C_p values are only marginally worse than then values typically occurring in wind farms where the C_p range is around 0.35-0.45[25–27].

In Fig. 3, the power coefficient C_p values are around 0.30–0.40 over the expected range of speeds operating in deep waters with 300 bar of pressure at the axis of the nacelle. Diameter of rotor is 5.65 m. Distance from the ocean floor is not enough to ensure the operation of the turbine does not suffer of the boundary layer profile.

This result suggests considering not more than one third of the power per unit area potential that may be inferred from the computations of the ocean current speed proposed in the next section as power eventually deliverable to grid.

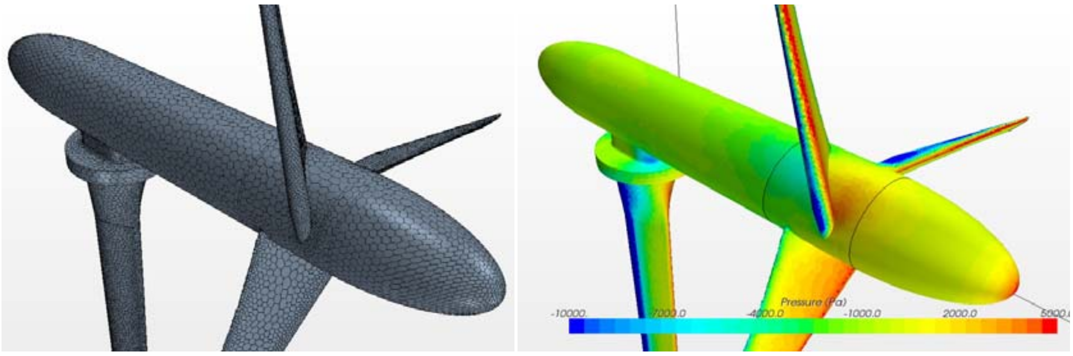


Fig. 3: CFD simulation of a standalone ocean turbine. Surface mesh (left), surface pressure (right)

4 Potentials of oceanic currents around Australia

A recent work[28] has provided a detailed assessment of Ocean Renewable Energy (ORE) potentials around Australia, including ocean waves, tidal and non-tidal ocean flows.

Preliminary maps of wave, tidal and non-tidal ocean flow energy distributions around the Australian coastline were produced from the best available existing information suggesting "*substantial but imprecisely quantified*" potentials.

The work in [28] has shown significant non-tidal ocean currents especially in the East Australian Current flows southwards from Queensland into New South Wales, with a small fraction of its flow continuing past eastern Tasmania. This makes the northern NSW-southern Queensland stretch of coast the most promising location in Australian waters for extracting energy from non-tidal currents[28]. Figs. 4 to 6 (from [29]) present the 10^{th}, 50^{th} and 90^{th} percentile values for non-tidal, near-surface (30–40 m depth) and close to the bottom (10–20 m off) ocean current speeds for Australia based on the 1/10 degree ($\sim$11 km) resolution CSIRO Blue Link ocean circulation model.

Blue Link is a global ocean forecasting system that provides information on oceanic conditions to help manage Australia's diverse area of maritime operations. This product is delivered in partnership by CSIRO, the Bureau of Meteorology and the Royal Australian Navy.

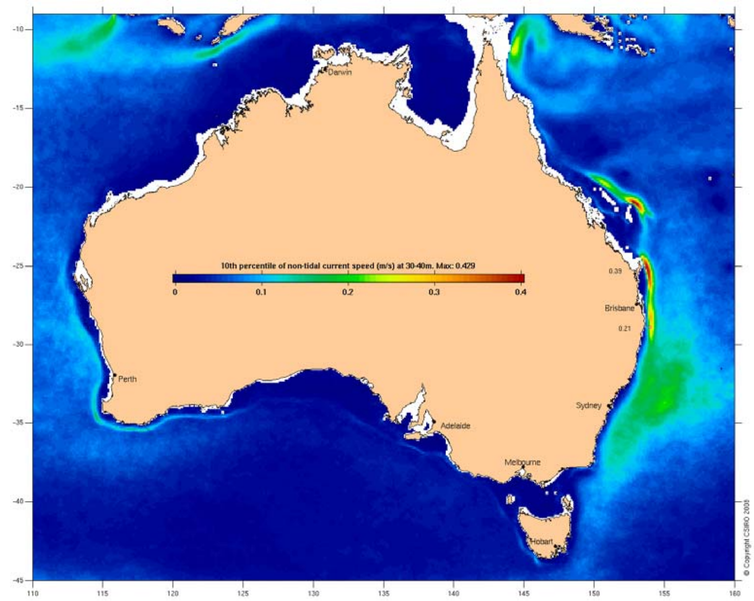
Near the surface, the maximum of 10^{th}, 50^{th} and 90^{th} percentile values of the current speed are about 0.429, 1.14 and 2.03 m/s respectively, translating in quite low maximum power densities of 39, 739 and 4170 W/m^2. These flow powers are not the powers that may be delivered to the grid. More realistically, only one third of these powers may be electric powers. Also considering the maximum values on the plots occur at single points, very large diameter devices or a significant number of devices are required to extract significant powers in areas that may be of interest for speed and proximity to coast and grid.

Near the ocean floor, the maximum of 10th, 50th and 90th percentile values of the current speed are about 0.243, 0.994 and 1.75 m/s respectively, translating in quite low maximum power densities of 7.2, 491.1 and 2679.7 W/m^2. Again, these powers are not electric powers and these maximum values on the plots occur at single points, probably in Torres Strait, and therefore very large diameter devices or a significant number of devices are required to extract significant powers in areas that may be of interest for speed, depth not excessive and proximity to coast and grid.

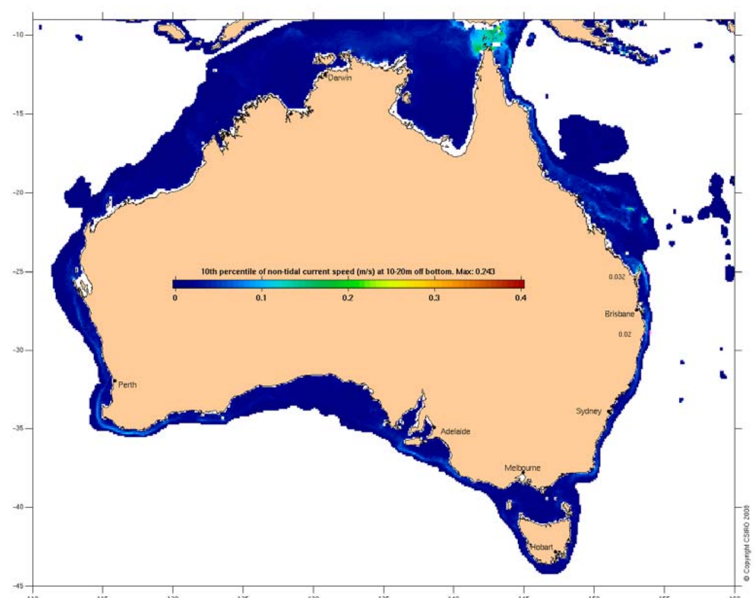
These data refer to a model study off the coast of Australia. This is a numerical model with limited validation. The data in the present form are not supposed to be used to infer any information on how large are the areas where locate ocean current farms, how deep are the areas, how many specific devices could be installed, at what spacing and how might this be cost competitive. The results are only intended to be used as a first assessment of the most promising areas where to perform further detailed studies.

Figs. 4-6 are an indication of the areas where to focus research and development to better understand the actual potentials, being these figures a result of a preliminary simulation based on few field measurements. A proper sitting of an ocean current farm only follows the detailed, repeated measurement of the velocity 10–20 metres off the bottom in selected locations of acceptable depth and close proximity to coast and grid to determine the actual power densities.

Figs. 4-6, coupled with the Australian Bathymetry and Topography Grid[30] indicates that some areas like the Coorong-Limestone coast south of Adelaide or the area front of Brisbane, Sunshine Coast or Gold Coast are sites of potential interest for further studies.



(a)

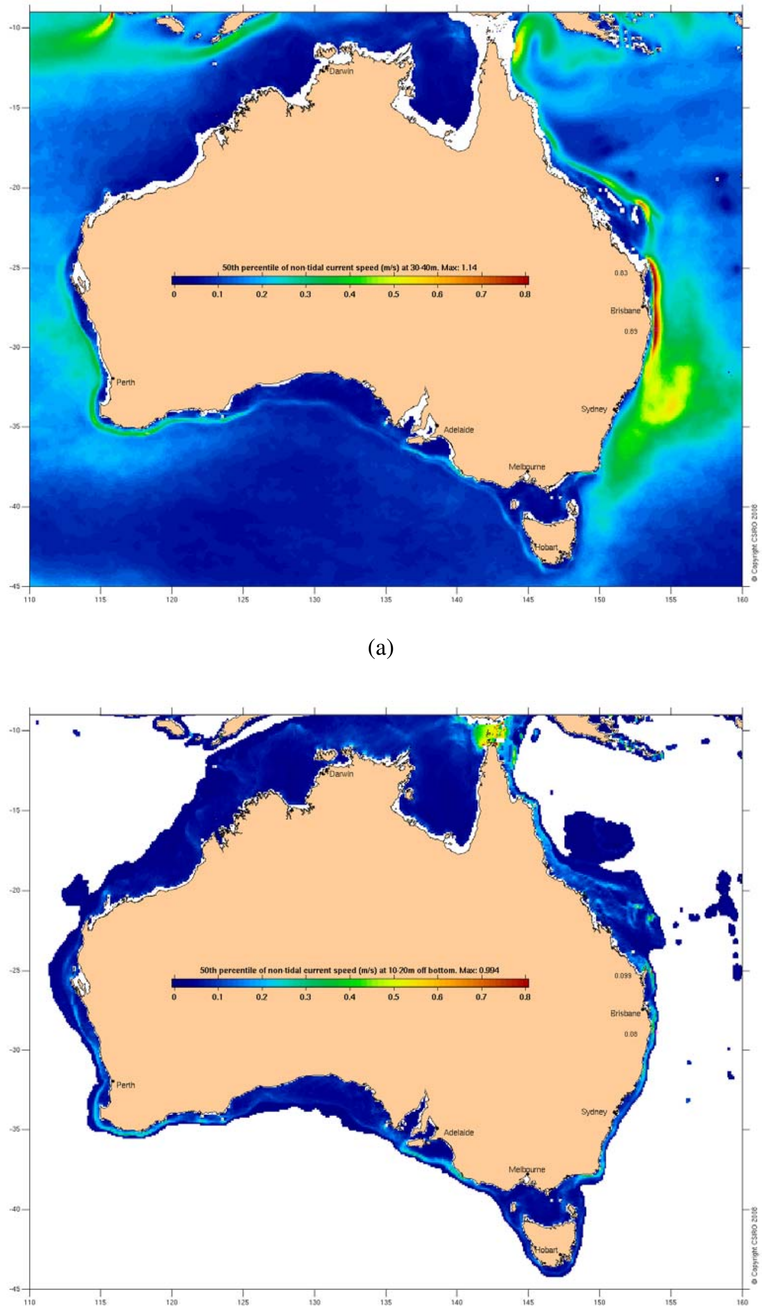


(b)

Fig. 4: 10th percentile values for non-tidal, at 30-40 m (a) and 10-20 m off the bottom (b) ocean current speeds for Australia based on the 1/10 degree (∼11 km) resolution CSIRO Blue Link ocean circulation model (image from [33])

5 Conclusions

As Australia a top net sequestering country for carbon dioxide[10], the major short term goal should be modernization of the obsolete coal fired power stations still providing more than 90% of the energy mix and



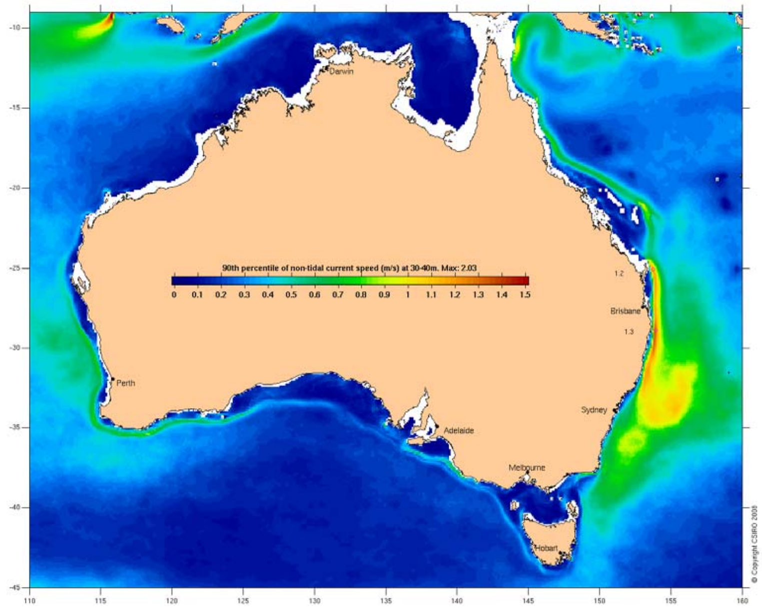
(a)

(b)

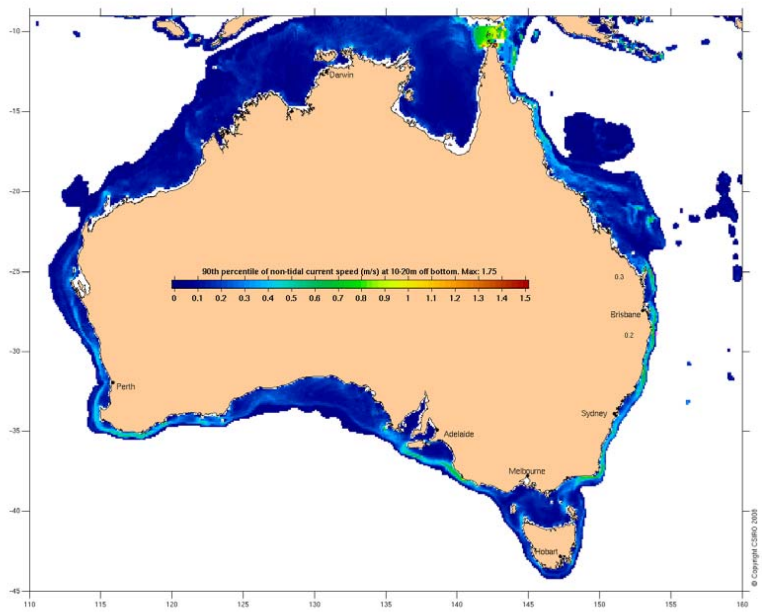
Fig. 5: 50th percentile values for non-tidal, at 30–40 m (a) and 10-20 m off the bottom (b) ocean current speeds for Australia based on the 1/10 degree (∼11 km) resolution CSIRO Blue Link ocean circulation model (image from [33])

valorisation of the huge biomass resources[2–4]. Instead of investing more resources in consolidated wind and solar technologies attention should be paid to the development of novel technologies.

A first assessment of the deep ocean currents energy resources around Australia is presented here as maps of non-tidal ocean current speeds of 30-40 m and 10-20 m off the bottom. Harvesting of ocean currents has many similarities with the harvesting of the wind power, and ocean current turbines have in principle the potential to provide comparable contribution to the global energy mix. Better appraisals of ocean energy resources[31–33] and further development of energy conversion technologies[34–36] are certainly key issues in harvesting the energy of ocean currents in the future.



(a)



(b)

Fig. 6: 90th percentile values for non-tidal, at 30–40 m (a) and 10-20 m off the bottom (b) ocean current speeds for Australia based on the 1/10 degree ($\sim$11 km) resolution CSIRO Blue Link ocean circulation model (image from [33])

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