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Plant siting and economic potential of ocean thermal energy conversion in Indonesia a novel GIS-based methodology

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ABSTRACT

Indonesia strives for a renewable energy share of 23% by 2025. One option to contribute to this goal is *Ocean Thermal Energy Conversion (OTEC)*. Despite a global theoretical potential of up to 30 TW, its economically deployable share remains unknown. This paper proposes a novel methodology, which enables to determine OTEC's economic potential for any regional scope considering technical, economic and natural variables. The methodology was tested for 100 MW_e OTEC in Indonesia on a provincial and national level. Against a regionally variable electricity tariff of 6.67–18.14 US$ct.(2018)/kWh, the national economic potential is 0–2 GW_e with a *Levelized Cost of Electricity* (LCOE) as low as 15.6 US$ct.(2018)/kWh. With an annual electricity production of 0–16 TWh, OTEC could provide up to 6% of Indonesia's electricity demand in 2018. The capacity factor, capital expenses and discount rate are the most sensitive variables of the LCOE on average. A nationally uniform feed-in tariff of 18 US$ct.(2018)/kWh or more could increase the economic potential significantly. The proposed methodology can be a helpful quick-scan tool for determining economically interesting OTEC sites for follow-up in-depth feasibility studies. Limitations are discussed and future research, amongst others upscaling scenarios with cost reducing effects like technological learning, is recommended.

1. Introduction

Indonesia is the biggest archipelago with the fourth largest population in the world. Its economic and demographic development is reflected by its energy demand, being the highest in Southeast Asia [1] with 5.7 EJ in 2018 and an average growth rate of 3.7% between 2008 and 2018 [2]. Like many other countries, Indonesia faces an "energy trilemma", as it has to address energy security, energy poverty and climate change mitigation simultaneously [3]. Regarding energy security, Indonesia has become a net oil importer in 2004 [4] and is exposed to increasing prices and geopolitical developments [5–7]. As the fourth largest coal producer worldwide [1], Indonesia strongly depends on coal for around 50% of its electricity generation in 2018 [8]. Regarding energy poverty, Indonesia's archipelagic geomorphology poses a significant challenge to the adequate distribution of energy across the nation [6]. Although the electrification rate increased from 66.0% to 98.3% from 2010 to 2018 [2,9], roughly 4.5 million people in Indonesia, mostly living in rural, off-grid communities, still have no access to electricity [10]. Lastly, the country is susceptible to the effects of climate change, such as the rise of sea levels and increased risk of flooding [5].

To address the energy trilemma, Indonesia is committed to the energy transition and the shift to regionally produced, decentralised and clean renewable energies. The government aims at a renewable share of 23% in the national energy mix by 2025 [1]. In 2018, the share comprised 14%, consisting of 7% hydropower and roughly 3% for geothermal and biomass each [8]. However, much of Indonesia's vast renewable energy potential remains unharnessed [1]. One untapped renewable energy is *Ocean Thermal Energy*

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Abbreviations

Abbreviation	Meaning Unit (if applicable)
BPP	*Biaya Pokok Penyediaan* (Basic cost of electricity provision)
CAPEX	Capital Expenses US$ (2020) million
c_f	Capacity Factor %
CRF	Capital Recovery Factor %
EEZ	Exclusive Economic Zone
E_t	Electricity Production kWh/year
FIT	Feed-In Tariff
GIS	Geographic Information System
HC	High Cost
HYCOM	Hybrid Coordinate Ocean Model
i	Interest/Discount Rate %
LCOE	Levelized Cost of Electricity US$ct.(2020)/kWh
LC	Low Cost
N	Project Lifetime Years
OPEX	Operational Expenses US$ (2020) million per year
OTEC	Ocean Thermal Energy Conversion
η	Transmission Losses %
PPA	Power Purchase Agreement US$ct.(2018)/kWh

Conversion (OTEC), which uses the temperature difference between warm surface seawater and cold deep-sea water to generate electricity [11]. Although OTEC's global theoretical potential could be as much as 30 TW [12], it has not reached commercialisation yet. Unfortunately, there is no long-term practical experience and current cost estimates only offer rough indications about OTEC's economics [13].

A recent literature review on OTEC economics identified seven knowledge gaps, sparking a broader research agenda for the further development of OTEC as a major option to provide renewable baseload power in the future [14]. Knowledge gaps include (i) absence of spatial economic analyses, (ii) omission of natural influences on the real net power output, (iii) uncertainty of system and component costs, (iv) operational uncertainty, (v) impact of various risks on interest and discount rates, (vi) omission of technological learning and (vii) omission of further economic assessment tools.

This paper aims to contribute to the proposed research agenda by shedding more light on the knowledge gaps (i), (ii), (v) and (vii). Knowledge gap (i) is addressed by developing and testing a methodology to estimate the economic potential of closed-cycle, moored OTEC not only for individual plants but also for any regional scope, using a *Geographic Information System (GIS)* approach. The economic potential builds upon a set of practically suitable sites of OTEC, which form a practical potential based on physical, technical, and non-technical limitations of the technology. To account for differences in local conditions, a rough correlation between *Capital Expenses (CAPEX)* and external influences is proposed to contribute to knowledge gap (ii). Regarding knowledge gap (vii), the economic analysis of OTEC is expanded by a cash flow analysis and determining the *Internal Rate of Return (IRR)*. The developed methodology also includes a sensitivity analysis, showing how variations in inputs alter the *Levelized Costs of Electricity (LCOE),* the metric used to measure OTEC's economic potential. By analysing the sensitivity of inputs like capacity factor, interest rates and CAPEX, knowledge gap (v) is addressed as well.

For Indonesia, OTEC might be a viable alternative to produce clean, steady electricity for both urban and rural areas and to contribute to the country's renewable energy transition. Therefore, the proposed methodology is applied to determine the economic potential of closed-cycle 100 MW_e in Indonesia. Next to refining the potential of OTEC in Indonesia beyond technical and practical levels, this study aims to shed more light on what cost-optimal regions for OTEC deployment are in Indonesia and to what extent OTEC might be currently profitable in those regions. This paper builds and expands on several earlier studies on OTEC at TU Delft [15–18].

The paper is structured as follows. Section 2 gives an overview of current works on GIS for techno-economic renewable energy analysis and on OTEC potentials globally and in Indonesia. Section 3 presents the methodology for OTEC siting, calculation of LCOE and determination of the economic potential. In section 4, the methodology is applied for 100 MW_e closed-cycle OTEC in Indonesia. Section 5 provides a discussion and ends with a conclusion and recommendations in sections 6 and 7, respectively.

2. Literature overview

2.1. GIS for renewable energy potential determination

In the field of renewable energy, GIS has not only been used for the assessment of both technical and economic potential, but also for site selection optimisation, i.e. for biogas in a Polish province [19], hydropower worldwide [20], solar power in Brazil [21], as well as wind power in China [22], India [23,24], UK [25] and on a global level [26]. The economic potential of tidal energy in the Bristol Channel was also mapped [27,28]. Furthermore, an analysis of hybrid systems consisting of several technologies on small island development states was conducted with GIS [29]. For OTEC, GIS has been used to map available resources in the form of seawater temperature differences [30–32] and real power outputs forming technical potentials [12,33–35]. To the authors' knowledge, a GIS-based methodology which determines the economic potential of OTEC is not available in current literature.

2.2. OTEC's potential worldwide and in Indonesia

OTEC's oceanographic and climatic requirements include among others a temperature difference between surface and deep sea water of at least 20 °C, with the latter being extracted from a depth of around 1000 m using a cold water pipe [13]. For grid-connected OTEC, a steeply declining seabed is needed to implement the pipe close to shore to reduce submarine cable costs and transmission losses [11,36]. The global zones fulfilling these natural requirements were already shown in several studies [13,37–40]. On national and territorial levels, suitable sites were mapped for the Caribbean Sea [41], Reunion Island [42,43], Mauritius [31], Philippines [44,45] and for the coasts of several African countries like Tanzania and Mozambique [46], as well as the Seychelles, Madagascar and Kenya [47]. However, a maximum depth induced by mooring limitations has not yet considered so far. With rising depth, the strain on mooring lines increases significantly, due to its own mass and deep sea currents amongst others [48], adding complexity to the system design [49].

In current literature, OTEC's potential is merely mapped on theoretical, technical and practical levels, which subsequently include physical (i.e. Carnot efficiency), technical (seawater temperature and water depth amongst others) and non-technical (marine protected areas amongst others) limitations of the technology, respectively. The global theoretical potential can be as much as 30 TW [12], while the technical level ranges between 3 and 5 TW [50,51]. The potential of OTEC has also been studied in literature on a national level, including Indonesia with a theoretical, technical and practical potential of 57, 52 and 43 GW, respectively [45]. Moreover, it was found that an OTEC plant with a nominal power output of 100 MW at 20 °C seawater temperature difference could produce approximately 1200 GWh of electricity per year in Indonesia due to seawater temperature differences far higher than the nominal value [38].

Site-specific criteria affecting the economic performance of individual plants, such as seawater temperature difference and water depth, have mostly not been considered hitherto in existing economic OTEC potential calculations. This might be critical, as more favourable site conditions allow for cost and performance optimisations of components like heat exchangers and submarine cables [36]. Moreover, current studies on OTEC potentials do not account for its profitability when compared to local electricity marketing schemes [14]. These shortcomings as well as the ones mentioned in the introduction are addressed in the methodology proposed in the next section.

3. Methodology

The GIS methodology foots on five steps as shown in Table 1. As steps *Problem Description* and *Recommendations* are discussed in sections 1 and 7, respectively, only the steps *Data Collection, Data Pre-Processing and Economic Analysis* are described here.

The methodology employs the following approach. A mesh of data points with a distance of 27.8 by 27.8 km is spanned over the oceanic waters of Indonesia. The choice of distance is elaborated in section 3.2, but can be adjusted in the download setup as elaborated in section 3.1.2. At each data point, it is assumed that one 100 MW_e OTEC plant can be installed. The size of 100 MW_e is vindicated by OTEC's strong cost-reducing economies of scale and its frequent assessment within academic and industrial OTEC research, thus allowing better validation of results [11,36,52,53]. The mesh of data points is filtered for suitable sites which form the practical potential, using the technical exclusion criteria of local seawater temperature difference and water depth as well as the non-technical criterion of marine protected areas. The practically suitable sites for OTEC are then connected to adequately populated onshore connection points within the same province. To account for local seawater temperature variations and their seasonal fluctuations, the plants are assumed to be designed to generate a real net power output of 100 MW to maintain comparability. For example, at a site with continuously higher seawater temperature difference, components like heat exchangers are assumed to be designed at a smaller size, resulting in a lower CAPEX. Heat exchanger costs as well as submarine cables costs are calculated using a linear approximation function. The LCOE is calculated for each individual plant and then compared to the local electricity tariff at the connection point. The economic potential of OTEC is embodied by those plants with a LCOE below the respective tariff.

3.1. Data Collection

The collected data was grouped in three categories, namely (1) country- and province-specific data, (2) environmental data, and (3) technical and economic OTEC data.

3.1.1. Country- and province-specific data

The layers with land and sea borders of Indonesia and its provinces was obtained from OpenStreetMap. Alternatively, the *Exclusive Economic Zones (EEZ)* of a country can be used. Marine protected areas unsuitable for OTEC implementation can also be included [55].

As mentioned in section 2.2, the distance from plant to shore should be optimised [36]. However, since Indonesia consists of more than 17,000, often uninhabited, islands [1], an OTEC plant might not be connected to the closest shoreline. Instead, it may require longer power lines to reach inhabited locations with sufficient electricity demand. Thus, a dataset containing all capitals at regency level of Indonesia was added to the country and provincial layers of the GIS model. These capitals serve as *Connection Points* to which the analysed OTEC plants can be connected, as visualised in Fig. 1.

Renewable energies in Indonesia are renumerated via *Power Purchase Agreements (PPA)* based on the basic cost of electricity provision or *Biaya Pokok Penyediaan (BPP).* The BPP can

Table 1
Methodology for the determination of the economic potential of OTEC (five-step methodology based on [54]).

Step	Activity	Result
1. Problem description	• Problem statement • Clarification of research objectives • Setting key design choices and boundaries	*What is the economic potential of 100 MW_e closed-cycle OTEC in Indonesia?*
2. Data Collection	• Collection of possible data sources • Validation of data sources • Collection of required data	• *National and provincial land and sea borders* • *Alternatively: Exclusive Economic Zone (EEZ)* • *Grid connection points* • *HYCOM temperature data* • *Water depth* • *Marine protected areas* • *Local electricity tariff (i.e. wholesale price, feed-in tariff, or power purchase agreement tariff)* • *CAPEX + OPEX of OTEC* • *Discount rate* • *Lifetime of plant* • *Capacity factor*
3. Data Pre-Processing	• Evaluation of data quality and completeness • Removal of unsuitable data points • Alignment of all datasets into one file	• *Pre-processed, condensed data* • *Suitable sites for OTEC with all necessary properties for further analysis*
4. Economic Analysis	• Mapping of practically suitable sites (forming the practical potential) • LCOE calculation • Determination of economic potential	• *Assignment of practically suitable OTEC sites to grid connection point* • *LCOE for each site* • *Cumulated economic potential* • *Cash flow diagram* • *Internal rate of Return (IRR)*
5. Recommendations	Deducing next steps from results	• *Recommendations for future research* • *Deeper investigations at cost-optimal/-favourable sites*

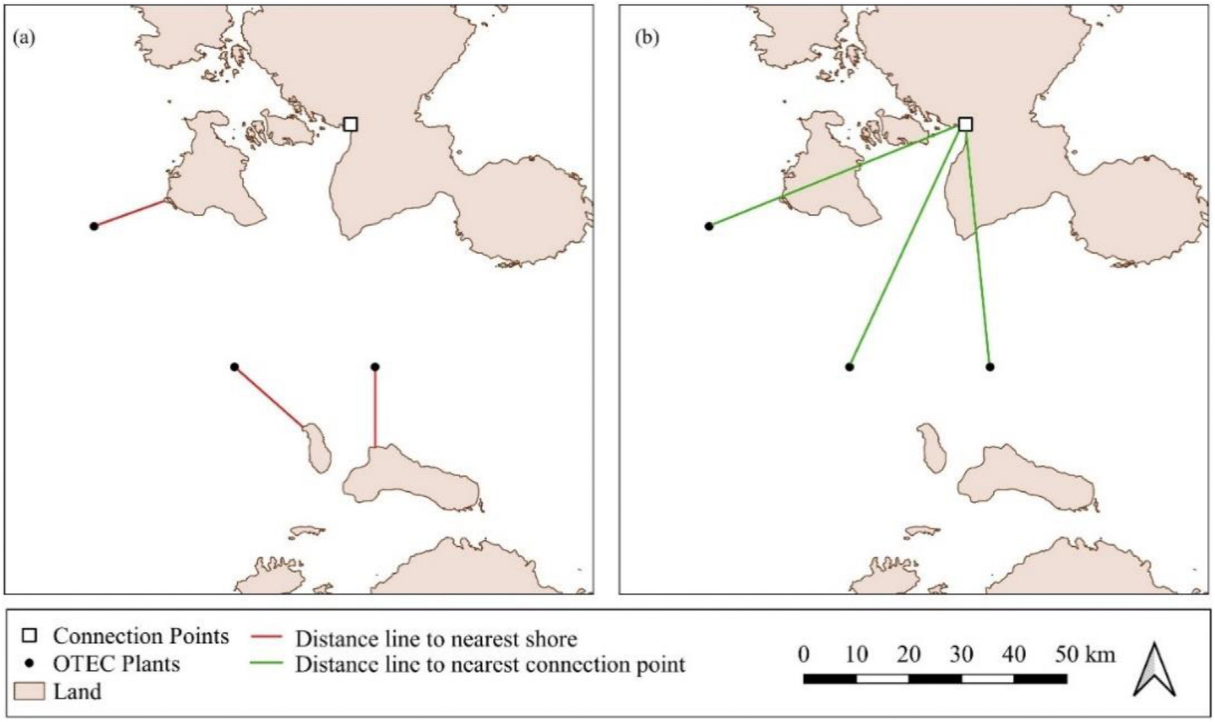

Fig. 1. Illustration of OTEC Plants (black points) distance measurement for (a) the closest distance to any shore, and (b) the distance to potential connection point (inhabited region).

considerably vary regionally between 6.91 and 21.34 US$ct./kWh (both 2018 values) [56]. There is also a national BPP, set at 7.85 US$ct.(2018)/kWh in 2018. If the local BPP is higher than the national BPP, the PPA tariff for the plant operator is up to 85% of the local BPP, resulting in a range of tariff assumed in this paper between 6.67 and 18.14 US$ct.(2018)/kWh [57].

3.1.2. Environmental data

The temperature data from 0 to 1000 m depth were obtained from *HYbrid Coordinate Ocean Model (HYCOM)* for the time period between August 2013 and November 2018. Datasets of the global bathymetry can be downloaded from the *National Oceanic and Atmospheric Administration (NOAA)* with a resolution of roughly 0.03 decimal degrees or 3.7 km, respectively. The metadata of both temperature difference and bathymetry are shown in Table 2.

3.1.3. Technical and economic OTEC parameters

Following Langer et al. [14], the cost estimations for different

Table 2
Metadata of temperature difference layer and bathymetry layer.

Title	Temperature Difference Layer
Description	The layer that contains difference between surface (0 m) and deep water (1000 m) temperature
Creator	Naval Research Laboratory: Ocean Dynamics and Prediction Branch
Publisher	HYCOM.org
Dataset	HYCOM + NCODA Global 1/12 Degree Analysis/GLBa0.08/expt_91.2/2017 Data: Jan-01-2017 to Dec-31-2017/Data at 00Z (temp)
Coordinate System	World Geodetic System1984 (WGS84)
Vertical Datum	Mean Sea Level
Spatial Range	95° E to 142° E and 7.5° N to 12° S
Spatial Resolution	0.25° (approximately 27.8 km)
Data Type	Raster
Parameter Unit	°C
Depth Levels	0 m and 1000 m
Time Period	21 August 2013 to 27 November 2018
Title	Bathymetry Layer
Description	The layer that contains the depth of the sea in relation to the sea surface
Creator	National Oceanic and Atmospheric Administration
Publisher	National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce
Dataset	2-Minute Gridded Global Relief Data (ETOPO2v2) June 2006
Coordinate System	World Geodetic System1984 (WGS84)
Vertical Datum	Mean Sea Level
Vertical Precision	1 m
Spatial Range	90° W to 90° E and 180° N to 180° S
Spatial Resolution	0.03° (approximately 3.7 km)
Data Type	Raster
Parameter Unit	metre

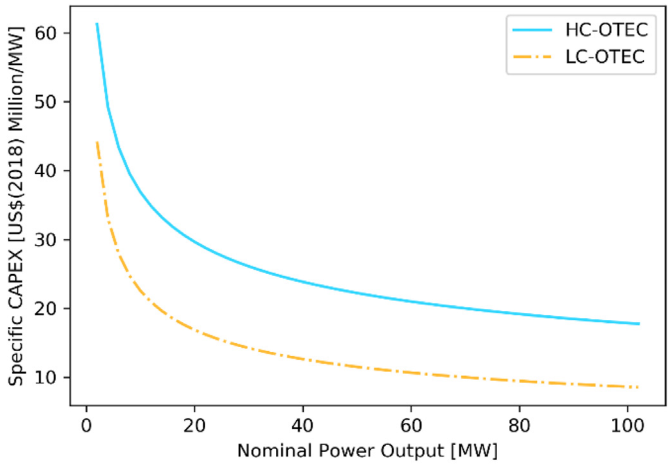

Fig. 2. Low-Cost (LC) and High-Cost (HC) curves for moored OTEC from representative OTEC literature. A third, even lower cost curve was omitted due to lack of validity [14].

system sizes in the OTEC literature form three scale curves, displaying how their specific CAPEX decrease with increasing scale. However, it was found that the lowest cost curve was based on studies with system designs and cost assumptions that have not yet been validated within the OTEC research field. Therefore, the lowest of the three scale curves may not be representative and was omitted from this study.

For the remainder of the paper, the two curves as shown in Fig. 2 are referred to as *Low-Cost (LC)* and *High-Cost (HC)* curve, respectively. The former cost estimations are commonly found in scientific literature [11,58,59], while the latter costs stem from a U.S. defence contractor [36], who incorporated significant cost contingencies to account for the first-of-its-kind character of initial OTEC projects. However, the cost estimations reflected by these curves are based on system designs with specific site conditions, excluding regional deviations. To refine this, it is proposed to differentiate between location-dependent and location-independent cost components. This is done by subtracting the location-dependent components from the scale curves shown in Fig. 2. The adjusted scale curves are then used to calculate the total costs for location-independent components of any OTEC plant. Next, the costs of location-dependent components are calculated using approximation functions deduced from several recent OTEC studies [36,58]. For example, the real power output of an OTEC plant rises by 10% per 1 °C of increase of seawater temperature difference [14]. Therefore, to establish a real power output of 100 MW_e of all plants across Indonesia, the heat exchangers are assumed to be adjusted to the local seawater temperature differences and their seasonal fluctuations. If the seawater temperature difference in one region is continuously higher throughout the year than in other regions, the heat exchangers of the plant in the warmer region are consequently downsized. Thus, this paper follows the approach of Martel et al. [36], who reduced the evaporator area of a 100 MW_e plant by almost 160,000 m^2 by adjusting the heat exchanger design specifically to the local range of seawater temperature. It is acknowledged that in academic literature, an alternative approach is to design components like heat exchangers to cover large ranges of seawater temperature differences, thus potentially leading to real power outputs of OTEC plants far beyond the nominal power at 20 °C [12,34,58]. However, this approach is not pursued here in order to maintain comparability between plants in different regions and to limit investment costs.

Some cost components are assumed to be location-independent to maintain simplicity, i.e. deployment & installation as well as platform & mooring. The scale curves and approximation functions as used in this paper are listed in Table 3.

The remaining parameters related to OTEC to calculate the LCOE are listed in Table 4. The discount rate of 10% is based on the recommendation for the social discount rate by the World Bank and Asian Development Bank [60,61]. The use of a social discount rate was assumed here, as OTEC might be implemented as a government-backed development project whose objectives might go beyond profitability. The sensitivity of the discount rate is determined in section 4.

3.2. Data Pre-Processing

The next step deals with the pre-processing of the collected data. First, the raster data of the average seawater temperature difference from the previously downloaded HYCOM data set was converted to point data using GIS tools. The temperature values at each data point are processed to reflect the average temperature from August 2013 to November 2018. Each of the resulting data points is perceived as one OTEC plant, with a 27.8 km distance from other OTEC plants. A distance of 27.8 km stems from the resolution of the temperature data, which is 0.25° as listed in Table 2 and is in line with other works that map global OTEC resources [34]. A sufficient distance between plants is expected to be beneficial from both a technical and environmental perspective, as too densely deployed OTEC might lead to local thermal degradation. If more cold deep sea water is extracted by a plant than what is restored by natural oceanic circulations, the water temperature at this layers would increase. This would not only hamper the technical performance of the plant due to a lower seawater temperature difference, but also potentially affect the stability of the ecosystem negatively [37,63]. The raster data of water depth was converted to point data as well. To add the bathymetric data to the set of OTEC plants, a GIS function was used to account for the differences in resolution between OTEC plants and water depth (27.8 vs. 3.7 km, respectively). The values of the pixels that overlap with an OTEC plant are averaged and added as a single mean value to the respective OTEC point.

Table 3
Cost assumptions in US$ (2018) Million used in this paper. ΔT is the seawater temperature difference, d the distance from plant to connection point, P_{net} the nominal plant size in MW_e. One approximation function for power transfer was used due to the similarities in costs of underlying OTEC studies. Low costs based on [58], high costs on [36].

Cost Component	Location-dependent?	Scale Curves/Approximation functions	
		LC-OTEC	HC-OTEC
Platform & Mooring Power Generation Water Ducting Deployment & Installation Others	No	$39,574*P_{net}^{-0.418}$	$51,833*P_{net}^{-0.315}$
Heat Exchangers	Yes, seawater temperature difference [36]	$(1.97 - (\Delta T - 20\,°C)*0.19)*P_{net}$	$(5.82 - (\Delta T - 20\,°C)*0.56)*P_{net}$
Power Transfer	Yes, distance to connection point [36,58]	$(0.0497*d + 0.304)*P_{net}$	

Table 4
Remaining technical and economic assumptions regarding OTEC.

Parameter	Value [Unit]		Reference
	LC-OTEC	HC-OTEC	
OPEX	5% of CAPEX per year	3% of CAPEX per year	[36,58]
Nominal Size	100 MW_e		
Lifetime	30 Years		[36,40]
Capacity Factor	91.2%		[11,36,58,62]
Discount Rate	10%		[60,61]
Transmission Efficiency	$(100-2*10^{-4}*d^2 - 1.99*10^{-2}*d)$ %		[14,36]

The resulting dataset of possible OTEC plants was filtered by removing plants (1) outside national boundaries, (2) within marine protected areas [55], (3) with a seawater temperature difference below 20 °C and (4) with a depth less than 1000 m and above 3000 m [48,64].

The remaining plants were then linked to the closest connection point within the same province, using a combination of GIS tools and Python scripts. The PPA tariff of each connection point was added in the GIS interface manually. Next, all relevant information of the connection points was transferred to the respective OTEC plants. Ultimately, the final OTEC dataset fed into the economic analysis consists of the following data:

- Longitude and latitude of the OTEC site
- Longitude and latitude of connection point
- Province of connection point
- Distance between plant and connection point *d* in kilometres [km]
- Seawater temperature difference ΔT in degrees Celsius [°C]
- Water depth in metres [m]
- PPA tariff at connection point in US$ct.(2018)/kWh

3.3. Economic analysis and sensitivity analysis

For each site, the LCOE was calculated for both LC- and HC-OTEC in accordance to equations (1) and (2) below, commonly found in OTEC economics literature. Transmission losses from plant to connection point were included by applying equation (3) [14].

$$LCOE = \frac{CRF*CAPEX + OPEX}{E_t} \quad (1)$$

$$CRF = \frac{i*(1+i)^N}{(1+i)^N - 1} \quad (2)$$

$$E_t = \eta * P_{net} * c_f * 8,760 \frac{hours}{year} \quad (3)$$

CAPEX: capital expenses.
OPEX: operational expenses.
E_t: produced electricity in year t.
CRF: capital recovery factor.
N: project lifetime
i: discount rate
η: transmission losses
c_f: capacity factor.

All obtained LC-LCOE and HC-LCOE were first mapped in GIS to highlight economically promising areas for OTEC deployment. Next, the sets of LCOE were compared to the local tariff. A LCOE lower than the local tariff indicates a profitable operation of the plant within its lifetime. The economically viable plants were accumulated for each province and then summarised to show the national economic potential of OTEC in Indonesia. A cash flow diagram indicates cash balance at the end of the plant's useful lifetime for the most economic LC- and HC-OTEC plant in Indonesia.

Subsequently, the correlations between the LCOE and external influences were assessed as well as the sensitivity of all inputs of equations (1) and (2). Each parameter was changed by ± 20%, while keeping all other parameters constant. Finally, the sensitivity of the national economic potential in Indonesia was evaluated by varying the tariff in the form of a national uniform *Feed-In Tariff (FIT)* and the discount rate.

4. Techno-economic assessment of 100 MW_e OTEC in Indonesia

4.1. Plant siting and economic potential of OTEC

Based on the filtering process in Fig. 3, a total of 1021 suitable OTEC sites were identified within Indonesian provincial borders. These are connected to a total of 116 connection points as displayed in Fig. 4. For 100 MW_e OTEC, a practical potential of 102.1 GW_e was calculated. Fig. 4 also shows that OTEC could be widely deployed throughout the country, with regions void of suitable sites being the northern and eastern side of Sumatera, the southern and western parts of Kalimantan, North Java and the southern part of Papua. The implications of implementing a maximum water depth are most notable for the Banda Sea as presented in Fig. 5. Here, many sites were removed due to water depths more than 3000 m, despite a high seawater temperature difference. In contrast, only one site was removed because of a seawater temperature difference below 20 °C, showing Indonesia's favourable climatic conditions for OTEC.

Fig. 4 shows the wide range of LCOE across Indonesia. While the LCOE of many sites is below 30 US$ct.(2018)/kWh for LC-OTEC, most sites exceed a LCOE of 40 US$ct.(2018)/kWh for HC-OTEC.

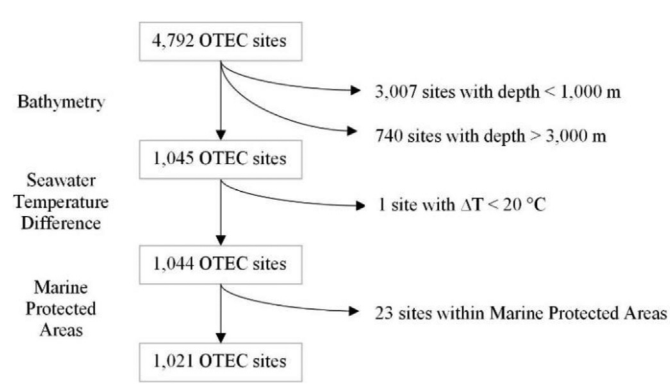

Fig. 3. Filtering process for OTEC site selection. The 1021 sites form a practical potential of 102,1 GW_e in Indonesia.

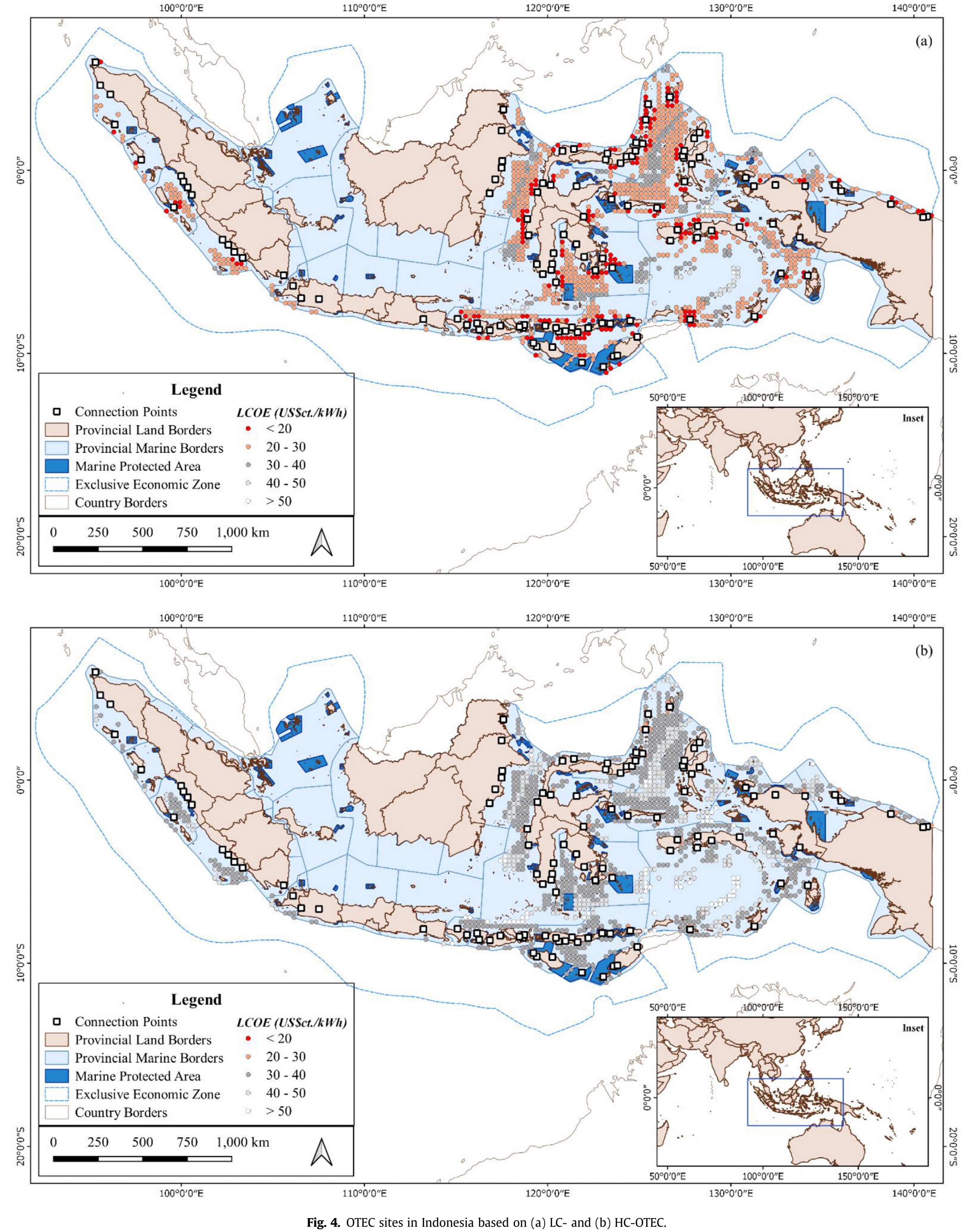

Fig. 4. OTEC sites in Indonesia based on (a) LC- and (b) HC-OTEC.

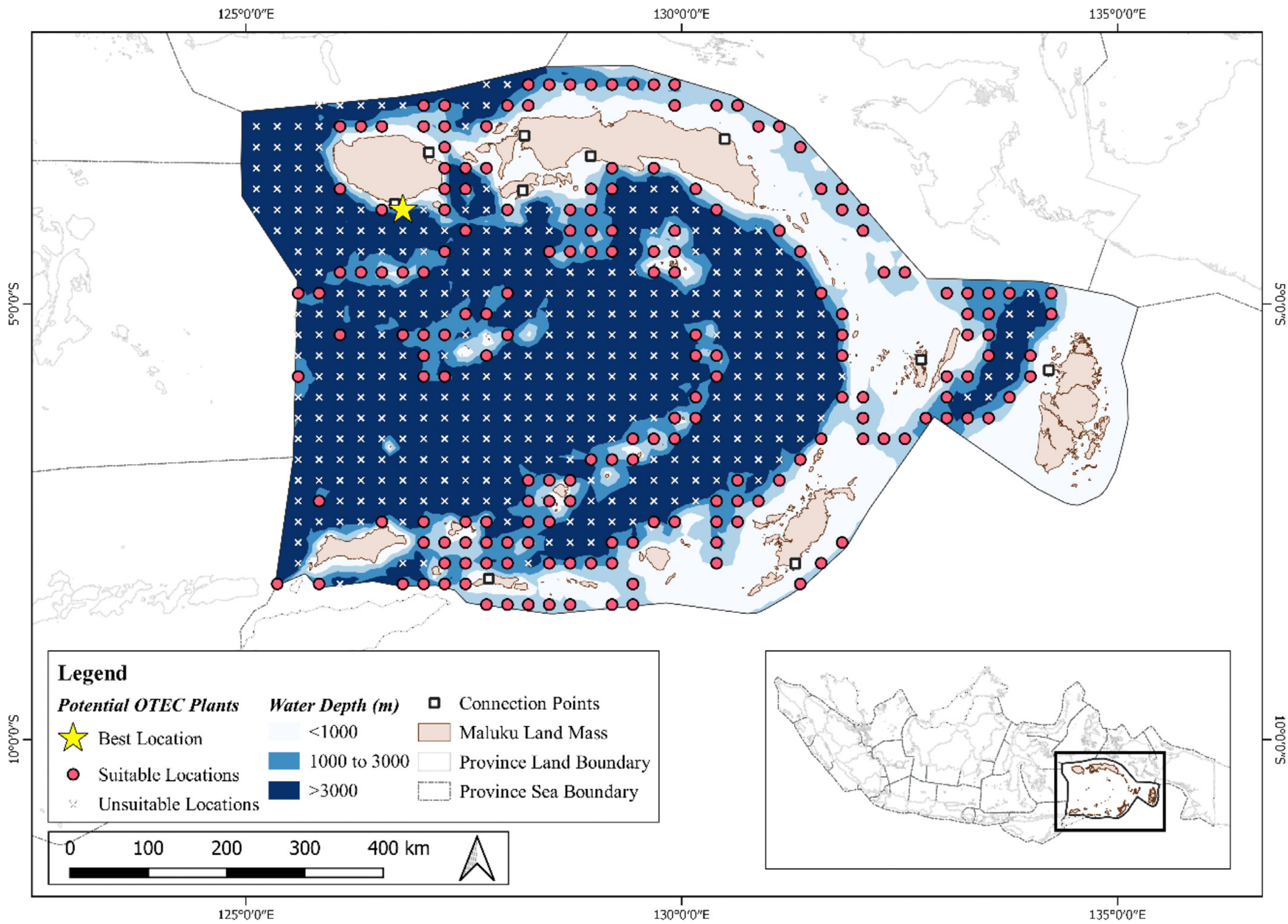

Fig. 5. Implications of including maximum water depth when mapping OTEC site in Banda Sea, Maluku.

The economic OTEC potential spans over 0–2 GW_e in Indonesia. With an annual electricity production of 0–16 TWh, OTEC could cover up to 6% of Indonesia's electricity demand in 2018 [2]. Out of all practically suitable OTEC sites, 0–2% of them are economically viable based on the assumptions of section 3.1.3. The provincial distribution of the economic potential is listed below in Table 5.

By far the highest economic potential can be found in Maluku, followed by Nusa Tenggara Timur. In both provinces, not only the seawater temperature difference and water depth are favourable for OTEC, but also the PPA tariff, indicating high electricity prices, especially in rural areas. Conversely, despite an abundance of suitable sites around Sumatera, eastern Kalimantan and western Sulawesi, none of these are economically sound due to low local tariff and partly economically suboptimal natural conditions. The difference in technical and economic performance between economically favourable and unfavourable sites are contrasted in Table 6. The proximity to the connection point seems to be a key factor when choosing a site for OTEC, as Table 6 shows not only that the CAPEX rises significantly due to submarine power transmission, but also that the effective electricity production decreases due to transmission losses. Cost savings via cheaper heat exchangers cannot compensate such sharp increases in power transmission costs if the plant is too far away from the connection point.

Table 5
Distribution of economic OTEC potential across provinces in Indonesia.

Province	Economic Potential [MW_e]	
	LC-OTEC	HC-OTEC
Maluku	1400	0
Nusa Tenggara Timur	300	0
Papua	200	0
Maluku Utara	100	0
Total	**2000**	**0**

The most favourable site in Fig. 5 and Table 6 is 13 km away from the connection point at Namrole in Maluku, with a LC- and HC-LCOE of 15.6 and 28.5 US$ct.(2018)/kWh, respectively. Against a local electricity tariff of 18.01 US$ct.(2018)/kWh, the cash flows of LC- and HC-OTEC at this site are depicted in Fig. 6. While the HC-OTEC plant stays unprofitable throughout its whole lifetime, the LC-OTEC plant breaks even after 15.2 years with a positive cash balance of US$ 185 million (US$ 2018) and an *Internal Rate of Return (IRR)* of 18%. The cash flows flatten gradually due to the discount rate of 10%.

4.2. Correlations and sensitivity analysis

Fig. 7 shows the correlations between the LCOE and the distance from plant to connection point, as well as the seawater temperature difference. There is a strong correlation between LCOE and distance. While the variation of LCOE is relatively high for distances below 150 km, especially in the case of HC-OTEC, the variation

Table 6
Technical and economic comparison of the economically most and least favourable OTEC site in Indonesia.

Connected to	Most favourable site **Namrole, Maluku**		Least favourable site **Binamu, Sulawesi Selatan**	
Distance to connection point *d* [km]	13		405	
Seawater temperature difference ΔT [°C]	24		23	
Transmission efficiency [%]	100		59	
Effective Electricity Production [GWh/year]	797		473	
PPA tariff [US$ct.(2018)/kWh]	18.01		7.01	
	LC-OTEC	**HC-OTEC**	**LC-OTEC**	**HC-OTEC**
CAPEX [US$ (2018) Million]				
Constant cost components	577	1215	577	1215
Heat Exchangers	123	363	137	404
Submarine Power Transmission	93	93	2041	2041
Total	**793**	**1671**	**2755**	**3660**
OPEX [US$ (2018) Million per year]	40	50	138	110
LCOE [US$ct.(2018)/kWh]	15.6	28.5	91.0	105.3

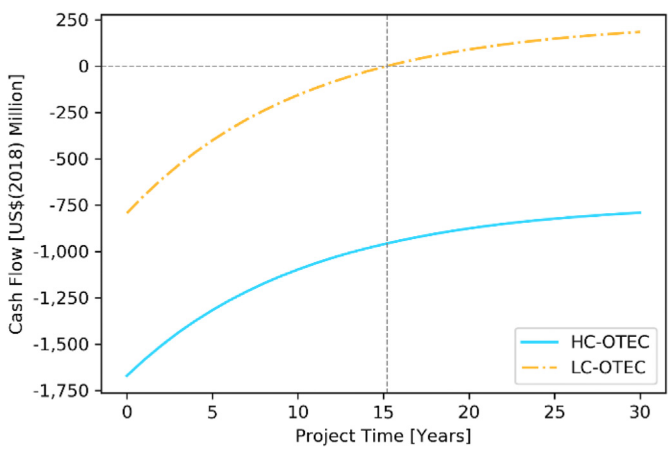

Fig. 6. Cash flow of LC- and HC-OTEC and the economically most favourable site in Indonesia at Namrole, Maluku.

becomes smaller for larger distances. It can also be seen that there are many suitable sites for OTEC deployment within 100 km from shore, which is in agreement with previous works [33]. Between the LCOE and temperature, the correlation is not as prominent. The general trend of the LCOE points downwards with rising temperature difference, but even at a difference of 24.5 °C, the LCOE within Indonesia can vary between around 20 and 60 US$ct.(2018)/kWh for LC-OTEC and between around 30 and 80 US$ct.(2018)/kWh for HC-OTEC. Hence, Fig. 7 indicate that the positive effects of a higher seawater temperature difference on the real power output as frequently discussed in OTEC literature [11,12,14] could be hampered by a large distance from plant to shore and the resulting increases in cable costs and transmission losses.

Fig. 8 shows the average (n = 1021) sensitivity of the seven parameters used to calculate the LCOE. The dashed bars show the sensitivity of a parameter if it is increased by +20%; the hatched ones for parameters that are decreased by −20%, respectively. The sensitivity analysis revealed the capacity factor to be a peculiar parameter due to its inverse, asymmetrical behaviour. If it is decreased by −20% (from 91.3 to 73.0%), the LCOE increases by 25%. The capacity factor's asymmetry can be explained by its upper limit of 100% (representing non-stop operation throughout the whole year), which can be already achieved by an increase of capacity factor by +8.7%. The strong sensitivity of the LCOE to the capacity factor shows that, similar to coal and nuclear power, OTEC would need continuous operation to be profitable and its downtime must be minimised. However, experimental data showed that an availability of 92.3% can be practically possible with a modular system design using multiple power units [58]. Two other relatively sensitive parameters are CAPEX and discount rate as already indicated above in Table 6 and Fig. 6.

Two striking details of Fig. 8 are (1) the differences in sensitivity for temperature difference between LC- and HC-OTEC and (2) the relatively small sensitivity of distance to connection point. The first

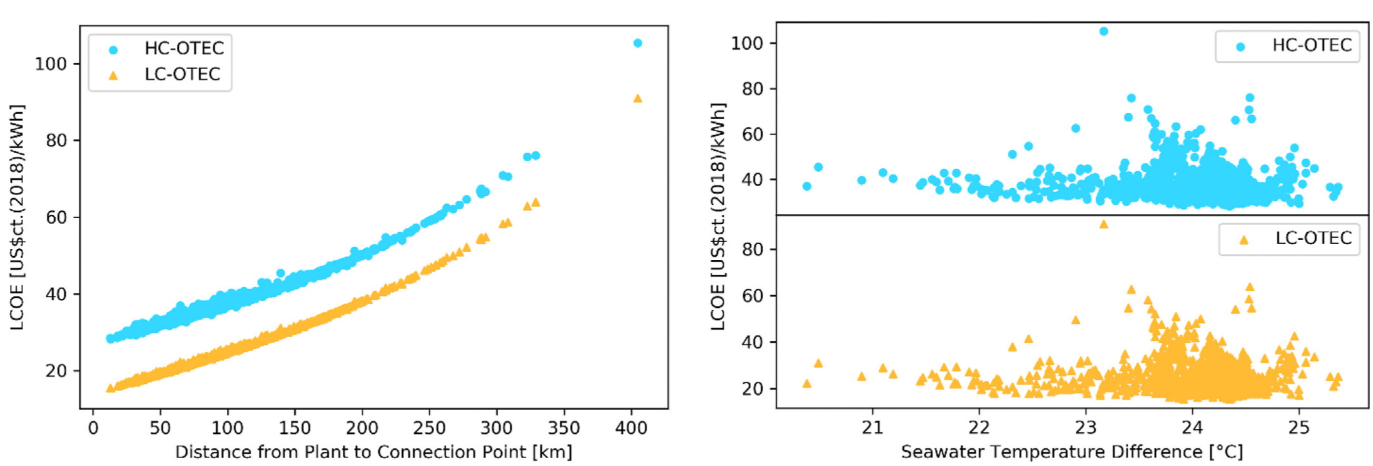

Fig. 7. Correlation between LCOE and distance from plant to connection point (left) and seawater temperature difference (right).

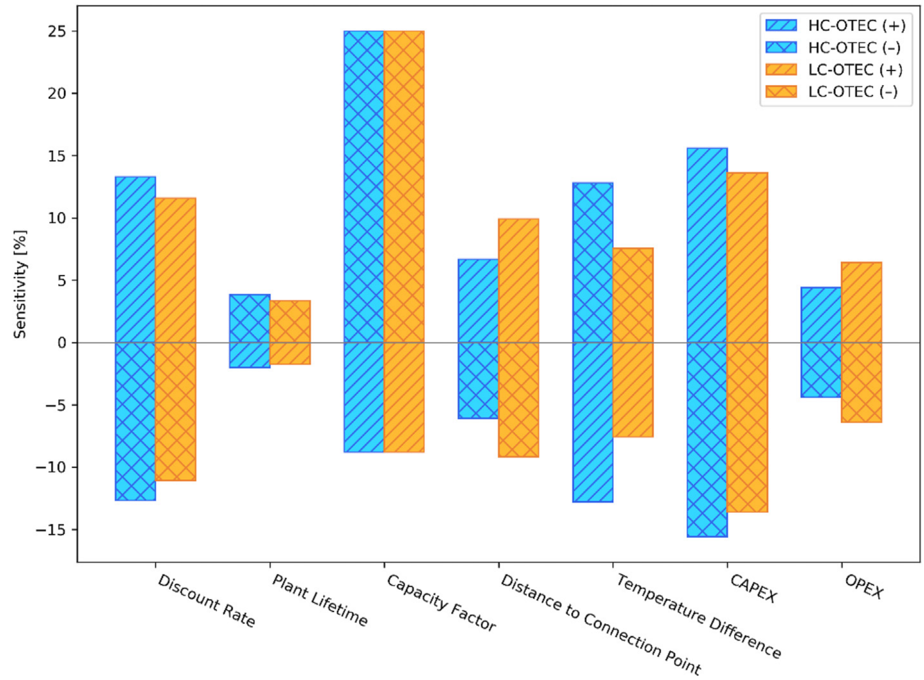

Fig. 8. Average (n = 1021) sensitivity of LCOE parameters.

stems from the differences in cost assumptions, where temperature-dependent components like heat exchangers take up a larger proportion of total costs for HC-OTEC than for LC-OTEC (19% vs. 14% of total CAPEX for the most favourable site in Table 6). The second point can be explained by the siting of the OTEC plants. For most sites the connection distance is relatively short due to the large number of available connection points and the restrictions set by the maximum water depth, as sites further away from shore tend to exceed the maximum depth of 3000 m, and were thus removed from further analysis. Shorter distances have less impact on the LCOE due to lower costs and transmission losses, resulting in a lower sensitivity.

Fig. 9 shows the sensitivity of the nationally uniform FIT and discount rate on the economic potential of OTEC in Indonesia. For the former, the locally varying PPA tariff was replaced by a homogeneous FIT applicable nationwide. When increasing the national FIT, the economic potential of OTEC rises sharply. For instance, if the FIT equals to 18 US$ct.(2018)/kWh, similar to the current local PPA tariff at Namrole, Maluku, the economic potential of LC-OTEC would be 5.2 GW_e, more than double the potential with a locally varying PPA tariff. Another peculiarity is that HC-OTEC's economic potential still remains zero even at a high FIT of 26 US$ct.(2018)/kWh, while LC-OTEC's economic potential would be 61.9 GW_e at such a FIT.

Regarding the sensitivity of the discount rate, the FIT was reset to the locally varying PPA tariffs and only the discount rate was changed. HC-OTEC's economic potential exceeds zero for discount rates smaller than 4%. In the case of LC-OTEC, a discount rate of 10% results in a relatively small economic potential compared to a potential of up to 40.4 GW_e for a discount rate of 2%. This backs up the insights gained from the cash flow analysis in Fig. 6, as a high discount rate devalues future cash flows stronger than a low one. Therefore, its choice affects the results of economic analyses tremendously.

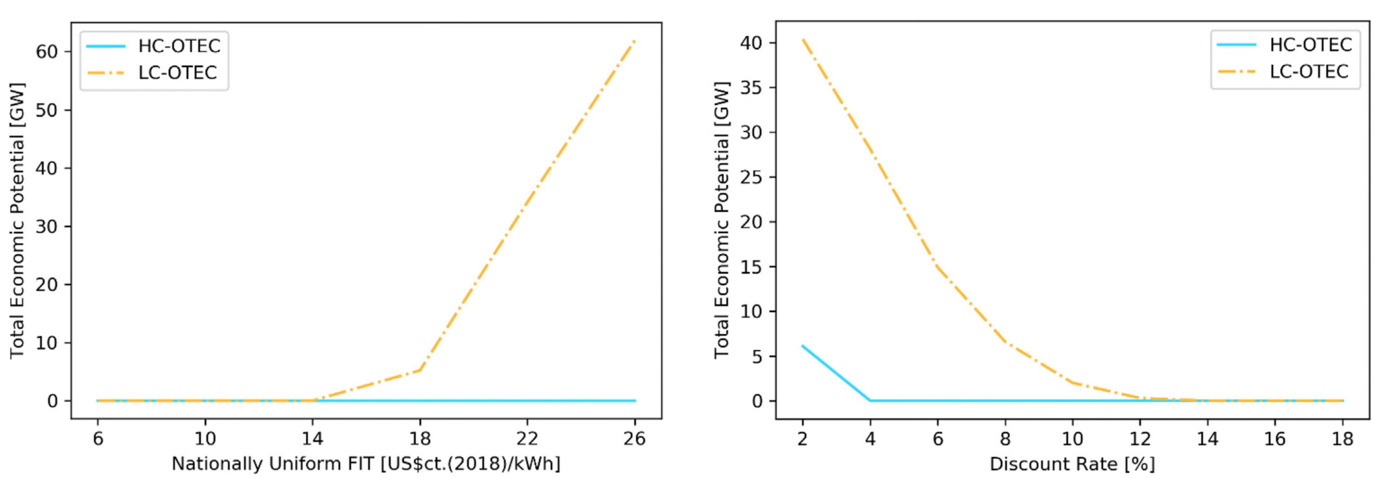

Fig. 9. Sensitivity of economic OTEC potential in Indonesia.

5. Discussion

5.1. Validity of results

Regarding the validity of the results presented here, a minimum LC-LCOE of 15.6 US$ct.(2018)/kWh in Maluku is in line with another study, in which a LCOE was calculated of less than 18 US$ct.(2010)/kWh (or 20 US$ct.(2018)/kWh) in Hawaii with a similar discount rate, capacity factor and distance to shore [11]. The differences between the two locations might be explained by a higher seawater temperature difference in Maluku, leading to lower CAPEX and OPEX due to smaller heat exchangers, and by the assumed time-span of 30 years here instead of 15 years there. The HC-LCOE of 28.5 US$ct.(2018)/kWh shown here harmonises with a LCOE of a comparable case study of 17.7 US$ct.(2010)/kWh or 26.7 US$ct.(2018)/kWh if adjusted for the assumptions in Table 4 [36]. A range of 15.6−28.5 US$ct.(2018)/kWh is also in good agreement with the estimation of the International Energy Agency, who estimate a LCOE of 15−25 US$ct.(2014)/kWh for a 100 MW plant at 10% discount rate [65]. In Table 6, it was shown that the OTEC plant at the economically most favourable site produces 797 GWh per year, which is considerably lower than the 1200 GWh calculated in another study [38]. This is explained by the choice of heat exchanger design as elaborated in section 3.1.3, where the heat exchangers were adjusted to maintain a real power output close to the nominal value. In contrast, the heat exchangers in Ref. [38] cover a wide range of seawater temperature differences and thus allow for a real power out far beyond the nominal output. Regarding the sensitivity analysis, this paper confirms the stronger sensitivity of the discount rate compared to the plant's lifetime [40]. However, the outstanding sensitivity of the capacity factor on the results has hitherto not been quantified in OTEC research and requires validation.

5.2. Limitations of the methodology

A first limitation is that the study sheds limited light on the practical costs of OTEC, leading to a wide range in the economic potential. Therefore, the results presented here merely offer a rough indication of what OTEC's economic potential might be once cost estimations are specified. Furthermore, cost components like (1) deployment & installation as well as (2) platform & mooring are simplified as constant here, although they might vary with location in practice. Regarding (1), it would require a deep understanding of Indonesian infrastructure, supply chains and other localised factors for a more detailed assessment, which would add additional complexity to the methodology. Regarding (2), the assumption of constant platform costs is adapted from literature, while mooring costs only entail a relatively small proportion of the total CAPEX and its variation seems unjustified in this context [36].

Second, the distances between plants and connection point are merely linear distances, excluding the cable duct from plant to grid connection along seabed and shore. The actual cable length should be longer than assumed. Since the most profitable OTEC sites found in this study are relatively close to their connection points, the implications of longer submarine cable lengths on the LCOE should be moderate. A counteracting effect on the power transmission costs might be the assumption that submarine cable costs also apply to the onshore sections from shore to connection point. However, these costs are presumably lower in practice, since regular onshore transmission lines would be used there.

Third, the results of this study depend on the accuracy of the HYCOM model from which the seawater temperature data was retrieved. Since the power output of an OTEC plant increases with the seawater temperature difference [11,14], slight variations between simulated and practical values might affect the plant's economics. Nevertheless, the HYCOM data still provides an adequate foundation for an initial evaluation of OTEC's economics. Moreover, the data used here merely represents average temperatures between August 2013 and November 2018, not taking into account seasonal fluctuations that would affect the effective power production as shown in Ref. [34]. Although the inclusion of water depth for OTEC siting is a novelty of this paper, other natural influences like surface and deep-sea currents, waves, salinity, and others were left out. If these influences were considered too, the number of suitable OTEC sites would become more refined.

Fourth, the exclusion of the EEZ is another limitation from a socio-political perspective. The intention was to perform an economic analysis of OTEC on a provincial level, followed by their aggregation to obtain a national economic potential. Since the EEZ does not distinguish between provincial sea borders, this approach was not possible. Especially for provinces like Papua, Fig. 4 shows how the omission of the EEZ led to the exclusion of many potentially suitable OTEC plants relatively close to shore beyond the provincial border.

Fifth, the economic potential calculated here does not take into account cost reductions via technological learning. Instead, 100 MW_e OTEC is assumed to be implemented overnight assuming current knowledge, experience and costs. However, OTEC would first have to be piloted starting with small prototypes, followed by a continuous process of upscaling. By the time OTEC is scaled up, both CAPEX and OPEX of OTEC might get significantly reduced due to technological advances, expanded global networks and accumulated experience. In this regard, under current conditions an economic potential of 2 GW_e serves as a motivation to develop OTEC to full scale, as the resulting cost reductions might encompass even a larger economic potential. The inclusion of learning-induced cost reduction might also improve the currently limited profitability of HC-OTEC, which includes significant cost contingencies due to OTEC's first-of-its-kind character.

Lastly, the analysis performed does not reflect practical market conditions, as the electricity demand at OTEC connection points as well as competing suppliers are omitted. Economically weaker provinces like Maluku might benefit from an oversupply of electricity from large-scale OTEC, boosting its socio-economic development. However, as such development might take years or even decades, 100 MW_e OTEC as proposed in this paper might not be adequate for these regions yet. Considering the importance and necessity of quasi-continuous operation for OTEC's profitability, its supply and demand should match. Furthermore, OTEC's economic potential must be evaluated against other baseload renewables like hydropower or geothermal, as OTEC would have to compete with these more mature alternatives in Indonesia.

Considering these limitations, the methodology suggested here should not be seen as a replacement for a thorough feasibility study, but instead as a pre-assessment tool to reveal interesting sites suitable for a more detailed analysis.

5.3. Implications

Revisiting the energy trilemma mentioned in the introduction, this study shows that OTEC is an promising technology to improve energy security, energy poverty and climate change mitigation simultaneously in Indonesia. Regarding energy security, domestically produced electricity from OTEC up to 16 TWh per year might help Indonesia to become less dependent on fossil fuel imports and enables a renewable baseload power on the long-term. OTEC might also make a considerable contribution to fight energy poverty, as most of the economically favourable OTEC sites are situated in Maluku, one of the economically weaker provinces in Indonesia in terms of their gross domestic regional product [66]. Regarding climate change mitigation, the spacing of plants was designed to limit detrimental effects like thermal degradation of an otherwise relatively environmentally friendly energy technology. However, a denser spacing of plants might be possible, although this requires a better understanding of local oceanic flows [63]. Hence, this study shows that OTEC might be a promising option for the Indonesian government to reach their energy transition goals on the long term.

Next to evaluating OTEC based on current renewable energy policy, the insights presented here could be considered for new energy policies, i.e. the introduction of national FIT instead of regional PPA tariff. Returning to the 57, 52 and 43 GW of theoretical, technical and practical OTEC potential in Indonesia as mentioned in section 2.2, these potentials could be achieved economically with a national FIT of around 26 US$ct.(2018)/kWh. A uniform FIT could also aid in spreading OTEC to further regions with high electricity demand like Bali and the provinces on Java, where current PPA tariffs tend to be relatively low and not adequate for OTEC funding [56].

On a global scope, this study shows that OTEC could be an interesting investment option for socio-economic development. As Fig. 9 illustrates, OTEC's potential rises sharply with the reduction of the discount rate. If the discount rate represents the interest rate of a concessionary loan such as from the Asian Development Bank, countries like Papua New Guinea, Timor-Leste and Palau could potentially finance OTEC at an interest of 2% [67] and thus face the opportunity to tap their respective economic OTEC potentials at large scale.

6. Conclusion

As a first-of-its-kind study this paper proposed a methodology to roughly estimate the economic potential of closed-cycle OTEC within any regional scope. By considering natural influences like seawater temperature difference, water depth and distance from shore to populated grid connection points, economically favourable sites and their economic performed can be investigated. The methodology was applied to determine the economic potential of 100 MW_e OTEC in Indonesia. It shows that the economic potential spreads over four provinces within an aggregated range of 0–2 GW_e with an annual electricity production of 0–16 TWh. For the economically most favourable plant, a LCOE of 15.6 US$ct.(2018)/kWh was calculated at a discount rate of 10%. Since Indonesia is one of the most promising countries for OTEC, this paper could serve as a motivation to analyse other countries too, especially in Pacific and Caribbean waters. However, both CAPEX and OPEX must be optimised to avoid the HC-scenarios shown here, as no economic potential could be calculated for HC-OTEC even for high nationally uniform FIT. Furthermore, achieving a maximum operational availability above 90% under extreme marine and submarine conditions can be ambitious, but not impossible, given the current state of development.

The results of this study contribute to the OTEC research field by refining the global potential beyond technical levels as currently reported in the academic literature. This methodology might serve as a quick-scan tool to indicate promising regions, followed by a more elaborate and complex analysis to further specify OTEC's profitability. As the latter step cannot be provided by this methodology yet, it would benefit from further development and expansion, i.e. by adding seasonal temperature fluctuations and sea currents. Other shortcomings of this study include the simplification of certain cost components like power transmission and installation, which could be further specified too.

This study builds upon previous academic and industrials works on OTEC economics [11,36,40,58,68]. With the methodology proposed here, OTEC can be assessed beyond the technical potential, taking into account its profitability at economically optimal sites, and the maximum water depth when mapping OTEC's potential. As Figs. 3 and 5 show, a considerable proportion of otherwise suitable OTEC sites is filtered out if technical limits of mooring lines are considered.

Considering the development of other technologies like solar PV and onshore wind, OTEC's role in the global energy transition must be clarified. If it is ought to be implemented by private stakeholders, policy makers must provide adequate support mechanisms to boost OTEC's competitiveness at least at early stages of development, i.e. via national FIT of more than 20 US$ct.(2018)/kWh. If OTEC projections ought to be deployed by public actors, OTEC's contribution to society might have to go beyond electricity generation. Especially in socio-economically disadvantaged regions, OTEC might provide many development-enhancing applications like freshwater production, cooling and mariculture [11,13]. Combining such use cases with the outlook of clean, locally produced electricity, OTEC might be a promising gateway for Indonesia and many other countries to tackle their energy trilemmas.

7. Recommendations

It is noted that the implementation of pilot plants and the collection of practical data is deliberately not included here, since these recommendations were already stated in previous studies [11,14]. Nevertheless, several recommendations can be given in line with the *Recommendations* step.

1. Application and refinement of methodology with further case studies

This paper only estimated the economic potential of OTEC in Indonesia. However, there are myriad other countries with vast practical potentials, especially in Pacific and Caribbean waters. Therefore, OTEC's economic potential should be studied for many more regions to span a global network of economically favourable sites. Besides electricity production, the methodology presented here could be expanded to include other promising applications like freshwater production and cooling.

2. Assessment of different policies for OTEC development

Fig. 9 shows that a nationally uniform FIT of more than 18 US$ct.(2018)/kWh could boost OTEC's economic potential considerably compared to the existing, regionally varying PPA tariffs. Therefore, it is recommended to dive deeper into this topic and to analyse policy instruments like FIT, auctions, subsidies, tax deduction and others for OTEC development. It could be assessed what types of policies can stimulate and facilitate OTEC development, whether they should also target other energy technologies and what costs these entail for public and private stakeholders. With regards to the first recommendation above, a rough sketch for an international OTEC fund could be conceived.

3. Development of upscaling scenarios with learning effects

As mentioned in section 5, upscaling and technological learning are excluded in this study. Therefore, large-scale OTEC might be considerably cheaper than presented here, taking into account the gradual emergence of standardised production processes, knowledge hubs and international networks. Upscaling scenarios with learning effects might create visions and roadmaps of how OTEC might be commercialised and what rates of cost reduction are needed for OTEC to reach maturity. As OTEC's development to maturity would not only take place in Indonesia, a global network of economically promising sites as mentioned in the first recommendation above might help to lift these upscaling scenarios to a global level.

4. Evaluation of OTEC's market potential

Under practical terms, OTEC would have to compete against other baseload renewables like hydropower and geothermal. The conditions under which OTEC might claim market shares against competitors could be studied. This might be achieved by determining OTEC's profitability for multifunctional use, such as freshwater and hydrogen production, cooling or mariculture [14]. The combination of these applications is a unique selling point of OTEC, thus providing reasons for its implementation beyond clean electricity production.

Author contributions are as follows

Jannis Langer: Conceptualization; Data curation; Formal analysis; Investigation; Extension of Methodology; Writing – original draft, Aida Astuti Cahyaningwidi: Conceptualization; Data curation; Formal analysis; Investigation; Original Methodology; review & editing, Charis Chalkiadakis: Original Methodology; Validation; review & editing, Jaco Quist: Contributions to methodology; Supervision; Validation; Writing – review & editing., Olivier Hoes: Contributions to methodology; Supervision; Validation; Writing – review & editing., Kornelis Blok: Contributions to methodology; Supervision; Validation; Writing – review & editing.

Data availability

The dataset related to this article can be found under the DOI 10.4121/13606559, hosted at the repository 4TU.ResearchData [69].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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