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Optimizing energy futures in the Maldives: A study of Ocean Thermal Energy Conversion technology energy Mixes

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ABSTRACT

Ocean Thermal Energy Conversion (OTEC) offers a stable baseload renewable energy source for Small Island Developing States (SIDS), reducing reliance on fossil fuels by harnessing the ocean's temperature gradient. Despite its potential, OTEC remains underdeveloped due to high capital costs and limited integration into SIDS-specific energy models. This study evaluates OTEC's feasibility, developing energy mix scenarios that incorporate OTEC, solar PV, waste-to-energy, and battery storage. Using a high-resolution bottom-up energy system model, it explores transition pathways (2025–2055), assessing OTEC's role in achieving a 100 % renewable system. Findings validate OTEC's technical and economic viability in the Maldives, achieving a low Levelized Cost of Electricity (LCOE) of 0.15 USD/kWh in fully renewable scenarios, where it provides reliable baseload power. The OTEC60 scenario, with 57 % renewable energy penetration, maintains the same low LCOE while minimizing capital costs. Sensitivity analysis identifies fuel prices and OTEC capital costs as key factors, highlighting the need for cost reductions. Carbon pricing disincentivizes fossil fuel use, making full renewable adoption more viable over time. These results position OTEC as a resilient energy solution for high-demand islands, providing policymakers with actionable insights for sustainable energy transitions in SIDS.

1. Introduction

The Maldives, like many Small Island Developing States (SIDS), faces significant challenges in transitioning to sustainable energy due to its heavy reliance on imported fossil fuels, high energy costs, and climate vulnerabilities. Despite efforts to achieve United Nations Sustainable Development Goal 7 (SDG7), which promotes universal access to clean energy, the country remains 8.3 % behind in SDG progress [1]. These challenges are compounded by heavy reliance on imported fossil fuels, high energy costs, energy insecurity, and susceptibility to climate change impacts such as rising sea levels, coastal erosion, and extreme weather events [2]. The country's reliance on imported fossil fuels is costly, consuming 13.5 % of its gross domestic product in 2023, making electricity expensive and vulnerable to price fluctuations. However, renewable energy adoption has been slow due to high upfront costs, grid integration challenges, and dependence on subsidies that make fossil fuel artificially cheaper [3].

Due to its dependence on fossil fuels, the Maldives has one of the highest per capita CO_2 emissions among SIDS, reaching 3 tCO_2/capita annually [4]. To address these concerns, the Maldives Energy Roadmap (2024–2033) [3] presents an ambitious yet necessary transition plan toward a low-carbon energy future. The roadmap aims to achieve 33 % renewable electricity generation by 2028, emphasizing solar PV expansion, regulatory reforms, and infrastructure modernization. While the roadmap acknowledges ocean energy and waste-to-energy as potential resources, there is a lack of feasibility and techno-economic analysis. The primary strategy for achieving carbon neutrality in the near term relies on floating solar PV installations, a challenging approach given that only 1 % of the country's territory is land with the rest open ocean, raising concerns about feasibility, costs, and long-term scalability. Land scarcity limits large-scale solar farms, while rooftop PV alone cannot meet rising demand. Onshore wind is constrained by low wind speeds (<6 m/s) [5], limited space, and noise concerns. Additionally, solar and wind variability pose grid stability challenges, requiring costly battery storage and grid upgrades.

A major limitation of the roadmap is the lack of integration plans for Ocean Thermal Energy Conversion (OTEC), despite the Maldives' ideal oceanic conditions for its deployment. Unlike intermittent solar and wind energy, OTEC offers a stable and continuous baseload power source, making it particularly valuable for energy security and grid stability in isolated island nations. By harnessing the temperature

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Glossary

SDG	Sustainable Development Goals
OTEC	Ocean Thermal Energy Conversion
SIDS	Small Island Developing States
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
CAPEX	Capital Expenditure
HOMER	Hybrid Optimization Model for Electric Renewables
GEBCO	General Bathymetric Chart of the Oceans
STELCO	State Electric Company Limited
RES	Renewable Energies Synergistic

difference between warm surface water and cold deep ocean water, OTEC can provide continuous operation, independent of weather variability as sea temperatures remain stable. However, OTEC remains underexplored in Maldives-specific energy models. Current techno-economic models of OTEC focus either on large-scale offshore OTEC feasibility [6–8], while onshore pilot plants are of smaller scale simulations (<1 MW) [9,10] due to infrastructural constraints. Previous research has primarily examined theoretical OTEC potential (e.g., La Réunion [11] and Kiribati [12]) or its role in supply security [13], energy storage [14], and cost feasibility [15–17]. However, many of these studies overlook the critical challenges of practical grid integration, which are necessary for designing resilient, island-based energy systems.

This gap is particularly concerning given that the Maldives Energy Roadmap, while setting a short-term goal of 33 % renewable generation by 2028, lacks a clear long-term strategy for achieving full carbon neutrality or energy autonomy beyond 2033. A key issue in this transition is that renewable energy (RE) capacity is not the same as RE utilization. The capacity factor for solar and wind in the Maldives is expected to remain low due to intermittency, weather dependence, and space constraints. Solar PV in the Maldives has an estimated capacity factor of 15–18 % [18], meaning a 100 MW solar farm would generate, on average, only 15–18 MW of continuous power. Onshore wind fares even worse, with low wind speeds (<6 m/s) limiting capacity factors to below 25 % [19]. As a result, high installed capacity does not guarantee proportional energy availability, requiring substantial energy storage or backup fossil fuel generation to ensure grid reliability.

Given these limitations, scenario analyses integrating baseload sources like OTEC are essential. Unlike solar and wind, OTEC provides continuous, predictable power, reducing storage needs. Considering the global trend toward carbon neutrality and the advancement of OTEC technology, scenario analyses—especially those focused on OTEC in the Maldives—are crucial. Thus, the aim of this study is to present a feasibility analysis, develop energy mix scenarios for decision-making, provide baseload power, highlight the benefits of carbon pricing, and offer comprehensive modeling to demonstrate the viability of energy independence and transition pathways.

Specifically, this research:

1. Develops energy mix scenarios (2025–2055), incorporating OTEC, solar PV, wind power, waste-to-energy, and battery storage under different transition pathways.
2. Evaluates the technical, economic, and environmental feasibility of OTEC implementation.
3. Conducts high-resolution temporal energy modeling to assess long-term impacts on supply-demand stability.
4. Analyzes carbon pricing mechanisms to determine their role in accelerating the energy transition.

The findings provide a relevant blueprint for SIDS facing similar energy security and climate vulnerability challenges, helping policymakers optimize energy mix strategies and transition pathways by integrating OTEC, solar, wind, and storage solutions to the mix. By extending beyond the short-term goals outlined in the Maldives Energy Roadmap, this research contributes a long-term vision for achieving complete fossil fuel independence and a sustainable energy future.

2. Literature review

2.1. The working principles of OTEC

The OTEC technology was introduced by D'Arsonval in 1881. Since then, it is estimated that the resource covers 100 million km^2 across tropical oceans. The system utilizes the temperature difference between the ocean's surface and deep layers to generate electrical power, requiring a temperature gradient of at least 20° [9]. OTEC plants can be categorized into closed cycle, open cycle and hybrid cycle, each with their distinct advantages. The main feature of the closed cycle is the utilization of low boiling point working fluid, such as ammonia, propane, and Freon-type refrigerant, which undergoes heating in an evaporator utilizing the Surface Ocean Water (SOW), the gas then passing through a turbine, converting thermal energy to mechanical energy, and finally to a condenser that uses Deep Ocean Water (DOW) where it is cooled to repeat the cycle. There are several kinds of closed cycle systems, including the organic Rankine cycle [20], Kalina cycle [21] and Uehara cycle [22].

The open cycle OTEC was first introduced by Georges Claude [23], and utilizes the seawater directly as a working fluid. In this system the warm SOW is pumped into the evaporator and converted into steam to drive the turbine, generating power. The steam is then cooled, giving the added advantage of freshwater production. The hybrid cycle combines both the closed and open cycle, where the warm SOW is evaporated to the steam like the open cycle and the working fluid is heated by the steam like the closed cycle. Other hybrid forms of the OTEC system focus on increasing the temperature differential between DOW and SOW by integrating solar [24] and waste heat recovery [25], while others utilize OTEC byproducts [26] in other sectors such as aquaculture for improved economic performance. A summary of OTEC demonstration facilities and their costs are listed in Table 1. The primary components of an OTEC plant, which account for most of the capital cost, include heat exchangers, turbine, cold and warm water pipes, pumps, control and monitoring system, and the working fluid for closed-cycle plants. A detailed list of these components along with their respective prices is provided in Table A. 1.

Under conservative assumptions it has been estimated that OTEC's worldwide maximum power output could be as high as 8000 GW [33]. OTEC's feasibility is intricately tied to geographic considerations as seen in Fig. 1. The cost structure of OTEC involves high initial capital investment for constructing cold water pipelines and heat exchangers. For instance, offshore pipelines require specialized materials to withstand deep-sea conditions, contributing to operational challenges. However, OTEC's operational costs are significantly lower than fossil fuel-based systems due to the absence of fuel costs, and the technology provides long-term economic benefits. With its constrained financial bases, SIDS like the Maldives needs help securing the necessary funding for large-scale OTEC projects. Currently, two OTEC pilot facilities exist globally [34], in Hawaii and Japan [35], each featuring approximately a modest 100 kW net power capacity. These facilities focus on research and development, emphasizing the co-benefits of OTEC, such as desalination and aquaculture that utilize the deep ocean water. This highlights a significant disparity in the distribution of OTEC testing and pilot projects, with SIDS often unable to initiate such financial endeavors due to financial constraints. The commercially operational plant in Nauru, operated by a Japanese company in 1981 was the only such endeavor in a SIDS country. It generated 120 kW of electricity and provided insights to the feasibility and operation of the plant until the cold-water intake pipe was damaged in a tropical storm [36,37].

Table 1
Summary of OTEC demonstration facilities, their costs and challenges.

Project, Location	Year	Gross Power (kW)	Installation Cost (USD)	Operational challenges	Lifecycle challenges	Reference
Claude, Cuba	1930	22	Not specified	Not specified	Early experimental design; faced technical challenges due to the nascent state of technology at the time.	[27,28]
Mini OTEC, Hawaii	1979	53	Not specified	Not specified	Demonstrated feasibility; limited by small scale and short operational period.	[29]
OTEC-1, Hawaii	1980	1000	Not specified	Not specified	Served as a test platform; provided data but was not intended for long-term operation.	[30]
Toshiba & TEPC (Japan), Nauru	1982	120	Estimated at $10 million (adjusted for inflation)	High due to pipeline maintenance and energy-intensive pumping.	Short operational lifespan; high capital and operational costs; lack of long-term government support; technical challenges with early-stage technology.	[31]
Saga University, Japan	1984	75	Not specified	Not specified	Academic research facility: contributed to technological advancements but not commercialized.	[32]
NELHA Open Cycle, Hawaii	1992	210	Not specified	Not specified	Demonstrated open-cycle OTEC; faced challenges with biofouling and system efficiency.	[32]
Saga University, Japan	1995	9	Not specified	Not specified	Continued research efforts; provided insights into small-scale OTEC applications.	[32]
NELHA, Hawaii	1996	50	Not specified	Not specified	Furthered research in OTEC technology; limited by small scale.	[32]
NIOT, India	2000	1000	Estimated at $10–$15 million	Not specified	Project remained incomplete; faced challenges with deep-water pipe deployment.	[30]
Naval Group, La Reunion Island	2012	15	Not specified	Not specified	Aimed to develop sustainable energy solutions; specific lifecycle challenges not documented.	[32]
KRISO, South Korea	2012	20	Not specified	Not specified	Served as a prototype; provided data for future larger-scale projects.	[32]
Kumejima, Japan	2013	100	Estimated at $3.5–$4 million	Moderate; benefits from integration with aquaculture and cooling applications.	Challenges with cold-water pipe deployment in typhoon-prone regions; maintenance of integrated systems; ensuring economic viability through multiple revenue streams.	[30]
NELHA, Hawaii	2015	100	Estimated at $5 million	High due to deep seawater pumping (~30 % of total energy output); maintenance and biofouling management.	Pipeline maintenance and biofouling; high operational costs due to energy-intensive pumping; need for integration with byproducts like desalination to improve economic feasibility.	[31]
K-OTEC1000 Barge (KRISO), South Korea	2019	338–1000	Estimated at $15–$20 million	Expected to be lower due to design improvements in heat exchangers and pumps.	Designed for scalability; challenges include offshore deployment and maintenance.	[31]

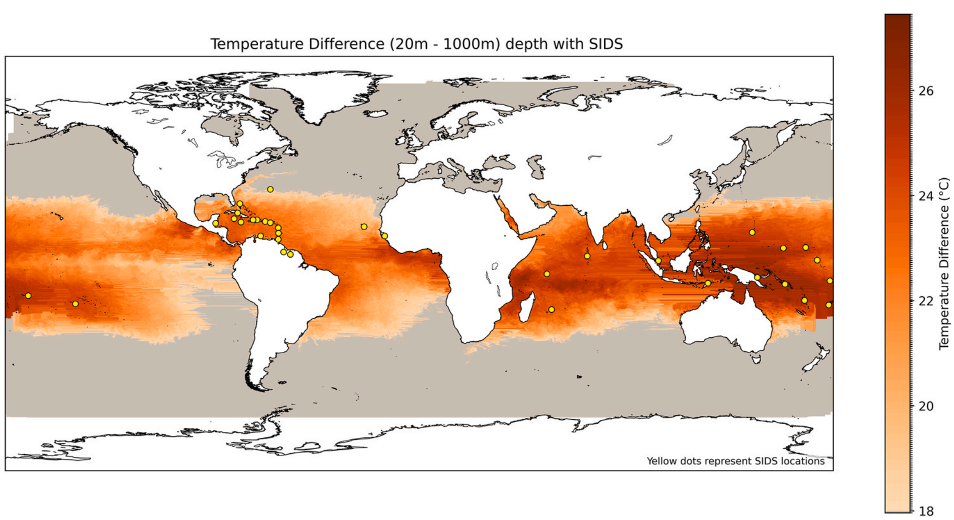

Fig. 1. Mean Annual Temperature difference between the typical OTEC depths of 20 and 1000 m. Data obtained from [38,39]:

2.2. The context of the Maldivian energy system

The Maldives is an archipelago of 1192 islands spanning 870 km North to South of the Indian Ocean, exhibiting a distinctive geographical and demographic profile. Predominantly characterized by its marine expanse, which accounts for 99.6 % of the total area, the land area is a mere 298 km^2. Situated within the sunbelt, the Maldives experiences tropical and warm temperatures throughout the year. As of the year 2022, the population of Maldives stands at 515,132 [40]. The dispersed nature of the islands, ranging in size from 1 to 2 km^2, contributes to population distribution across 187 administrative islands, each accommodating an average population of approximately 1000 individuals. Presently, the nation has achieved 100 % electrification. However, each island is an autonomous mini-grid with a diesel-based generation system and an independent distribution system. The distribution systems on smaller islands employ low voltage at 400 V, while larger islands are equipped with medium voltage 11 kV distribution systems. With a notable economic reliance on tourism, constituting 21 % of the GDP

[41], the Maldives encompasses 200 resort islands, each possessing discrete and isolated energy grids. The initiation of local tourism in 2010 has precipitated additional development on the locally inhabited islands, subsequently driving an increase in energy demand, as portrayed in Fig. 2.

The country imports oil to meet the demands of its primary energy sectors, and in the year 2020, the import of oil products is shown in Table 2. Imported diesel makes up 84 % of oil imports and is mainly used for electricity and transport.

Based on the census data, in the past 22 years, the country has seen a steady urbanization rate, and the most significant population density is found in the capital city, Malé, where 41 % of the inhabitants reside [44]. This study will focus on this area as the highest demand in the country is found here, with an energy demand of 65 MW peak in 2019, as seen in Fig. 3. The energy demand has steadily increased with the country's economic activity. The dip in 2020 is due to the adverse effects of coronavirus disease (COVID-19), after which the demand continues to rise again.

In 2021, the islands of Malé and Hulhumalé were interconnected via a 132 kV high-voltage line, creating the country's singular primary grid. Despite the country's substantial PV potential, only 1 % of the final energy is generated from renewable resources [4]. Originally aspiring to achieve SDG7 by 2030, the government revised this goal to attain 30 % of daytime peak load through renewables due to a lack of progress in carbon neutrality [45]. The main challenges impeding this goal are the limited land availability [45], technological constraints [46], storage capacity requisites owing to the intermittent nature of renewables [47], high initial investment costs [48], and inefficiency in risk analysis [49].

According to the IRENA report [19], the Maldives exhibits considerable potential for OTEC and should analyze the economics of this technology. This is further verified by Langer et al. [17] in a global techno-economic analysis which estimates a significant electricity generation capacity of 5.24 GWh/km^2 through OTEC in the country [50]. Efforts such as the Bardot Groupe's planned 300 kW OTEC plant and Global OTEC's feasibility study highlight progress but face challenges, including scaling capacity and adapting to local conditions [50]. A 150 kW OTEC demonstration barge was expected to be deployed in 2021, targeted for the island of Fenfushi, an island with a peak load of 362 kW in 2021. Collaborating with the University of Exeter, Global OTEC addressed challenges associated with offshore OTEC platforms in the Maldives, employing hindcast datasets from global weather to analyze environmental conditions comprehensively [51].

Based on this background, it is necessary to analyze the utilization of OTEC in Maldives and comprehend the synergies between the different generation methods that can be employed in the country. As a country with an extreme reliance on fossil fuels, it is essential to understand the financial impact of an OTEC plant and how it will affect the energy system. The following section will investigate to answer these questions through an effective energy modeling system.

Table 2
Import of oil products for the year 2020 [43].

Items	Qty/toe
Kerosene	8
Lube Oil	2671
Gasoline	58,639
Diesel	516,108
Aviation Gas	21,827
LPG	13,124
Total	**612,377**

3. Methodology

3.1. Resource mapping

Renewable energy resources and consumption patterns vary significantly based on several factors, including land topology and climate conditions in distinct regions. Hence, resource mapping is essential to understanding the technical feasibility of island resource planning. Although developed in the early 2000s, the Renew's Island [52] methodology is simple and effective for assessing resources. The yearly solar and wind resources potential are from the National Renewable Energy Laboratory database. This data is used due to its rigorous data collection standards and long-term records. For areas that are not directly measured, the Ångström's relationship between irradiation and sunshine is utilized to obtain an estimation. The study island Malé, with coordinates 4.1755° N and 73.5093° E, receives an annual average solar global horizontal irradiance of 5.23 kWh/m^2/day [53]. Based on the island's topography, no hydro, geothermal, or fossil fuel resources exist. Due to the sparse vegetation on inhabited islands where land is cleared for residential buildings, biomass is not used for energy-intensive work.

There is a need to assess the ocean resource availability for the island, especially in terms of OTEC. Fig. 4 (a) depicts the temperature profile obtained from bathymetric data close to the island, showing that the required temperature difference can be achieved. The OTEC resource data is necessary for energy system modeling. Hence the temperature profile for the area is downloaded from Hybrid Coordinate Ocean Model [39], and the yearly resource data and price is calculated for a 30 MW OTEC plant according to the method given by Langer et al. [54]. The main parameters used in the calculation are given in Table A. 2 and are taken from Ref. [54]. A 30 MW plant was chosen as it is the baseline demand of the island. The resource data is depicted in Fig. 4 (b). The waste to energy resources is taken from a project run for energy recovery from waste produced on the island. This is currently underway and is expected to be a 13 MW waste-to-energy plant. The project is to be implemented in three phases, with the development of the required

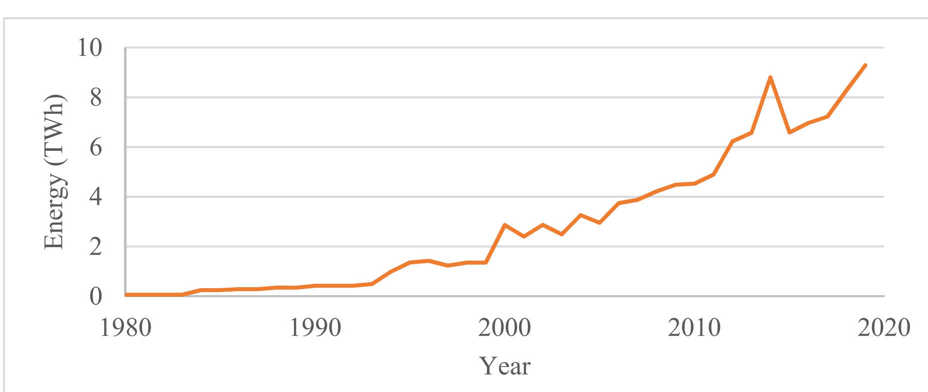

Fig. 2. Primary energy consumption in the Maldives [42].

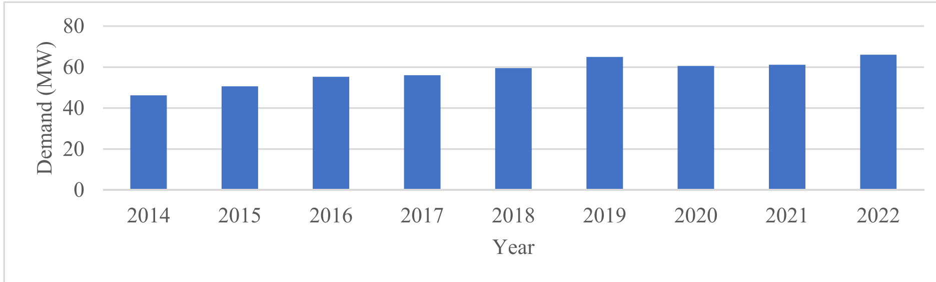

Fig. 3. Yearly Peak Demand of Malé [Data obtained from State Electric Company, Maldives].

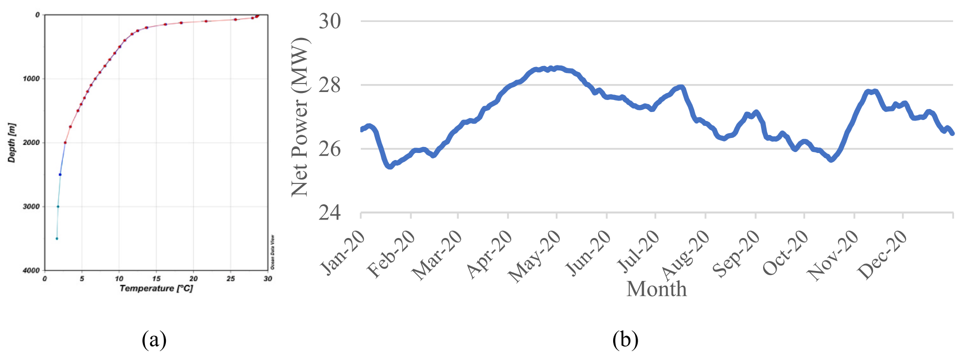

Fig. 4. (a) Temperature profile based on depth near Malé shore (b) yearly OTEC resource variation for a 30 MW net power plant for the Maldives.

infrastructure being the first. The plant is expected to run continuously, transporting waste to the facility from nearby islands.

3.2. Demand estimations

Electricity demand projections for the next 30 years have been estimated using historical electricity consumption data obtained from the State Electric Company Limited (STELCO), alongside population and urbanization rate projections derived from census data as seen in Fig. 5.

Using these datasets spanning from 2007 to 2020, historical daily demand was obtained from the utility company, State Electric Company and analyzed to ensure the reliability and validity of the demand forecast. It is noted that in Maldives, the luxury tourism sector operates as self-contained resorts and marinas, having an independent power and water generation. Hence, the demand of Malé is not significantly affected by the tourist arrival as seen from Fig. 5. However, seasonal variations can be observed in electricity generation with demand peaking at the hot monsoon season of April and May. Overall, the energy demand is increasing year by year with an influx in population from outer islands to the central area. A linear regression model was developed to establish the relationship between population size and energy demand. The model was constructed using historical annual energy demand and population data, with the equation:

$$E_{demand} = \alpha Population_{size} + \beta \quad (1)$$

Where $\alpha = 1455$ represents the rate of change in energy demand with respect to population size, and $\beta = 63493683$ represents the baseline energy demand independent of population. The analysis yields an 83 % R square value showing robustness and strong correlation between population and energy demand. Subsequently, the function is used to predict the demand for the years 2025 and 2055 with population projections obtained from census data. The results are summarized in

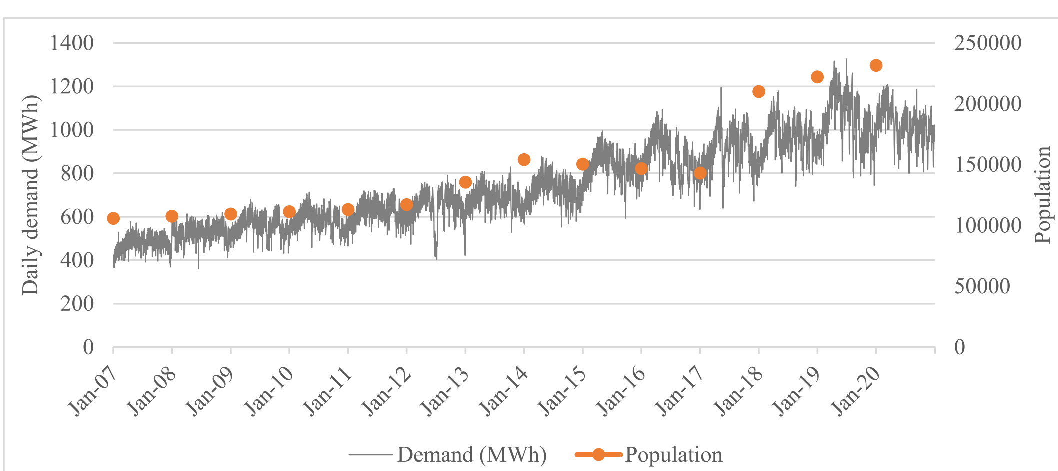

Fig. 5. Historical daily demand and population from 2007 to 2020 obtained from State Electric Company and census data [55] for Malé.

Table 3
Population and Electricity demand estimations.

	2025	2055
Population in Malé	263,814	514,159
Average Electricity Demand	1.23 GWh/day	2.22 GWh/day

Table 3 and show a 3 % increase year by year in the demand from 2020 until 2055. Historical data further demonstrate a strong correlation between urbanization rates and peak electricity demand, emphasizing the relevance of urbanization trends in demand forecasting. The hourly electricity demand for the island, measured over a year (as shown in Fig. 6), serves as the basis for baseline hourly demand forecasting, necessary for the energy model's low temporal divisions.

The primary industrial activity on the island is construction, and it is assumed that its energy demand will remain relatively stable due to land constraints and the government's current development plans. Given these limitations, a significant increase in construction-related energy consumption is unlikely. This study does not account for the island's transport sector, as land transport energy demand is relatively low compared to electricity consumption. Gasoline accounts for only 9.6 % of land transport fuel use, while diesel dominates with 84.3 %. Given its predominance, the focus of this study remains on electricity demand. Furthermore, the country's primary transport energy demand arises from sea transport between islands, which falls outside the scope of this paper.

3.3. Modeling method

This study's energy system modeling and optimization are conducted using the Hybrid Optimization Model for Electric Renewables (HOMER) Pro, a software program developed by UL Solutions. It is commonly used for energy modeling and evaluation of off-grid and on-grid power system designs [56]. HOMER Pro was chosen since it is a tool for standalone microgrids presented in the case of islands. It can also simulate the system at low temporal resolutions with different renewable energy resources, as discussed in Ref. [57]. OTEC technology is not built into the tool and must be simulated as a custom technology with custom resources that must be input separately. Before inputting the resource costs, diesel generation costs are separately calculated from data obtained from STELCO, the utility company mentioned above. The calculations are as follows in Table 4.

The cost of the 30 MW OTEC plant was calculated as mentioned before in the resource mapping using the method given in Ref. [54]. The given paper shows the calculation of capital expenditure (CAPEX) for offshore plants. To contextualize the costs of OTEC systems, the case studies of OTEC pilot plants worldwide are presented in Table 1 and the estimated capital costs of OTEC plants taken from Refs. [58,59] are presented in Table 5. These examples provide insights into installation and operational costs, as well as long-term lifecycle considerations. As of 2023, onshore Ocean Thermal Energy Conversion (OTEC) facilities are operational, relying on seawater intake infrastructure, with key demonstrations in Hawaii (NELHA) and Japan (Kumejima). MW-scale facilities require significantly larger intake capacities, driving up costs, especially for onshore systems due to longer intake pipes. Offshore implementation can reduce intake costs but adds expenses for platforms and cables. A 1 MW OTEC facility in Kumejima, Japan, demonstrates the technology's potential. Operating with an annual temperature difference of 21 °C, it achieves a net power supply of 1000 kW. The capital cost, based on a Japanese New Energy and Industrial Technology Development Organization-backed project, is $22 million (adjusted for inflation). Annual operational costs, using long-lasting materials like titanium heat exchangers and autonomous systems, are $145,200, as demonstrated by Okinawa's facility. While high capital costs remain a challenge, onshore OTEC offers low maintenance requirements and efficiency for long-term operation. For OTEC plants, the lifespan is estimated based on the lifecycles of individual components and values referenced in Refs. [15,17,54,60,61]. This approach is necessary as commercial OTEC plants are not yet operational, and the technology has been demonstrated only through a limited number of pilot plants. The length of the required pipelines was modified based on the bathymetric and shoreline profile obtained from the General Bathymetric Chart of

Table 4
Calculation of cost of Diesel Generator Unit.

Item	Total (USD)
Cost of Gensets (7 × 2 MVA) with control panels	$ 2,776,000
Cost of Civil Work	$ 598,000
Cost of Medium Voltage Switchgear	$ 171,600
Cost of cables	$ 215,000
Installation cost	$ 79,000
Diesel Generator Cost/kW	$ 274

Table 5
Estimated capital cost of OTEC plants. Data obtained from: [58,59]. Note: Costs per kW vary based on specific technology choices, particularly the heat exchangers, and whether desalinated water production is included in the calculation. These costs do not include installation and assembly which adds a significant amount to the overall project cost.

Plant Type	Size	Capital Cost (millions USD)	Cost per kW (USD)
Closed Cycle OTEC	10 MW	286.3	21,606–27,012
Closed Cycle OTEC	50 MW	886.9	11,223–16,578
Open Cycle OTEC	10 MW	378.4	33,962–35,697
Open Cycle OTEC	50 MW	1308.6	22,722–24,459
Onshore Open Cycle OTEC	1.36 MW	42.8	31,471

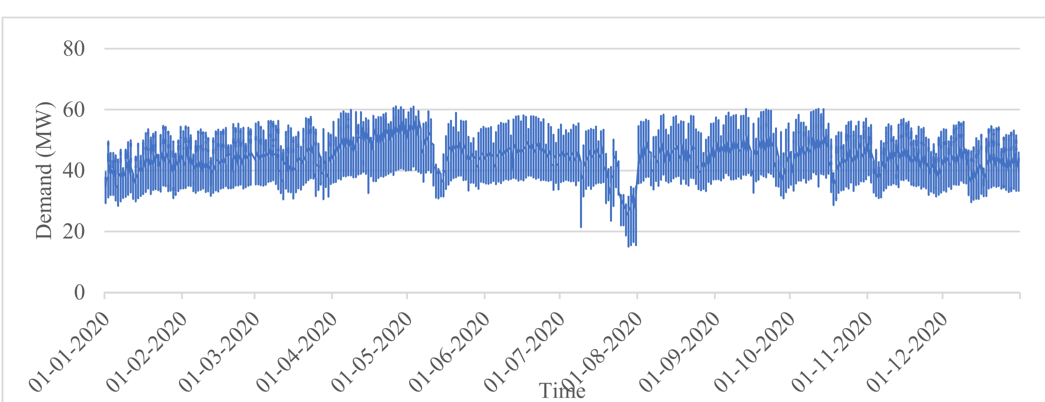

Fig. 6. Hourly demand in Malé for 2020.

the Oceans (GEBCO) [38] for the current powerhouse location at Malé (4.1709° N, 73.5136° E) and is calculated at USD 11750/kW. The project parameters used in the system are presented in Table 6. The modeling software incorporates the lifetimes of various system components, accounting for additional capital costs required to replace components with shorter lifespans. It calculates the total cost of the system over the 30-year project lifespan, factoring in these periodic replacements. While components with residual value at the end of the project are assigned a salvage value, this salvage value is excluded from the cost of energy calculations throughout the project's duration ensuring a comprehensive assessment of costs incurred during the project's operational period.

3.4. Analyzed scenarios

Four scenarios were created to assess the potential of OTEC in the future energy system of Malé. These scenarios are outlined in Table 7, where the different installed capacities are identified. Hourly energy demand profiles are used to estimate the power balance between supply

Table 7
Summary of the generation capacity of each scenario by 2055.

Scenario	PV	OTEC	Waste to Energy	Battery	Diesel
Baseline	6 MWp	–	–	–	150 MW
OTEC30	6 MWp	30 MW	–	–	120 MW
OTEC60	6 MWp	60 MW	12 MW	–	80 MW
100 % RES	6 MWp	145 MW	12 MW	4MVAh	–

Table 6
Parameters used in HOMER Pro simulation.

	Parameter	Value Used	Reference
Project	Inflation Rate	2 %	[41]
	Project lifetime	30 years	Used based on energy modeling studies done for 25–30 years as seen in Refs. [11,62].
	Nominal Discount Rate	3 %	The average of the projected inflation obtained from [41]
	O&M cost increase	2 %/year	[41]
	PV degradation	1 %/year	[63]
	Load increase	2 %/year	Calculated from the population and energy demand model as obtained from data of Fig. 5 and regression equation (1).
	Carbon Price	130USD/ton CO_2	Value obtained from the high scenario used in Refs. [64,65].
Diesel	Diesel Generation CAPEX	$274/kW	Calculation given in Table 4.
	Diesel Generation O&M	$1500/hour	Calculated based on [62]
	Lifetime (hrs)	262,980 hrs (30 years)	
	Diesel fuel price	$1.06/liter	Current market price in Maldives
	Fuel curve	0.25 L/h/kW	[66]
OTEC	OTEC CAPEX	$ 117,000/kW	Calculated using methods given in Ref. [54]. Different cost components available at Table A. 1.
	OTEC OPEX	$ 4,000,000/year	Calculated from Kumejima Deep Ocean Water Industries Report [67]
	Lifetime (years)	30	A lifetime of a conventional power generation turbine [66]
Waste to Energy	Waste to Energy CAPEX	$330/kW	Calculated based on waste-to-energy project price in Ref. [68]. Since the project is conducted in 3 parts, the first part is a 12 MW used in this model. Hence, the price is divided into three parts.
	Waste to Energy OPEX	$40,000/year	
	Lifetime (years)	30	
Solar PV (onshore)	Onshore Solar CAPEX	$535/kWp	Calculated based on [62]
	Onshore Solar OPEX	$10/year/kWp	
	Lifetime (years)	30	
Solar PV (offshore)	Offshore Solar CAPEX	$758/kWp	Calculated based on [62]
	Offshore Solar OPEX	$20/year/kWp	
	Lifetime (years)	25	
	Derating Factor %	96	
Power Converter	CAPEX	$300/kW	[69]
	Replacement cost of converter	$300/kW	
	Lifetime (years)	10	
	Efficiency	95 %	
Storage	CAPEX	$300/kWh	[69]
	Replacement cost of battery	$300/kWh	
	Battery OPEX	$10/year	
	Lifetime (years)	10	

and demand based on the energy mix portfolios. In the three scenarios with OTEC integration, the base power is provided by OTEC with diesel being used to adjust the supply for the hourly demand at each point of time. OTEC integration starts from the year 2025 which is the start of the energy modeling period.

1. Baseline Scenario: This is the business-as-usual scenario with no policy changes by the government. Renewable energy is utilized in the 6 MW solar panels currently installed on the island.
2. OTEC30 scenario: Introduces a 30 MW OTEC plant in 2025, meeting the island's base power demand. Renewable energy includes the 6 MW solar panels from the baseline, with the remaining demand supplied by diesel
3. OTEC 60 scenario: Expands renewable integration with a 60 MW OTEC plant, 6 MW solar, and a 13 MW waste-to-energy system. Diesel generation covers the remaining demand.
4. 100 % renewable energy power generation scenario (100 % RE): Achieves 100 % renewable energy with OTEC as the primary power source. OTEC capacity is added in stages (60 MW in 2025, 30 MW in 2045, and 55 MW in 2050), supported by 4MVAh battery storage for grid stability.

The recommendations for OTEC in Table 7, particularly the 100 % RES scenario with a 90 % OTEC capacity, are not intended as immediate solutions but as exploratory pathways to address Malé's unique energy challenges. While acknowledging the complexities of OTEC deployment, including high capital costs and installation difficulties, the scenarios leverage key advantages of economies of scale and address the severe land constraints and growing energy demand. The phased approach outlined in scenarios like OTEC30 and OTEC60 allows gradual adoption, spreading operational risks and capital investments over time. These recommendations align with global renewable energy targets and consider advancements in OTEC technology to enhance feasibility by 2055. Achieving carbon neutrality is challenging, yet essential, making it imperative to explore viable transition pathways. By integrating OTEC with complementary renewables such as waste-to-energy and battery storage, these scenarios optimize energy security, economic feasibility, and sustainability. Ultimately, this framework provides a replicable model for other geographically constrained regions seeking a stable, carbon-neutral energy future.

3.5. Sensitivity analysis

Sensitivity analyses were conducted for all scenarios across 13 parameters to identify those with the most significant impact on the Levelized Cost of Energy (LCOE). As noted in Ref. [70], the uncertainty in input parameters can influence the type and scale of technology investments, particularly in long-term energy models. This uncertainty often leads to overcompensation in storage and generation capacities, driving up capital expenditures and, consequently, electricity costs. Understanding the influence of these parameters is critical to optimizing the energy mix and minimizing overall costs.

In scenarios with high OTEC penetration, the LCOE is particularly sensitive to the capital expenditure (CAPEX) of OTEC plants. Since large-scale OTEC plants are not yet operational and rely on simulation data and prototypes, estimating accurate CAPEX values remains a challenge. For scenarios using fossil fuels, such as the baseline and OTEC60 scenarios (with a 50 % reliance on non-renewables), operational costs are highly affected by fuel price volatility. Fossil fuel markets are unpredictable and influenced by geopolitical events, supply-demand imbalances, and economic uncertainties. To capture these effects, the sensitivity analysis applies a −/+30 % variation in key parameters, providing insights into their impact on LCOE and informing strategies to mitigate financial and operational risks in the energy system.

4. Results and discussions

4.1. Impacts on the installed capacity

Fig. 7 shows the progressive adoption of renewable energy technologies across scenarios. These results highlight the development of energy mix scenarios incorporating OTEC, solar PV, waste-to-energy, and battery storage under different transition pathways. In the baseline scenario, diesel power generation constitutes 96 % of the installed capacity as it remains the primary energy source. In contrast, the OTEC30 scenario introduces 30 MW of OTEC, reducing fossil fuel dependence to 77 % of installed capacity. The OTEC60 scenario expands this integration, with OTEC contributing 38 % of capacity, waste-to-energy adding 8 %, and solar remaining at 4 %, while diesel is further reduced. The 100 % RE scenario eliminates fossil fuels entirely, expanding OTEC capacity to 145 MW (87 % of total installed capacity). Solar and OTEC are the renewable energy generation sources utilized in this scenario. This is because wind resources are relatively low in the location, as seen from the wind atlas of the Maldives emission [4]. However, to address the intermittent nature of solar, batteries are introduced as a reserve for grid stability. As no spinning reserve power is available since diesel power generation is phased out, the batteries play a critical role in managing any fluctuations during low generation of solar PV or grid fluctuations, ensuring a consistent and reliable energy supply.

The results highlight that OTEC is a more cost-effective baseload power source than floating solar, as higher solar penetration requires substantial energy storage, increasing the levelized cost of electricity (LCOE). Additionally, battery storage is introduced for grid stability, ensuring supply consistency in the absence of diesel-powered spinning reserves. These findings support the need for OTEC integration as a stable renewable source within the Maldives' energy transition pathways.

4.2. Impacts on the future production mix

The results of the simulation for the generation mix in 2055 for the different scenarios are shown in Fig. 8. These results achieve the objective of conducting high resolution temporal energy modeling to assess the long-term impacts on supply demand stability. In the baseline scenario, diesel generation dominates reaching 818 GWh/year, reflecting continued reliance on fossil fuels. The OTEC30 scenario shifts the generation mix with OTEC producing 229 GWh/year and enables a 30 % renewable fraction, while the OTEC60 scenario achieves a 56 % renewable fraction, producing 458 GWh/year from OTEC. In the OTEC60 scenario, the combined contribution of OTEC (56 %), waste-to-energy (8 %), and solar (4 %) significantly reduce fossil fuel dependence, with diesel production falling to 281 GWh/year. In the 100 % RE scenario, diesel generation is completely phased out, with OTEC contributing 739 GWh/year achieving a 90 % penetration rate.

These results emphasize the feasibility of OTEC in addressing Malé's energy challenges, particularly given its ability to provide reliable baseload power. The 100 % RE scenario underscores OTEC's potential as a reliable, continuous energy source, unlike intermittent renewables such as solar and wind, which require substantial storage. This inherent advantage is particularly crucial in small islands like Malé, where land constraints and geographic isolation limit the deployment of large-scale energy storage or alternative renewable systems. The results emphasize that integrating OTEC with other renewable sources can enable a self-sufficient, sustainable energy future for the Maldives.

4.3. System cost

In this section, the financial aspects of the different scenarios are shown in Fig. 9, emphasizing OTEC's economic viability. These results achieve the objective of evaluating the technical, economic, and environmental feasibility of OTEC implementation. The baseline scenario's

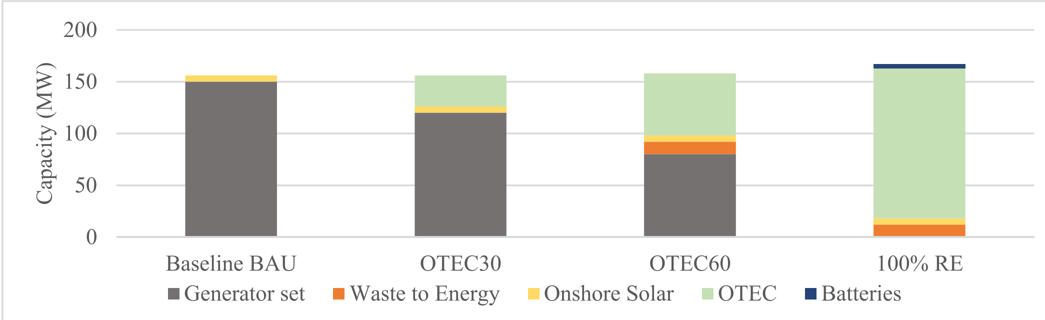

Fig. 7. Changes in the installed capacities of different resources by the end of 2055.

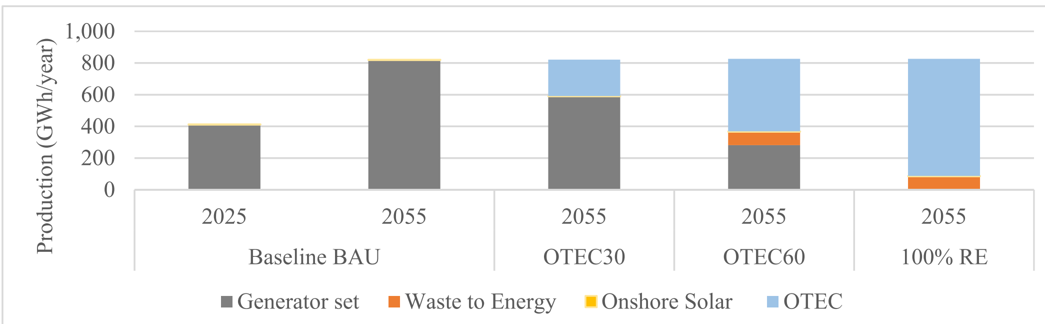

Fig. 8. Electricity production from different sources.

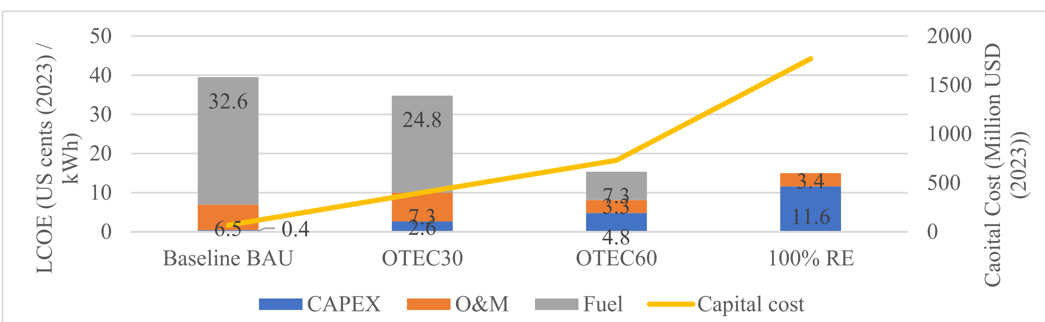

Fig. 9. Total system cost including LCOE and the capital costs incurred through the 30-year project period.

LCOE is 0.40 USD/kWh, consistent with current energy costs in Malé. However, 82 % of expenditures stem from fuel costs, highlighting fossil fuel dependency. As OTEC penetration increases, capital costs rise reaching 77 % of the LCOE, but operational costs decrease, leading to lower LCOE values in high-renewable scenarios. In the OTEC60 and 100 % RE scenarios, the LCOE drops to 0.15 USD/kWh, demonstrating OTEC's long-term cost-effectiveness. It also shows that OTEC 60 can be a practical stepping stone for the energy transition. Although OTEC involves higher upfront costs, its low operational expenditure—relying on the natural temperature gradient of ocean water—makes it cost-

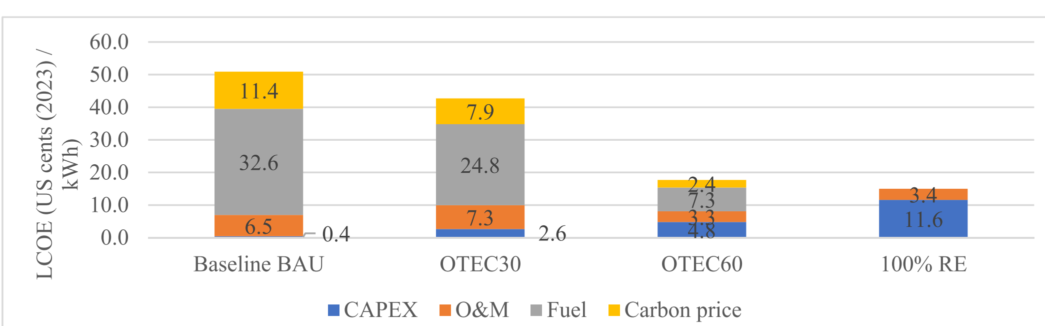

Fig. 10. Effect on LCOE with the addition of carbon pricing for all scenarios.

effective in the long term. Sensitivity analysis confirms the robustness of these scenarios, considering variations in capital costs and fossil fuel prices.

Fig. 10 highlights the effect of adding carbon pricing to curb fossil fuel generation, achieving the objective of analyzing carbon pricing mechanisms to determine their role in accelerating the energy transition. The introduction of carbon pricing results in a 29 % increase in the LCOE of the baseline scenario. The total LCOE increases to 0.51 USD/kWh. The percentage increase in LCOE is directly proportional to fossil fuel generation. The increase in LCOE of both the OTEC30 and OTEC60

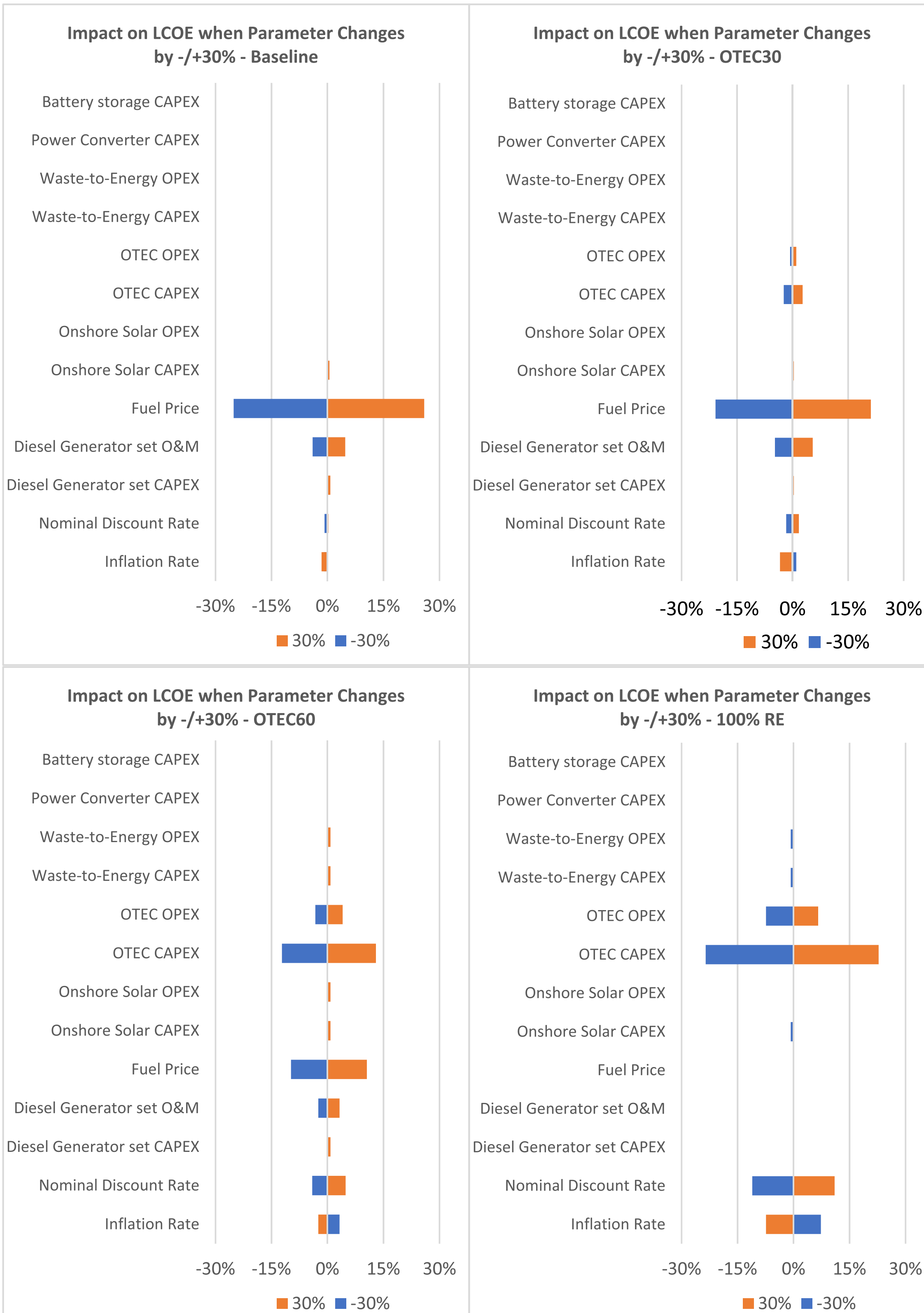

Fig. 11. Sensitivity Analysis for the main components of the scenarios.

scenarios is also seen at 0.43 USD/kWh and 0.18 USD/kWh, respectively. Adding carbon pricing results in the 100 % RE scenarios having a lower LCOE. This reinforces the economic viability of a fully renewable system, particularly OTEC as a baseload power source under carbon pricing policies. The findings suggest that strategic OTEC deployment, complemented by waste-to-energy and solar PV, can ensure cost-competitive, carbon-neutral energy production. This reinforces the necessity of long-term energy policies that go beyond the Maldives Energy Roadmap (2024–2033), which currently lacks a comprehensive pathway to full energy autonomy.

4.4. Sensitivity analysis

Fig. 11 displays the results of the sensitivity analysis conducted for each of the main scenarios in this study. 13 parameters are analyzed to identify their impact on the different scenarios. The effect of a 30 % increase and a 30 % decrease in each parameter was studied. The LCOE is sensitive to nominal discount rates and inflation rate changes. A reduction of nominal discount rates favors higher renewable energy penetration scenarios. Whereas at higher nominal discount rates, nonrenewable energy generation is advantageous. An increase in the inflation rate has the opposite effect on the LCOE. Scenarios with a higher renewable penetration rate have a more significant deviation in the LCOE concerning changes in the inflation rate. These two parameters underline the importance of sound financing structures for OTEC infrastructure projects.

Regarding the different scenarios, in the baseline and OTEC30 scenarios, the highest impact on the LCOE is observed in changes to the fuel price, with the baseline scenario having a 25 % change in LCOE. The change is directly proportional to the increase and decrease of the parameter. This is mainly due to fuel price being the highest contributor to the LCOE. The operational cost of diesel generation has a lower change at approximately 4 % in both the baseline and OTEC30 scenarios.

The OTEC60 scenario is the most robust, with fuel price changes impacting the LCOE by only 10 % and OTEC CAPEX changes by 13 %, highlighting the benefits of diversifying energy sources. In contrast, the 100 % RE scenario is more sensitive to OTEC CAPEX due to its reliance on OTEC for 85 % of generation, emphasizing the need for innovation to reduce infrastructure costs and improve financial feasibility.

The Maldivian energy sector, as seen in the baseline scenario, is heavily reliant on fossil fuels, making it vulnerable to oil price volatility. Over the past 50 years, global oil prices have fluctuated dramatically due to geopolitical events and market dynamics, ranging from peaks like $165 per barrel in 2008 to lows of $26 per barrel in the 1980s [71]. Future oil prices are expected to remain volatile, influenced by supply shortages, geopolitical tensions, and renewable energy transitions [72]. Sensitivity analysis shows a 25 % LCOE impact from oil price changes in the baseline scenario, posing significant risks as energy demand is projected to double over the next 30 years. In comparison, the higher initial costs of the OTEC60 and 100 % RE scenarios offer improved energy security by reducing reliance on volatile fossil fuel markets.

4.5. Discussion and policy recommendations

This study employs a detailed energy model at low temporal resolutions to evaluate the integration of Ocean Thermal Energy Conversion (OTEC) alongside other renewable energy sources in the Maldives, using historical energy consumption, population growth, and resource data. The optimization via HOMER Pro highlights scientifically grounded solutions for energy mix transitions, ensuring hourly load demands are met with minimal oversizing.

A key discovery is OTEC's ability to serve as a stable baseload power source, leveraging the natural thermal gradient of the ocean, which eliminates the intermittency challenges seen in solar and wind energy. Wind energy, despite its initial consideration, is shown to be unsuitable for large-scale deployment due to low wind speed of 6.4–6.5 m/s at 50 m with power densities ranging from 300 to 325 W/m^2 [5].

The baseline scenario underscores the Maldives' vulnerability due to fossil fuel dependence, with sensitivity analyses revealing a 25 % impact on the Levelized Cost of Energy (LCOE) from fuel price volatility. By contrast, the OTEC60 scenario demonstrates remarkable robustness, achieving a low LCOE of 0.15 USD/kWh, with only 10 % and 13 % LCOE sensitivity to fuel price and CAPEX changes, respectively. This scenario reduces fossil fuel imports by 64 % by 2055, enhancing energy security and economic sustainability. The high CAPEX of OTEC in the 100 % RE scenario (13 % higher than OTEC60) underscores the need for innovation to drive cost reductions, but the economic feasibility improves significantly with carbon pricing, deterring fossil fuels and making the 100 % RE scenario more favorable.

The scientific insight from this analysis emphasizes OTEC's synergy with renewable resources to create an optimized energy mix. For instance, OTEC's inherent stability, independent of weather, offsets the intermittency of solar power, and its surplus energy during low demand can support grid stability via battery storage. The analysis also highlights the inefficiency of floating solar as analyzed in Refs. [62,63], compared to OTEC in the Maldivian context, providing LCOEs lower than the global average for ocean energy technologies (0.30–0.55 USD/kWh). Furthermore, co-benefits such as freshwater production, aquaculture, and cooling applications improve OTEC's cost-efficiency and overall viability.

To alleviate the high capital costs of OTEC plants, reflecting the benefits of renewable energies compared to nonrenewable sources becomes crucial. Rewarding energy operators for lower greenhouse gas production or implementing emissions penalties could help to achieve this, as seen from the results. The funds generated could serve as financial aid for capital costs, fostering increased renewable generation. Policy instruments such as Feed-In Tariffs, emissions penalties, and infrastructure incentives are crucial for overcoming OTEC's initial capital costs. These findings reinforce the role of OTEC as a transformative solution for SIDS like the Maldives, addressing their unique challenges of land scarcity, high energy demand, and reliance on imported fuels. The OTEC60 scenario emerges as the most practical stepping stone for energy transition, reducing emissions while ensuring economic and energy security. This analysis provides a framework for global application, emphasizing the potential of OTEC to meet year-round energy needs, enhance energy resilience, and drive sustainable development in island nations.

5. Conclusion

This research analyzes the feasibility, economic viability, and long-term energy transition potential of Ocean Thermal Energy Conversion (OTEC) technology alongside other renewable energies in the Maldives. Through high -resolution temporal energy modeling, incorporating hourly historical energy consumption patterns, population growth projections, and resource data for solar and wind, multiple energy mix scenarios (2025–2055) were developed to assess different transition pathways and the economic trade-offs.

The findings confirm that OTEC is a technically and economically feasible solution in the Maldives, capable of providing stable, low cost baseload energy at a low Levelized Cost of Energy (LCOE) of 0.15 USD/kWh even at 100 % renewable power generation scenarios. By reducing dependence on imported fossil fuels, OTEC enhances energy independence and economic resilience. Among the proposed scenarios, OTEC60 emerges as the most cost-effective, balancing low LCOE with moderate capital investment while ensuring robust energy security and flexibility. This makes it an ideal intermediate step in the Maldives' energy transition before fully phasing out fossil fuels.

The sensitivity analysis highlights the vulnerabilities of the current energy system to fossil fuel price fluctuations. Any escalation in oil prices would amplify the financial strain through heightened fuel procurement costs bringing down the energy security of the country. The 100 % renewable energy scenario with increased OTEC penetration ensures grid stability without heavy reliance on battery storage, further improving long-term cost-effectiveness. However, reducing OTEC's initial capital costs through innovation remains crucial for widespread adoption. Incorporating carbon pricing enhances the economic attractiveness of a 100 % renewable energy scenario, further lowering electricity costs to 0.15 USD/kWh. The study also demonstrates that a 100 % renewable system with OTEC can maintain robust grid stability without requiring extensive battery storage.

This research showcases the transformative potential of OTEC to meet low-carbon energy goals of the Maldives while offering reliable baseload power. The scenario-based approach aids policy development and investment planning, ensuring that future energy strategies align with economic constraints, grid stability requirements, and the Maldives' long-term carbon neutrality goals. These insights serve as a replicable model for other Small Island Developing States (SIDS) facing similar energy security and climate challenges.

CRediT authorship contribution statement

Aminath Saadha: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Keiichi N. Ishihara:** Writing – review & editing, Supervision, Conceptualization. **Takaya Ogawa:** Writing – review & editing, Supervision. **Hideyuki Okumura:** Writing – review & editing, Supervision.

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.

There are no financial and personal relationships related to potential competing interests.

Appendix A

Table A. 1
The cost of different components of an OTEC plant

Item	Economic Value	Reference
Turbine capex	328 USD/kW_{gross}	[73]
Pumps capex	1674 USD/kW_{pump}	[60]
Seawater pipes capex	9 USD/kg_{pipe}	[74]
Heat Exchangers capex	215 USD/m^2	[60]
Project Engineering capex	3113 USD/kW_{gross}	[60]
Extra cost	3 % of total CAPEX	[17]
OPEX	3 % of total CAPEX/year	[17]
LCOE Calculation		
Project lifetime	30 years	[62]
Discount rate	3 %	[62]
Capacity factor	96 %	[75]
Fuel consumption	0.286 l/kWh	[75]
Carbon Emission	2.8 kg/l	[76]
Carbon price	130 USD/ton CO_2	[77]

Table A. 2
Values of Parameters used for the calculation of OTEC plant size and cost [54].

Technical Value	Assumption
Properties of Ammonia & Seawater	
Density liquid ammonia $\rho_{NH3,liq}$ [kg/m^3]	625
Specific heat capacity seawater c_p [kJ/kgK]	4.0
Density surface seawater ρ_{WW} [kg/m^3]	1024
Density deep seawater ρ_{CW} [kg/m^3]	1027
Heat Exchangers	
Pinch-Point temperature difference evaporator and condenser $\Delta T_{pp.}$ [K]	1.0
Nominal overall heat transfer coefficient evaporator $U_{evap,nom}$ [kW/m^{2}K]	4.5
Nominal overall heat transfer coefficient condenser $U_{cond,nom}$ [kW/m^{2}K]	3.5
Turbine + Generator + Power Transmission	
Isentropic efficiency turbine $\eta_{is,turb}$ [%]	82
Mechanical efficiency turbine $\eta_{mech,turb}$ [%]	95
Electrical efficiency generator $\eta_{el,gen}$ [%]	95
Ammonia and Seawater Pumps	
Isentropic efficiency pump $\eta_{is,pump}$ [%]	80
Electric efficiency pump $\eta_{el,pump}$ [%]	95
Seawater Pipes	
Pipe thickness t [m]	0.09
Density HDPE ρ_{HDPE} [kg/m^3]	995
Density FRP-sandwich pipe ρ_{FRP} [kg/m^3]	1016

(continued on next page)

Table A. 2 (*continued*)

Technical Value	Assumption
Roughness factor z [mm]	0.0053
Pressure drop coefficient evaporator & condenser $K_{L,evap/cond}$ [−]	120
Nominal flow velocity in the pipes $v_{pipe,\ CW/WW}$ [m/s]	2.0
Nominal flow velocity in the heat exchangers $v_{evap/cond,\ nom}$ [m/s]	1.0
Maximum inner diameter $d_{\max}$ [m]	8

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