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Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda

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ABSTRACT

Ocean thermal energy conversion (OTEC) is a *Renewable Energy Technology (RET)* with a global theoretical potential of up to 30 TW. However, OTEC's economic potential is unknown as it is still an immature technology with no commercial plant operating. This paper reviews recent academic and industrial literature since 2005 to provide an overview and critical discussion of current practices in assessing OTEC's economics. Seven knowledge gaps are identified; (1) Current economic analyses focus on individual plants instead of the collective economic potential within spatial boundaries; (2) Natural, location-specific influences on the real net power output are mostly omitted. There is uncertainty about (3) the capital costs on both system and component level as well as the (4) operational costs and properties like useful lifetime. (5) The impact of interest rates and its selection are often not argued for in literature. (6) Technological learning is predominantly omitted in OTEC literature and if treated, it deviates from insights on technological learning. (7) Economic analyses are mostly limited to the *Levelized Cost of Electricity* (LCOE), while other tools like payback period and *Internal Rate of Return* (IRR) are neglected. These shortcomings originate mainly from the lack of experience and long-term operational data. For each knowledge gap a recommendation for future research is proposed resulting in a research agenda on OTEC and its economics.

1. Introduction

Ocean Thermal Energy Conversion (OTEC) is a *Renewable Energy Technology* (RET), which utilises the temperature difference between warm surface water and cold deep sea water to generate steady electricity free of hazardous emissions [1,2]. In recent years, simulations resulted in a global theoretical OTEC potential of up to 30 TW [3]. The technical potential varies between 3.4 and 10.0 TW within literature. However, commercial OTEC does not exist yet, although many countries meet its stringent oceanographic and climatic requirements [4]. Instead, there are some pilot plants with power outputs ranging between some kW and 1 MW at locations like Hawaii, Nauru and Martinique [5–7]. Besides technical and administrative roadblocks [7–9], OTEC also faces major economic barriers that have not thoroughly addressed in contemporary OTEC literature [4]. Consequently, the economic potential of OTEC is unknown. Due to the absence of commercial experience, cost reducing mechanisms like technological learning are rarely treated either. However, if OTEC becomes successful, it can provide baseload power to tropical regions with sufficient seawater temperature differences, contributing to renewable energy transitions there. In particular *Small Island Developing States* (SIDS) could benefit from successful OTEC development, but its economics still raise major issues.

This paper aims to contribute to this by providing an overview of the current state of OTEC economics. A literature study is conducted to review how and to what extent OTEC economics have been assessed between 2005 and 2019 within academia and industry, including cost reducing learning effects. Additionally, the reviewed content is compared and discussed critically to reveal representative studies, methodological shortcomings and knowledge gaps. OTEC's competitiveness against other energy technologies based on the *Levelized Cost of Electricity* (LCOE) is contrasted as well. By only considering recent literature since 2005, this study differs from other existing reviews on OTEC economics [2,9–11] that also include studies from the last century, while our study also includes the most recent studies until the end of 2019. Moreover, while existing reviews on OTEC economics compare factors like costs, plant size and type of plant, this paper aims to dive deeper and reviews additional economic inputs like interest rates, plant availability and annual real power output. Consequently, the paper contributes to contemporary OTEC research by offering a more

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List of abbreviations

Abbreviation Meaning Unit (if applicable)

β	System-Specific Coefficient MW/(m^3/s)
CAPEX	Capital Expenses US$
CC	Closed-Cycle
CRF	Capital Recovery Factor %
CWP	Cold Water Pipe
E_t	Annual Electricity Production kWh
FCR	Fixed Charge Rate %
HINMREC	Hawaii National Marine Renewable Energy Center
i	Interest Rate %
IRR	Internal Rate of Return %
LCOE	Levelized Cost of Electricity US$/kWh
N	Project Lifetime yr
OC	Open-Cycle
O&M	Operation & Maintenance % of CAPEX or US$/yr
OPEX	Operational Expenses % of CAPEX or US$/yr
OTEC	Ocean Thermal Energy Conversion
P_{Loss}	Power Loss MW
Q_{CW}	Cold Water Flow Rate m^3/s
RET	Renewable Energy Technology
SIDS	Small Island Developing States
ΔT	Temperature Differential 1
WACC	Weighted Average Cost of Capital %

comprehensive overview of current practices in assessing OTEC's economics. A critical discussion as well as the detection of knowledge gaps might provide a motivation for broader and deeper investigations to gain a better understanding of OTEC's potential under more practical conditions. This study does not review technical or ecological aspects of OTEC, since these aspects have already been covered in several other overviews [2,4,11,12].

The paper is structured as followed. Section 2 elaborates the methodology of the literature review, including the (1) collection, selection and evaluation of current publications and the (2) assessment of the economic potential of RET. Then, section 3 presents the results of the literature study. Subsequently, section 4 discusses the gathered information critically, leading to the identification of seven knowledge gaps. After that, a conclusion section summarises the insights presented in this paper. Finally, section 6 provides recommendations on how future research might tackle the identified shortcomings.

2. Methodology

2.1. Obtaining and selecting literature

To obtain contemporary OTEC literature, search engines like Science Direct, Scopus, Google and Google Scholar have been used. Search terms include "economic potential", "economics", "Ocean Thermal Energy Conversion", "OTEC", "renewable energy", "energy" and combinations of the mentioned expressions. Snowballing was also applied with two iteration cycles. Further iterations did not yield additional references that met the two inclusion criteria, namely: (1) Included studies must be written in English language and (2) studies should not be older than 15 years, thus published between 2005 and 2019. However, if the findings of older publications are referred to in at least two independent contemporary studies, they are perceived as still relevant today and included in this review. Besides papers in peer-reviewed journals, publications like non-peer-reviewed conference papers and master theses have also been considered with close attention to the validity of their contents. Industrial publications by companies associated with OTEC were either retrieved from their websites or, if their research was financed by national grants, from the online archives of the departments that granted the funds, for instance the U.S. Department of Energy.

Even though there are also other potential revenue sources of OTEC as mentioned in section 3.1, the literature study in this paper is limited to power production due to its high coverage in OTEC research. Furthermore, studies about hybrid OTEC systems with additional side systems like solar PV or hydrogen storage are included, but only occasionally discussed in detail due to limited comparability with pure OTEC systems. To compare the cost estimations and results within literature, all currencies are converted to US$ (2018) using the CPI inflation calculator and Statista Online Database. If the time value of a currency is not known, the value of the year of publication is assumed.

In total, 49 publications were collected, with 32 selected for further review based on the criteria above. Among the selected sources 17 case studies could be extracted. These cases provide the backbone for the evaluation of OTEC economics as outlined in the next subsection. Each of the case studies is evaluated for representativeness, based on the criteria (1) valid system designs and methods, (2) comprehensiveness and transparency of technical and economic assumptions, (3) congruency with other, independent studies.

2.2. Levelized Cost of Electricity

In 14 of the 17 case studies, the *Levelized Cost of Electricity* (LCOE) is calculated to assess the economics of OTEC. The LCOE is the minimum average price at which electricity needs to be sold to reach parity with all expenditures of a project at the end of its useful lifetime [13,14]. It can be computed using equation (1) below.

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

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

CAPEX: capital expenses.
OPEX: operational expenses.
E_t: produced electricity in year t.
CRF: capital recovery factor.
N: project lifetime
i: interest rate.

Equation (1) can be expanded on both cost and revenue side with components like financial costs, taxes, system degradation among others. Based on the LCOE, the economic potential of RET niches can be determined, i.e. by modelling regional [15], national [16] or global [17] cost-supply curves. The next section of this paper scrutinises the extent of how the LCOE is applied in OTEC literature. Therefore, every input of equations (1) and (2) is addressed by an individual subsection, namely capital expenses (3.3), operational expenses (3.4), project lifetime (3.5), interest and discount rates (3.6) and annual real power output (3.7). The coverage of the impact of learning effects on the LCOE in literature is also covered (3.8).

3. Current literature on OTEC economics

3.1. Markets for and possible commodities by OTEC

OTEC could penetrate distinct markets in the future, especially in Pacific, Caribbean, Central American and African regions. While large-scale OTEC with a net power output of at least 50 MWe are most suitable for large tropical maritime countries for power production, SIDS are eligible for small-scale plants of 1–10 MWe with additional functions like freshwater production via desalination [2,4]. Other possible use cases of OTEC encompass seawater air conditioning, cultivation of maritime species and the production of hydrogen [18,19]. Concerning the latter, previous works revealed the technical feasibility of the concept, albeit its economic competitiveness depending on noticeable increases of fossil fuel costs to about 400 $US (2010)/barrel [20]. Business cases for the applications above comprise research facilities like Ocean Technology Ecoparks [18]. Notwithstanding, contemporary OTEC literature predominantly focusses on power production.

3.2. Scope of economic analyses in OTEC literature

Currently, the economic analysis of OTEC has been limited to individual models without the consideration of the OTEC sector as a whole. Some academic and industrial publications specify the reference location of their model plants, i.e. Puerto Rico [21], Hawaii [2,20,22–24], Florida and Guam [23], as well as Nigeria [25], Iran [26] and South Korea [27]. Out of the 17 case studies, nine do not specify the location of their OTEC model. Moreover, there are currently no studies on the collective economic potential of OTEC on regional, national or global levels.

In general, most LCOE calculations are kept at a basic level as shown in equation (1) and provide indications of an OTEC plant's potential profitability [2,25,28,29]. Regarding industrial research, the U.S. company Lockheed Martin offers a more detailed calculation of the LCOE, addressing aspects like corporate and project finance [23]. Some key results of the literature study are summarised in Table 1 below.

Other economic assessment tools like the payback period or *internal rate of return* (IRR) find little attention in OTEC literature. The IRR was not calculated in any of the reviewed cases. A payback period is only calculated in two studies, one comprising twelve years for a 100 MWe OTEC plant [25], the other being around eight years for a 1.6 MWe OTEC-PV-Hydrogen hybrid plant [26]. These values will be discussed in section 4.2.

3.3. Capital expenses

There is consensus in literature that *Capital Expenses* (CAPEX) are a major roadblock for the development of OTEC [2,28,30]. Generally, OTEC's cost components can be divided into seven categories, namely (1) platform and mooring, (2) power generation, (3) heat exchangers, (4) water ducting, (5) power transfer, (6) deployment & installation and (7) others [9,10]. However, when estimating CAPEX of OTEC, academic scholars preferably regard to total system instead of individual

Table 1
State of the art of case studies on OTEC economics (ordered by ascending power Output; F: Floating, L: Land-based, CC: Closed-cycle, OC: Open-cycle, H: Hybrid).

Reference	Plant Location	Plant Type	CAPEX [mil.]	OPEX [% CAPEX/yr]	Plant Size [MWe]	**LCOE [curr./kWh]**	LCOE [US $(2018)/kWh]	Interest Rate [%]	Lifetime [yr]	Availability [%]	ΔT [°C]	Representative?
[27]	South Korea	L, CC	0.248 US$ (N.A.)	7	0.02	0.363	0.38	5	20	91.3	21.3	No, cost composition missing
[26]	Iran	N.A, CC	2.38 US$ (N.A.)	26	1.6	0.096	0.094	7.5	25	N.A.	22	No, unvalidated system design and cost estimations
[32]	N.A.	L, CC	37.78, 33.37 (€ (N.A.))	3.3	2.35	0.269, 0.237	0.30, 0.26	9.4	30	91.3	24	No, unvalidated cost estimations
[22]	Hawaii	F, CC	133.46 US$ (2011)	–	2.5	–	–	–	–	–	21.6	Yes
[33]	N.A.	F, CC	123.1 € (2013)	2–3	10	0.19	0.23	8	30	95	22.0	Yes
[9]	N.A.	F, CC	144–553.4 US$ (2009)	5.2–5.7	20	0.13–0.65	0.15–0.76	10	20	70–90	22.0	Yes
[29]	N.A.	F, N.A.	110 € (N.A.)	1.4	50	0.04	0.07	8–10	30	90	70.0–100.0	No, unvalidated system design and cost estimations
[20,24]	Hawaii	F, CC, OC	451, 551 (US$ (2010)	4.5, 4.2	53.5, 51.25	0.188, 0.07–0.15	0.209, 0.078–0.167	8	15	92.3	20.0	Yes
[21]	Puerto Rico	F, CC	600 US$ (N.A.)	–	75	0.15	0.18	–	30	100	>20.0	No, references for cost estimations missing
[2]	Hawaii	F, CC	780 US$ (2010)	5	100	0.18 0.14	0.20 0.16	8, 4.2	15, 20	92.3	20.0	Yes
[25]	Nigeria	F, CC	795 US$ (2015)	2	100	0.11	0.12	13	25	100	24.0	No, unvalidated results
[28]	N.A.	F, H	420 US$ (N.A.)	1	100	0.07	0.08	10	30	N.A.	21.5	No, unvalidated system design and cost estimations
[10]	N.A.	F, CC	1.400 US$ (2010)	3.2	100	0.194	0.22	7.4	30	95–97	N.A.	No, partly unvalidated methods
[31]	N.A.	F, CC	128.8 £ (N.A.)	1.5	100	0.029	0.03	8	30	80	20.0	No, unvalidated cost estimations
[30]	N.A.	F, CC	420, 265 (US$ (N.A.))	–	100	–	–	–	–	–	–	No, unvalidated system design and cost estimations
[34]	N.A.	F, CC	400 US$ (N.A.)	8.8	100	–	–	–	30	95	25.0	No, unvalidated system design and cost estimations
[23]	Hawaii, Guam, Florida	F, CC	1.506, 2.494, 4.044 (US$ (2010))	3	100, 200, 400	0.177, 0.149, 0.122	0.20, 0.17, 0.14	4	30	92	21.4 24.0 20.4	Yes

component costs [25,28,31]. Cost estimations for components of two floating, *Closed-Cycle-OTEC* (CC-OTEC) systems with 53.5 and 100 MWe nominal power output are compared in Fig. 2. In both studies, the main cost categories are (1) platform & mooring with over 25% and (3) heat exchangers with over 20% of total costs, respectively. Regarding (5) power transfer, both plants are relatively close to shore with a distance of around 10 km, resulting in relatively low transmission costs. However, none of the two cases above and only one out of the 17 cases projects CAPEX as a function of the distance from plant to shore due to longer transmission cables [28]. Thus, although the proportions of transmission costs are low in Fig. 2, this might change for OTEC plants further away from shore. Another interesting detail in the illustrations below is the exclusion of category (7) others in one of the case studies. In fact, many works on OTEC economics exclude aspects like project costs and price contingencies related to pilot projects [32]. The reasons for this will be discussed in section 4.3.

When plotting size-specific CAPEX against the nominal power output, scale curves as shown in Fig. 1 emerge. Key insights from the figure are (1) the discrepancies in cost estimations within literature and (2) considerable effects of economies of scale. However, many scholars refer to other publications for their assumptions. For example, the middle curve by Refs. [2] in Fig. 1 is used in Refs. [25], while the costs in Refs. [10] are based on [23]. Additionally, many academic studies draw their cost estimations from sources published in 1992 [2] and 1979 [9].

For a nominal 100 MWe plant, Martel et al. [23] estimate total CAPEX of roughly US$ 1.5 billion (US$ 2010) at the reference site in Hawaii. This exceeds Vega's [2] estimation of roughly US$ 780 million (US$ 2010) for the same capacity and location significantly. Furthermore, some scholars estimate CAPEX for a 100 MWe plant of as low as US$ 242–420 million (US$ 1999, 2009 & 2010), although these estimations occasionally do not provide any references [28,31,34]. Consequently, the considerable differences in cost estimations within the OTEC sector precipitate in the formation of three cost curves, which will be discussed in section 4.3.

3.4. Operational expenses

Operational Expenses (OPEX) comprise the costs of operations, maintenance, repair and replacement of components as well as personnel costs and monitoring. For OTEC, these costs are expected – but not yet proven – to be relatively low compared to CAPEX [2]. A common trait of most representative OTEC studies is the detailed analysis of OPEX in their economic analyses [9,20,23,24]. However, in other studies, OPEX are merely given as either a total value or a percentage of CAPEX, ranging from 1.4% [29], 2% [25], 3–3.3% [10,32,33], 8.8% [34] and even 26% [26], albeit the latter being unvalidated. The variation in OPEX is explained by the lack of practical experience [2].

3.5. Project lifetime

Regarding the operational lifetime of an OTEC plant, there are differences among the 17 case studies independent of representativeness. Nine of them assume a lifetime of 30 years as seen in Table 1. Other, more conservative lifetimes include 15 [20,24], 20 [2,9,27] and 25 years [25,26].

3.6. Interest and discount rates

In most OTEC publications, the LCOE is calculated using a *Capital Recovery Factor* (CRF). As shown in equation (2), the CRF depends on the interest rate and its choice varies significantly among scholars. Mostly, the interest rate is based on national bank loans [2,9,20,24,25], the *Weighted Average Cost of Capital* (WACC) [10,33] or a *Fixed Charge Rate* (FCR) [32]. Only in three cases government bonds are used or suggested [2,20,23,24]. Consequently, the interest rate can vary between 4 and 13% as seen in Table 1. Regarding nominal and real interest rates, there is no clear trend and both options find application.

Only three of the 17 case studies mention the sensitivity of the discount rate explicitly [9,23,33]. Moreover, only Vega [2] evaluates the suitability of chosen interest rate within the context of OTEC and its stage of development. There, the financial assumptions are stated as realistic, but not backed with references. Another peculiarity of that study is the comparison of LCOE for two different interest rates. With an interest rate of 8%, the LCOE is 0.18 US$/kWh, whereas the LCOE is 0.14 US$/kWh when using government bonds at 4.2% (both US$ (2010)). Thus, Vega's [2] study is the only of the 17 cases that compares OTEC's economics for different interest rates. The limitations of chosen discount rates are not discussed in any of the reviewed case studies.

3.7. Annual real power output

Not all of the electricity produced by an OTEC plant can be

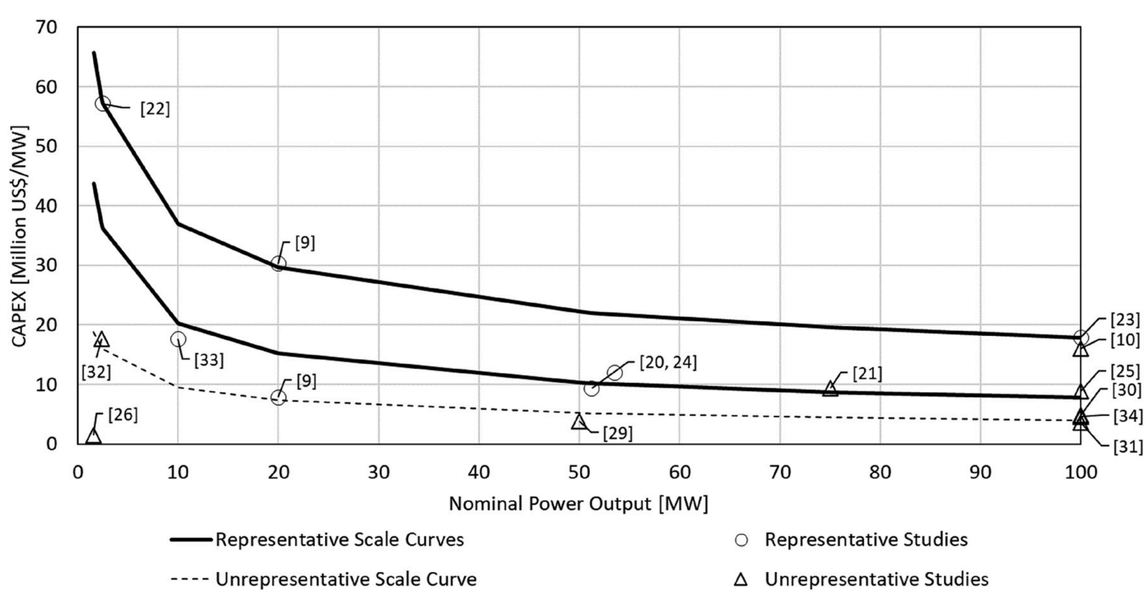

Fig. 1. Scale Curves of OTEC According to Contemporary Literature (Adjusted to US$ 2018). The Scale Factor, the Power by which the Increase of Output Increases CAPEX, is Calculated as 0.69 for the Upper Curve, 0.58 for the Middle Curve [2] and 0.63 for the Lower Curve [35].

Distribution of Cost Components for Floating CC-OTEC in [%] (left 100 MWe, right: 53.5 MWe)		
Reference	[23]	[20,24]
Platform and Mooring	25.5	27.5
Power Generation	3.1	14.2
Heat Exchangers	27.2	21.1
Water Ducting	9.5	18.6
Power Transfer	6.3	9.1
Deployment & Installation	12.0	9.5
Others	16.3	0.0

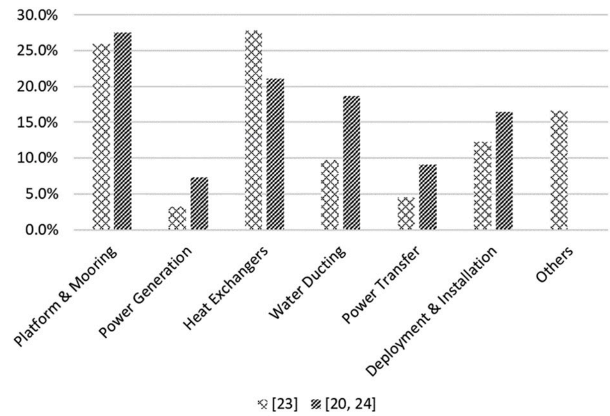

Fig. 2. Coverage of cost components in OTEC literature [20,23,24].

transmitted to the consumer. Instead, around 30% of the gross power is either lost due to inefficiencies or used to drive system components like pumps and compressors [2,24]. But even after subtracting these losses from the gross power output, the real net power output of an OTEC plant can still differ from its nominal name-plate value, depending on the (1) settings of the plant and the (2) external, natural conditions it is exposed to. Regarding (1), a 210 kW *Open-Cycle-OTEC* (OC-OTEC) experimental plant, which operated from 1993 until 1998 in Hawaii, proved that control parameters to regulate power production are among others the flow rate of warm and cold water as well as the compressor subsystem settings for OC-OTEC. For CC-OTEC, the same parameters apply except for the latter, which would be replaced by the working fluid flow rate [2]. Concerning (2), the most important ones are the (i) local temperature difference between surface and deep sea water and the (ii) deep sea water availability around the tip of the CWP [22–24,29,36]. For (i), scholars usually choose fixed temperatures when designing their OTEC model. The sensitivity of temperature changes on the technical and economic results is not explicitly treated. Sea water temperature differences used in literature are summarised in Table 1. Although (ii) poses a great influence on the performance of an OTEC plant as it determines the availability of cold water as a heat sink, it is only mentioned in one academic OTEC study [2]. Albeit considered in industrial reports, the impact of the cold deep sea water availability is researched on a theoretic level and still requires practical validation [36].

Regarding the correlation between seawater temperature difference and real net power output, there are slight differences between industry and academia. In Ref. [36], the correlation was found to be fairly linear with a slope of 13.6 MW/°C. In Ref. [2,24], a relation is established as shown in equation (3).

$$P_{net} = \beta * Q_{CW} * (\Delta T)^2 - P_{loss} \quad (3)$$

β: system-specific coefficient.
Q_{CW}: cold water flow rate.
ΔT: temperature differential.
P_{loss}: power losses.

In equation (3), the net power is proportional to the square of the temperature differential and the cold water flow rate. According to academic literature, a change of temperature difference by 1 °C changes the net power by 15% [2,24]. However, this is slightly inaccurate as it was revealed during the review process of this paper that a value of 10%/°C is more appropriate. Fig. 3 visualises the two approaches described above. There, differences in slopes are visible, as the upper graph converges towards the lower one. However, Fig. 3 does not include variations in system design and chosen flow rates, which also influence the net power output as seen in equation (3). Taking this into account, both approaches are representative for the range of temperature differences shown in Fig. 3.

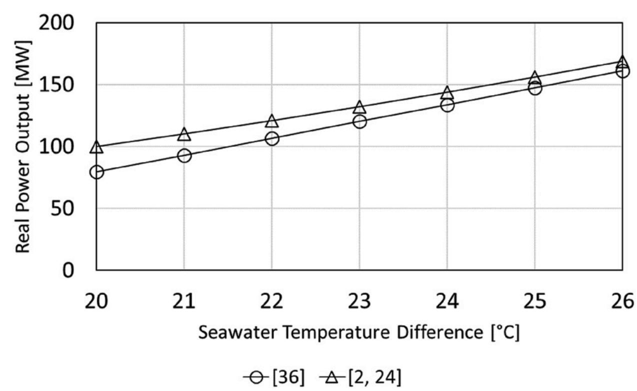

Fig. 3. Correlation temperature difference versus net power output (100 MW_{nom}) [24,36].

Besides the aspects above, the annual real power output of an OTEC plant is also determined by its downtime due to maintenance, overhaul and replacement. The availability of the plant is predominantly set above 90% in OTEC literature. More conservative values are only occasionally chosen, for instance 70 or 80% [9,31].

Another aspect affecting the real net power output are transmission losses through power cables. Cable losses from plant to shore are mostly ignored in academic OTEC research due to the short distances as mentioned above [2,34], or because the plant is land-based and does not require submarine power cables [32]. However, one study did include distance-dependent transmission losses for both 60 kV and 132 kV AC cables [23]. The respective graphs are displayed in Fig. 4.

3.8. Cost reductions via learning effects

In OTEC economics literature, learning effects are predominantly excluded apart from some exemptions [2,20,23,24,37]. Within academia and industry, a learning rate of 7% is generally estimated [23,37] with a total cost reduction potential of 30% of today's CAPEX [2,20,24]. In this regard, Vega [2,20,24] implicitly and Martel et al. [23] explicitly state that cost reductions via learning are finite and converge to an asymptote after the 4th or 5th doubling of installed power output as shown in Fig. 5. The limited potential for learning is justified by the maturity of many OTEC components, such as turbines and generators, which benefit from the experience from other sectors like shipbuilding, petroleum and utility engineering [2,23,37]. Within academia, no work on learning curves of OTEC could be found. One case compares the investment costs of a 2.35 MWe OTEC plant for a base and a cost reduction scenario. In the latter, it is scrutinised how the LCOE of the plant changes

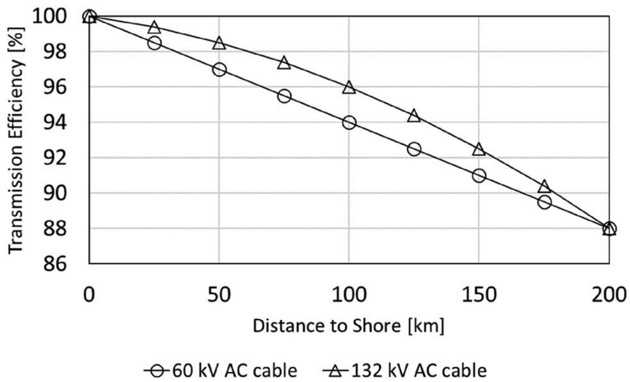

Fig. 4. Transmission efficiency versus distance to shore [23].

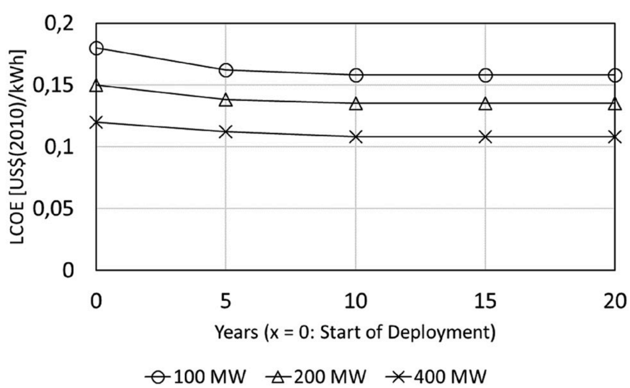

Fig. 5. Learning curves for 100, 200 and 400 MW OTEC [23].

due to a decrease of the costs of heat exchangers and the CWP by 15 and 30%, respectively. However, learning is not explicitly mentioned as the reason for these cost reductions, but instead development of these partly early-stage components [32].

The claims concerning learning effects and cost reduction potentials in OTEC literature are not backed by literature on technological learning. The complications from this are discussed in the next section.

4. Discussion

4.1. Validity of source material

The review of contemporary literature on OTEC economics reveals several shortcomings.

First, there are currently no representative contemporary primary sources on OTEC economics published in peer-reviewed journals. One recently published paper from 2019 provides unprecedented cost estimations, however without mentioning references or methods for acquiring them [26]. Other recent primary sources encompass conference papers, reports and industrial feasibility studies. In most of the selected conference papers, it is stated that the content was not reviewed [11,20,21,34]. For some them, the justification of chosen values are opaque, as these sources either refer to previous works of the same main author, or to no source at all [28,30,34]. As the results of these works except for [20] do not coincide with other OTEC studies, they still need to be validated.

Second, the relevance of references used within contemporary literature can be challenged. Almost every publication reviewed here contains source material from the 20th century, with cost estimations originating from as far as 1979 [9]. Although the monetary values of these estimations are adjusted for modern conditions [2], it remains ambiguous whether they still apply today considering technological progress due to innovation.

Third, it was only possible to retrieve feasibility studies of two companies involved in OTEC. For other companies, it was not possible to trace openly available studies on OTEC economics. Thus, it remains unclear whether the observations made here apply for the whole OTEC industry.

Out of the 17 reviewed cases, six are seen as representative as shown in Table 2. They share a deep level of technical and economic consideration, valid system designs, transparent lists of cost components and tangible insights on operational processes. Especially the works by the *Hawaii National Marine Renewable Energy Center* (HINMREC) and Lockheed Martin offer a valuable foundation for future research on OTEC economics. While there is an equal distribution of academic and industrial studies in Table 2, the focus on closed-cycle, floating systems for electricity production becomes apparent. Only one representative study assesses open-cycle plants with desalinated water as a by-product, while land-based OTEC remains disregarded. Another interesting detail is the distribution of representative studies across difference system sizes, virtually covering all relevant scales. Except for 100 MWe OTEC, there are no two independent studies that cover the same or similar system sizes in their case studies.

4.2. Scope of economic analyses and validity of results

OTEC's economic potential is currently merely assessed for individual models at highly specific locations. Two complications arise from this, both originating from the strong sensitivity of OTEC's technical performance to external natural conditions.

First, the results of the analysis of OTEC's economic potential for individual models are only valid for the chosen location. As the change of external conditions precipitates a change of system size and costs, there is limited room for generalisation. For example, a higher seawater temperature difference leads to smaller and cheaper heat exchangers to maintain the same real power output. Therefore, the insights gained from current OTEC literature do not reflect the collective economic potential across broader spatial boundaries.

Second, the validity of the results of existing economic analyses on OTEC might be distorted by differences in external conditions between the reference material and the case to which it is applied. For example, Oko & Obeneme [25] use the scale curve created by Vega [2] to estimate CAPEX of a 100 MW OTEC plant in Nigeria. However, Vega's [2] research is based on the conditions met in Hawaii. Depending on the different external influences in Nigeria and Hawaii, the changes in system size and cost as elaborated above might lead to different economic results. Moreover, location-based cost factors like submarine cables, transportation and personnel costs are not accounted for. Thus, it remains unclear to what extent the assumptions made in the source material apply in contemporary literature.

It was also found that economic analyses of OTEC mainly focus on the calculation of the LCOE, while mostly leaving other assessment tools

Table 2
Contemporary, representative studies on the economics of OTEC (own illustration).

Reference	Year of publication	Origin	System Size [MWe]	Type of OTEC	Product(s)
[22]	2011	Industrial	2.5	CC, F	Electricity
[33]	2014	Industrial	10	CC, F	Electricity
[9]	2012	Academic	20	CC, F	Electricity
[20,24]	2010, 2014	Academic	53.5, 51.25	CC, OC, F	Electricity, Desalinated Water
[2]	2012	Academic	100	CC, F	Electricity
[23]	2012	Industrial	100, 200, 400	CC, F	Electricity, Ammonia

like payback time and IRR out. For example, a payback period of around eight years as calculated in Ref. [26] foots on unvalidated cost estimations as elaborated in section 4.1. In Refs. [25], a LCOE of 0.11 US$/kWh is compared to the municipal energy price, given as 0.1 US$/kWh and 0.01 US$/kWh. It is unclear, how these municipal energy prices enable a payback period of twelve years, if a LCOE of 0.11 US$/kWh is needed to breakeven with all project expenses after its useful lifetime of 25 years. Hence, both payback periods still need to be validated.

4.3. Choice of CAPEX and scale curves

The results of the review of CAPEX within OTEC economics literature underlines the inherent uncertainty and ambiguity in both academia and industry. The emergence of three possible scale curves in Fig. 1 show that OTEC's capital intensity is difficult to quantify. The costs arising from the lowest and highest scale curve in Fig. 1 can differ by almost fourfold. However, while the upper and middle curve are based on representative studies, the lower curve foots on system designs and/or cost assumptions that are not validated yet within the OTEC research niche. Therefore, only the former curves are seen as representative here. The differences between these two curves might be explained by the inclusion of price contingencies. While the middle curve represents the engineering costs of an OTEC plant, the upper one also considers surplus costs related to the novelty of the project as shown in Fig. 2. After all, rigid supply chains might not be established and organisational processes not standardised yet. Consequently, the middle curve represents OTEC's feasible costs at a more mature level, while the upper scale curve provides conservative cost estimations for pilot projects that should not be exceeded. Regardless, these scale curves are some of the most valuable products of OTEC research, as they show both the potentials and challenges of lifting OTEC to commercialisation. As seen below in Table 3, large-scale OTEC can be cost competitive with fossil fuel and nuclear power plants. But to scale up to such sizes, experience must be gained with smaller, less economic plants.

The differences in cost estimations are not exclusive to the system, but the component level as shown in Fig. 2. When considering the seven types of components enumerated in section 3.3, it was not possible to compare two independent representative studies of the same system size. Even when comparing studies independent of their representativeness, their comparison proves to be difficult due to two reasons. First, most studies only use total system costs. Second, one study blended costs of different plant sizes into one range of possible component costs [10]. The comparability of component costs for varying plant sizes can be limited by the strong effects of economies of scale. Thus, it becomes unclear whether the differences in costs originate from the effects of economies of scale or from inherently lower costs due to other phenomena like learning-by-doing or technological innovation. These shortcomings are acknowledged in regards to Fig. 2, where a 53.5 MWe plant is compared to a 100 MWe plant. But these illustrations merely try to highlight general trends perceived at all system sizes, i.e. the dominance of platform and heat exchanger costs, and to show the impact of the exclusion of other, project related costs.

Table 3
Comparison of OTEC's economic competitiveness to other energy technologies [40]. All LCOE for OTEC were calculated or adjusted using Table 1, Fig. 1 as well as equations (1) and (2) with an interest rate of 12%.

Energy Technology (Unsubsidised)	LCOE [US$(2018)/kWh]
10 MWe OTEC (original interest rate)	0.15
10 MWe OTEC (adjusted interest rate)	0.20–0.67
100 MWe OTEC (original interest rate)	0.03–0.22
100 MWe OTEC (adjusted interest rate)	0.04–0.29
Solar PV Crystalline Utility Scale	0.04–0.046
Wind	0.029–0.056
Gas Peaking	0.152–0.206
Nuclear	0.112–0.189
Coal	0.06–0.143
Gas Combined Cycle	0.041–0.074

Despite the short distances from plant to shore assumed in literature, there are currently no representative studies that project CAPEX as a function of cable costs. This might distort the results on economic analyses if further distances are assumed in future studies. But since the representative studies found here provide estimations on both the distance to the shore and the total cable costs, it is possible to calculate the specific costs of submarine power cables per kilometre and thus extrapolate the costs for any short-to mid-ranged distance.

Regarding the use of total system costs as a proxy for economic analyses, a critical aspect is the extent of inclusion of the seven types of OTEC components listed above. For example, some scholars do not explicitly mention whether the platform and mooring, water ducting and power transmission are considered. The omission of certain cost components might be a reason why the total cost estimates within OTEC literature differ so strongly. Then again, the necessity of certain components also depends on the type of OTEC system, i.e. closed-vs. open-cycle or floating vs. land-based plants. The only representative studies comparing CC- and OC-OTEC showed that the latter type is more expensive, but still fairly close to the middle cost curve in Fig. 1 [2,20,24]. This is because Vega [2] included all plant types mentioned above in that curve. However, there are strong differences in the cost structures of land-based and floating plants, as i.e. the former does not need mooring and submarine cables, but longer water ducting pipes [9,32]. Due to the absence of representative work on land-based OTEC, it is currently not possible to validate the combination of both land-based and floating plants into the middle curve.

Thus, three valuable insights of this review are the (1) importance of transparency when estimating CAPEX of OTEC, the (2) validity of the scale curves for floating CC- and OC-OTEC and the (3) necessity of validating the scale curves for land-based systems.

4.4. Choice of interest and discount rate

When calculating the LCOE, the interest and discount rate can have significant effects on the results [33]. However, its choice is barely argued for in OTEC literature. The assumed values mostly reflect national interest rates on bank loans or notional WACC without empirical justification. Consequently, the rates might not reflect the uncertainty inherent to OTEC, which is a capital-intense technology with no commercial experience. Considering that most of the suitable countries for OTEC deployment comprise SIDS, it is also questionable to what extent factors like political, economic and financial stability are included [14,38,39]. As these interest rates coincide with values found in other RET research fields like PV solar and onshore wind power, it is suggested that all these technologies might entail the same risks despite their differences in constitution, development and application.

By choosing inherently low interest rates, current OTEC studies also disregard the potential of cost reductions due to increasing maturity and experience. Lower risks combined with lower CAPEX due to learning effects could precipitate in lower interest rates, potentially further boosting OTEC's economic prospects.

4.5. Uncertainty in LCOE

All the aspects described above lead to a wide range of possible LCOEs, as shown in Table 3. In this table small- and large-scale OTEC are compared to other energy technologies to show their economic competitiveness. Lazard [40] analysed a wide range of technologies using an interest rate of 12%. To maintain comparability, the LCOE related to OTEC are adjusted for this rate, while using the same inputs as listed in Table 1 for all other variables of equations (1) and (2).

For a 100 MWe OTEC plant, the adjusted LCOE varies between 0.04 and 0.29 US$(2018)/kWh, highlighting the high sensitivity of the interest rate compared to the original range of 0.03 and 0.22 US$(2018)/

kWh. When put into perspective, the range of LCOE for large-scale OTEC implies cost competitiveness against other RET like utility scale solar PV and wind power, if low cost estimations hold true. It could also compete with conventional energy technologies like nuclear, coal and natural gas. By contrast, the cost competitiveness of 10 MWe OTEC is rather limited against other technologies. Especially against solar PV and wind, small-scale OTEC is not competitive and would need financial support to thrive. Under the light of current uncertainty, it is not possible to make a distinct statement concerning OTEC's economic competitiveness.

4.6. Technological learning

Within OTEC literature, a learning rate of 7% is vindicated by observations made in similar fields like petroleum and utility engineering [2,23,37]. Notwithstanding, this rate is not backed by references and it was not possible to trace its origins. When compared to modern literature on learning in petroleum engineering, this learning rate could not be confirmed. The scrutiny of 30 companies within the fields of petroleum exploration and production resulted in a learning rate of 3–4% [41]. For the natural gas sector, a learning rate of 13% was calculated [42]. Offshore wind power, a technology also benefitting from the experience in offshore engineering, comprises a learning rate of 0–3%, however with a relatively low R^2 value [43]. For onshore wind, the learning rates even oscillates between −3 and +33% [44]. Consequently, it can neither be argued for nor against an OTEC learning rate of 7%.

In contrast, the claim of finite learning coming to a halt after the 4th or 5th doubling of cumulative output as stated in OTEC literature stands in stark contrast to the observations in literature on technological learning. All experience curves reviewed here showed continuous cost reductions without the convergence to an asymptote [41–46].

The methods used in the Lockheed Martin study to create experience curves do not match with other academic studies, pointing to two shortcomings. First, the Lockheed Martin study analysed learning for segregated system sizes, namely 100, 200 and 400 MWe. However, this approach assumes that OTEC implementation starts and ends with these systems without any down- or upscaling in between. Instead, a more likely development scenario might consider the intertwined effects of economies of scale and organisational learning, starting from small pilot plants in the range of some kW, followed by a natural evolution to larger dimensions. If learning is supposed to start and end at larger scales as according to Lockheed Martin, the doubling of output and thus the effect of cost reduction would refer to these sizes as well, which is far more difficult to achieve than with small-scale plants. Intuitively, it is more likely that the stronger learning effects are gained from small pilot plants, paving the way for steadily increasing systems over time. This is a pattern that generally emerges when upscaling systems, and realising economies of scale.

Second, in Lockheed Martin's learning curves, the LCOE is plotted against time instead of cumulative energy output, which is not practiced in literature on technological learning. Learning is an ongoing process more related to cumulative production than to time [45]. If learning is assessed by time, it is not fully clear how much OTEC capacity has been implemented within that period. The intensity of industrial activity within the OTEC niche would be omitted as well. Furthermore, Lockheed Martin calculates the halt of cost reductions after approximately ten years due to the maturity of most OTEC components as shown in Fig. 5. However, there are still tangible learning-induced cost reductions observed within the oil sector, an industry of over 150 years of experience. So, the validity of the statements made by Lockheed Martin must be perceived critically.

4.7. Knowledge gaps in OTEC economics literature

In the course of the literature study, a total of seven knowledge gaps have been identified.

1. Absence of Spatial Economic Analyses

Currently, the economic performance of OTEC is merely studied for individual plants. Due to the strong sensitivity of the real power output to external natural conditions, single plants cannot give sufficient insights on the economic potential within a region, country or the globe. Based on current literature, it is unclear what proportion of the global theoretical potential of OTEC can be tapped economically.

2. Omission of Natural External Influences on the Real Power Output

The influence of external natural conditions on the real power output of an OTEC plant is mostly disregarded when estimating its economics. While the seawater temperature difference is occasionally covered in academic literature, other factors like deep sea water availability are not. Thus, if OTEC researchers draw information from other studies to analyse their own use cases, the differences in external conditions between source material and use case might distort the results of the technical and economic analyses considerably.

3. Uncertainty of System and Component Costs

The review of current OTEC literature lead to the emergence of three scale curves. Based on these curves, the range between maximum and minimum system costs can vary by a factor of almost 4. Although the lowest curve is most likely unrepresentative, it still remains unclear how capital intense the technology truly is. Since many scholars use total system costs for their analyses instead of aggregated component costs, it is not possible to thoroughly assess the composition of the system costs found in literature.

4. Operational Uncertainty

In OTEC literature, OPEX are mostly seen as a fraction of the CAPEX. However, these fractions vary strongly between studies. Generally, there is no validation of OTEC's operational expenses due to the lack of experience and long-term operational data of pilot plants. This problem also affects the uncertainty surrounding the total useful lifetime of an OTEC plant which also differs significantly within literature.

5. Impact of Various Risks on Interest and Discount Rates

Currently, limited attention is paid to the choice of interest rate when calculating OTEC's LCOE. However, it is a highly sensitive input that distorts the technologies profitability if selected wrongly. There is no work within OTEC literature that assesses the choice of interest rate based on societal, economic, financial, political, organisational and ecological risks. It is argued that the currently chosen interest rates, mostly national bank loans, might not reflect the risk inherent to OTEC appropriately.

6. Omission of Technological Learning

Despite OTEC's capital intensity, the cost reduction potential via technological learning is predominantly not considered in literature on OTEC economics. Thus, existing economic analyses only draw a picture of the status quo with limited insights on future potentials and developments. When discussed, the assumptions made for OTEC learning are not backed by literature and have no or loose connections to other literature on technological learning. Existing experience curves show methodological flaws and do not reflect the practices within the research field of learning. Consequently, the information on OTEC learning lacks validation and congruency.

7. Omission of Further Economic Assessment Tools

Currently, most economic analyses of OTEC only focus on the LCOE. However, this value merely reveals the electricity price needed to breakeven with all project expenses at the end of its useful lifetime. To evaluate the LCOE's competitiveness, it must be compared to local commodity prices for electricity. While OTEC's profitability might be limited where commodity prices are low, interesting cases might emerge in countries where they are high like SIDS. Even if a breakeven within the plant's lifetime is not feasible under market conditions, further economic analyses might reveal the amount of public support needed to kick-start commercial OTEC and to enable profitability.

5. Conclusion

A literature review was performed to provide an overview of contemporary literature on OTEC economics. Moreover, the methods and insights found there were critically discussed and seven knowledge gaps have been identified.

It can be concluded that there is a strong uncertainty for almost every input for LCOE calculation of OTEC, which among others led to the emergence of three distinct scale curves reflecting the capital costs of OTEC versus its nominal power output. Furthermore, technological learning is only scarcely covered in OTEC literature and the methods employed there are not in line with other studies on learning. There is a lack of primary sources in contemporary literature and almost all publications foot on research from the last century to varying extent. Current economic analyses of OTEC solely focus on individual plants instead of the collective economic potential within regional, national or global boundaries. Moreover, external natural conditions like seawater temperature difference only occasionally find attention in literature, notwithstanding its strong influence on the real power output. Nevertheless, large-scale OTEC might be cost competitive with other energy technologies under certain circumstances, although the wide range of possible LCOE between 0.03 and 0.22 US$(2018)/kWh leaves space for speculation.

This paper has provided a more detailed overview of OTEC economics and its calculations than could be found in contemporary literature. Based on the critical assessment of the reviewed content, it was possible to identify several methodological shortcomings as well as seven knowledge gaps. Based on the knowledge gaps, this review offers recommendations for future OTEC research as reported in Section 6. It must be mentioned that due to the abundant use of historical primary references in contemporary literature, this overview still builds partly on outdated data. Therefore, a projection of OTEC economics based on state-of-the-art technology was only possible to a limited extent. Although the uncertainty of OTEC's economics is obvious, this review was only able to shed a bit more light on this. While the validity and transparency of critical studies can be discussed, their underlying assumptions and consequent results can neither be fully proved nor disproved. To do so, more practical and transparent data is needed, which is not publicly available yet. For example, it might be possible that companies involved in OTEC do have better but undisclosed data. Nevertheless, the benefit of doubt prevails.

Current literature on OTEC economics is thus affected by the lack of empirical and operational data. Since commercial plants as well as pilot plants close to commercial scale do not exist yet, almost all cost estimations foot on no or historical references. Most of the seven knowledge gaps originate from this problem and the most effective remedy to the current guesswork seems to lie in the deployment of OTEC plants and the transparent revelation of their economic and technical data. The chance of cost competitiveness of large-scale OTEC however, as well as its possible benefits beyond power production, should serve as motivation to dive deeper into the matter and to contribute to the development of this potentially promising technology.

6. Recommendations and research agenda

The following recommendations are provided to tackle the seven knowledge gaps surrounding OTEC economics. They can contribute to a larger research agenda that also includes technical, environmental and societal research on OTEC. A possible object of investigation within that agenda could be the inclusion of other revenue generating applications (see section 3.1) in economic analyses on OTEC. Especially the production of desalinated and potable water from OTEC might provide motivation for further research [2,19]. Besides that, the research agenda could investigate the environmental impacts of OTEC on local ecosystems, like increased algal bloom from nutrient rich deep sea water [31]. By setting attention on these and other fields, the agenda proposed here follows the recommendations of other OTEC related studies [2,12,20,24].

The recommendations regarding OTEC economics below follow the order of knowledge gaps and are not ranked by priority in the list below. The general recommendation to OTEC research is to put these recommendations into practice.

1. Deeper Economic Analyses of OTEC on Spatial Levels

Instead of focussing on individual plants, research should expand economic analyses to broader spatial levels. For example, by using the geographic information system approach, the natural conditions discussed here can be mapped for regions, countries and the globe and provide the inputs for economic calculations on these levels. Moving from individual plants to broader spatial scopes would contribute to OTEC research by providing more tangible projections on the technology's economic potential as a whole. When estimating OTEC's costs, plants should not be perceived as black boxes and costs should be listed as transparently and detailed as possible. Cost estimations should orient themselves towards the middle and upper scale curves in Fig. 1.

The seventh knowledge gap in section 4.7 could be tackled with a more spatial approach as well. Economic analyses of OTEC could be expanded with other tools like IRR and payback periods by including local commodity prices of electricity. If OTEC proves economically competitive locally, tangible business cases might emerge. If not, the amount of required public support, i.e. via subsidies, could still be projected. The first step towards a more spatial approach is taken by the several master studies at TU Delft [47–49].

2. Inclusion of External Natural Conditions

When analysing the economic potential of OTEC, external conditions like seawater temperature difference need to be considered more thoroughly. Instead of taking estimations by other scholars at face value, it should be critically assessed how changes in external influences affect the sizing and performance of an OTEC plant and thus its economics. By doing so, regional trends can be observed, with some areas more suitable than others. Based on this, the OTEC niche could focus on implementing its first plants at economically optimal sites. The master thesis by Chalkiadakis [47] provides first insights on the local, practicable OTEC potential based on natural influences as mentioned above. One option to obtain detailed site-specific information on seawater temperature differences is the database of HINMREC, in which the temperature differences for any location in the world can be found [50].

3. Stronger Cooperation Between Industry and Academia

The current practice of resorting to cost estimations from the last century should be replaced by building stronger connections between academic and industrial research. Cost estimations need to become more transparent, comprehensible and relevant to modern standards. Refreshed cost estimations would optimally lead to one scale curve based not on outdated sources, but on the state of the art. One way of achieving this might be the fostering of data exchange and validation within a pre-competitive setting.

4. Pilot Plants and the Publication of their Operational Performance

Most problems revolving around OTEC originate from the lack of experience and mid-to long-term operational data. Thus, the availability of more publications based on existing and future pilot or experimental plants would aid in creating a more tangible and practicable foundation for OTEC research. Regarding new pilot plants, it is important to design them under the light of commercial requirements, so with system sizes in the range of MW.

5. Finance Risks of OTEC

The choice of interest rate when calculating the LCOE should be more transparent and considerate. OTEC comprises risks other technologies might not face, starting from its lack of experience to its deployment in politically and financially unstable countries. Thus, more research on the risks comprising OTEC, precipitating in more adequate interest rates would contribute to the projection of more realistic results of the economic potential of OTEC. With further development of OTEC, it would then be possible to reassess the risks of OTEC and to quantify the change in interest rates over time.

6. Inclusion of Technological Learning

Future research on OTEC's economics should place a stronger focus on technological learning. For a capital-intense technology like OTEC, cost reductions via learning are crucial. Thus, the inclusion of learning would not only project OTEC's economics beyond the status quo, but also provide an outlook for the future as well. This could be achieved applying the practices in literature on technological learning to OTEC, i. e. by modelling theoretical global experience curves. This can build on existing work works of Samadi [43] and Junginger [45].

As a final note, initial work was recently started at Delft University of Technology in line with the proposed research agenda on the economic aspects of OTEC, for instance Ref. [47–49]. In addition, enhancing the understanding of the economics will not only depend on the agenda suggested above that suggests to become more specific on the conditions of OTEC sites, to use better operational data based on (forthcoming) pilots and to take better into account insights from innovation economics with regard to learning effects. Although some studies address upscaling a single OTEC plant or at a specific site [2,23], applying different kinds of scenarios and scenario analysis to study the interaction of economics and technology development may also add to this. For instance, exploratory scenarios mapping complexity and possible uncertainties can increase the understanding of conditions and external factors that may enable or constrain the large-scale development and diffusion of OTEC in the future while normative scenarios using roadmaps or backcasting [51] can be used to develop implementation pathways for strong OTEC development and diffusion, as this needs to be done at a global scale.

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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