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Future role of ocean thermal energy converters in a 100% renewable energy system on the case of the Maldives

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ABSTRACT

Energy transition on small islands is limited by the scarce availability of land, restricting large-scale implementation of onshore renewable energy technologies such as solar photovoltaics and wind power. Ocean energy technologies provide novel opportunities for land-constrained islands to achieve 100% renewable energy systems. While wave power is increasingly implemented in energy system modelling research, ocean thermal energy converters are not yet a standard technology in renewable energy technology portfolios. This research aims to study the impacts of ocean thermal energy converters on the energy system of the Maldives through a structured sensitivity analysis for the two scenario clusters covering e-fuel import and domestic production. The ocean thermal energy conversion plants are modelled using spatially and temporally resolved resource data and cost assumptions from a global upscaling scenario, considering the technology's current development stage. Results show that ocean thermal energy converters play a limited role in 'purely' cost-optimised sub-scenarios due to the availability of very low-cost offshore floating photovoltaics, making it difficult for them to compete. Nevertheless, reduced requirement of energy storage technologies due to the stable electricity production of ocean thermal energy converters offers an option to diversify the renewable energy technology portfolio with only a minor increase in cost.

1. Introduction

Low-lying, small islands are significantly exposed and vulnerable to the effects of climate change [1]. The repercussions of climate change are already well noticeable. Besides consequences such as increased extreme weather events [2], coral bleaching [3], and increased conflict potential [4], increasing sea levels [5,6] pose the biggest threat to small, low-lying island states such as the Maldives. To mitigate climate change, the Maldives signed the Paris Agreement in 2015 [7]. While most countries commit to reaching a net-zero emission energy system by 2050, the Maldives set a more ambitious net-zero target of 2030 [8,9].

The Maldives is located in the northern part of the Indian Ocean (cf. Fig. 1) and consist of more than 1000 islands, even though a minor share of about 1.4% of the islands are inhabited [10]. With an average maximum elevation of 2 m above sea level, the non-solid, coral-based islands of the Maldives are especially threatened by rising sea levels [10].

The transition of the energy system in the Maldives is challenging, since the average size of the islands is rather small, which prevents the installation of area-demanding utility-scale power plants such as solar photovoltaics (PV). In addition, the energy system is heavily dependent on liquid fuels for power generation and transport, the latter due to the active tourism industry and location far away from the main land [11]. Alternative solutions are indispensable for small island developing states (SIDS), such as the Maldives, to allow for a sustainable defossilisation of the energy system. Previously, Alphen et al. [12], Liu et al. [13], Keiner et al. [11], and Khare et al. [14] proposed 100% renewable energy (RE) systems in the Maldives. A study by Keiner et al. [11] already showed that offshore floating solar PV and wave power offer a promising alternative to conventional onshore RE technologies. Additional options, however, are possible, such as ocean thermal energy converters (OTEC). These are increasingly the focus of research (cf. section 2) and seem to be promising, especially in the Sunbelt region due to the warm surface water temperatures. However, a dedicated impact study of OTEC for the case of the Maldives has not yet been done and remains rare in energy system analyses.

The novelty of this study lies in identifying the future role of OTEC in

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Nomenclature

e-Fuels	Electricity-based fuels
eF-DP	Electricity-based fuel domestic production scenario
eF-I	Electricity-based fuel import scenario
FLH	Full load hours
ICE	Internal combustion engine
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOFE	Levelised cost of final energy
LCOS	Levelised cost of storage
OTEC	Ocean thermal energy converter
PV	Solar photovoltaics
RE	Renewable energy
SIDS	Small island developing state

energy systems and to find structural insights for island states in the Sunbelt, with the Maldives as a case study. Thus, this study provides a novel structured sensitivity analysis for OTEC on the energy system in the Maldives based on.

- an hourly resolution of the energy system including power, heat, and transport sectors.
- two scenario clusters for the import of electricity-based fuels (e-fuels) or domestic production of e-fuels.
- two target years: 2030 complying with the Maldives' net-zero target and 2050.
- a gradually forced implementation of OTEC capacity in the RE technology portfolio (structured sensitivity) to study its impacts on other RE technology capacities, energy storage, total annual system cost, levelised cost of final energy (LCOFE), and levelised cost of electricity (LCOE).

This analysis gives a novel impression on the role of OTEC in a typical energy system of SIDS in the sunbelt, whether OTEC is cost-competitive to low-cost electricity from other RE technologies such as solar PV, wind offshore, or wave power, or if OTEC is not able to compete. The study aims to close the research gaps on structured sensitivity analysis for OTEC included in an energy system, as such research is not yet available apart from one recent example [15] and a very early study in the 1990s [16,17] and the competitive investigation on the feasibility of OTEC in the Maldives. Including the novel technology option in an energy system analysis has to be widened, as such studies are not yet available in sufficient detail and spatial coverage (cf. section 2). The results of this study will advance the research on energy transition solutions, considering novel, non-conventional RE technologies, in particular ocean energy technologies of SIDS, island nations and comparable regions globally. The applied structured sensitivity analysis aims to give detailed insights in near-optimal solutions including OTEC for the identification of possible value add of this technology for energy systems apart from economic assessment.

2. Literature review on ocean thermal energy converter for energy system integration

The interest in OTEC as an ocean energy technology option is increasingly reflected in the published literature, especially on 100% RE system studies on islands [18]. Table S1 in the supplementary material 1, note 1, gives an overview of recent articles published in the context of OTEC. Contemporary literature mainly assesses OTEC from a technology perspective and focuses on engineering designs [19–21] and the techno-economic assessment of plants, either in general cases [22] or for specific locations. Vega [23] and Martel et al. [24] investigated large-scale OTEC for the United States and its territories as a promising

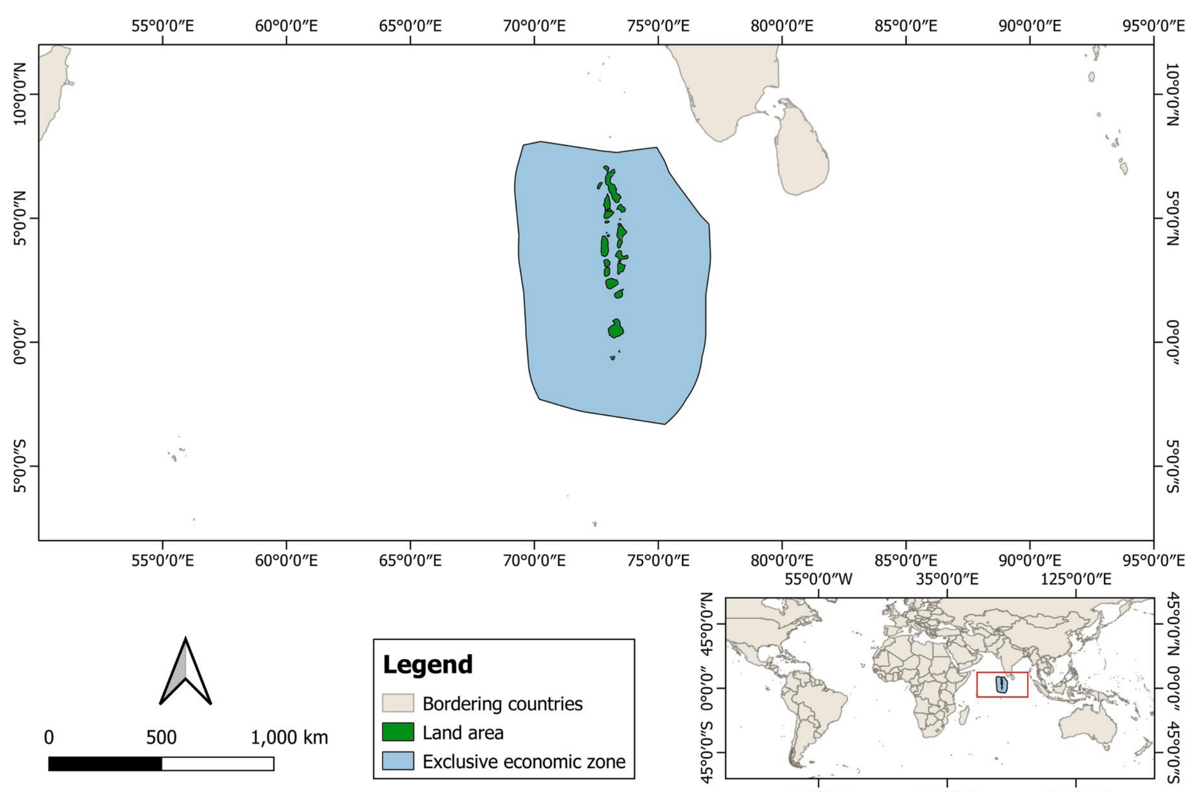

Fig. 1. Location of the Maldives and its Exclusive Economic Zone (EEZ).

base generation RE technology. Herrera et al. [25] find the San Andrés island of Colombia to be a most suitable location for the implementation of OTEC. A somewhat less optimistic conclusion has been drawn by Adesanya et al. [26] on the case of West Africa and in particular the coastal region of Nigeria, however, the general outcome was still in favour of OTEC as a viable option. Farhan et al. [27] estimate OTEC to be a promising candidate for the power generation portfolio of Pakistan. Two different locations in Indonesia for possible OTEC deployment have been studied by Rahmawati et al. [20], Andrawina et al. [28], and Sinuhaji [29], while all three articles come to the conclusion that Indonesia is a most suitable location. Almost all feasibility studies mention side products that could boost OTEC's economic feasibility, like nutrition-rich deep-sea water for mariculture, or potable, desalinated water in the case of open-cycle OTEC. More recently, Giostri et al. [30], Langer et al. [31], and Fan and Chen [32] found that spatial and temporal seawater temperature fluctuations significantly affect OTEC's techno-economic performance and that these fluctuations should be accounted for in the plants' designs. Other studies expand the analysis to larger geographic areas, from global [33–35] to more regional assessments in Malaysia by Thirugnana et al. [36] and the Aguni Basin by Liu et al. [37]. The global analysis by Langer and Blok [33] found that OTEC's most important niche application at its current development stage are the SIDS, such as the Maldives. In the future OTEC's application could spread to larger coastal regions once it is sufficiently developed, which resonates with von Jouanne and Brekken's [38] findings, who reviewed ocean energy technologies more generally.

None of the studies above assessed OTEC in the broader context of a whole energy system. Nordman et al. [39] see OTEC as a feasible option for the energy system in Cape Verde, however, the final solution for the region does not include OTEC. Most other energy system modelling studies are done for Réunion by Selosse et al. [40,41], Drouineau et al. [42], Bouckaert et al. [43], and Praene et al. [44]. Even though OTEC is part of the system solution for a 100% RE system, none of the studies discuss the role of OTEC for the energy system of Réunion in more detail, and no specific conclusion on the role of OTEC is available from these articles. Langer et al. [45] modelled scenarios for OTEC's development from small pilot plants to full-scale, commercial plants in Indonesia. The model considers cost reductions from technological learning and upscaling, local electricity demand and demand growth until 2050, but disregards competition from other (renewable) electricity generation technologies. This limitation was addressed in a follow-up study [15], where it was found that OTEC could cost-effectively contribute 84 TWh, or 7% of the demand in 2050, to a fully decarbonised power system in Indonesia, provided that OTEC reaches full commercial scale by then.

No study focuses on OTEC's role in the context of a whole energy system, considering spatial and temporal seawater temperature fluctuations and the cost-reducing effects of OTEC's commercialisation. The system implementation of OTEC in the literature is mainly limited to one island in the Indian Ocean and, therefore, has to be rolled out more comprehensively with dedicated studies on the role of OTEC for future energy systems in the respective regions and islands. This study has the aim in overcoming this research gap in the case of the Maldives.

3. Methods and data

The EP-ALISON-LUT tool [46] in combination with EnergyPLAN [47] is used to conduct a structured sensitivity analysis on the role of OTEC in the Maldives' energy system. The tool allows for presetting capacities of any RE technology, as done in the case of this study with the OTEC capacity to study the impact of gradually increasing this capacity on the entire energy system. In this way, possible benefits of the novel technology beyond the cost optimisation can be analysed.

3.1. Reference energy system and future demand estimation

As a reference the energy system of 2017 is chosen following a previous research on the Maldives [11]. Fig. 2 gives an overview on the primary energy mix of the Maldives in 2017.

Most of the primary energy consisted of oil, including respective oil-based products such as diesel, petrol, kerosene, and LPG. About 5.21 TWh of primary energy was used in form of diesel, of which about 2.03 TWh for electricity generation, about 1.96 TWh was used as diesel for domestic and international marine transport including fishing boats, and about 1.20 TWh for road transport, mainly buses. Gasoline consumption was ca. 0.68 TWh, of which about 0.36 TWh was used in road transport, about 0.22 TWh for domestic, and about 0.10 TWh for international marine transport. Kerosene consumption was ca. 0.49 TWh, of which more than half or about 0.26 TWh went to international aviation, while about 0.23 TWh was used in domestic aviation. About 0.16 TWh of liquified petroleum gas (LPG) is assumed to be used for cooking, which is probably also the case for about 0.04 TWh of biomass.

A total capacity of 266 MW diesel-based internal combustion engines (ICE) were the backbone of electricity generation [49]. In 2017, RE technologies played only a minor role in the Maldives. A total capacity of 10.8 MWp solar PV generated ca. 0.014 TWh of electricity; wind power capacity of 0.21 MW generated 0.002 TWh of electricity [49]. The total CO_2 emissions in 2017 accumulated to 1.82 $MtCO_2$, or 3.67 tCO_2/cap [50], at a total electricity demand of 0.656 TWh [48]. Heating apart from cooking does not play a role in the Maldives, as year-round warm temperatures do not require space heating, and the main income sector of the country is tourism, and no heavy industry requiring process heat is located in the archipelago [10]. Domestic hot water demand can be estimated at 0.148 TWh in 2030 and 0.213 TWh in 2050. It is assumed to be fully electrified already in the reference scenario and is considered part of the electricity demand in the power sector. Table 1 summarises the final energy demand used as inputs for the simulations. For details on the demand estimation, please refer to Keiner et al. [11].

Due to the growing gross domestic product (GDP) of the country, electricity demand will significantly increase by 2050. A major part of liquid fuel consumption is switched to electric mobility, which significantly decreases the final energy demand of the Maldives in the future. Biomass and LPG, presumably used for heating, are assumed to be phased-out by 2030 and substituted by electricity [51], and therefore, it is included in the power sector electricity demand.

The electricity demand profile for the 2017 reference scenario, as well as the 2030 and 2050 future scenarios are taken from Toktarova et al. [52]. Fig. S1 in the supplementary material, note 2, shows a visualisation of the profiles normalised to the annual total electricity demand.

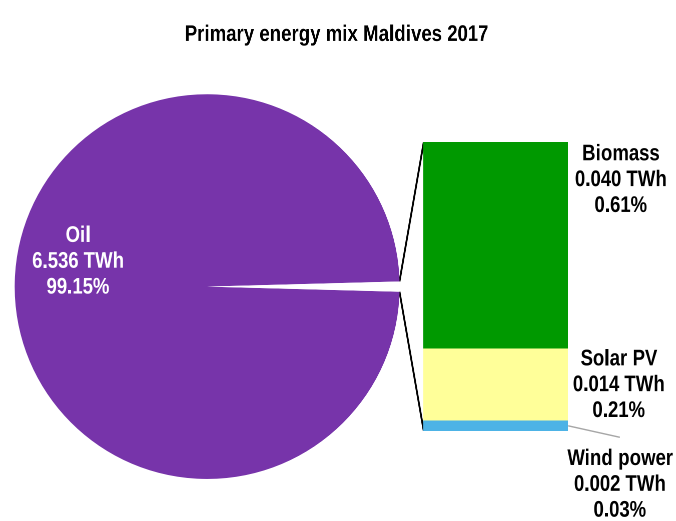

Fig. 2. Primary energy mix of the Maldives in 2017. Data source: [48,49].

Table 1
Final energy demand input data for the energy system simulation of the Maldives of the reference system and future years to be simulated. Source: [11].

Sector	Demand type	Unit	2017	2030	2050
Power	Electricity	TWh	0.656	1.683	4.726
Transport	Diesel	TWh	3.175	0.495	0.656
	Petrol	TWh	0.067	0.361	0.522
	Kerosene	TWh	0.488	0.787	1.766
	Electricity	TWh	0	0.207	0.233
Heat	Biomass	TWh	0.040	0	0
	LPG	TWh	0.163	0	0

3.2. Renewable energy technologies and potentials

The RE technologies apart from OTEC include rooftop solar PV, offshore floating solar PV, offshore wind power, and wave power. As available land area is the main limiting factor in archipelagic countries, ground-mounted utility-scale solar PV or onshore wind power is assumed to be not a feasible option. The profiles of these RE technologies are calculated according to Bogdanov and Breyer [53] using global weather data from 2005 from NASA [54,55] reprocessed by the German Aerospace Centre [56]. According to Keiner et al. [11], the yield of rooftop solar PV using the same solar PV profile as offshore floating solar PV is corrected to include typical rooftop losses [57]. In the case of offshore floating solar PV, no yield improvement is assumed. The reason is on average high seawater temperature in the Maldives [58,59]. Due to the lack of significant land mass, the onshore wind power method of Satymov et al. [60] is applied to calculate the offshore wind power profiles. The wave power profile is calculated based on Satymov et al. [61]. The profiles are visualised in Fig. S2 in the supplementary material 1, note 2.

The potential for rooftop solar PV is taken from Keiner et al. [11] and can be estimated at 340 MW_p in 2030 and 440 MW_p in 2050. This estimation includes an increase in the average efficiency of solar PV modules from 17% in 2017 to 30% in 2050 [62]. No further capacity limitations are applied to other RE technologies, as it can be assumed that the sea area is abundantly available. Furthermore, a planned 8 MW waste-to-energy facility is implemented in the system, which will be realised to deal with the problem of waste handling in the Maldives [63, 64].

3.3. Ocean thermal energy converter modelling

The open-source model pyOTEC [33] is used to model the net power production profiles, i.e., the power that reaches the electricity grid, transmitted from the floating OTEC plants. For the Maldives, OTEC systems with a size of 136 MW_{gross} (≈100 MW_{net}) are modelled, which reflects OTEC at full scale with limited potential for further cost reductions from upscaling [23,65].

pyOTEC uses spatiotemporally resolved surface and deep-sea water temperature reanalysis to size OTEC systems for best economic performance (i.e., lowest LCOE) under off-design conditions from seasonal ocean thermal energy resource fluctuations. The model solves the saturated, single-stage Rankine cycle with ammonia as the working fluid. To account for the partial loads imposed by the off-design conditions, pyOTEC uses a sliding pressure control logic, where evaporation and condensation pressures in the heat exchangers are adjusted if necessary. Moreover, the partial load behaviour of the heat exchangers, e.g., mass flows and heat transfer coefficients, is modelled iteratively, assuming single-flow plate heat exchangers. Pressure drops are calculated for seawater pipes and heat exchangers and omitted elsewhere.

The sites at which OTEC could be implemented were determined previously via a site suitability analysis using Geographic Information System (GIS) software. By default, pyOTEC uses the Global Ocean Physics Reanalysis [66], which comes in daily, i.e., 24 h, time steps from 1993 to 2020, and a spatial resolution of $1/12^{\circ} \times 1/12^{\circ}$ (≈9 km × 9 km) across 50 depth layers. The technical and economic assumptions underlying pyOTEC are available in Langer and Blok [33]. For the Maldives case, seawater temperature data from 2005 is used to design the OTEC plants and calculate their daily net power production at all technically feasible sites (N = 3515 sites). Then, the daily profiles are resampled to hourly values via linear interpolation to match the temporal resolution of the other time series data.

For the economic analysis, pyOTEC uses a cost model that accounts for component-specific economies of scale. Given OTEC's highly uncertain costs as of today, the user can choose between low-cost and high-cost assumptions, reflecting the range of cost estimations found in literature [45]. In this study, low-cost assumptions are used in combination with further cost reductions from technological learning, considering OTEC's development towards maturity. Based on existing OTEC upscaling scenarios for Indonesia [45], OTEC's costs are assumed to decline with each doubling of installed capacity by a single-factor, systemwide learning rate of 7%. For current costs, therefore, costs returned by pyOTEC are used as-is and multiplied with the cost reduction rates which are based on global OTEC installation rate of 28% per year (cf. Table S2 in supplementary material 1, note 3).

3.4. Techno-economic modelling

The modelling of the energy system of the Maldives is done using the EP-ALISON-LUT tool [46,67], which works in combination with the EnergyPLAN simulation software [47]. EP-ALISON-LUT allows for a linear cost-optimisation of the power and hydrogen balances. The objective function for cost-optimisation is the sum of the total annual cost for RE technologies, electricity storage, electrolysers, hydrogen storage, and hydrogen re-electrification units. Short-term energy storage is provided via stationary batteries and for long-term storage, a power-to-hydrogen-to-power system comprising of electrolyser, compressor unit, hydrogen energy storage, and multi-fuel ICE is implemented. The latter is chosen over fuel cells due to several aspects hindering the large-scale commercialisation of fuel cells in the future [68]. Techno-economic input data for all applied technologies can be found in Table S3 in the supplementary material 1, note 3. Each simulation represents an overnight transition of the energy system.

3.5. Applied scenarios

Similar to the previous research [11], two main scenario clusters are applied: the import of e-fuels (e-fuel import, eF-I) and the domestic production of e-fuels (e-fuel domestic production, eF-DP). As visualised in Fig. 3, both scenario clusters include several sub-scenarios. In those scenarios, the preset capacity of OTEC is varied and either preset in 100 MW increments up to 1000 MW or not set at all. Starting point for the structured sensitivity analysis is a free cost optimisation (FCO), where none of the capacities is set manually and all renewable electricity generation technology capacities are set by the optimisation algorithm. Subsequently, the capacity of OTEC, wave power, or a combination, is set manually in said 100 MW increments, while the rest of the capacities is subject to the cost optimisation. The OTEC capacities refer to the gross installed capacity. Since large capacities by 2030 and 2050 do not comply with the total installed capacity assumed for cost estimations, such capacities especially in 2030 are to be interpreted as a theoretical investigation, as the implementation of such capacities are rather unlikely. Nevertheless, this study aims to show the theoretical impact of OTEC on 100% RE system solutions if such capacities are theoretically available.

To be able to assess the positive or negative impact of OTEC on the energy system more accurately, the structured sensitivity is also made for wave power, which is also an alternative to conventional RE sources like solar PV and wind power for regions with limited available land area. The second alternative assumption is a structured sensitivity analysis of a combination of OTEC and wave power. In this case, it is

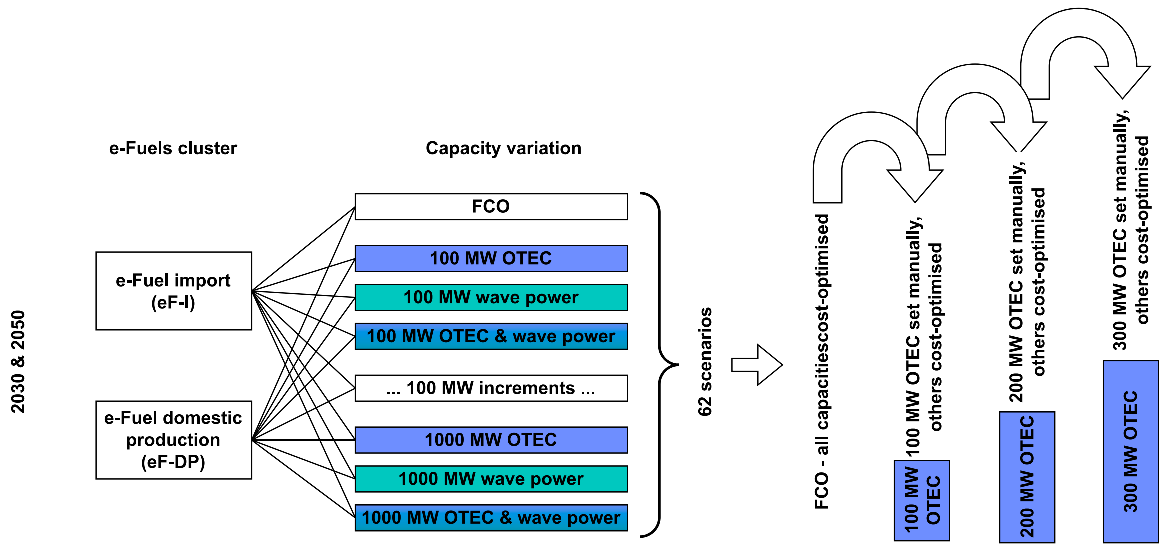

Fig. 3. Scenario setup including two main scenario clusters for e-fuels import (eF-I) and e-fuels domestic production (eF-DP) and combination of capacity variation sub-scenarios. Each e-fuels scenario cluster contains one free cost optimisation scenario (FCO) and scenarios with gradually increasing capacity for either OTEC, wave power, or both. The increments are 100 MW. In case of the combined OTEC and wave power scenarios, each technology capacity increment is 50 MW. The remaining energy system (other RE capacities, energy storage, etc.) is found in a cost optimisation. The figure shows an example for the OTEC scenarios.

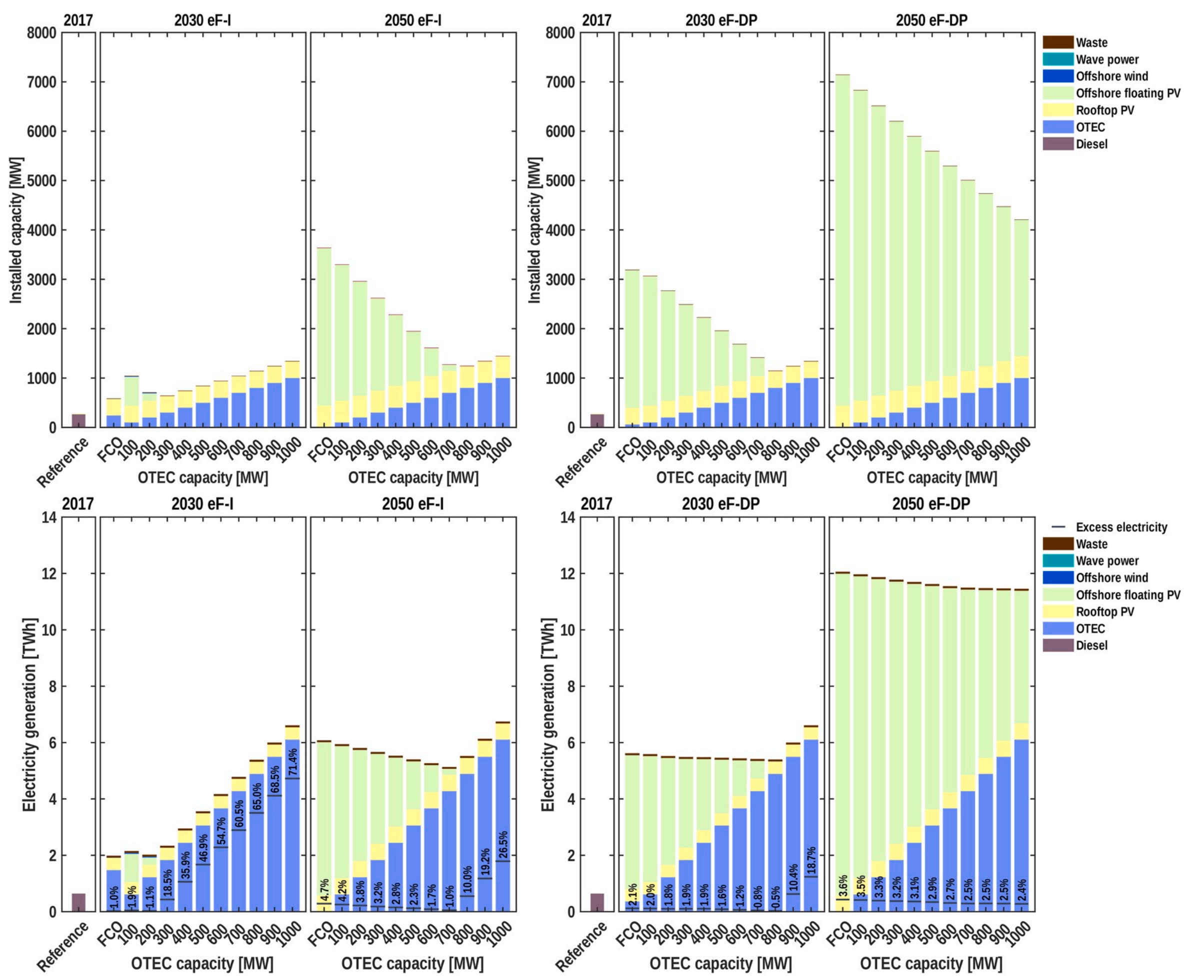

Fig. 4. Installed power generation capacities (top) and electricity generation (bottom) in 2030 and 2050 for the eF-I (left) and eF-DP (right) scenario cluster in comparison to the 2017 reference system.

assumed that the 100 MW increments consist of 50% of the capacity each, which means a 100 MW combined installation would include 50 MW of OTEC and 50 MW of wave power capacity. The assessment is made for the years 2030, in line with the country's net-zero targets [8,9], and 2050 as the common target year for the 1.5 °C target. All other technologies of the energy system are scaled via a cost optimisation, as documented in the model documentation [46,67]. Further sensitivities are not part of the scope of this study.

4. Results

The focus of this section lies on the main scenario, including OTEC capacities. The figures and numeric results for the wave power, OTEC and wave power scenario clusters can be found in supplementary material 1, note 4, and supplementary material 2.

4.1. Power generation capacities and electricity generation

The generation capacities for OTEC are preset manually for the structured sensitivity analysis. In addition, the rooftop PV capacity was assumed to be a fixed value at 340 MW_p in 2030 and 440 MW_p in 2050, as well as 8 MW installed waste-to-energy capacity. Fig. 4 shows the total composition of RE technologies for all assessed OTEC capacities, as well as the electricity generation and excess electricity. Since no transmission line capacities outside of the Maldives are assumed in this study, excess electricity equals curtailment.

If e-fuels are imported in 2030, OTEC can be part of the FCO scenario with 241.6 MW of installed capacity, outplaying floating offshore PV, which is not installed in this case. In addition, a small capacity of 1.5 MW offshore wind supports the power generation portfolio. For a preset OTEC capacity of 100 MW, offshore floating PV takes over the required capacity with 588.5 MW_p. In this case, offshore wind capacity increases as well to 12.4 MW. If more than 200 MW of OTEC is installed, the electricity generation is already sufficient to power the whole energy system of the Maldives, as no offshore floating PV or offshore wind capacities are part of the solution thereafter. For the eF-DP scenarios, the situation is quite similar, however with some differences. OTEC is still part of the FCO structure, however, compared to the eF-I case, reduction in installed capacity of 58.9 MW is observed. The major share of installed capacity comprises of offshore floating solar PV at 2788.8 MW_p. Offshore wind only plays a minor role at 1.3 MW installed capacity. Even though the electricity demand is more stable due to the significant e-fuel production facilities assumed, the optimisation tends to use a combination of offshore floating PV and batteries to supply the demand. The reason is that with more electricity demand, curtailment for a solar PV-based system can be reduced, as electrolysers can act as a main flexibility option, adapting the production of hydrogen to the availability of cheap electricity from solar PV. Therefore, the combination of electrolysers with solar PV is economically favourable over OTEC in this case. Additionally, the electrolysers are already at a low enough cost level to work in a flexible way, which favours solar PV deployment as hydrogen storage capacity is cheaper than electricity storage capacity in batteries. The cost level of OTEC in 2030 seems to be on the edge of being competitive with low-cost solar PV in the sunbelt. Hydrogen production via electrolysers also causes efficiency issues, which finally triggers solar PV deployment on a larger scale than OTEC.

Similar results are also noticed in the scenarios for 2050. The declining cost of solar PV, battery storage, and electrolysers, results in OTEC, despite its good resource availability in the Maldives and stable electricity generation, not being part of the least cost solutions for the FCO. Without domestic e-fuel production, the optimisation installs 3192.6 MW_p of offshore floating PV. Offshore wind and OTEC do not share any power generation capacity. For the eF-DP FCO scenario, the installed offshore floating solar PV capacity reaches 6700.9 MW_p. These results underpin the significant dominance of solar PV in the sunbelt, which makes it hard for other RE technologies to compete.

In terms of electricity generation, OTEC contributes about 1.4 TWh and 0.4 TWh in the 2030 FCO cases for eF-I and eF-DP, respectively. Even though the installed OTEC capacities are less than the solar PV options, the electricity generation is significantly higher due to the stable resource availability over the whole year. The excess electricity share in the eF-I FCO case is about 1.0%, while it is higher in the eF-DP case with a higher solar PV capacity at around 2.1%, which is still within acceptable levels. When forcing OTEC capacity into the system, the electricity generation from OTEC significantly increases as well. The high excess electricity share of 18.5% for an installed OTEC capacity of 300 MW in the eF-I scenario cluster indicates that at this point the system is provided with large power generation capacity, or overcapacity, and the electricity generation significantly surpasses the electricity demand. If in 2030 all e-fuels are produced domestically, this effect will occur if more than 800 MW of OTEC capacity is installed. This refers to the significant increase in electricity demand induced by additional hydrogen demand for e-fuels production.

By 2050, the domestic electricity demand without e-fuels production will increase strongly, which can be seen as up to 700 MW of OTEC capacity can be installed before the excess electricity increases to almost 10%. Interestingly, at exactly 700 MW of OTEC capacity, the excess electricity is at its lowest, at about 1.0%. At this point, OTEC generates ca. 4.3 TWh, or almost 90% of the total electricity demand (cf. Table 1). If all e-fuel production were realised domestically, the investigated maximum OTEC capacity of 1000 MW would not be enough to cover all the demand. While the maximum OTEC capacity makes up 23.8% of the installed capacity in the respective sub-scenario, the electricity generation share is more than half at 53.3%. However, the generation capacity of OTEC is estimated to require another doubling to be able to cover all the electricity demand if domestic e-fuel production is realised in the Maldives by 2050.

4.2. Storage capacities and energy discharge

In this study, three types of storage technologies were considered: stationary batteries, hydrogen storage for power system balancing, and hydrogen storage for e-fuel production. The results for the energy storage capacities and the electricity discharge of the stationary batteries and balancing hydrogen storage can be seen in Fig. 5.

Hydrogen energy storage, either for power balancing or e-fuel production, shows the highest installed storage capacities by far for all scenarios and years. If e-fuels are imported, hydrogen energy storage is needed up to 300 MW of OTEC capacity in 2030, and a minor share of stationary batteries is required up to 400 MW of installed OTEC capacity. For 100 MW of OTEC installations, the storage demand is the highest for both balancing hydrogen energy storage and stationary batteries. The relatively high share of offshore floating PV triggers the stationary battery capacities, since highly efficient short-term energy storage such as batteries are usually tied to solar PV installations. The hydrogen energy storage is needed for the seasonal variation of solar PV yield since the solar yield in the Maldives is very good in the first quarter of the year; however, the solar yield is noticeably affected by the monsoon season in South Asia [69] in the second and third quarters of the year. Higher OTEC capacities in 2030 and 2050 scenarios, reduce the overall demand for energy storage due to almost constant electricity generation. However, due to the absence of OTEC in the FCO, this sub-scenario requires the largest energy storage capacities, as solar PV generates almost all the electricity. In this case, stationary batteries are required for all investigated OTEC capacities, however, hydrogen energy storage is not required for 900 MW of installed OTEC capacities or more.

If e-fuel production is included in the domestic energy system, hydrogen energy storage for e-fuel production becomes the biggest storage technology. The hydrogen demand for e-fuels production triggers the deployment of electrolysers, which act as a flexibility provider for the system, however, it also entails the hydrogen energy storage demand for e-fuels. Due to the lower OTEC capacity in the 2030 FCO

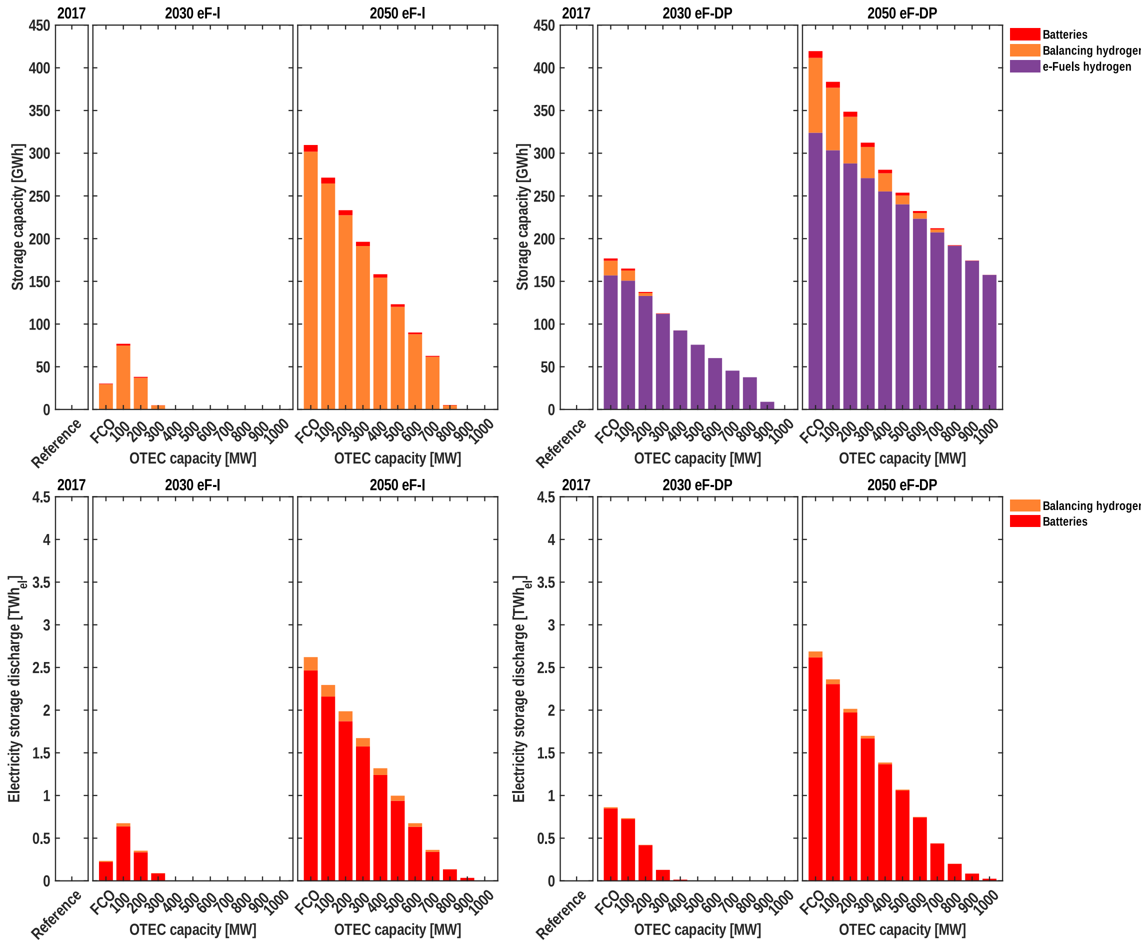

Fig. 5. Installed energy storage capacities (top) and electricity discharge from stationary batteries and balancing hydrogen energy storage (bottom) in 2030 and 2050 for the eF-I (left) and eF-DP (right) scenario cluster in comparison to the 2017 reference system.

results in the highest storage requirement. The stationary batteries are not required with 500 MW of OTEC capacity or more, power balancing hydrogen energy storage with 400 MW of OTEC capacity or more. The hydrogen energy storage for e-fuel production is required for all the OTEC capacities, although it can be reduced to 0.1% of the storage capacity in the FCO if 1000 MW of OTEC technology is installed in 2030. A similar picture can be drawn in 2050. Even though power balancing hydrogen energy storage is eliminated from 900 MW OTEC capacities, stationary batteries are still needed for all capacities studied. The hydrogen energy storage for e-fuel production can be reduced to less than 50% of the FCO capacity.

Despite the dominating capacity of hydrogen energy storage for power balancing compared to stationary battery capacity, the electricity discharged from stationary batteries is significantly higher than from the hydrogen balancing system. This is an indication that stationary batteries are cycled far more often during the year than hydrogen energy storage, which is observed in solar PV-battery dominated energy systems [70]. The hydrogen energy system acts as a seasonal storage. Even though there is no seasonal variation comparable to North America, Europe, or Northeast Asia in the Maldives that would alter the energy demand situation significantly, the monsoon season has a major impact on resource availability. Thus, seasonal storage is required to balance the monsoon variability in the energy system. The structure of the results is very similar for the eF-I and eF-DP scenario clusters. Interestingly, besides the differences due to the different OTEC capacities in the FCO sub-scenarios, the general storage requirement for power balancing between the eF-I and eF-DP scenario clusters does not change significantly. The reason is the abovementioned flexibility of electrolysers for e-fuel production. This indicates that the e-fuel production sub-system and the rest of the domestic energy system could be realised in parallel without significant disturbance.

4.3. Total annualised system cost and levelised cost of final energy

The total annualised system cost and its respective components give a good indication of the cost drivers of the overall system. However, as presented in Fig. 6, the total annual system cost has to be considered in reference to the total final energy demand of the country to allow for a more reasonable analysis of the cost situation for energy.

The total annualised system cost of the reference system in 2017 amounted to 486 m€. Both FCO sub-scenarios in 2030 manage to bring this cost down to 386 m€ for the eF-I case and 442 m€ for the eF-DP case. While the eF-I scenario cluster can maintain a competitive situation in terms of total cost until it has an installed OTEC capacity of 400 MW, the eF-DP cluster can provide a competitive system with up to 500 MW of OTEC. However, if the LCOFE is considered, neither of the e-fuel options are able to provide a lower cost per energy unit compared to the reference system, though in the eF-I case, the LCOFE markup is within a 5% range for the FCO, as well as 100 MW and 200 MW of OTEC installations. The markup for the eF-DP scenario cluster is at least 18% for the FCO, with an increasing trend. The reason for these opposing results for the total cost and LCOFE is the reduced final energy demand. Even though RE technologies show a significant and promising cost development until 2030, which leads to less total system cost, especially due to the discontinued use of fossil diesel for electricity generation, the energy efficiency mainly of the transport sector with large direct

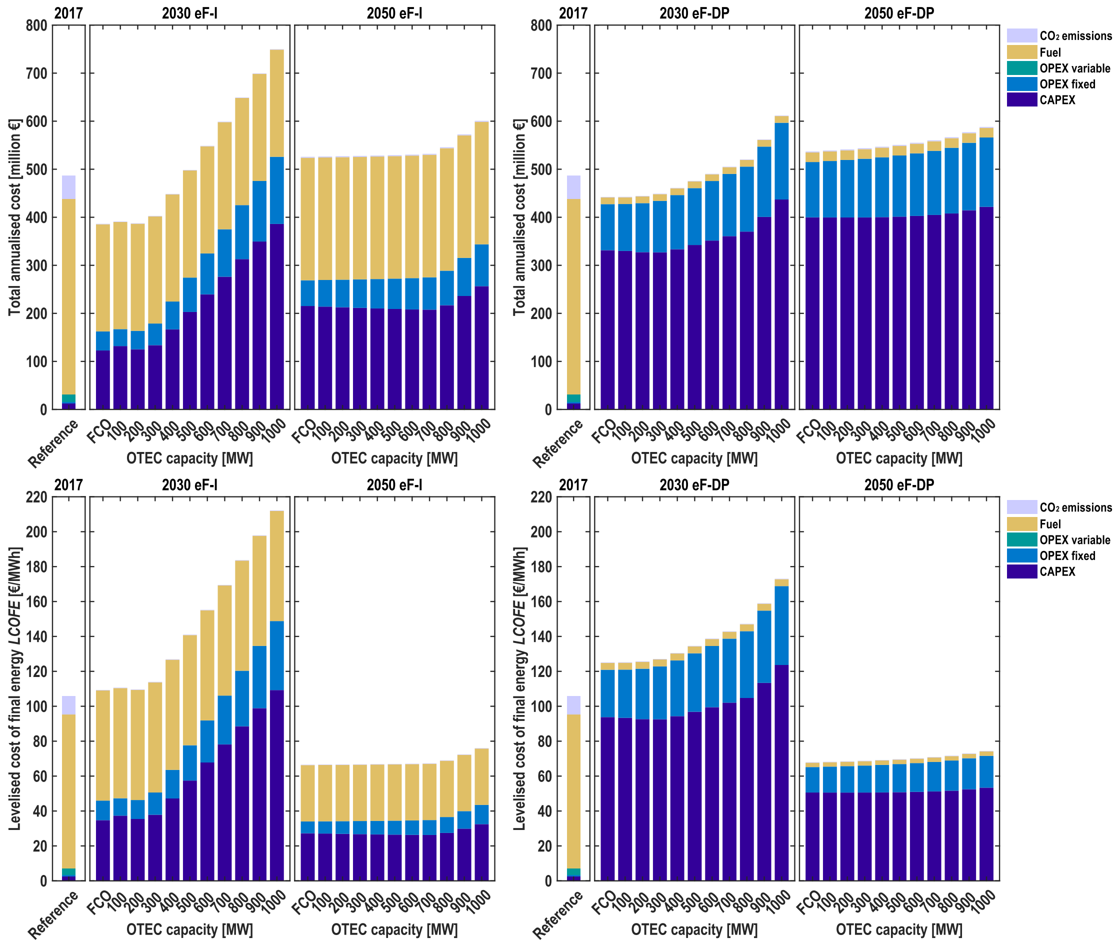

Fig. 6. Total annualised system cost (top) and levelised cost of final energy (bottom) in 2030 and 2050 for the eF-I (left) and eF-DP (right) scenario cluster in comparison to the 2017 reference system.

electrification increases the cost per energy unit. In addition, imported e-fuels are on the edge of being cost-competitive with their fossil counterparts in 2030, as large-scale production and trading of e-fuels are still expected to be in their major ramping phase.

In 2050, however, the opposite development can be seen. While the total annualised system cost surpasses the total cost of the reference system, the LCOFE of the energy system is significantly lower than in 2017. Especially noticeable is the relatively stable LCOFE for increasing OTEC capacities in both scenario clusters. If e-fuels are imported, the total system cost of 526 m€ and LCOFE of 66.5 €/MWh of the FCO increase by a mere 1.1% until an OTEC capacity of 700 MW, before the increase starts to be more significant. The cost increase for domestic production of e-fuels is slightly more prominent. The total FCO cost of 537 m€ or LCOFE of 67.9 €/MWh surpasses a 1% increase with 300 MW

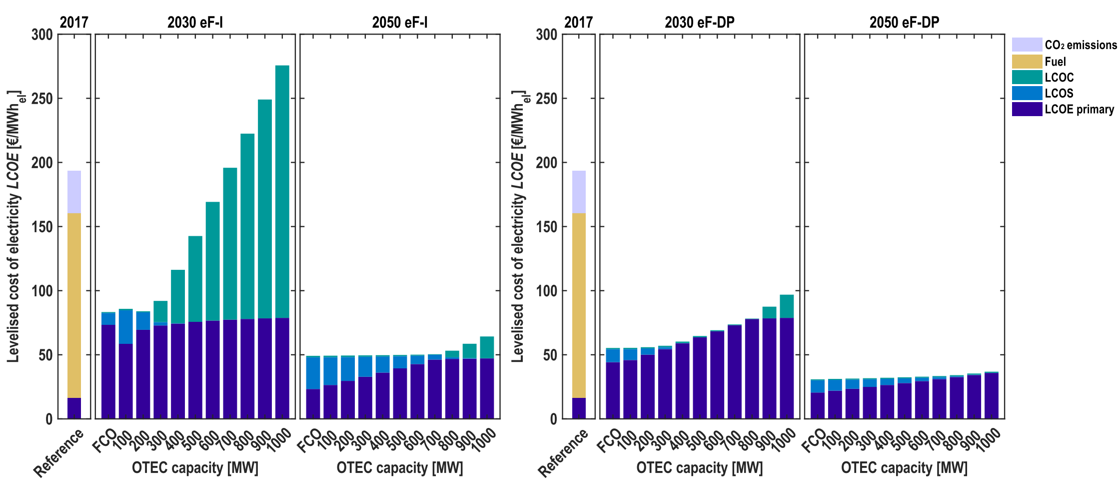

Fig. 7. Levelised cost of electricity in 2030 and 2050 for the eF-I (left) and eF-DP (right) scenario cluster in comparison with the 2017 reference system. Abbreviations: LCOS – levelised cost of storage; LCOC – levelised cost of curtailment.

installed OTEC capacity, 2% at 500 MW, and 5% at 800 MW.

4.4. Levelised cost of electricity

Future energy systems will undergo major direct or indirect electrification, especially in the transport sector via battery electric vehicles, or e-fuels as an option for indirect electrification, as well as e-chemicals in countries with respective industries [71]. Fig. 7 shows the LCOE of the 100% RE system of the Maldives in the context of OTEC capacity implementation. The method for calculating the LCOE is described in supplementary material 1, note 6.

Due to the major share of diesel-based electricity generation, the LCOE in 2017 was 193.3 €/MWh$_{el}$. The fuel for power generation made up 144.0 €/MWh$_{el}$, or 74.5% of the total LCOE. If no major overcapacity is realised in the system, the LCOE can be significantly reduced. In case of the eF-I scenario cluster, in 2030, the LCOE can be kept between 83.3 €/MWh$_{el}$ and 85.8 €/MWh$_{el}$ for the FCO and OTEC capacities of 100 MW and 200 MW. In 2050, the LCOE is stable, between 49.2 €/MWh$_{el}$ and 50.4 €/MWh$_{el}$ for the FCO and for OTEC capacities up to 700 MW. After these capacity thresholds, the overcapacity of OTEC in the system has a significant impact on the LCOE, as the cost of electricity is then gradually more driven by the levelised cost of curtailment (LCOC). The overcapacity drives the excess electricity, which in the case of this study is interpreted as curtailment as no transmission lines are available to neighbouring countries, and in return increases the cost of electricity used in the system.

In the eF-DP scenario cluster, the cost is not as stable as in the import scenarios. In 2030, the LCOE gradually increases from 55.3 €/MWh$_{el}$ to 78.2 €/MWh$_{el}$, after which overcapacity is present, as indicated by the increasing LCOC. However, in 2050, the LCOE is more stable and increases from 30.9 €/MWh$_{el}$ in the case of the FCO to 36.8 €/MWh$_{el}$ for 1000 MW of installed OTEC capacity. The LCOE stability has two main reasons. The first is that the stable electricity generation of OTEC decreases the requirement for energy storage. Therefore, the higher LCOE of OTEC compared to the other more dominant RE technologies (cf. Table S4, supplementary material 1, note 5) is compensated by a decreasing levelised cost of storage (LCOS). In the case of the eF-DP scenario cluster, the increased electricity demand for e-fuel production leaves more space for increasing the OTEC capacity without risking high curtailment; therefore, the LCOE increases with the OTEC share in electricity generation. This is more significant in 2030 than in 2050, as in the latter, OTEC still plays a subordinate role in a system strongly dominated by low-cost electricity from solar PV.

The LCOE of the different RE technologies underpins the dominant low-cost potential of solar PV in the Sunbelt. Nevertheless, OTEC has a great potential to become another option for Sunbelt regions, especially island states, as the LCOE also shows a promising development by 2050. This makes OTEC a superior option against wave power and offshore wind, as both options suffer from relatively low resource availability near the equator.

5. Discussion

In the following discussion, several results of this study are put into context with available literature and discussed in a broader context, such as the option for energy source diversification, the comparison of LCOE for OTEC, the environmental impact of the technology, and the competitiveness of OTEC compared to other options.

5.1. Renewable energy technology diversification

The structured sensitivity analysis made in this study showed that in a cost-optimised system, it will be hard for OTEC to compete with other low-cost options, such as solar PV. An important aspect, besides the mere economic optimisation of energy systems is the issue of energy security. Among the many dimensions included in the definition of energy security, diversity is an important aspect [72].

The case of diversity in this context applies to the diversity of fuels, though in this case in the form of either imported fuels or domestically produced fuels, and the diversity of sources. Being dependent only on imported fuels makes fuel-importing countries especially vulnerable to volatility in the global fuel market. This problem is accelerated if monopolies exist. This lesson had to be learned in an unfortunate way due to the recent developments after Russia's invasion of Ukraine [73,74]. Even though the interpretation of results of this study finally concludes that e-fuel import is a more economically viable option for the Maldives, a diversification of fuel availability as a mix of domestically produced e-fuels and imported e-fuels could provide additional security and resilience against external developments. The second aspect of energy security, the diversity of sources, or more specifically, the diversity of RE technologies in a 100% RE system, is similarly important. Techno-economic optimisations of energy systems as the primary target function in the Sunbelt tend to almost rely on solar PV entirely, as shown in this study for the FCO sub-scenarios. Diversification cannot be quantified, however, several studies have discussed the advantages of a more diverse RE technology portfolio, e.g., Ahmed et al. [75] in the case of Nordic countries, Aslani et al. [76] for Finland, Aghahosseini et al. [77] via a transition pathway comparison, or Keiner et al. [46] in the context of structured sensitivity analysis for the Seychelles, even though it might not be the cost optimum. Furthermore, the emerging Modelling-to-Generate-Alternatives (MGA) approach, as implemented in energy system models like PyPSA [78], LUT-ESTM [79,80], and Calliope [81,82], or done with EnergyPLAN [83], allows for the exploration of near-optimal, but diversified energy system configurations. This might entail some hindrance for economic growth especially for low-income countries, in the context of diversifying the energy system from fossil fuels to RE if no long-term policy strategies are in place [84]. Similar research providing evidence in the context of diversification in 100% RE systems has yet to be done.

5.2. Comparison of levelised cost of electricity

Between 2030 and 2050, OTEC's nominal LCOE on the Maldives decreases from 82.3 €/MWh$_{el}$ to 49.7 €/MWh$_{el}$ in this study due to the cost reductions from technological learning. The latter LCOE matches well with the 2050 LCOE of 49.4 €/MWh$_{el}$ (original value: 61.7 USD (2018)/MWh$_{el}$) for Indonesia by Langer et al. [45]. Most of the other studies mentioned in the literature review (cf. section 2) do not consider technological learning. Without these cost reductions, the nominal LCOE of OTEC on the Maldives becomes 102.2 €/MWh$_{el}$. This is well within the ranges reported by Farhan et al. of 58.3–158.3 €/MWh$_{el}$ for Pakistan and by von Jouanne and Brekken [38] of 83.3–150 €/MWh$_{el}$, and close to findings from other studies, like 90.8 €/MWh$_{el}$ by Rahmawati et al. [20] for Indonesia and 125.0 €/MWh$_{el}$ by Adesanya et al. [26] for Nigeria. For the Maldives specifically, the learning-adjusted LCOE in this study is much lower than the average LCOE of 162.8 €/MWh$_{el}$ (original value: 203.5 USD(2021)/MWh) in Langer and Blok [33], where pyOTEC was first demonstrated. This is because the latter study did not account for an increased future electricity demand from electrification and sized the OTEC plants for 70.4 MW instead of 136 MW as in this study, leading to lower cost reductions from economies of scale. Furthermore, a real discount rate of 10% was used in contrast to the nominal rate of 7% used in this study. Acknowledging the high uncertainty of OTEC's costs, location-dependent aspects like seawater temperature, as well as methodological differences, e.g., in demand forecasting and discounting, the LCOEs calculated in this study are well-embedded in the current body of literature.

OTEC is currently only limitedly addressed in the energy system modelling literature (cf. section 2). Consequently, the key findings of this paper, namely the reduced need for generation and storage capacity through OTEC but also its limited cost-competitiveness against offshore floating PV, could not be validated with other studies and therefore necessitate additional future research. This is important as long-term cost modelling, as done in this study on the case of the Maldives, in combination with a structured sensitivity analysis of the system-integrated technology is indispensable for assessing the future role of this promising technology in respective energy systems. Wave power or a combination of wave power and OTEC in this system context, only has a small to no cost advantage in particular cases. A more detailed discussion on the alternative scenarios is provided in the following subsection.

5.3. Ocean area demand and environmental impact

The advantage of ocean energy technologies is that they do not require valuable land area, which is particularly scarce on islands. On the Maldives, the situation is even worse, as land is basically not available and is probably one of the most valuable, as land is already threatened by climate change and land reclamation is an ongoing adaptation strategy [85]. Land reclamation is a mature and widespread procedure for densely populated areas on the Maldives and is not considered very costly; however, the situation for remote islands is the opposite [86].

As discussed by Keiner et al. [11], about 45,404 km^2 of sea area of the total territorial area would be available if excluding land area and atoll reefs [10]. A total of about 623 km^2 of marine and coastal area is under protection in the Maldives [87]. However, as not all available sea areas might be suitable, the power densities of ocean technologies are still of importance. Offshore floating PV has the highest power density of 100–200 MW/km^2 [88], wave power arrays can reach 14.8 MW/km^2 [61], and offshore wind power can reach 10 MW/km^2 [89]. Langer and Blok [33] used a simplified gross area of 9×9 km^2 for a single OTEC unit based on the spatial resolution of the underlying seawater temperature dataset used by pyOTEC, which leads to a capacity density of ca. 1.7 MW/km^2 for the 136 MW plants on the Maldives. However, Langer and Blok [33] point out that an even larger spacing might be necessary to account for the availability of cold-water resources [90] and local environmental pressures exerted by OTEC [91], amongst others. Despite the low capacity density of OTEC compared to other ocean energy options, in all cases, the used gross ocean area could be kept below 1.5% (cf. supplementary material 1, note 6). If considering only the net area demand, i.e., the area occupied by the floating OTEC platform, the area demand would drop significantly, and the required net area demand would be insignificantly low. Therefore, the environmental impact of the area occupation of floating offshore technologies is rather minimal. Nevertheless, the technologies will require mooring and anchoring in the sea bed, which could locally disturb marine life [92]. In any case, the technologies must be designed to withstand extreme weather events like tropical storms or the monsoon season to avoid any damage to the environment.

5.4. Competitiveness of ocean thermal energy converter and research outlook

So far, OTEC's economic performance has mainly been assessed from a technology perspective in the literature. This study highlights the importance of zooming out to an energy system level as new insights are revealed that would not come to light by the mere comparison of the LCOEs. For the Maldives, it is shown that 241.6 MW of OTEC are cost-effective in 2030, despite OTEC's LCOE being higher than that of floating PV coupled with battery storage and electrolysers. However, the expected rapid cost decline of the latter technologies would push OTEC out of the system by 2050. Thus, OTEC's future does not only depend on its own development but also on the development of its competitors.

The historic decline of solar PV and battery storage costs has been unprecedented, and following current projections [62], the global energy systems of the future will be based mainly on these technologies [79]. However, while the costs of solar PV and battery storage will decrease with high confidence wherever they are deployed, it is less clear how future costs will vary per region. In IRENA's 2022 cost projection report, utility-scale PV CAPEX ranged from 469 €/kW_p (640 USD (2022)/kW_p) in India to 1397 €/kW_p (1905 USD(2022)/kW_p) in Japan due to location-specific cost drivers and technologies' local maturity, as well as different technologies being implemented per region (e.g., optimally tilted, single-axis tracking, and floating solar PV systems) [93]. The dominant solar PV utility-scale market has been below 664 €/kWp (830 USD(2021)/kW_p) in the year 2021, for about 100 GW_p of the 173.5 GW_p total global PV market [94].

For the Maldives, the future costs of solar PV might follow the trend of India given the proximity of the countries, or that of China given the latest political collaboration of the two countries, while both India and China represent the least cost markets in the world [94]. On islands further away from such low-cost regions, local costs might decrease at a slower rate for solar PV and battery storage, which might render OTEC cost-competitive by 2050, provided the technology matures by then. This will be challenging considering OTEC's current pre-commercial stage and kW-scale pilots. For full-scale commercialised OTEC to materialise by 2050, global growth rates akin to the historic rates of PV and wind power are required, which can only be achieved via strong and sustained global support [45]. Albeit theoretical in nature, the scenarios investigated in this paper show that such global efforts could be worthwhile as OTEC would reduce the need for generation and storage capacity. Moreover, OTEC would add resilience to the energy system and secure energy supply in years where annual solar irradiation is lower, e.g., due to prolonged monsoon periods. Beyond electricity production, OTEC offers further benefits, like mariculture, as currently being tested by a pilot plant in Okinawa, Japan [95], as well as freshwater production, e.g., via open-cycle OTEC [23]. These co-benefits might further accelerate OTEC's development as it would cover the water-food-energy nexus essential to island communities, making use of this unique advantage among RE technologies.

6. Conclusions

This study conducted a structured sensitivity analysis for the energy system integration of ocean thermal energy converters on the case of the Maldives. The linear optimisation tool EP-ALISON-LUT was used in combination with the EnergyPLAN energy system simulation model. A total of 122 scenarios comprising free cost optimisations and forced ocean energy technology capacities have been assessed. While focussing on the main scenario set, including ocean thermal energy converters, additional results for wave power, an ocean thermal energy converter, and wave power combination are provided. Two main scenario clusters for the import of e-fuels and domestic production of e-fuels have been assessed for 2030 and 2050. A detailed techno-economic modelling approach for ocean thermal energy converters in the Maldives is provided.

The results indicate a rather limited role of ocean thermal energy converters in the free cost optimisation sub-scenarios, though in 2030, ocean thermal energy converters are part of the free cost optimisation in the case of e-fuel import. Even though ocean thermal energy converters are most promising in areas with warm seawater temperatures in the Sunbelt, cost-competitiveness is basically impossible to reach due to very low-cost solar photovoltaics, if capacity is not limited, e.g., via offshore floating photovoltaics. Nevertheless, ocean thermal energy converters are able to reduce the energy storage requirement due to year-round stable electricity generation. This has the effect of keeping the total annual system cost, levelised cost of final energy, and levelised cost of electricity at a stable value with a minor cost increase for preset ocean thermal energy converter capacities. If importing e-fuels, in 2030 up to 200 MW of ocean thermal energy converter capacity can be installed without major curtailment, keeping the levelised cost of electricity between 83.3 €/MWh_{el} and 85.8 €/MWh_{el}. In 2050, up to 700 MW of ocean thermal energy converter capacity does not lead to major electricity curtailment with levelised cost of electricity of 49.2 €/MWh$_{el}$ and 50.4 €/MWh$_{el}$. If producing e-fuels domestically, up to 800 MW of ocean thermal energy converter capacity can be installed for a range of levelised cost of electricity of 55.3 €/MWh$_{el}$ to 78.2 €/MWh$_{el}$. In 2050, the levelised cos to electricity can be kept within a range of 30.9 €/MWh$_{el}$ in the case of the free cost optimum to 36.8 €/MWh$_{el}$ for a theoretically installed 1000 MW of ocean thermal energy converter capacity.

As a conclusion, this technology can play a vital role for the diversification of the renewable energy technology portfolio, increasing energy security for small island nations and small island developing states, and be an attractive solution for the Maldives and countries with similar conditions. However, this study showed that such energy systems with a major share of ocean thermal energy converters in generation technologies will most probably not be the most economic option.

It might not be possible to set up large-scale production capacities for ocean thermal energy conversion until 2030 or 2050 to make it a major player for the energy transition by 2050 for respective countries. Since there are alternatives established, such as wave power and offshore floating solar photovoltaics, area-limited island states are not hindered in their sustainable development. Especially the fast-growing solar photovoltaic industry can be estimated to be able to provide enough capacities for a fast and low-cost energy transition for small island developing states.

CRediT authorship contribution statement

Dominik Keiner: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Jannis Langer:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Ashish Gulagi:** Writing – review & editing, Validation, Formal analysis. **Rasul Satymov:** Writing – review & editing, Validation, Resources. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.133620.

Data availability

No data was used for the research described in the article.

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