Chapter

# Can Ocean Thermal Energy Conversion and Seawater Utilisation Assist Small Island Developing States? A Case Study of Kiribati, Pacific Islands Region

*Michael G. Petterson and Hyeon Ju Kim*

## Abstract

The deployment of a land-based Ocean Thermal Energy Conversion (OTEC) plant in South Tarawa, Kiribati, Pacific Islands Region, in 2020/2021, represents a major technical achievement, alongside an international development opportunity. Pacific Small Island Developing States (PSIDS) are archipelago nations with small land areas and large oceanic exclusive economic zones. Geographical isolation and large transport distances make economic development a challenge. A lack of affordable and reliable energy in many PSIDS is a development inhibitor. PSIDS are situated within the areas of highest ocean thermal potential in the world. Temperature differences between surface and 1 km depth waters, are in excess of 24°C. Regional geology and tectonics allow access to deeper, colder, waters within few kilometres of many shorelines, and close to market. Seawater Utilization technologies can catalyse varied industrial development (e.g., fresh water/aquaculture/agriculture/mineral salts). The KRISO (Korean Research Institute of Ships and Ocean Engineering)-Government of Kiribati OTEC partnership is already 7 years old (2013–2020) and has involved extensive negotiations, awareness raising programmes, and inclusive collaboration. The project will test OTEC technologies and explore a range development opportunities for Kiribati. The programme could become a role model for the application of the concept of 'Interconnected Geoscience'.

**Keywords:** ocean thermal energy conversion, OTEC, international development, Kiribati, green energy, Pacific

### 1. Introduction: why OTEC, seawater utilisation, and SIDS?

This paper examines aspects of the application of ocean thermal energy conversion (OTEC) and seawater utilisation within a Pacific Small Island Developing States (or PSIDS) development context. OTEC was first proposed in 1881 by a French physicist, Jacques-Arsene d'Arsonval, and the first OTEC plant was built in Cuba, in 1930, by Georges Claude. The principles of OTEC are discussed in later sections. It is worthwhile, at this stage, considering questions such as "why has such an old technology taken so long to be realised on a large scale?" and "why deploy at this time within a Pacific Islands context?"

There are a number of potential replies to the first question. Many technological ideas and inventions do not end up as large-scale commercial successes. There may be long incubation periods for some technologies before their application need becomes apparent, or the technology may not allow development on a large or mass-produced scale until scientific advances occur. The idea of space travel or mobile communication devices, for example, was common in science fiction, long before they were technologically realised. With respect to energy, there has been, and remains, an abundance of hydrocarbon energy, with oil in particular, being highly transportable and flexible as an energy source. The advent of climate change and global warming social and political movements, particularly since the 2015 COP 21 meeting in Paris, France [1], are heralding the gradual demise of fossil fuels and the rise of less polluting renewable energies. This change in thinking, policy, and economics has allowed OTEC to become, again, a renewable energy source that may, finally, come of age. Technical and commercialisation challenges remain for OTEC, particularly in the sphere of large (100 MW plus) fully ocean-deployed energy platform development, and this will impede progress for some time to come. Only small (<1 MW) land-based, ocean-adjacent, OTEC systems have been developed thus far, as experimental plants or provision of small-scale energy, drinking water, agriculture/aquaculture, or space heating/cooling units in places such as France, Hawaii, India, Mexico, and South Korea. There remains a wide gap between commercialisation need (for large electricity generation plants) and current OTEC technical capabilities.

The second question may, at first, appear cryptic, but does, on analysis, make a degree of logical sense. Why, from all the world's markets would an advanced country such as South Korea choose a small Pacific atoll island nation to be the target of, potentially, the world's first-ever 1 MW OTEC plant? Why not China, the USA, Canada, South America, or the European Union? One answer is scale. Large developed countries, or even medium-sized emerging countries, require far more electricity than a small OTEC plant can provide. Then there is geography. An OTEC plant requires oceanic temperature conditions that are only met year-round, in tropical and subtropical waters. So SIDS and Pacific SIDS (PSIDS), from the viewpoint of this paper, start to become appealing. Many PSIDS are surrounded by enormous ocean energy potentials (if only the energy can be tapped) and geological/topographic conditions that allow for rapid access to deeper, cold water, alongside the warmest ocean surface temperatures in the world. PSIDS in particular have underdeveloped electricity generation and supply infrastructure, much of which is old, expensive, inefficient, unreliable, and dependent on imported oil. Total electricity demand for the smaller PSIDS is low, between 5 and 20 MW. Therefore, the development of even a 1 MW OTEC plant within a small PSIDS can add significant amounts of energy to the grid, reduce reliance on imported oil, generate new skills and employment opportunities, and have additional benefits in the area of drinking water provision, refrigeration/air conditioning, agriculture, aquaculture, and, even, mineral salt/cosmetic manufacture. In theory, there are many development 'wins' for the deployment of OTEC within a small PSIDS. Alongside the concept of OTEC is the concept of seawater utilisation, which describes the manifold applications of seawater such as in the fields of aquaculture, agriculture, and mineral salt and cosmetic manufacture. Deep seawater has a number of characteristics that make it useful, such as a lack of potentially harmful pollutants and organic substances and a chemical composition that promotes aspects of human health.

This paper will examine a number of aspects of OTEC deployment within the Pacific Islands region, particularly focusing upon the 1-year period deployment and testing of an OTEC plant in South Tarawa, Kiribati. It will critically examine the application of new science and technology to the Pacific region from the philosophical lens of 'interconnected geoscience' [2] and the sustainable development goals (SDGs) [3] and develop the conversation of developmental needs and futures of PSIDS and where OTEC could fit in.

## 2. OTEC, seawater utilisation, and the sustainable development goals

Seawater utilisation plants use seawater as a base resource to produce food, energy, and drinkable water through ocean thermal energy conversion systems such as seawater cultivation, seawater energy, and seawater desalination technologies. Seawater energy and seawater utilisation plants can be developed in tropical SIDS to utilise its seawater as a heat source to produce renewable energy and heat, water, and food. These technologies can assist with the sustainable development of coastal communities.

The Korean Research Institute of Ships and Ocean Engineering (KRISO) has led research and development on OTEC and seawater utilisation of discharged deep seawater since 2010. A 20 kW OTEC pilot plant was designed and fabricated as a prototype model of the 1 MW demonstration OTEC plant (to be deployed in Kiribati in 2020). Results and discoveries made from the prototype OTEC/seawater utilisation plant have been used to design the 1 MW OTEC Kiribati plant.

The application of discharged deep seawater from a land-based OTEC plant, or from individual cold water pipes, alongside technologies for desalination, has been developed by KRISO and the Korean R&D team. Seawater desalination plants with carefully designed features can enhance, and control, the constituent seawater mineral balance/composition to make it particularly useful for public health, cosmetics, mineral salt manufacture, and other industrial applications. Seawater utilisation plants are green technologies, reducing $CO_2$ emissions, and supplying renewable energy. They can be used to develop a 'blue infrastructure' (technologies based on the utilisation of the neighbouring ocean) in coastal regions, which help to promote the UN sustainable development goals (see [4–8], for further details).

If the 1-year duration experiment in Kiribati can evolve into a long-term OTEC + seawater utilisation plant, it has the potential to address a wide series of the sustainable development goals [3]. In particular the SDGs 7 (affordable and clean energy), 6 (clean water and sanitation), 9 (industrial innovation and infrastructure), and 13 (climate action) will be addressed through the provision of renewable and affordable, reliable energy, and the development of innovative technologies and related industries, particularly from a PSIDS perspective. If the OTEC/seawater utilisation plants work inclusively with local people, offering education and training to enable the localization of technologies with time, and if industries such as agriculture, aquaculture, mineral salt, and cosmetic manufacture, and so on, are developed, then SDGs such as 1 (no poverty), 2 (zero hunger), 3 (good health and wellbeing), 4 (quality education), 8 (decent work and economic growth), and 11 (sustainable cities and communities) can be promoted. These are serious claims and will not occur without a great deal of long-term investment and effort (which is not guaranteed at the time of publication). However, there is a genuine vision alongside the mere technical deployment of a 1 MW OTEC plant. If locally based agriculture/aquaculture industries develop, they can address the limited diet available to I-Kiribati people, promoting sustainable food resources and healthy eating. The provision of high-quality education and training alongside locally owned ancillary industries to OTEC will address the areas of poverty, quality livelihoods, and education opportunities. The growth of new, green technology-based industry can contribute towards decent work, economic growth, and sustainable cities/communities. Of course, none of this will occur without longer-term investment and planning.

## 3. An 'interconnected geoscience' approach to OTEC in the Pacific Islands region

The approach taken to the introduction of OTEC into the Pacific Islands region is a good model for the application of sustainable development principles and the concept of *interconnected geoscience* (**Figure 1**, [2]). Sustainable development was defined in detail in the 1989 Brundtland Report, Brundtland [9], which coined the *phrase* 'meeting the needs of today without compromising the needs of tomorrow' and demonstrated the dynamic links between society, economy, environment and politics/governance.

*Interconnected geoscience* is a conceptual model of geoscience/technological/engineering application to international development. A definition of interconnected geoscience is 'a philosophy that combines geoscience expertise with an equivalent expertise/consciousness in the understanding of developmental situations, conditions, and context, including the integration of diverse world views/wisdom and values, placing development-goals at the heart of the interconnected-approach' [2].

International development requires a complex series of human, knowledge, and often technical interactions and activities undertaken for the purpose of improving the quality of life of the world's less empowered and least-wealthy. It involves aspects of nation building such as economic strengthening, infrastructure development, job creation, improved social welfare such as health and education, and improved governance. It is impossible to reduce this grand aspiration to only simple reductionist activities, such as the building of a bridge, road, or railway or even the installation of an OTEC plant *alone*. Of course reductionist activities can and have been undertaken alone, almost as an isolated, totally independent project. They may

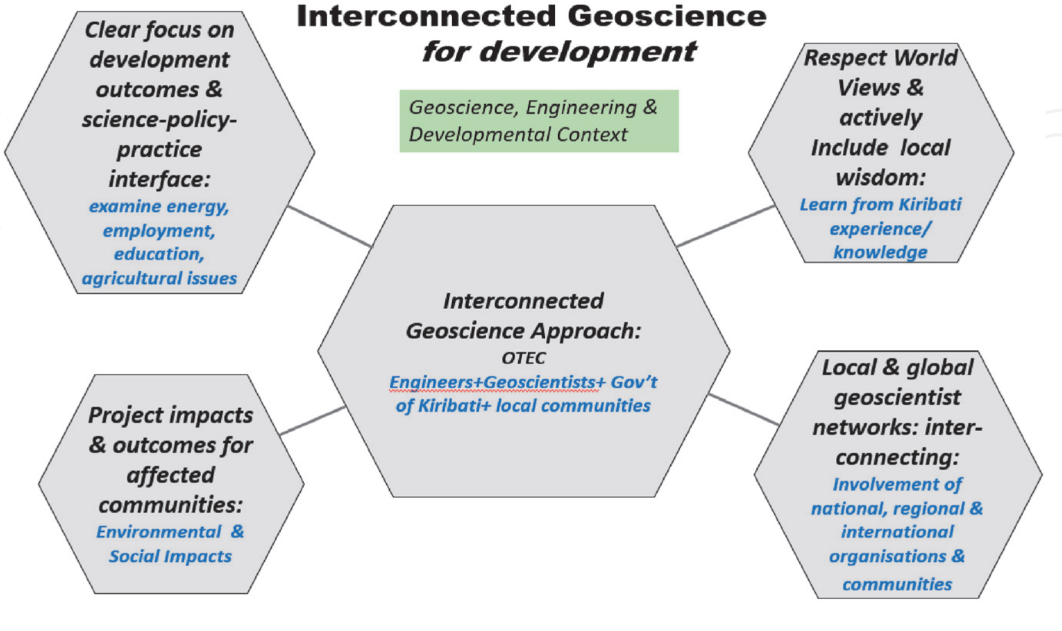


**Figure 1.**
*Interconnected geoscience is a concept advocating the application of excellent geoscience/engineering/technical work to international development that includes contextual conditions such as community, level of development, and local world views/wisdom. This diagram summarises the key 'interconnected' components of the Kiribati OTEC-seawater utilisation programme (adapted from Petterson [2]).*

indeed create good results, such as improved communications. However, if activities and interventions are not planned, taking the context of a development situation into account, difficulties can arise, and situations may result where more harm than good is effected, e.g. through increased corruption, money wastage, local communities adversely affected, and so on.

Work by authors such as Gill and Bullough [10], Stewart and Gill [11], and Stewart [12] points towards a deeper, non-reductionist, holistic, and inclusive guiding philosophy, which encourages the application of geoscience (or OTEC technology), within a development framework that takes account of the local situational context in terms of culture, community, society, governance, planning, environment, and local wisdom/world views.

The deployment of the OTEC plant within Kiribati is the pinnacle of a series of actions that have occurred from late 2013 to 2020. The process has included a wide range of stakeholders including the Korean government, KRISO, the Fiji-based Korean Pacific diplomatic mission, KOICA (Korean Aid), the Pacific Community (SPC), and representatives from Pacific Island governments, particularly interactions with the governments of Kiribati, Tuvalu, and the Marshall Islands, community representatives, private sector, and others. Preparatory activities have included numerous one-to-one and one-to-many meetings, workshops, training sessions, scientific surveys, inter-government and community negotiations, and training/education courses at institutes such as the Kiribati Marine Training School. These activities and stakeholder interactions have allowed for the gradual raising of awareness of all parties to many aspects of OTEC and its application potential within the Pacific Islands region.

One interesting aspect of this interaction is the connections between two quite distinctive and different cultures: the South Korean Asian culture and the Pacific Islander culture. Without descending into stereotypes, but simplifying the description of two cultures, this article highlights aspects of the respective cultures of Korea and the Pacific Islands. South Korea, prior to recent developments in China, is, perhaps, the country that has become 'developed' (in modernistic industrial economics terms) the fastest: from a post-conflict agrarian society following the 1950s Korean War to an industrial giant of today (the eleventh, out of 193, richest economy in 2019, [13]). South Korea prizes social values such as a strong work ethic, competition, high educational achievement, innovation, and industrial/commercial progress. Pacific Island cultural values are quite different to mainstream South Korean values. Pacific Islanders come from a largely agrarian, fishing, and hunter-gatherer society, which has become more urbanised during the twentieth and twenty-first centuries, whilst retaining a high element of a traditional lifestyle that extends back hundreds and thousands of years. The role of the community, tribe, and extended family is strong. Individualistic values and lifestyles, whilst existing, are not necessarily admired. Pacific societies can have strong societal hierarchies, and the role of a Chief, Paramount Chief, or equivalent, is of great importance. Most Pacific Islanders are committed to a Christian Church which also acts as a communal societal institution. Land ownership concepts are quite different to Asian or Western mindsets. Land is not individually but communally 'owned' (including reefs and oceans). The 'ownership' concept is better described as custodianship. The land is kept within communities and is an intrinsic part of communal identity and religion (particularly pre-Christian religious-philosophical beliefs which remain extant). The land is nurtured and tended and must be passed on to future generations in better health than the present time. Livelihoods and values, of course, do not remain static and, inevitably, change. The onset of the money economy and the nation state in the Pacific region has changed lifestyles and values, but longstanding beliefs and cultures remain strong. Many Pacific Islanders now live in modern urban centres such as Suva, Port Vila, and Apia and work in jobs similar to anywhere in a globalised world. However, many also retain traditional lifestyles and are strongly attached to a Pacific world view (see [14] or further details).

The OTEC project team, working with the Korean Diplomatic and KOICA missions in Fiji, has worked closely with the Pacific Community (SPC). SPC is a regional scientific and technical organisation, operative since 1947, with 22 Pacific Island countries and territories as members. The Pacific Community organisation is experienced in designing and delivering international development projects across the region. Development partnerships and a generous lead-in time (some 6 years) from concept to OTEC deployment in Kiribati, together with numerous initiatives from the Korean side, closely involving Pacific Islanders, have allowed the key tenets of *interconnected geoscience* to be deployed [2]. Specifically these interconnected characteristics include (1) the realisation of the OTEC technology and the identification of the optimal OTEC site locations from geoscientific and engineering principles, data generation, data modelling, and scenario development; (2) early project scoping discussions between the Korean side and SPC; (3) the delivery of c. 20 workshops in numerous locations involving Pacific Islanders, international agencies, and Korean stakeholders, with the objectives of introducing Korean thought and technology to a Pacific audience and providing platforms for Pacific Islanders, and others, to share knowledge and world views/wisdom; (4) working closely with Pacific Island governments who expressed a particular desire to become more heavily involved in OTEC issues (e.g. Tuvalu, the Marshall Islands, Kiribati); (5) working with the Kiribati government on all aspects of OTEC deployment in South Tarawa (Kiribati), particularly in relation to economic opportunities, land ownership, community awareness, governance, and environmental and social impacts; (6) designing the OTEC technology deployment and testing programme with Kiribati and Pacific needs in mind; and (7) increasing awareness of the developmental context of the Pacific region. Development, in a situation such as the OTEC deployment in Kiribati must be mindful of power asymmetries with respect to economic standing, relative levels of education, finance, and technology. The power asymmetry is quite acute when 'developed' countries work with PSIDS: in this case South Korea (11/193 in 2019 economic league tables) is working with Kiribati (191/193 in 2019 economic league tables) [13].

Project deployment will commence in 2020/21. There remains much work and learning to be undertaken. Projects and aspirations do not, of course, always run to plan. However, the preparation of the KRISO-OTEC programme with respect to the principles of *interconnected geoscience* has been a positive model.

## 4. Pacific Islands geography and geology

The Pacific Islands region occupies an area of close to 30 million km$^2$, mainly in the western and central Pacific, east and north of Australia, and north of New Zealand (**Figure 2**). Most island groups are in the southern hemisphere, with countries such as Kiribati, the Marshall Islands, Federated States of Micronesia, and Palau mainly in the northern hemisphere, close to the equator. Cook Islands, French Polynesia, and Pitcairn are the easternmost island groups (see [14] for further details). There are 22 PSIDS, some of which are independent nations such as Fiji, and some of which are territories of western countries, particularly France (e.g. New Caledonia). Papua New Guinea (PNG) is unusual in that it contains a large area of continent in addition to islands and has a relatively large land surface area (460,000 km$^2$) and population (>8 million people). If PNG is excepted from the

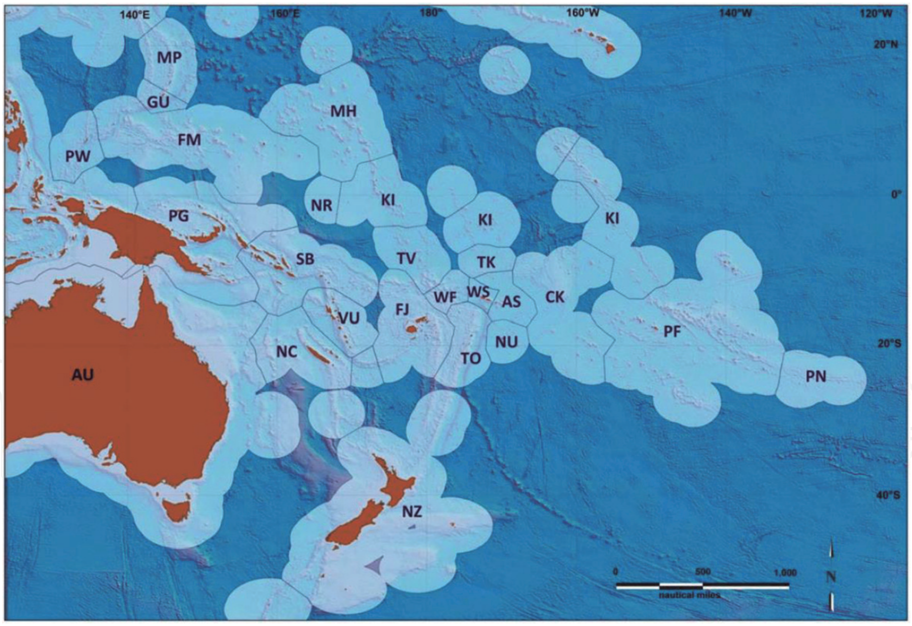


**Figure 2.**
*Geography of the Pacific Islands region. Note the archipelago nature of most PSIDS with islands scattered over large areas of ocean. AS, American Samoa; AU, Australia; CI, Cook Islands; FM, Federated States of Micronesia; FJ, Fiji; PF, French Polynesia; GU, Guam; KI, Kiribati; MH, Marshall Islands; NR, Nauru; NC, New Caledonia; NU, Niue; NZ, New Zealand; MP, Marianas Islands; PG, PNG; PN, Pitcairn; PW, Palau; WS, Samoa; SB, Solomon Islands; TK, Tokelau; TO, Tonga; TV, Tuvalu; VU, Vanuatu; WF, Wallis and Futuna.*

analysis, the remaining countries have a combined land surface area of c. 87.000km$^2$. The Pacific Islands geographical context therefore is similar to a country with a land area of Austria set in an ocean the size of Africa. Most PSIDS are archipelago nations, some with hundreds or over one thousand islands and tens of island groups within their jurisdiction. Many PSIDS are not only small island states but also large ocean states with exclusive economic zones extending up to 5 million km$^2$. Populations vary between 900,000 (Fiji) and 10,000 (Tuvalu).

The Pacific Islands region contains a high degree of geodiversity (**Figure 3**). The region is one of the best examples of a spectrum of oceanic tectonic phenomena in the world, displaying geological features such as ocean trenches, island arcs (islands formed from the subduction of one ocean plate beneath another), ocean plateaux (formed from rapid, voluminous mantle plume head eruptions), ocean basins (main component of oceans resulting from seafloor spreading), seamounts and seamount chains (extinct volcanoes produced as ocean plates pass over static mantle plumes), and rifted, submerged, and aseismic continental materials. The main plates are the enormous Pacific and Australian plates, together with a number of smaller 'microplates', such as the deep ocean basins south of PNG-Solomon Islands in **Figure 3**.

Arc-linear archipelago chains of islands characterise island arcs such as the Solomon Islands, Vanuatu, and Tonga (**Figure 3**). These islands are located on the subduction side of equally long curvilinear ocean trenches, up to c. 10–11 kms beneath sea level. The trenches mark the sites of interaction between the Australian and Pacific plates and produce earthquakes to depths of c. 700 kms and magnitudes of up to >8 on the Richter scale. Island arcs form the largest Pacific Islands which contain the larger human populations. The region contains two of the world's largest ocean plateaux: the Ontong Java and Manihiki Plateau (**Figure 3**). Much of the SW Pacific region comprises the deep ocean abyssal plains, some 4–6 kms deep. Volcanism is evident throughout the region and exhibits a range of styles from explosive to quiet (effusive). The region contains abundant seabed minerals which may, one day, form the basis of a significant industry in the region.

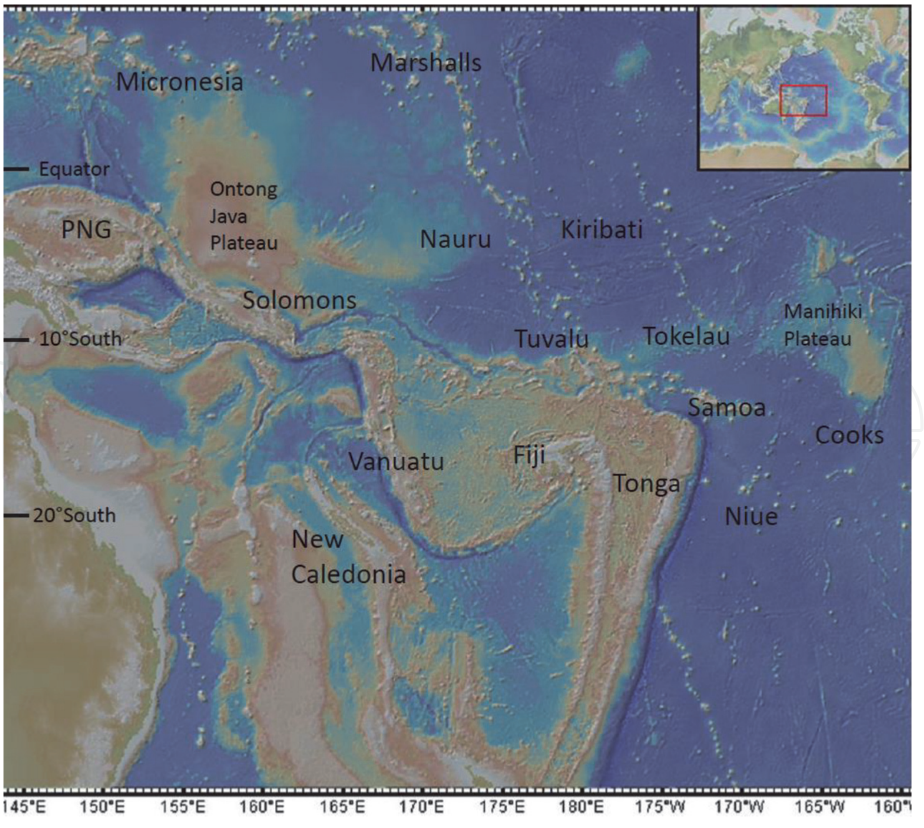


**Figure 3.**
*The Pacific regions contain a wide geodiversity and present a range of ocean geological features, see text for details. Colour code: Deep blue/purple represents deepest ocean depths, pale blue represents shallower ocean, and browns and white/pale grey (within the ocean) represent topographic highs, the highest points of which form islands (acknowledgements to Google earth for the base topographic map).*

**Figure 4** illustrates an example of a typical atoll island, such as South Tarawa, Kiribati or the Marshall Islands. Islands tend to be up to tens of kilometres long by tens of metres to 1–2 kms wide. The islands form from the aggradation and erosion of coral reefs which develop around slowly subsiding, extinct volcanoes. Seamount slopes are very steep: often depths of 1–3 km beneath sea level are attained within 1–4 kms of the outer shoreline of atolls. Atoll islands themselves are composed of broken up coral in the form of rock blocks and boulders, but mainly sand and

**Figure 4.**
*Photograph of a remote island atoll from the Gilbert Group of Kiribati, Pacific Islands region. Atoll islands form annular rings of low-lying (<1–4 m above sea level) made of sand, gravel and deeper igneous rock. An inner, shallower lagoon is separated from the deep ocean by the atoll islands (Photograph: Petterson).*

gravel. The inner lagoon is shallow (tens of metres deep) and contains shifting sands and muds which are transported via tidal currents within the lagoon. Life on atolls is dependent on a freshwater lens which forms from rainfall: freshwater lies on top of seawater (as it is less dense) and forms drinkable groundwater. Groundwater is supplemented by rainwater harvesting. Atoll soils have a low fertility as they are largely composed of sand, mud, and gravel with limited organic material. They may be moderately saline. Coconut and breadfruit trees, alongside slow-growing swamp taro, are the main terrestrial edible atoll crops.

From an OTEC perspective, the geology and tectonics of the Pacific region are important in terms of determining the optimal location of OTEC plants. Firstly a market is needed, and these will be the larger towns of the Pacific region. Secondly, access to deep ocean, close to the market, is needed: Many sites fulfil this requirement with seamounts being outstanding examples. Thirdly, access to shipping and ports will be needed to maintain the OTEC plant. Natural disaster considerations are important as earthquakes, landslides, ocean-based landslides, volcanic eruptions, and extreme weather systems such as cyclones, can destroy an OTEC plant. Atoll island nations such as Tuvalu, Kiribati, and the Marshall Islands are situated upon seamounts (extinct volcanoes), with a relatively low earthquake risk, and quiet equatorial waters from where cyclones originate, but then away to the north or south, causing little/no damage to equatorial islands. Ocean climates tend to be calmer close to the equator.

## 5. Pacific Islands development needs

Readers are referred to Petterson and Tawake [14] for a more detailed analysis of this subject and to SPC [15], UN [16], and UNDP [17]. Traditionally the economy of the Pacific has relied on agriculture, fisheries, and traditional handicrafts/cottage industry. Countries such as PNG and Fiji have a reasonably well-developed service, industrial, and mining sector. Tourism is important for some Pacific countries, particularly French Polynesia, New Caledonia, Vanuatu, Fiji, and Cook Islands. Expatriate communities resident in countries such as Australia, New Zealand, and the USA send significant remittances back to their original home countries: Samoa and Tonga benefit from such remittances. A significant proportion of the population of many Pacific Island countries live traditional lives with only limited excursions into the cash economy, living instead on subsistence agricultural and fisheries livelihoods and being self-sufficient for shelter and infrastructure needs. **Figure 5** illustrates the GDP/Head in US dollars for Pacific economies. Countries which are territories (even if self-governing) or are politically part of western economies, such as French Polynesia, New Caledonia, Wallis and Futuna, Cook Islands, Guam, and Niue, have relatively high GDP/Head figures, particularly PSIDS such as French Polynesia with a GDP/Head of US$36,000 (higher than South Korea). Independent PSIDS have GDP/Heads of between US$8000 and c. US$1700. Levels of acute poverty, with people earning ≤US$2/day, are low in the Pacific Islands region. Subsistence livelihoods are difficult to account for in terms of traditional economic parameters such as GDP/Head. People have sufficient food to survive, although some diets may be limited, or lead to obesity, heart disease, and diabetes (levels of non-communicable diseases (NCDs) are high in the Pacific region). Pacific populations are small by Asian standards: The whole Pacific region has a total population of c. 11 million people. PNG is by far the most populous country with >8 million people, and other populations include Fiji (900,000), Solomon Islands (610,000), Vanuatu (264,000), Samoa (187,000), Kiribati (109,000), Tonga (103,000), and Marshall Islands (54,000).

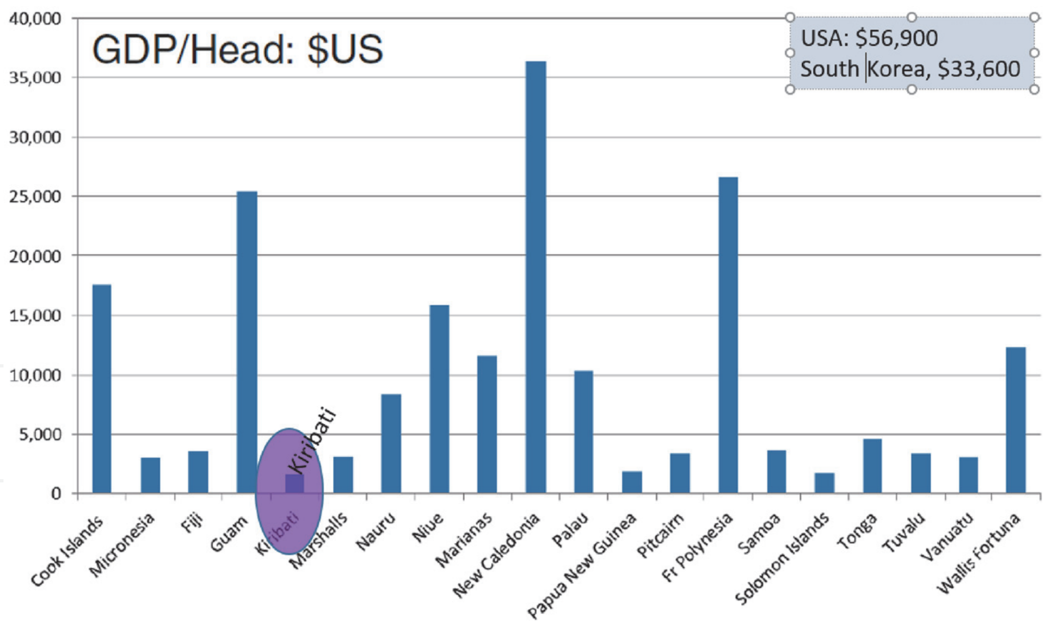


**Figure 5.**
*Graph of GDP/head for Pacific Island countries and territories. GDP/head for Korea and the USA for reference. Note how the independent PSIDS have the lowest GDP/head values. Kiribati is highlighted (figures from SPC [15] and UN [16]).*

Poverty and development challenges for the PSIDS are different to those of the poorest populations in sub-Sahara Africa, South Asia, and similar regions. PSIDS do not experience the desperate poverty of the c. 1 billion people in the world who live on <US$2 a day. The term 'persistent poverty' is sometimes applied to the lower-income populations in PSIDS which expresses a lifestyle at the limits of income/need and a situation that struggles if economic shocks impact on individuals and families (e.g. [14]). Archipelago nations can be challenging to govern and administer. The costs of providing even basic services to a widely scattered population are very high for many PSIDS. There is a trend for populations moving towards urbanised centres such as Suva, Nadi, Labasa, and Lautoka (Fiji), Honiara and Ghizo (Solomon Islands), Nuku'alofa (Tonga), and Majuro (Marshall Islands). For many PSIDS, employment opportunities are limited within the cash economy, and young people in particular, can struggle. Fertility rates are relatively high in the PSIDS region, although falling in some countries. Most PSIDS populations are youthful. Highest fertility rates (≥4 children per woman) include the Solomon Islands, Samoa, PNG, Vanuatu, and the Marshall Islands. Lowest fertility rates (2.1 children or less per woman) occur in French Polynesia and Palau, with other PSIDS somewhere between these end-member situations [18]. Life expectancies are relatively low in many PSIDS and particularly low for Kiribati, PNG, and Nauru (<59), with many other PSIDS having a life expectancy of 69 [19]. NCDs may be a contributory factor to the relatively low life expectancies within PSIDS. Many countries exhibit a classic pyramid-shaped demographic curve of age vs. percentage of population, with a high young/old population ratio (**Figure 6**).

The geographical isolation of PSIDS including distance to markets is a significant barrier to economic development. This leads to high transportation and import/export costs. Some PSIDS businesses have developed a global reach in spite of these handicaps: mineral groundwater from Fiji is a good example here. Industries that can develop independently of geography, such as the knowledge economy, and internet-based businesses may be a way forward, particularly if fast broadband develops (again geographical distances make the laying of fibre optic cables expensive). Niche agricultural and manufactured products have small market bases in

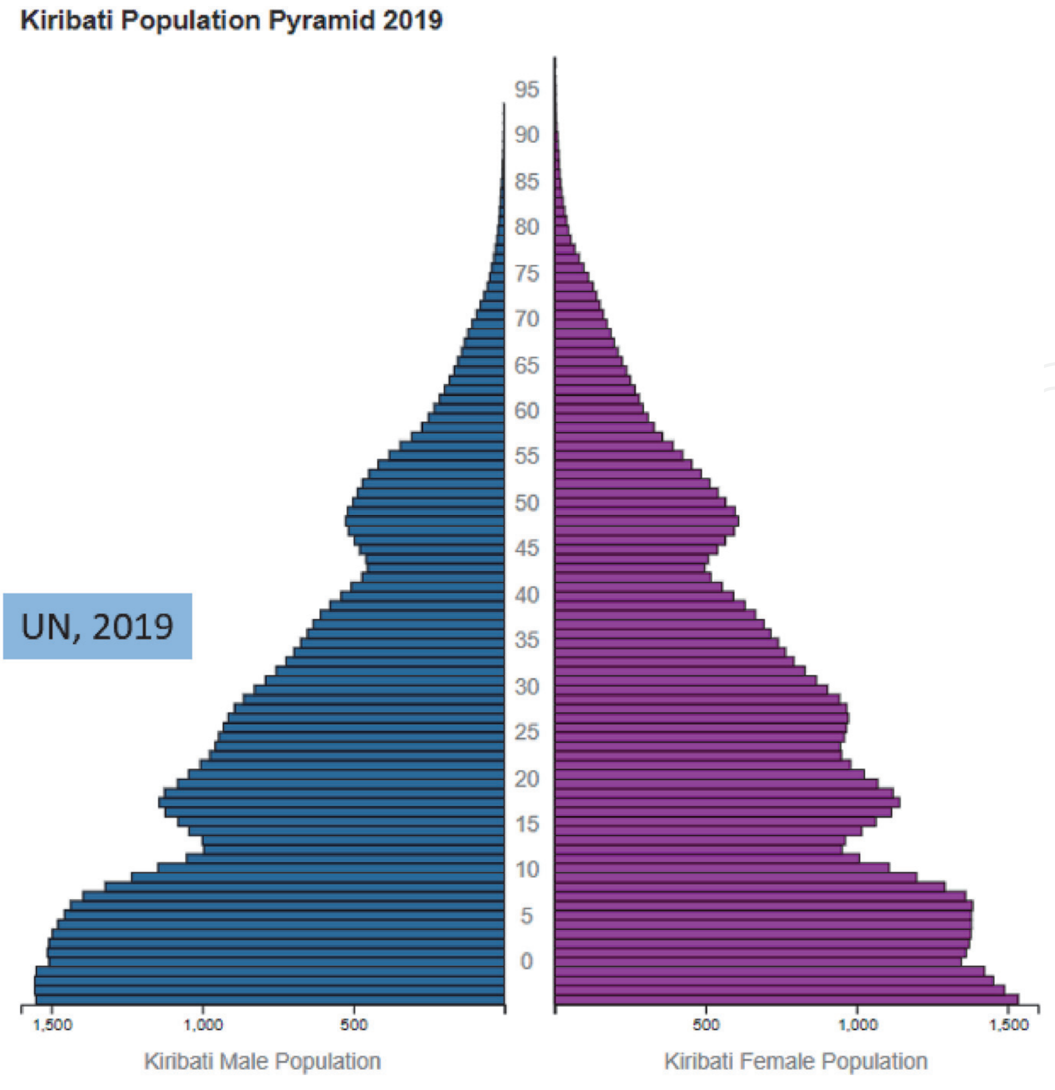


**Figure 6.**
*Age-frequency diagram for males and females in Kiribati. Note the pyramidal form of the curve indicating a high fertility rate. 'Indentations' in the curve correspond to I-Kiribati who may study or work overseas for part of their life. The proportion of people >60 is low, and the ratio <25/>60 is very high indicating the dominance of young people within the demography. Kiribati has a fertility rate of between 2 and 4 births per woman and a life expectancy of 55–59 (acknowledgements UN [16]).*

- 22 Small Island States, 16 sovereign nations
- Papua New Guinea is 'unusual' as it has a large landmass and population (460,000km2, >8 million population)
- ***Archipelago nations: many islands spread over large ocean area***
- Subsistence Economy remains strong in rural areas
- ***Limited opportunities for economic development & jobs***
- Country size varies from 28,000km2 (Solomons) to 12km2 (Tuvalu)
- Country populations vary from 900,000 (Fiji) to 1500 (Niue)
- ***Geographical isolationism***
- ***High transportation costs by sea***
- Communal culture and Indigenous peoples societal values
- ***Comprehensive, affordable, reliable, green, electricity can assist with development***

**Table 1.**
*Summary of development challenges for the Pacific Islands region.*

Australia and New Zealand. Fisheries are in high demand, and PSIDS are receiving higher returns on fisheries than in previous times. There are, however, threats to diminishing fish stocks. Small internal populations with limited spending power are an additional constraint on the development of locally based internal economies.

As a specific example, Kiribati is typical of the smaller atoll PSIDS (**Tables 1** and **2**, [17, 20]). The country is spread over three island groups (Gilbert, Line, and Phoenix) with only the Gilbert Islands being particularly populated, although Kiritimati (or Christmas Island), a second urbanised island, is situated in the northern part of the Phoenix Islands. Thirty three island groups are spread over an ocean area of 3.5 million km$^2$, presenting tremendous challenges for a small



- 33 island atolls, 3.5 million km2 total area, land area 810 km2
- Population 115,000 in 24 islands. >50,000 live in South Tarawa, 6,500 in Kirimati
- Primary Income: fishing, coconut products: *imports >>>exports*
- Limited availability of water supplies (ground water, rainwater harvesting)
- GDP/Capita: $1838 *(South Korea, $33,600,742, USA $56,900, Laos, $2,457, Fiji, 5,589)*
- High dependence on imported oil. 49% of imported oil for S. Tarawa power generation. This cost $6.1M US.
- 24.5GWh of electricity demand in S. Tarawa, 1.65GWh demand in Christmas Island
- Electricity demand: 41% residential, 34% government, 19% commercial
- Peak load in South Tarawa c. 3-4MW
- South Tarawa: 5.45MW of installed capacity (diesel). Solar power to add c. 1.4MW (0.5MW solar power installed in 2015, more on-stream)
- Kirimati: 1.5MW installed capacity (diesel) + solar power
- Outer Islands have smaller diesel and solar generating capacity
- Kiribati Integrated Energy Roadmap 2017-25: 45%-60% reduction in fossil fuels by 2025
- South Tarawa Renewable Energy Project to fund: 4.1MW of solar power/2.6 MW of storage

**Table 2.**
*Summary of the development and energy context of Kiribati (UN [16], World Bank [20], NZMFAT [21], United Nations [22]).*


**Figure 7.**
*Many atoll PSIDS have developed high-density concentration urban centres which attract populations from the outer islands. These islands are characterised by high densities of housing, many of which are traditional houses and some of lower-quality informal style. Examples of urbanised centres include Funafuti (Tuvalu), South Tarawa (Kiribati), and Ebeye/Majuro (Marshall Islands).*

PSIDS in terms of administration, governance, service provision, and monitoring of foreign fishing fleets. Around 24 islands are populated. The total population of Kiribati is 115,000 of which almost half live in South Tarawa and over 6000 in Kiritimati. The remaining population live on small islands within village communities and a subsistence economy. Industry and employment revolves around the government and administration, services, fishing, and coconut products, together with marine services. Many I-Kiribati males serve as mariners. Tourism is small and limited and appeals to a niche market (e.g. game fishing around Kiritimati). The total GDP/Head is c. US$ 1800 which is one of the lowest figures for PSIDS. South Tarawa is an example of an urbanised atoll which comprises high densities of population and housing: Similar centres exist in the Marshall Islands and Tuvalu (**Figures 7**–**9**).

**Figure 8.**
*Typical traditional house in South Tarawa, Kiribati. Urban houses such as this comprise a thatched roof and cement lower part and floor. People may keep pigs close to the house if planning regulations permit. Note the sandy soils, tropical vegetation, and standing water (Photograph: Petterson).*

**Figure 9.**
*The enchanting attractions of atoll islands (here North Tarawa, Kiribati) include the seamless change from land to ocean. Atoll islanders are equally at home on land and in the ocean and can spend much of their day working or enjoying recreation in the shallower waters that surround their low-lying islands (Photograph: Petterson).*

## 6. Pacific Islands region energy overview

A number of countries are considered here for context with respect to the deployment of OTEC in Kiribati. Regional data presented are taken from the United Nations Department of Economics and Social Affairs, 16 February 2016, 'Electricity Profiles' publication which is part of the 'Energy Balances and Electricity Profiles' series that documents a range of electricity statistics for all nations for 2013 and the previous 5 years and related sources [15, 19–22]. From geographical and economic considerations presented in the above sections, it is apparent that the solutions for the provision of power in the Pacific region cannot rely on gridded electricity networks alone: This is an unrealistic and costly proposition. Gridded electricity is an option for centres of higher population such as Apia, Honiara, South Tarawa, and Funafuti. It is also a good solution for islands with numerous population centres within close geographic proximity on one island such as Viti Levu and Vanua Levu in Fiji. More distributed, scattered, and remote populations require a range of electricity solutions, including local village grids or small stand-alone grids for a few neighbouring houses. At present many villagers rely on discrete diesel generators, with solar energy providing alternative solutions for remote rural communities.

Electricity generation will rely far more on renewable energy technologies, rather than traditional fossil fuel-powered and centralised electricity systems, as we look to the future. Solar energy technologies have dropped exponentially in price over the past 10–20 years, and battery life now extends to over 8 h or so (e.g. [23]). This has the consequence that solar energy is now becoming an increasingly attractive option for low-power-intensity-consumption solutions in remote Pacific Island locations, as well as supplementing power supply in urban regions. Hydropower will become increasingly important. Pacific countries such as Fiji, PNG, and Samoa all utilise hydropower to a significant extent already as part of their overall energy mix (in Fiji hydropower already contributes 60% of the installed energy capacity). In the future a range of scales of hydropower from mega to micro will be employed for solutions in different geographical and social settings. Wind energy has hardly been realised in the Pacific, although a few countries have invested in small wind farms (Fiji and Vanuatu as examples). The usage of wind energy will undoubtedly grow with time, as it has in Europe over the past decade, for example. Other options include biomass-generated power plants (as tropical countries have rapid biomass growth rates: One biomass plant will shortly come on line in Fiji, developed by South Korea) and wave and tide energy (SPC has been involved in the waves and coasts in the Pacific (WACOP) project funded by the European Union, which has recommended that countries with a mean wave energy flux in excess of 7kw/m of wavelength have a particularly high potential, e.g. New Caledonia, Tonga, Cook Islands, and countries south of latitude 20° south [24]). Geothermal energy sits alongside possible options for electricity generation in Pacific countries.

Access to electricity is highly variable, and in many parts of Melanesia (e.g., PNG, Vanuatu, Solomon Islands), 60% to c. 90% of the population does not have access to electricity, with the exception of local diesel generators/solar energy. Specific national figures for percentage of population without access to electricity are Tonga (5%), Samoa (5%), Fiji (25%), Kiribati (55%), Solomon Islands (85%), and PNG (87%) [23].

**Figure 10** presents a global view of GDP/capita vs. electricity usage. Once GDP/capita rises above around US$15–18,000 per capita, utilisation of energy is consistently high (c. 8–10,000 kilowatt hours per person). At lower levels of GDP/capita ($10,000 US or less), electricity utilisation is at much lower levels and is highly variable (e.g. compare a GDP/capita of c. $3000 US and electricity/capita utilisation

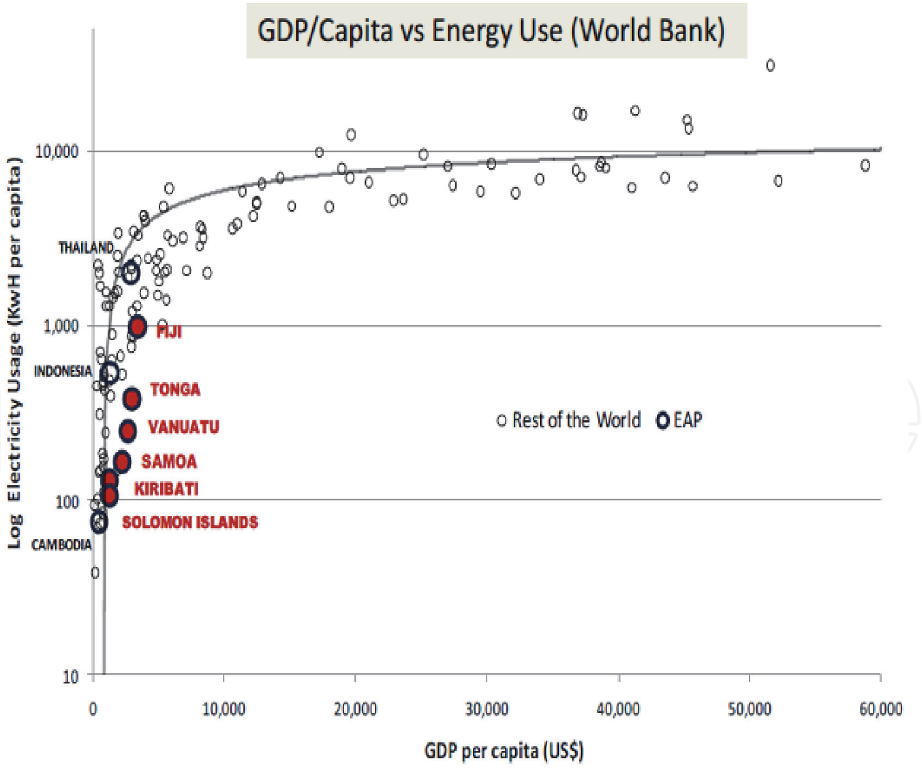


**Figure 10.**
*Graph of GDP/capita vs. electricity usage per capita. See text for details [23].*

of c. 4000 kilowatt hours/capita for Thailand to a GDP/Head of <$1000 US and electricity utilisation/capita of c. 80 kilowatt hours/capita for Cambodia). Many Pacific Island countries plot within the lower part of the global curve with a GDP/capita of between c. US$1500 and $5000 and electricity utilisation between 70 and 1000 kilowatt hours/capita. The evidence suggests that Pacific Island countries are, in the main, at the lower to lowest end of global development, when it comes to electricity utilisation per capita.

**Figure 11** presents installed electricity generation capacity of selected Pacific Island countries. Papua New Guinea, with its larger population and global mining industry, generates the highest amount of electricity, with an installed electricity capacity of 827 MW, with Fiji at 255 MW, Samoa at 42 MW, and down to Kiribati, with only c. 6 MW of installed generation capacity. These are extremely low levels of installed electricity capacity by world standards. By comparison, note the installed generation capacities of China, 1.3 million MW; the USA, c. 1 M MW; India, c. 300,000 MW; the UK, 92,000 MW; Thailand, 48,000 MW; and Iceland (with a Pacific-like island population of c. 332,000) 3000 MW [16].

**Figure 12** presents a more detailed analysis of installed generating capacity/Head vs. GDP/Head. What is apparent from this graph is that countries such as Fiji, Samoa, and the Marshall Islands have significantly higher installed generation capacity with respect to the strength of their economy, than countries such as Kiribati and the Solomon Islands in particular. The evidence suggests that most Pacific Islands are 'under-energised' at the present time. Some PSIDS are the most under-energised countries in the world. This lack of access to electricity is a serious inhibitor of economic social development.

**Table 2** summarises a number of characteristics of the capital of Kiribati (South Tarawa) present-day energy situation [20]. South Tarawa has 5.45 MW of installed capacity provided by an ageing diesel generator which experiences regular periods of non-transmission. The diesel capacity is supplemented by solar energy: Up to an

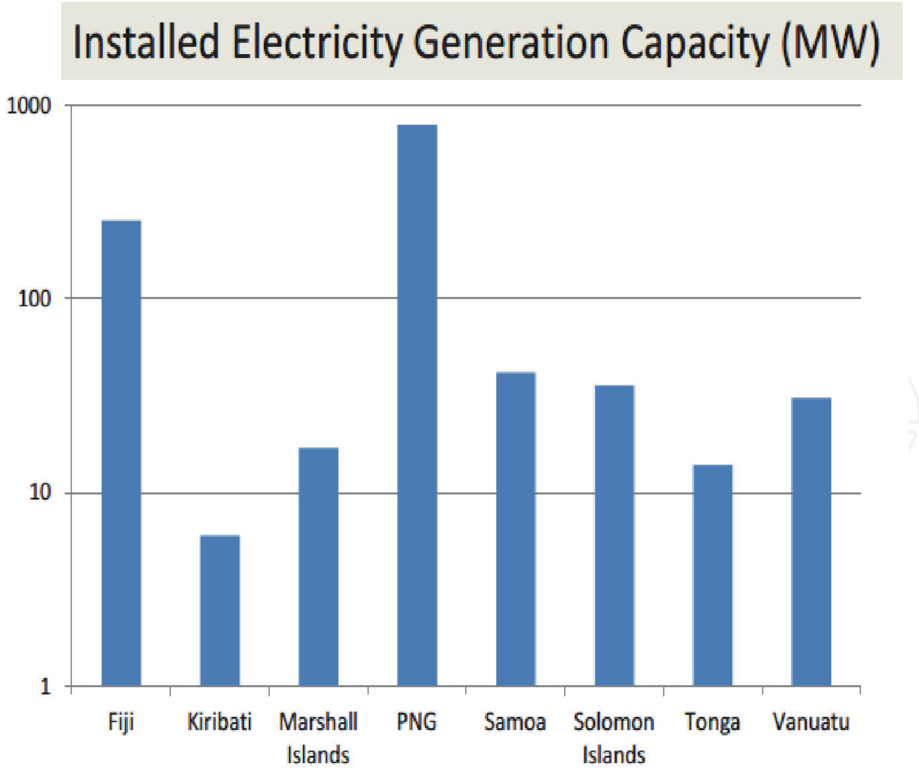


**Figure 11.**
*Installed electricity generation for selected Pacific Island countries (data, United Nations [22]). Note the logarithmic scale on the Y-axis.*

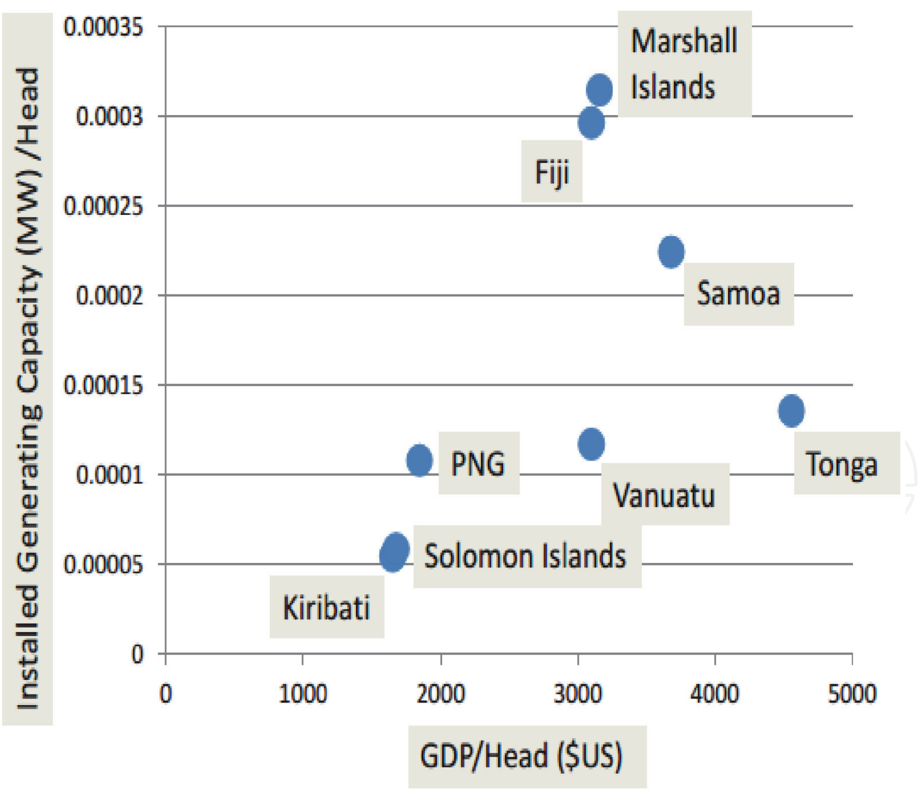


**Figure 12.**
*Graph of installed electricity capacity per head versus GDP/head for selected Pacific Island countries. Note how Kiribati and Solomon Islands are the least energized countries and Fiji/Marshall Islands the most energized from this analysis.*

additional 1.5 MW is on line or planned for the future. Peak demand in South Tarawa is around 3–4 MW. Kiritimati has 1.5 MW of installed capacity with smaller stand-alone diesel providers in the smaller islands. There is a Kiribati roadmap for energy which aims to move towards a less fossil fuel- and imported oil-reliant future, with solar power (and OTEC) planned to be the main renewable energy providers for the future. The 2017–2025 Kiribati energy roadmap plans for a c. 45–60% cut in fossil fuel generated energy by 2025.

## 7. OTEC and global OTEC resources

**Figure 13** shows the world map of realisable ocean thermal energy resources, with the greatest temperature gradients (from surface to water depths of 1 km) shown in red and the minimal possible realisable OTEC temperature gradient shown in blue. Ongoing and planned OTEC projects are named. A minimum temperature differential of 17–20°C between surface waters and those at 1 km depth is required for OTEC operations. This condition is met, year-round, for tropical and subtropical waters in all oceans. Some areas at the fringes of the ocean thermal resource, such as Japan, South Korea, and the Arabian Peninsula, have the capacity to generate power through OTEC for part of the year. Kiribati and its capital township, South Tarawa, are situated within an ocean area with the highest thermal difference between surface waters and waters at 1 km depth (c. 24–28°C).

**Figure 14** shows the principles of OTEC technology. In a closed cycle OTEC system, such as will be deployed on Kiribati, a working fluid of R32 (seawater can be used as working fluid in open cycle OTEC systems, e.g. Hawaii) is vaporised, with the vapour driving a turbine to create electricity. The vapour is condensed by heat exchange with colder ocean water and then heated/vaporised via heat exchange with warmer waters, and the cycle continues. OTEC boasts little to no seasonal variation throughout the day and seasons. For remote islands and coastal villages that have no power grids, OTEC can provide clean, self-reliant, sustainable energy.

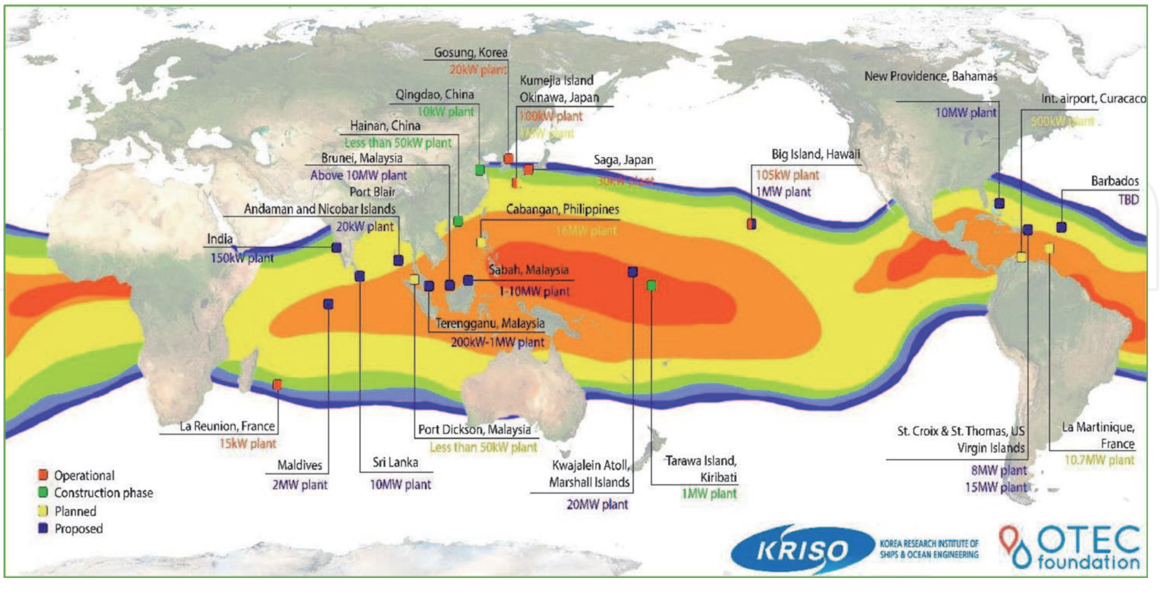


**Figure 13.**
*Global map of OTEC activities and resource in terms of the temperature difference between surface seawater and seawater at a depth of 1 km. The highest temperatures (and highest potential OTEC energy resources) are situated NE and E of Papua New Guinea, Indonesia, and the Philippines. Significant thermal resources are present within tropical and subtropical waters in all oceans and can benefit SIDS and continental countries within this area. Kiribati and its capital township of South Tarawa lie within the 'bulls eye' of thermal energy resources. A minimum temperature difference of 17°C between surface waters and waters at 1 km depth are required for OTEC at the present time (acknowledgements KRISO).*

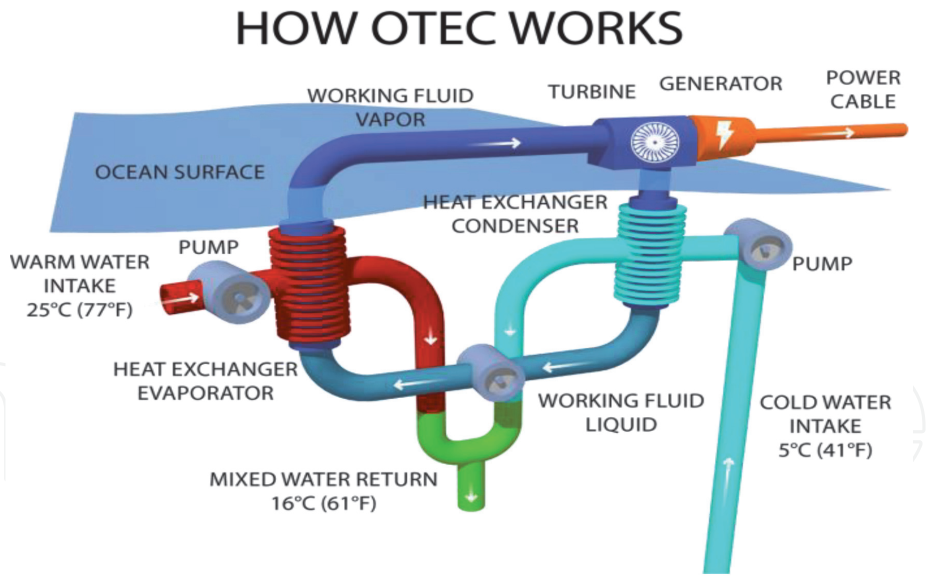


**Figure 14.**
*Principles of OTEC. A working fluid (R32 within closed cycle OTEC plant such as on Kiribati) is vaporised, with the vapour turning a turbine to create electricity. The vapour is cooled from deeper seawater and then heated via heat exchanges to be vaporised once more. OTEC plants can also provide desalinated drinking water and waters for agriculture/aquaculture at downstream (acknowledgements Scientific American [25]).*

## 8. Design and fabrication of the KRISO 1 MW OTEC demonstration plant

As part of the development of the KRISO 1 MW plant, a closed cycle OTEC system was initially designed and implemented. Closed cycles require a working fluid to transport and exchange heat within the system. The selected working fluid for the KRISO example was R32 (difluoromethane) which has a relatively high heat transfer coefficient and low environmental impact. Typical environmental characteristics of R32 include a relatively low ozone depletion index (ODP) and global warming potential (GWP) of 0 and 675, respectively. Various studies have been conducted to improve the performance of OTEC cycles, utilising multistage cycles, Kalina cycles, Uehara cycles, and so on [5, 6]. For the KRISO case, a simple Rankine cycle was applied to demonstrate the long-term operational potential of the OTEC plant. **Figure 15** shows the experimental temperature-entropy (heat transfer divided by the temperature) performance behaviour of the OTEC cycle, for the KRISO-OTEC plant, with field conditions of

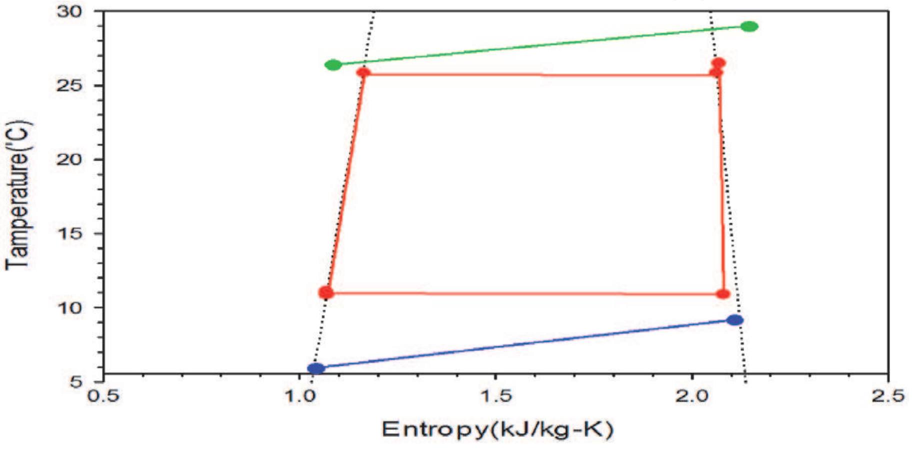


**Figure 15.**
*Temperature-entropy (heat transfer divided by the temperature). Diagram of an OTEC cycle (after [5, 6]).*

29°C surface seawater temperatures and 5°C deeper seawater temperatures. Closed cycles are circulated by the working fluid pump, so an endless cycle of power is formed when a heat source is supplied. The turbine output (Wt) of a closed cycle OTEC plant is given by Eq. (1). The net power generation (Wnet) is given by Eq. (2). The cycle was designed using Aspen HYSYS ver8.0, a process design program [5, 6].

$$W_t = m_r \bullet (h_{ti} - h_{to}) = m_r \bullet \eta_t \bullet (h_{ti} - h_{tos}) \tag{1}$$

$$W_{net} = W_t - w_{wwp} - w_{cwp} - w_{rp} \tag{2}$$

where mr is the mass flow rate of the refrigerant, $ht_i$ and $ht_o$ are the inlet and outlet enthalpy of the turbine, ηt is the efficiency of the turbine, and $h_{tos}$ is the turbine outlet enthalpy of the isentropic process. $\omega_{\omega\omega p}$, $\omega_{c\omega p}$, and $\omega_{rp}$ represent the pump output of surface water, deep water, and working fluid, respectively.

The heat of evaporation of temperature difference generation is shown in Eq. (3), and the net power efficiency ($\eta_{net}$) is calculated by the ratio of the amount of net power generation (Wnet) and evaporation heat (Qω) as in Eq. (4) [5, 6].

$$Q_w = G_h \bullet C_h \bullet \Delta T_{in-out} \tag{3}$$

$$\eta_{net} = W_{net} / Q_w \tag{4}$$

where $G_h$ is the surface water flow rate, $C_h$ is the specific heat of seawater, and ΔTin-out is the temperature difference between the evaporator inlet and outlet (**Figure 14**).

| Parameter | Value | Unit |
|---|---|---|
| Hot water inlet temperature | 29 | °C |
| Hot water mass flow rate | 1948.5 | kg/s |
| Cold water inlet temperature | 5 | °C |
| Cold water mass flow rate | 1805 | kg/s |
| Sea water pump efficiency | 80 | % |
| Hot water pump power | 130.5 | kW |
| Cold water pump power | 188.3 | kW |
| Heat source capacity | 32,364 | kW |
| Heat sink capacity | 31,148 | kW |
| Refrigerant pump power | 82.63 | kW |
| Turbine inlet pressure | 1729 | kPa |
| Turbine inlet temperature | 26.5 | °C |
| Turbine efficiency | 85 | % |
| Gross power | 1278 | kW |
| System efficiency | 3.95 | % |
| Net system power | 876.57 | kW |
| Net system efficiency | 2.71 | % |

**Table 3.**
*Analysis result of Rankine cycle OTEC demonstration plant.*

Although machine efficiency conditions are dependent upon on the temperature and flow rate of surface and deep seawaters, it is assumed that the OTEC cycle operation satisfies the heat exchanger pinch temperature of 1.5°C. Results from the earlier KRISO-OTEC experiments indicated that at an 85% turbine efficiency, the power generation was 1278 kW and the new power efficiency was 2.71% (calculated using principles and equations in [5, 6]) (**Table 3**).

Based on earlier experimental results and experience, a new 1 MW OTEC plant, named *K-OTEC1000*, was designed, and core devices such as a turbine generator, condenser, and evaporator were manufactured from 2016 to the first half of 2019. The *K-OTEC1000* plant was installed on a barge ship and became a de facto offshore power plant for short-term experiments in the seas offshore from Busan, South Korea. When *K-OTEC1000* is installed on South Tarawa, Kiribati, it will be a land-based *onshore* power plant (see **Figure 16** for an artist impression of the plant).

A field experiment was conducted in the southern sea of South Korea's East Sea, offshore of Busan, to verify the OTEC plant *K-OTEC1000* performance

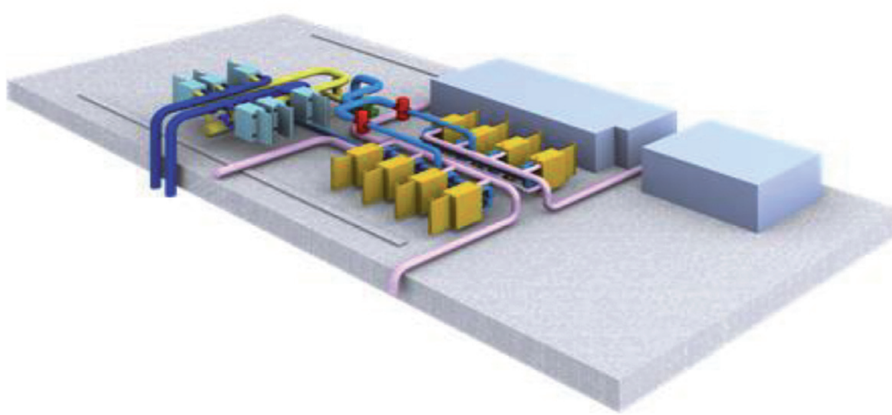

**Figure 16.**
*3D model/artist impression of the Kiribati-based KRISO 1 MW OTEC plant.*

| Deployment Stage | Variable | Wave | | Tidal | | OTEC | |
|---|---|---|---|---|---|---|---|
| | | Min | Max[1] | Min | Max | Min | Max |
| First array / First Project[2] | Project Capacity (MW) | 1 | 3 [3] | 0.3 | 10 | 0.1 | 5 |
| | CAPEX ($/kW) | 4000 | 18100 | 5100 | 14600 | 25000 | 45000 |
| | OPEX ($/kW per year) | 140 | 1500 | 160 | 1160 | 800 | 1440 |
| Second array/ Second Project | Project Capacity (MW) | 1 | 10 | 0.5 | 28 | 10 | 20 |
| | CAPEX ($/kW) | 3600 | 15300 | 4300 | 8700 | 15000 | 30000 |
| | OPEX ($/kW per year) | 100 | 500 | 150 | 530 | 480 | 950 |
| | Availability (%) | 85% | 98% | 85% | 98% | 95% | 95% |
| | Capacity Factor (%) | 30% | 35% | 35% | 42% | 97% | 97% |
| | LCOE ($/MWh) | 210 | 670 | 210 | 470 | 350 | 650 |
| First Commercial-scale Project | Project Capacity (MW) | 2 | 75 | 3 | 90 | 100 | 100 |
| | CAPEX ($/kW) | 2700 | 9100 | 3300 | 5600 | 7000 | 13000 |
| | OPEX ($/kW per year) | 70 | 380 | 90 | 400 | 340 | 620 |
| | Availability (%) | 95% | 98% | 92% | 98% | 95% | 95% |
| | Capacity Factor (%) | 35% | 40% | 35% | 40% | 97% | 97% |
| | LCOE ($/MWh) | 120 | 470 | 130 | 280 | 150 | 280 |

**Table 4.**
*Cost analysis in terms of capital expenditure (CAPEX) operational expenditure (OPEX), year-round availability/capacity, and the levelised cost equivalent (LCOE) (taking into account plant lifecycle production and operational costs) of OTEC power plant with other ocean energy systems [26].*

characteristics, in field conditions, prior to transport and installation on Kiribati. The experiment was conducted at the end of September, 2019, and proved to be successful, yielding a significant amount of operational data and proving the design concept [4]. During the experiment, the surface water temperature decreased, and the temperature difference between the surface and the deep water decreased to 18.7°C, with the output power level at 338 kW. This was a lower output than hoped for, but field conditions were suboptimal as the Korean winter was rapidly approaching. The data suggested however that the *K-OTEC1000* plant could likely produce 1 MW at a temperature differential of 24°C and 500 kW at a temperature differential of 20°C. The experiment produced the highest ever energy output from a seaborne OTEC plant, in the world, to date, setting a new world record [4].

The usefulness of OTEC-generated electricity to Kiribati and other islands will depend upon social acceptability and economic feasibility. As can be seen in **Table 4** [26], the unit production cost of electricity from the OTEC plant is estimated to be US$ 0.15 ∼ 0.65/kWh. Currently, electricity costs in Kiribati are between US$ 0.57 and 1.59/kWh. These data suggest that OTEC could be commercially competitive and viable for a Pacific Island situation. Because of Kiribati's favourable position in equatorial waters, it will be possible for OTEC plants to operate year-round on a 24/7 basis. If the OTEC plant proves successful, it could be scaled up to a 10 MW plant which would provide all of South Tarawa's current electricity requirements with no concomitant production of Greenhouse Gases.

## 9. Kiribati and OTEC deployment

KRISO plans to deploy a 1 MW land-based OTEC (K-OTEC1000) plant for 1 year in South Tarawa, Kiribati, in 2020 to 2021. If tests are successful, this may lead to longer-term projects and perhaps fully ocean-deployed OTEC systems. The OTEC plant will be located in the Eastern part of South Tarawa (**Figure 21**). This part of South Tarawa exhibits a rapid bathymetric gradient, reaching ocean depths of c. 3.5–4 km ocean depth within a 5-km horizontal distance (SOPAC [27]). This location allows land-based OTEC plants to access c. 1 km deep waters via pipes which hug the offshore underwater slopes and can be cemented and secured onto a solid rock foundation. Plans are now being made to transport the OTEC plant (**Figures 16–20**), by ship, from Busan to South Tarawa, in 2020/21. All environmental and planning permissions were granted by the Kiribati government in 2018. Ocean physical and chemical parameters have been measured in South Tarawa for a number of years, and the KRISO team have a good working knowledge of variations in temperature, pH, salinity, and redox conditions in the lagoon, and ocean, close to the proposed OTEC plant site.

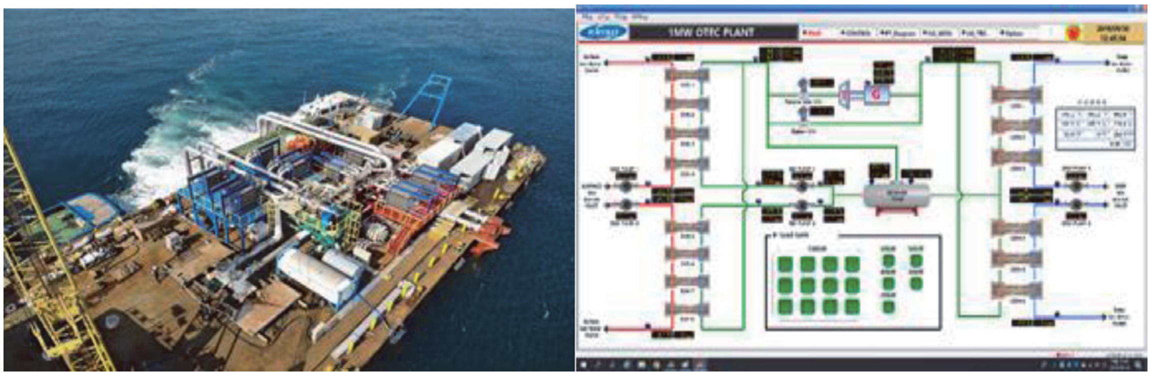


**Figure 17.**
*Operation scene of barge-mounted 1 MW OTEC plant (L) and monitoring system (R).*

Once the OTEC plant is deployed, it has funding and permissions to test the equipment in 2020/2021. During this time the whole programme will be assessing applications for the South Tarawa community for electricity and downstream utilisation for drinking water and agriculture/aquaculture. I-Kiribati people will be trained in OTEC-related engineering and science and the application of products for agriculture and aquaculture. If the project proves successful, the KRISO team will be making applications for funding for longer-term OTEC deployment on Kiribati, and for scaling up the 1 MW plant, with ambitions for a fully ocean-deployed OTEC plant generating 5–50 MW of electricity in the future (**Figures 21** and **22**).


**Figure 18.**
*Key components of 1 MW OTEC plant of K-OTEC1000, which was loaded onto a barge ship for experimental tests, offshore from Busan, South Korea.*

**Figure 19.**
*Perspective view of floating OTEC plant depicted by KRISO.*

**Figure 20.**
*K-OTEC1000 plant onboard a barge ship in the eastern seas, near Busan, South Korea. The full extent of the OTEC plant is shown within the box in the figure. The plant was successfully tested in September, 2019, and it will be transported to South Tarawa in 2020 (Photograph: Kim).*

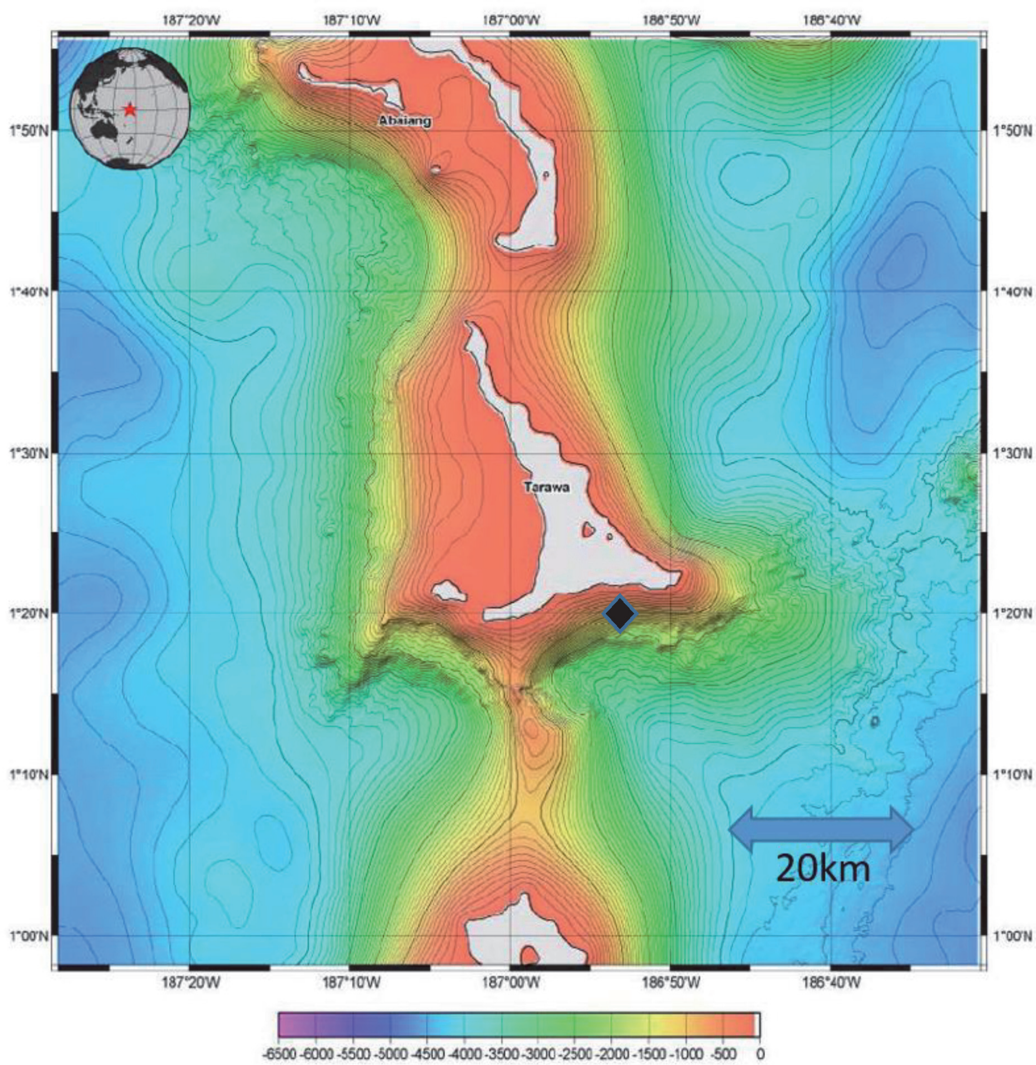


**Figure 21.**
*Bathymetric map of South Tarawa showing the probable location of the 1 MW OTEC plant (black diamond). Note the rapid drop-off in depth away from the atoll allowing an OTEC plant ready-access to deep water and the market of South Tarawa. South Tarawa is a seismically quiet area with extreme storm events occurring relatively infrequently and quiet seawater conditions (acknowledgements, SOPAC [27]).*

**Figure 22.**
*Bird's eye view/artists impression of the building for sustainable seawater utilisation Center (SSUC). Downstream utilisation of discharged seawater for district air conditioning, desalination, aquaculture, and agriculture applications will be delivered for capacity building and SDGs achievement in Kiribati and coastal communities along the tropical belt (acknowledgements, KRISO).*

## 10. Concluding statements

The deployment of an OTEC plant in South Tarawa is ambitious in technical and development terms. Technologically, the South Tarawa plant is destined, at least for a while, to become the largest OTEC plant in the world. The design and building of the plant represents a US$20 M investment and thousands of people-hours of highly expert time. The project has been ongoing since 2013, with predecessor OTEC laboratory-scale experiments extending back to 2010. Transporting the main plant and c. 3 km of piping from Korea to South Tarawa will be a difficult challenge.

The final deployment of the OTEC plant in Kiribati will represent a high water mark for Kiribati and the Pacific region in general. Infamous nuclear tests aside (in the Marshall Islands, Kiribati, and French Polynesia), it is rare for the Pacific Islands region to be the centre of major global-scale scientific-technological advances.

The KRISO-OTEC-Pacific project has been carefully planned from 2013. KRISO and the Korean government are to be commended for the effort and time invested in discussing the programme, awareness raising, and genuine inclusive reciprocal Pacific Islander activities that have predated the OTEC Kiribati deployment. It is challenging for widely different cultures to work together for common goals with development goals. The model here that combines science and technology with a developmental goal within the context of Pacific Island cultural values is commendable from an *interconnected geoscience* perspective.

The project, should, in theory bring benefits all-round. KRISO, the South Korean Government, and the world OTEC community will benefit from the on-site, 1-year technical testing and operation of a land-based 1 MW plant. If this is successful, it may lead to more ambitious, larger-scale OTEC developments, including a full-ocean OTEC plant. The project may encourage other OTEC workers around the world, in the Caribbean, Indian Ocean islands, and beyond, to accelerate their OTEC developments.

If, however, all that results from the OTEC Kiribati experience are technological benefits, this will be a disappointment.

As this paper has analysed, small atoll PSIDS and SIDS in general are in acute need of many of the benefits OTEC technologies can bring. A lack of affordable, reliable, and accessible electricity is a challenging constraint on development, anywhere in the world. It points to a chicken and egg situation: Minimal power results in minimal development, and limited development results in limited power infrastructure being created. Industry that is attracted to Kiribati, such as tuna canning factories, have to develop much of the infrastructure they require, such as power and water, themselves. This adds significantly to already-high start-up costs and is a major disincentive to inward investment into Kiribati and other SIDS. If the state can provide fundamental infrastructure, including reliable, affordable electricity and water supplies, conditions for inward investment are improved.

OTEC not only brings electricity but the promise of associated seawater technologies and industry. Deep ocean water has proven chemical and biological qualities that can be applied to products and services for human health, cosmetics, agriculture, and aquaculture. In Goseong, South Korea, next to the OTEC and seawater utilisation plant, a number of high-technology industries have developed that produce mineral salts, mineral waters, and cosmetics. These could develop, even in an unlikely setting such as South Tarawa, given training, investment, and the establishment of a Sustainable Seawater Utilisation Center (SSUC). Waters linked to OTEC operation can be used to develop hydroponic agricultural plants, refrigeration plants, and aquaculture plants for shellfish and fish farms. These developments can all contribute to many sustainable development goals.

Alongside science and technology, and the development of agriculture and industry, with related high-quality employment opportunities, is the potential for new education and training. KRISO is working with the Kiribati government in helping develop a science and technology of sustainable seawater utilisation at the centre. The presence of a fully operational and long-term OTEC plant would be a catalyst and encourager for the further development of these much-needed educational initiatives for Kiribati, which can then become a developmental model for other PSIDS and SIDS in general.

The 1-year testing of a land-based 1 MW OTEC plant in Kiribati in 2020/2021 and the 7-year lead up to this deployment is highly innovative and a good model for international development. Time will tell if the 1-year duration test develops into something far more significant from a Kiribati development perspective.

## Acknowledgements

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## Author details

Michael G. Petterson[1]* and Hyeon Ju Kim[2]

1 School of Science, Auckland University of Technology, Auckland, New Zealand

2 Seawater Energy Plant Research Center, Korea Research Institute of Ships and Ocean Engineering, Goseong-Gun, Gangwon-Do, South Korea

*Address all correspondence to: michael.petterson@aut.ac.nz

## References

[1] United Nations Paris Agreement. 2015. Available from: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[2] Petterson MG. Interconnected Geoscience for International Development. Episodes Journal of International Geoscience, International Union of Geological Sciences. 2019; **42**(3):225-233. DOI: 10.18814/epiiugs/2019/019018

[3] United Nations. Resolution A/RES/70/1. Transforming our world: The 2030 agenda for sustainable development. Records of the Seventieth Session of the General Assembly of the United Nations, Agenda Items 15 and 116; 21 October, 2015. p. 35

[4] Lee HS, Yoon JI, Son CH, Ha SJ, Seol SH, Ye BH, et al. Efficiency enhancement of the ocean thermal energy conversion system with a water-vapor ejector. Advances in Mechanical Engineering. 2015;**7**(3). DOI: 10.1177/1687814015571036

[5] Kim H-J et al. Demonstration of 1MW OTEC plant in Korean waters in 2019. In: Proceedings of the 7th International OTEC Symposium; 2019. p. 5

[6] Lim S-T, Kim H-J, Lee H-S. Dynamic simulation of performance change of MW-classOTEC according to seawater flow rate. Journal of the Korean Society for Power System Engineering. 2019; **23**(1):48-56

[7] Lim S-T, Lee H-S, Kim H-J. Simulation of power generation performance of MW-class open- and closed-cycle OTEC systems based on seawater temperature change. Journal of the Korean Society of Marine Engineering. 2019;**43**(6):420-426

[8] Lee DY, Nam BW, Hong SY, Kim H-J. An experimental study on the motion response of OTEC platforms. Korea Research Institute of Ships and Ocean Engineerng (KRISO). In: Proceedings of the 25th International Ocean and Polar Engineering Conference. Kona, Big Island, Hawaii, USA. 21–26 June, 2015

[9] Brundtland G. Report of the World Commission on Environment and Development: Our common future. United Nations General Assembly Document No. A/42/427; 1987

[10] Gill JC, Bullough F. Geoscience engagement in global development frameworks. Annals of Geophysics. 2017;**60**:1-10. DOI: 10.4401/ag-7460

[11] Stewart IS, Gill JC. Social geology—Integrating sustainability concepts into Earth sciences. Proceedings of the Geologists Association. 2017. DOI: 10.1016/j.pgeola.2017.01.002

[12] Stewart IS. Sustainable geoscience. Nature Geoscience. 2016;**9**(4):262

[13] CEBR. World Economic League Table, 2019. A World Economic League Table with Forecasts for 193 Countries to 2033. London, UK: Centre for Economics Business Research Ltd.; 2019. p. 214

[14] Petterson MG, Tawake AK. Toward inclusive development of the Pacific region using geoscience. In: Wessel GR, Greenberg JK, editors. Geoscience for the Public Good and Global Development: Toward a Sustainable Future. Geological Society of America Special Paper. Vol. 520. 2016. pp. 459-478

[15] SPC. Pocket Statistical Summary. Noumea, New Caledonia. 2013. p. 4. Available from: www.spc.int/prism

[16] UN. Gross National Product per Head Statistical Data. 2019. Available from: http://data.un.org/Search.aspx?q=GDP+per+capita

[17] UNDP. Human Development Indices and Indicators: 2018 Statistical Update. Kiribati. 2019. p. 9. Available from: http://hdr.undp.org/en/data

[18] SPC. Fertility Rates in Pacific Island Countries and Territories. New Caledonia: Noumea; 2019. p. 99. ISBN: 978–982–00-1203-5

[19] SPC. Mortality Trends in Pacific Island States. New Caledonia: Noumea; 2014. p. 81

[20] World Bank. Implementation Completion and Results Report TFOA5646 on a Small Grant in the Amount of US$ 0.3 Million to the Republic of Kiribati for the Scaling-up of Renewable Energy Program Investment Plan. Report No 138090-KI. Washington DC, USA; 2019. p. 112

[21] NZMFAT. Pacific Energy Country Profiles. Wellington, New Zealand: New Zealand Ministry of Foreign Affairs and Trade; 2016. p. 21. ISBN: 978–0–477-10250-6

[22] United Nations. Electricity Profiles: Energy Balances and Electricity Profile. Department of Economics and Social Affairs; 2016. ISBN: 9789211616088. https://unstats.un.org/unsd/energystats/pubs/balance/

[23] Asian Development Bank. Vanuatu National Energy Road Map. Port Vila, Vanuatu: Government of Vanuatu; 2013. p. 99

[24] Bosserelle C, Sandeep R, Kruger J. Waves and Coasts in the Pacific: Cost Analysis of Wave Energy in the Pacific. Publication of the Pacific Community. Suva, Fiji: SPC Publications; 2016. p. 45. ISBN: 978-982-00-094-8. Available from: www.spc.int/gsd/wacop

[25] Scientific American. Hawaii First to Harness Deep-Ocean Temperatures for Power. 2015. Available from: https://www.scientificamerican.com/article/hawaii-first-to-harness-deep-ocean-temperatures-for-power/

[26] IEA-OES. International Levelised Cost of Energy for Ocean Energy Technologies. 2015. p. 48

[27] SOPAC, Sharma A, Kruger J. Kiribati Technical Report. High Resolution Bathymetric Survey in Kiribati. SOPAC Project Report No 114. Suva, Fiji; 2008. p. 44