Applied Energy 308 (2022) 118360

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives

Dominik Keiner [a,*], Orlando Salcedo-Puerto [a], Ekaterina Immonen [a], Wilfried G.J.H. M. van Sark [b], Yoosuf Nizam [c], Fathmath Shadiya [c], Justine Duval [d,e], Timur Delahaye [e], Ashish Gulagi [a], Christian Breyer [a,*]

[a] *School of Energy Systems, LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland*
[b] *Utrecht University, Copernicus Institute of Sustainable Development, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands*
[c] *Faculty of Engineering, Science and Technology, The Maldives National University, 20371 Malé, Maldives*
[d] *École Polytechnique, 91128 Palaiseau, France*
[e] *CorPower Ocean AB, 126 30 Stockholm, Sweden*

HIGHLIGHTS

- Limited land area complicates renewable energy deployment in archipelagos.
- Renewable offshore floating technologies enable energy transition of islands.
- Synthetic e-fuels can be imported or self-produced cost-effectively until 2050.
- Energy transition in the Maldives until 2030 is possible with minor cost markup.
- Floating offshore solar PV and wave power emerge as the major energy sources.

ARTICLE INFO

Keywords:
100% renewable energy
Energy transition
Solar photovoltaics
Wave energy converter
Floating photovoltaic

ABSTRACT

Low-lying coastal areas and archipelago countries are particularly threatened by the impacts of climate change. Concurrently, many island states still rely on extensive use of imported fossil fuels, above all diesel for electricity generation, in addition to hydrocarbon-based fuels to supply aviation and marine transportation. Land area is usually scarce and conventional renewable energy solutions cannot be deployed in a sufficient way. This research highlights the possibility of floating offshore technologies being able to fulfil the task of replacing fossil fuels with renewable energy solutions in challenging topographical areas. On the case of the Maldives, floating offshore solar photovoltaics, wave power and offshore wind are modelled on a full hourly resolution in two different scenarios to deal with the need of transportation fuels: By importing the necessary, carbon neutral synthetic e-fuels from the world market, or by setting up local production capacities for e-fuels. Presented results show that a fully renewable energy system is technically feasible in 2030 with a relative cost per final energy of 120.3 €/MWh and 132.1 €/MWh, respectively, for the two scenarios in comparison to 105.7 €/MWh of the reference scenario in 2017. By 2050, cost per final energy can be reduced to 77.6 €/MWh and 92.6 €/MWh, respectively. It is concluded that floating solar photovoltaics and wave energy converters will play an important role in defossilisation of islands and countries with restricted land area.

1. Introduction

Burning fossil fuels increases the concentration of carbon dioxide (CO_2) in the atmosphere. The consequence of this human action is a greenhouse gas (GHG) induced climate change, which already leads to noticeable repercussions, globally [1], such as extreme weather events, rising sea-levels and coral bleaching [1,2]. The Maldives, an archipelago southwest off the Indian coast in the Indian Ocean, is one of many island states and coastal areas worldwide extremely vulnerable to these exemplary climate change impacts. With a maximum natural elevation

---

* Corresponding authors.
E-mail addresses: dominik.keiner@lut.fi (D. Keiner), christian.breyer@lut.fi (C. Breyer).

https://doi.org/10.1016/j.apenergy.2021.118360
Received 1 October 2021; Received in revised form 19 November 2021; Accepted 5 December 2021
Available online 24 December 2021
0306-2619/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

of 2.4 m [3], the country is facing severe threats of rising sea levels [4]. Increasing temperatures cause more frequent bleaching events of the coral reefs in the country [5]. Meeting the aims of the Paris Agreement of 2015 [6] signed by almost 200 countries including the Maldives, would mitigate the most threatening consequences for the low-lying island state [2]. However, research shows that even the 1.5 °C target of the Paris Agreement might not be enough to save low-lying countries and coastal areas in the long term [7]. The Maldives are an example of island countries having one of the most ambitious emissions targets of all island nations [8], as they aim to reach a net-zero energy system already by 2030 [9]. The Maldives is chosen as a case country for the analyses of this research, as it represents many islands and area restricted countries in the Sun Belt, also facing similar severe climate change induced threats, while having very ambitious energy transition targets, which are tested by this research for technical feasibility and economic viability.

As the Maldives developed from a least developed country to a middle-income country, the demand for energy is also increasing due to the change in the lifestyle of the Maldivians. The country faced a steep economic development, mostly due to tourism, since the first holiday resort opened in the 1970s [3]. The country's economy is characterised mainly by the service sector with a share of 81% in 2015, whereas industry (16%) and agriculture (3%) are much smaller sectors [10]. Tourism is the most important economic sector with a share of about 30% in the country's gross domestic product (GDP) [3]. Transportation of people and goods is challenging in the Maldives. The country consists of almost 1200 islands which span 870 km from North to South and 128 km from East to West [3], whereas only about 1.4% of the country's total area is land [3]. This makes an intensive use of air and marine transportation indispensable, leading to a fuel intensive transport sector, creating a bottleneck for a sustainable energy transition. Fuel imports account for about 10% of the country's GDP [11]. In addition, the restricted land area limits the possible deployment of conventional renewable energy sources (RES) to supply the energy needs of the growing economy in a sustainable way. The fluctuating international market of fossil fuel prices often has a major impact on the country's energy system. Many islands around the world face similar challenges [12,13].

The primary energy supply of the Maldives in 2017, which is the latest year with comprehensive energy system data [14,15], and which is used as the reference system in this study, was dominated by fossil fuels, as it is shown in Fig. 1. The majority, or 39% of the diesel consumption is due to the diesel-based electricity production. Domestic and international marine navigation account for 25% and 10% of the diesel consumption, respectively. Road transport, mainly buses, account for 23% of the diesel consumption. Industry-related diesel consumption in form of fishing boats was responsible for 2.7% of the diesel demand. Gasoline consumption can be divided into three categories: Road transport, domestic and international navigation, accounting for 53.4%, 32.7% and 13.7% of the total gasoline consumption, respectively. Domestic and international aviation are responsible for 52.4% and 47.6% of kerosene consumption, respectively. Liquified petroleum gas (LPG) was consumed for cooking, as well as a small amount of biomass. The energy supply structure of the Maldives is representative for small islands or small island development states (SIDS) in the Sun Belt [12,13].

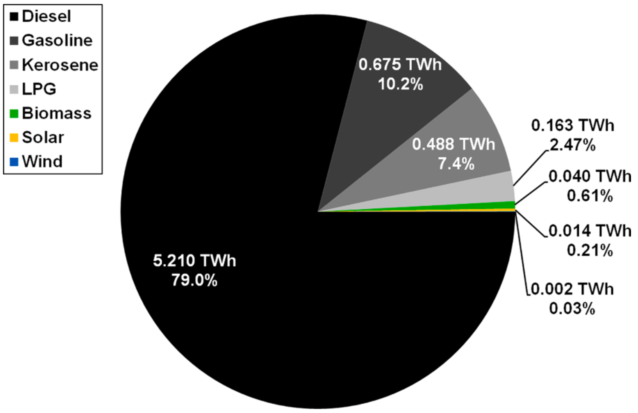


Fig. 1. Primary energy mix of the Maldives in the year 2017. Data are taken from [14,15].

Renewable Energy Sources (RES) play a subordinate role in the reference system. A total of 266 MW of diesel based internal combustion engine (ICE) capacity, of which the majority were installed on Malé and Hulhumalé islands [15], secured the electricity supply in the country [14]. A total of 10.8 MW_p of solar PV and 0.21 MW of wind capacity were installed as part of the renewable capacity [15]. The total electricity demand in 2017 can be quantified at 0.656 TWh. Transport was accountable for 4.198 TWh of the final energy demand [14]. The industry sector used 0.14 TWh of final energy (excluding electricity), however, the industry sector is dominated by fishery, which is in need of diesel for fishing vessels [14]. This fossil fuel-based energy system caused a total of 1.82 $MtCO_2$ emissions [16], or 3.67 tCO_2/cap (for comparison: The average of OECD countries was 8.83 tCO_2/cap) [17].

The absence of available land area, highly fossil fuel-based energy system and challenging topographic circumstances make the Maldives an interesting example for a case study to investigate the role of floating RES in such an environment. A techno-economic analysis of the Maldivian energy system overcoming the bottleneck of transport-intensity and limited land area with the novel approach of using offshore floating technologies is performed for the power and transport sector. The analysis of the Maldives serves as an exemplary study for land area restricted archipelago countries. The energy system is modelled for 2017 as the reference year and for 2030 as well as 2050, applying an economic optimisation of the energy system. Two scenarios were developed to show different pathways for reaching the country's bold target of a net-zero GHG energy system by 2030 and to ensure a sustainable system after further economic development by mid-century. This study aims to give a first overview of the potential of renewable offshore floating technologies to provide an archipelago with energy. The novel contribution of this research is an assessment of the potential of a broad set of offshore floating energy technologies with solar PV, wave energy converters and wind turbines, in an hourly resolved analysis for the entire energy system and strong sector coupling, which leads to a technically feasible, and economically viable energy system, based entirely on renewable resources.

2. Literature review: Energy system research on the Maldives and floating technologies

A brief overview on the state of research for future energy system options in the Maldives can be found in Table 1. Most of the studies focus on the power sector or technologies providing electricity. Liu et al. [18] is the only study providing information about the feasibility of a 100% renewable energy supply for the power sector and water supply of the country, however, a detailed modelling about pathways or RES capacities and technologies is not provided. Three studies by van Alphen et al. [19], Wijayatunga et al. [20] and IRENA [21] provide techno-economically modelled results for possible future energy systems, either country-wide or for exemplary islands. The results of these studies find hybrid diesel systems to be the most beneficial solution. It should be noted that mostly standard RES technologies are considered and a fully sustainable energy system is not achieved. Such a hybrid system has also been realised on Mandhoo island [22]. A more innovative approach by assessing the wind and wave potential around the Malé and Magoodhoo areas is provided by Contestible et al. [23]. It is highlighted that offshore wind and wave power have the potential of moving the energy system in the Maldives towards self-sufficiency. Ali et al. [24] assess the potential of roof-mounted solar PV on an exemplary island. Even though the

Table 1
Review of studies of the Maldivian energy system and renewable resource potentials.

Study	Year of publication	Geography	Sector	Study type	Limitation
Liu et al. [18]	2018	Country	Power, water	Feasibility analysis	No system modelling
van Alphen et al. [19]	2007	Country	Power	Techno-economic analysis	No 100% renewable system; Cost assumptions not anymore applicable
Wijayatunga et al. [20]	2016	Five exemplary islands	Power	Techno-economic analysis	No 100% renewable energy system
IRENA [21]	2015	Greater Malé region	Power	Optimal renewable energy integration	No 100% renewable system
van Sark et al. [22]	2006	Mandhoo island	Power	Hybrid system realisation	No 100% renewable system; Cost assumptions not anymore applicable
Contestible et al. [23]	2017	Malé, Magoodhoo	Power	Wind and wave energy assessment	No wind and wave power profile provided
Ali et al. [24]	2018	Hulhumalé	Power	Rooftop PV potential assessment	No nation-wide extrapolation

results are very detailed for the studied island, an extrapolation of the rooftop PV potential for the whole country is missing.

Offshore floating technologies have an enormous potential for electricity generation, and several studies dealt with feasibility analyses and case studies. Since floating PV installations experience a significant ramp-up [25] and show an enormous onshore potential [26], floating PV and respective offshore applications are garnering more and more interest. Already in 2013, Trapani and Millar [27] showed the advantages of using offshore floating PV for the decarbonisation of the Maltese energy system. A comprehensive review of floating PV plants was made by Sahu et al. [28]. This review states that even though some challenges need to be overcome, floating PV, as an offshore solution, is capable of being a major technology step for areas with limited land availability. Thus, for the South Asian region, Solanki et al. [29] showed that the west coast of India has excellent solar conditions for an exploitation of offshore floating PV. Similar findings were provided by Liu et al. [30], which tested floating PV performance in the tropical conditions of Singapore. Recently, a combination of offshore technologies in hybrid systems has been studied more intensively. López et al. [31] showed the benefits of combining offshore floating PV and offshore wind capacities for the case of Spain. Similar techno-economic benefits have been highlighted by Golroodbari et al. [32] for the case of the Netherlands. Another example by Soukissian et al. [33] exploits offshore wind and solar resources in the Mediterranean. Performance differences between on- and offshore floating PV in the North Sea have been modelled by Golroodbari and van Sark [34], claiming that energy yield of an offshore application in the respective conditions can increase up to 13% on an annual basis.

Wave power, as one of the offshore technologies is increasingly in focus, due to its enormous potential. The main focus in this area has been on reviewing different wave power technology options and the state of research [35–38]. Beyond that, global wave power resource assessments [39–41] and the need of standardisation [42] are part of an ongoing discussions about wave power. Nevertheless, case studies and feasibility analyses have already been published. Iglesias and Carballo [43] showed wave power to be a viable option for the case of La Palma island in Spain. Similar conclusion was highlighted by Castro-Santos [44], for Northern Spain. The coastal regions of Vietnam have been studied by Curto et al. [44] based on a wave converter prototype and compared it with offshore wind resources. The analyses showed that wave power might be a superior electricity generation technology with lower necessary feed-in tariffs. Jahangir et al. [45] showed on three exemplary cases in Iran, that wave power in sea areas cut off from the wider ocean might not perform very well. Additionally, they showed, that wave power has a chance to compete with wind turbines or solar PV depending on the location. Similar results were concluded by de Oliveira et al. [46] for the case of Brazil, claiming that wave power could become an interesting electricity generation option if different hurdles like low efficiency and pushing investments towards deployment of wave power are carefully handled. That wave power converters can be a viable option even in areas with moderate resources was shown by Lavidas and Blok [47], indicating that next generation and well-matched wave power devices profiting from economies of scale will have a high potential.

A detailed review on 100% RES on islands revealed that not a single study has been performed combining the three offshore energy technologies in an energy system analysis [48]. This study overcomes the research gap by analysing the interaction of different offshore floating technologies in the Maldives energy system.

3. Methods and data

The Maldivian energy system optimisation was performed using the EnergyPLAN model [49], version 16.0. New approaches for renewable energy (RE) generation via floating technologies and a new wave power design are modelled to supply the energy demands of the system. In this study, more light is drawn on the new wave power technology, for which capacity factors are not yet broadly available. EnergyPLAN is well suited for integration of large share of renewables in island energy systems, as 13 studies are known for 100% RES analyses on islands using EnergyPLAN [48], such as [50–53].

3.1. Applied technologies

The model has integrated all important technologies for the supply of the power and transport sector, which are included depending on the scenario:

- Electricity generation
- Energy storage
- Synthetic fuel production
- Fuel storage

All techno-economic parameters are listed in Table A.1 of the Appendix A. The assumptions for offshore technologies include all system components up to the point of connection on the mainland. Lifetime assumptions of rooftop PV is based on [54], with a slightly increased lifetime until 2050. The lifetime assumptions of the battery storage comply with data found in literature [55,56].

Electricity generation technologies of the future systems are solely based on RES technologies. Solar PV is divided into rooftop PV and offshore floating PV. Offshore floating PV is the utility-scale PV option in this study, as the restricted land area does not allow utility-scale ground mounted PV systems. The same is valid for onshore wind turbines, for which the available land area is not sufficiently available. Wind is therefore assumed to be a standard offshore wind application. For wave power, a newly designed technology approach of CorPower Ocean AB, Sweden [57], is taken into consideration. In addition to PV, wave, wind power and an already approved waste-to-energy facility for the main island Malé and its surrounding islands is implemented. This facility provides 8 MW of power to deal with the waste problems caused by intensive tourism and population density [58,59]. A further use of waste or biomass is not considered to be either practical or sustainable. Collecting waste over many islands, which are spread over a wide area, poses a large logistic effort. Furthermore, composting might be the most suitable way of dealing with the waste occurring, of which the majority is bio-degradable with a high amount of moisture [60]. Nevertheless, the current waste management of on-site incineration [61] or ocean dumping [62] requires improvement. Biomass-based electricity generation would heavily rely on imported biomass [63] and is not considered as a sustainable option in this study.

Floating offshore technologies require nearby port facilities for installation and maintenance. The design philosophy of CorPower's WEC includes the possibility of using small vessels for easier installation and maintenance. It is assumed that respective ports for small vessels are available in the Maldives. This is also valid for floating PV, which due to its modularity, is able to be assembled on land and launched to the sea on beaches, as e.g. commercially demonstrated [64]. It has to be mentioned that additional efforts might be necessary to connect the offshore technologies with the island grid. At this point of research, it is assumed that this is possible within the powerhouse of each island.

The main energy storage technology utilised are Li-ion batteries. For the modelling of an island system, a balancing energy storage is needed for times of low RE availability. As the Maldives is short of the necessary area and elevation for mid-or long-term electricity storage such as pumped hydro energy storage (PHES) or similar, a hydrogen system is chosen to act as the balancing system. This balancing system uses electrolysers for hydrogen production from available RES, via hydrogen compressors, the hydrogen is stored in large-scale, pressurised hydrogen tanks. If necessary, the storage medium is discharged and re-electrified via an internal combustion generator for modern multi-fuels (ICM). Modern multi-fuels are synthetic e-fuels, methane or as applied in this case, hydrogen. ICMs are chosen over fuel cells (FC) as they are expected to have a superior efficiency and are cheaper. On average, investment costs for utility-scale FCs can currently be estimated to about 1170 €/kW_{el} [65]. To be at a competitive cost level with ICMs until 2050 [66,67], the cost reduction would have to be about 60% for investment cost only. For FCs as a niche technology facing several challenges to commercialisation [68], this reduction may be challenging to achieve.

Technologies for coupling electricity and transport sector comprise of fuel synthesis technologies: Electrolysers [69], hydrogen storage [69], CO_2 direct air capture (DAC) [70] and a Fischer-Tropsch unit for fuel synthesis [71]. Capacities for diesel and petrol/kerosene storage are also included. Biofuel imports are not considered as a sustainable option for power generation and transport fuel.

3.2. Applied scenarios

In this research, two scenarios are studied for the future energy system of the Maldives: A fully renewable energy system with imported e-fuels from the global e-fuel market (100RE-SI) and a fully renewable energy system with domestic production capacities for e-fuels via Power-to-Liquid (PtL) production facilities (100RE-PtL). Imported e-fuels are CO_2-neutral and therefore, do not cause net CO_2 emissions. E-fuel imports are based on an investigation of optimised e-fuel production costs and regions solely based on renewable electricity input globally [72,73]. Along with the modelling of e-fuel production, global trading of e-fuels is also considered in the modelling. Typical export regions will be the Middle East and North Africa, sub-Saharan Africa, North and South America as well as Australia as those regions have the most abundantly available RES. Both scenarios are modelled for 2030 and 2050. In both years, the constraints for the system design are the same, which is that all of the electricity and fuel demand has to be satisfied for every hour of the year. No connection for electricity import or export from or to outside of the Maldives shall be available. The status of the system in 2017 is modelled as a reference scenario (2017 Reference).

3.3. Demand estimations

Power demand is based on electricity consumption data from Toktarova et al. [74]. The total electricity consumption is adapted by using updated population data from the United Nations database [75]. Electricity load distribution profiles are visualised in Fig. A.1 in the Appendix A. The fuel demand estimation for the transport sector is carried out based on the fuel and transport type. It is assumed that all road transportation is electrified in the future system. The conversion from an energy unit to a relative unit in km/cap is made via the factor of 1.5 km/kWh for combustion fuels. The needed electricity for electric vehicles is then estimated with the per capita demand, the total population, and a factor of 5 km/kWh, expressing the higher efficiency of electric vehicles. Table 2 shows the 2017 demand data and the respective conversion for road transport, domestic navigation and aviation and international marine and aviation bunkers. Table 3 shows the transportation demand data used to calculate the relative transport demand in 2017 and future years.

Demand numbers for 2030 and 2050 are calculated by using the transportation demand data from Table 2 and respective multiplication with the relative demand numbers obtained in Table 3. At this stage, marine freight is assigned to international marine bunkers and marine passenger to domestic navigation. In the case of aviation, the distinction cannot be made that easily. As only the fuel demand can be set in EnergyPLAN, it is assumed that aviation freight is handled mostly with passenger airplanes, therefore, the demand projection for kerosene is solely based on aviation passenger transportation demand.

An overview of the demand projection can be seen in Table 4. Statistics show that motorcycles by far exceed the number of cars and buses

Table 2
Input data and relative conversion of total demand for demand projection of the transport sector. 2017 total demand numbers are taken from [14], population numbers from [75] and transport demand numbers from [76].

Fuel type	Demand type	2017 demand	Total[1]	Relative[1]	Projection method
Diesel	Road	1.120 TWh	746.7 Mkm	1504 km/cap	Electrification, same per cap value
	Domestic navigation	1.314 TWh		203 kWh/p-km	Increase with GDP per capita
	Int. marine bunkers	0.523 TWh		0.13 kWh/t-km	Increase with GDP per capita
Petrol	Road	0.361 TWh	240.7 Mkm	485 km/cap	Electrification, same per cap value
	Domestic navigation	0.221 TWh		34.2 kWh/p-km	Increase with GDP per capita
	Int. marine bunkers	0.093 TWh		0.02 kWh/t-km	Increase with GDP per capita
Kerosene	Domestic navigation	0.256 TWh		1.63 kWh/p-km	Increase with GDP per capita
	Int. aviation bunkers	0.233 TWh		1.48 kWh/t-km	Increase with GDP per capita

[1] Mkm: million kilometer; p-km: person-kilometer; t-km: ton-kilometer.

Table 3
Transportation demand data from [76]. All 2017 numbers are the average of given 2015 and 2020 numbers.

Transport type	Unit[1]	Year				
		2015	2020	2017	2030	2050
Marine freight	Mt-km	3604	4293	3948	5954	12,749
Marine passenger	Mp-km	6	6	6	6	6
Aviation freight	Mt-km	8	11	10	20	65
Aviation passenger	Mp-km	144	171	157	254	569

[1] Mt-km: million ton-kilometer; Mp-km: million person-kilometer.

Table 4
Demand overview for the power and transport sector, input data and final energy demand. 2017 demand data are taken from [14], population data are from [75] and GDP per capita data from [74].

Sector/Data	Demand-/Data type	Unit	2017	2030	2050
Power	Electricity	TWh	0.656	1.683	4.726
Transport	Diesel[1]	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 (cooking)	TWh	0.040	0	0
	LPG (cooking)	TWh	0.163	0	0
Input	Population	–	496,400	519,350	586,100
	GDP per capita	€/cap	9942	16,327	35,624
Total	Final energy demand	TWh	4.589	3.534	7.903
	Power sector share	%	14.3	47.6	59.8
	Transport sector share	%	81.3	52.4	40.2
	Heat sector share	%	4.4	0	0

[1] incl. 0.134 TWh for fishery.

registered in the Maldives. For example, in 2017, there were 80,859 registered motorcycles stand against 5,823 registered cars and 168 buses [77]. Therefore, no smart charging is considered for the future electricity demand of the transport sector. Marine and aviation transportation is assumed to be dependent on economic activity and increases with the transport demand as described by Khalili et al. [76].

A consequence of the electrification of all road transport is the reduced final energy demand in 2030 compared to the reference system in 2017. The increasing energy demand until 2050 is mainly driven by the power sector and by a significant additional demand for aviation and therefore, kerosene, in combination with a continuous population growth. Cooking based on biomass and LPG is assumed to be phased-out already by 2030 due to reasons of health and efficiency, and fully substituted by electricity-based cooking [78].

3.4. Resource potentials

The capacity factor profiles for rooftop PV, floating PV (optimally fixed-tilted) and wind energy are calculated according to Bogdanov et al. [79] using global weather data for the year 2005 from NASA [80,81] and reprocessed by the German Aerospace Centre [82]. Using hourly average data from several years might capture yearly variabilities, but it will also disrupt the specific characteristics of an exemplary and complementary weather year, which is why one exemplary year is chosen. Visualised capacity factor profiles for solar PV and wind offshore can be found in Figs. A.2 and A.3 in the Appendix A. The electricity yield for floating PV is not adjusted compared to a land-based ground-mounted system, as the yield improvement for floating PV in the Maldives is neglectable due to shallow waters and high sea temperatures [83].

Rooftop PV and offshore wind however is adjusted by correction factors within EnergyPLAN to match the annual generation amount for the given 2017 values. As already mentioned, 10.8 MW_p of which is assumed to be only rooftop PV generated 14 GWh electricity. Without correction, the yield would be 18.4 GWh. Rooftop PV has therefore about 24% yield reduction. Reasons are usually shadowing by surrounding structures and vegetation, tilt angles of the roofs and insufficient ventilation [84]. For the case of wind generation, installed capacities in 2017 are too low and generation numbers rounded, however, the wind profiles lead to a lower yield per capacity if the capacity is scaled up. The correction factor which can be set in a range of −1 to 1 is chosen to 0.25, which increases the yield from wind turbines by 12.5%. In addition, it is assumed that the full rooftop PV potential will be exploited by 2030. The calculation of the rooftop PV potential is based on Ali et al. [24]. With the underlying assumption, that 50% of the roofs will be suitable for PV, the total available area for rooftop PV in the study is 39,504 m^2. With the given population of the island (Hulhumalé) of 15,769 [15], the relative available area is 2.505 m^2/cap. Given the total population of the Maldives in 2050 for the medium population growth scenario of the United Nations of 586,100 [75], the total available roof area will be 1.468 km^2. This area represents the area for the modules only. It is presumed that all settlements are on average equally densely populated, and the calculation made by Ali et al. [24] serves as a reference. Assuming a standard module with about 2 m^2 area requirement and an average nominal power of 350 W_p for the modules, this gives an available nominal power of 256.9 MW_p. Until 2030, the efficiency of solar PV modules is expected to increase from 17% in 2017 to 22–24% until 2030 and to 30% in 2050 [85], leading to a 31% and 71% higher power output of the modules. The available nominal power for rooftop PV is 336.6 MW_p and 439.4 MW_p in 2030 and 2050, respectively. In the model a rooftop PV potential of 340 MW_p is implemented for all scenarios in 2030 and 440 MW_p in 2050. Silicon based modules with a slightly higher rated power of more than 450 W_p are already commercially available [86]. Due to the vast availability of ocean area, no capacity limitation for floating PV and offshore wind is implemented.

As no wave buoy data exist for the Maldives, the capacity profile calculation for wave power is based on two wave models, the Copernicus

Marine Service of the European Union [87,88] and the WaveWatch III model of the Pacific Islands Ocean Observing System (PacIOOS) [89]. Due to data availability, 2017 is chosen for wave power calculations. The used wave energy converter (WEC) is the Gen 12 of CorPower Ocean AB's WEC system [57]. The specific power matrix named G12 corresponds to a device hull with 302 m^2 volume at equilibrium position. In this study, the same device performance for 2030 and 2050 is assumed, which is a conservative approach, as increases in annual yield can be expected over the device generations from G12 (2030) to G17 (2050) as the technology further develops and matures based on each learning cycle. The power matrix gives power generation at the WEC terminals (connection point to the offshore power collection grid), and provides time series representing a full wave farm, including intra-array and farm export losses for a typical wave farm of the CorPower design. The total farm efficiency η_{WEC} has been considered as a global factor using Eq. (1):

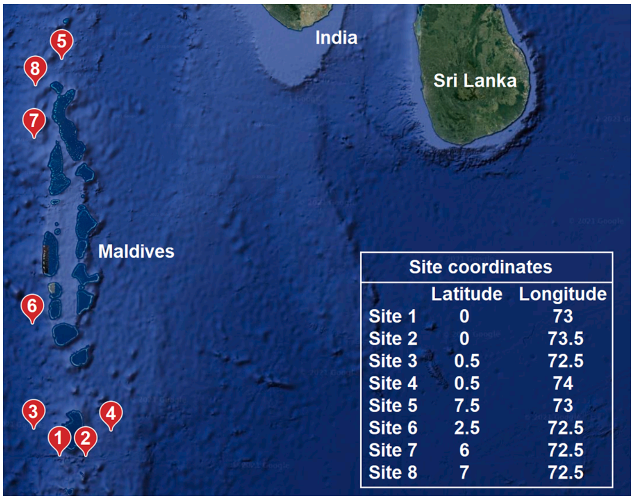
$$\eta_{WEC} = \eta_{availability} \cdot \eta_{array} \cdot \eta_{el,farm} \cdot \eta_{aux} = 0.93 \cdot (1-0.03) \cdot (1-0.04) \cdot (1-0.021) = 0.848 \tag{1}$$

corresponding respectively to $\eta_{availability}$: availability, η_{array}: array interaction efficiency, $\eta_{el,farm}$: electrical farm efficiency and η_{aux}: auxiliary consumption. The loss components are further described by CorPower's product roadmap [90]. Therefore, the time-series corresponds to a complete wave farm including power collection and power export to the shore. Finally, the annual profile is the average of eight studied sites around the Maldives, which are shown in Fig. 2.

The resulting capacity factor profile for wave power can be seen in Fig. A.4 in the Appendix A. Currently the WEC is in its fourth out of five development stages, taking the technology from technology readiness level (TRL) 6 to TRL 7 within two years. The WEC is tested in full scale currently and in real environment from next year onwards. First commercial projects are already prepared. Even though the technology is not yet fully commercially available, the well-advanced TRL of the technology allows to safely use technological models based on real performance testing in this study.

4. Results and discussion

The two scenarios were modelled based on the specific input data for the Maldives using the EnergyPLAN model, in addition to the reference scenario. For both scenarios, the cost advantage of wave power is discussed briefly, in order to define the role of wave power in the energy system. All results are an outcome of a cost optimisation. It has to be mentioned that EnergyPLAN does not provide an optimisation algorithm, so the optimisations have to be done iteratively by the user and the results may have some uncertainties. The cost optimisation is done while always ensuring satisfied energy balances. A comprehensive overview of the results can be found in Table A.2 of the Appendix A.



Site coordinates

	Latitude	Longitude
Site 1	0	73
Site 2	0	73.5
Site 3	0.5	72.5
Site 4	0.5	74
Site 5	7.5	73
Site 6	2.5	72.5
Site 7	6	72.5
Site 8	7	72.5

Fig. 2. Position of the Maldives in the Indian Ocean and location of the eight sites for wave power yield assessment including site coordinates. The map has been created using Google Earth web assembly [91].

4.1. Electricity generation and energy storage

In both scenarios, the novel technologies, floating PV and wave power are the most dominant in the case of installed capacity and electricity generation. In Fig. 3, the total installed capacities of the electricity generation technologies are shown for all scenarios.

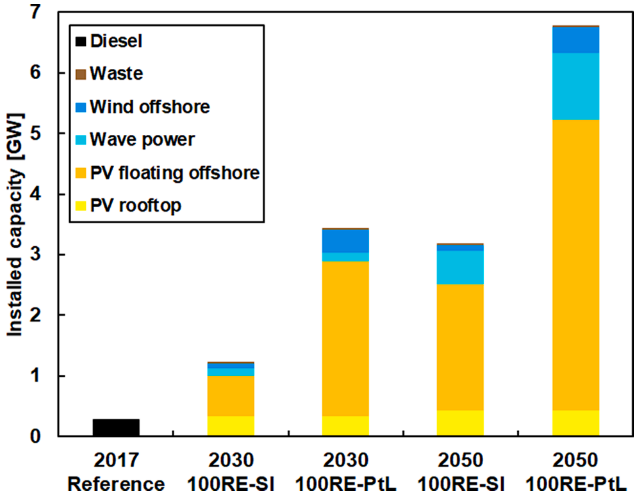


Fig. 3. Installed capacities of electricity generation technologies for the 2017 reference scenario, and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

For all scenarios, the role of floating PV clearly stands out. In addition to the 0.340 GW_p and 0.440 GW_p rooftop PV, for the 100RE-SI scenario, about 0.670 GW_p are needed in 2030 and 2.075 GW_p in 2050. In case of the 100RE-PtL scenario, the needed capacity is significantly higher with 2.550 GW_p in 2030 and 4.795 GW_p in 2050. Wave power becomes the technology with the second highest installed capacity. Even though the capital expenditures for wave power are still higher in 2030 than for wind offshore, the superior annual capacity factor and more stable electricity generation especially during the monsoon period makes wave power indispensable for the energy supply. For the 100RE-SI scenario, 0.115 GW and 0.550 GW of wave power capacity is needed in 2030 and 2050, respectively. While for the 100RE-PtL scenario, the values are 0.150 GW and 1.100 GW in 2030 and 2050. However, wind offshore plays an important supporting role in most of the scenarios. Whereas in 2030, wind offshore has a lower installed capacity than wave power of 0.090 GW in the 100RE-SI scenario. In the more energy intensive 100RE-PtL scenario wind offshore capacities of 0.372 GW are needed to secure the electricity supply for transport e-fuel production. By 2050, this changes to the favour of wave power with installed capacities of 0.106 GW and 0.426 GW for wind offshore. The waste power generation capacity stays same at 0.008 GW in all the 2030 and 2050 scenarios.

Similar characteristics can be found for the electricity generation of the technology mix, as it can be seen in Fig. 4.

In the reference scenario, about 98% or 0.64 TWh of the electricity is generated by diesel generators. Renewables play only a minor role with 0.014 TWh and 0.002 TWh of electricity generation from rooftop PV and wind offshore, respectively. Already in 2030, PV becomes the major electricity generation source for the Maldives. In case of no local transport e-fuels production, a total of 1.42 TWh and 3.23 TWh of

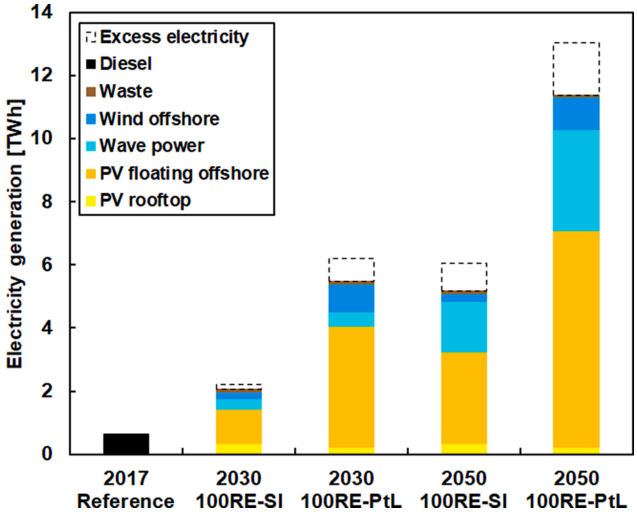


Fig. 4. Electricity generation of the studied technologies in the 2017 reference scenario, and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

electricity is supplied by PV in 2030 and 2050, in which, floating PV contributes with 1.08 TWh and 2.88 TWh. For the 100RE-PtL scenario, the PV electricity generation amounts 4.06 TWh and 7.08 TWh, whereas floating PV contributes with 3.83 TWh and 6.85 TWh, respectively. Wave power contributes 0.34 TWh and 1.61 TWh in 2030 and 2050 in the 100RE-SI scenario as well as 0.44 TWh and 3.21 TWh in 2030 and 2050 in the 100RE-PtL scenario. Apart from the 100RE-PtL scenario in 2030, wave power makes a greater contribution than wind offshore and slightly less than solar PV. Offshore wind is challenged by relatively low and unsteady wind resource conditions. However, for an energy-intensive 100RE-PtL scenario it is a better option in 2030. The contribution of offshore wind is 0.22 TWh and 0.26 TWh in 2030 and 2050 in the 100RE-SI scenario and 0.9 TWh and 1.02 TWh in 2030 and 2050 in the 100RE-PtL scenario. Especially noteworthy is that offshore wind shows only a limited growth potential between 2030 and 2050 in both the scenarios, whereas both floating PV and wave power gain substantial growth in electricity generation. Excess electricity is present, although in an acceptable range of 7.2% (2030 100RE-SI) to 14.5% (2050 100RE-SI) of the total generated electricity. Excess or curtailed electricity concerns PV generation only due to the simulation options of EnergyPLAN. This value is presumed to be able to optimise using a respective optimisation algorithm for the energy system. The overall dominance of solar PV in the electricity generation is a characteristic of the South Asian region, as this is also found in a research covering the entire region [92,93].

Necessary storage capacities depend on the combination of supply mix and demand structure, as shown in Fig. 5.

For the reference scenario, no information about storage capacities could be found. However, deployment of RES requires substantial storage options. In 2030, both scenarios require 2.7 GWh of battery capacity, which increases to 8.3 GWh for the 100RE-SI scenario and 3.9 GWh for the 100RE-PtL scenario until 2050. The demand structure of the 100RE-SI scenario is more variable, as, on the contrary to the 100RE-PtL scenario, non-existent e-fuel production technologies lead to a lower baseload demand. Therefore, the demand for flexible batteries is higher. Furthermore, in 2030 the presence of higher electricity generation capacities needed for transport e-fuel production also favour a lower demand for balancing storage capacity in case of the 100RE-PtL scenario.

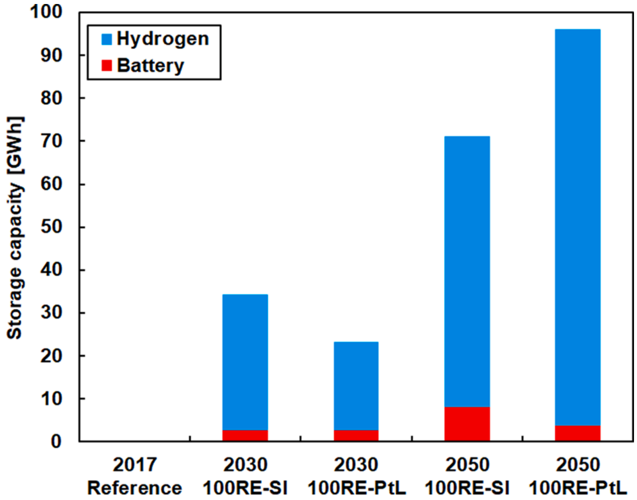


Fig. 5. Required storage capacities for electricity supply in the 2017 reference scenario, and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

This leads to a demand in hydrogen storage of 31.5 GWh for the 100RE-SI and 20.5 GWh for the 100RE-PtL scenario in 2030. In 2050, the situation changes due to an increasing demand for transport e-fuel production and more extensive use of wave power, which has a higher generation potential during the monsoon season. Therefore, the balancing storage capacity needed is 62.8 GWh for the 100RE-SI and 92 GWh for the 100RE-PtL scenario. As for electricity discharged from the storage technologies, in Fig. 6, typical short-term and long-term storage options can be seen. A total of 41.2% (2030) and 34.7% (2050) of the total electricity demand is covered by storage technologies in the 100RE-SI scenario. In the 100RE-PtL scenario, electricity covered by storage technologies has a share of 24.9% (2030) and 13.5% (2050). Profiles of the state of charge (SoC) of both storage options are shown in Figs. A.5 and A.6 of the Appendix A.

Batteries have a major share in total electricity discharged from the

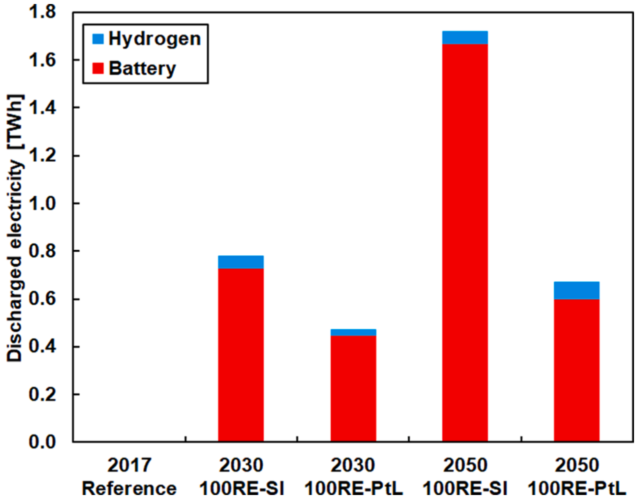


Fig. 6. Discharged electricity from the storage technologies in the 2017 reference scenario, and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

storage technologies. In the 100RE-SI scenario, in 2030, 0.73 TWh or 38.6% of the electricity demand is covered by batteries, whereas in 2050, 1.67 TWh or 33.7% of the electricity is supplied by batteries. In case of the 100RE-PtL scenario, batteries accounted for 0.45 TWh (23.8%) and 0.6 TWh (12.1%) in 2030 and 2050, respectively. Also important are the capacities of the storage electrolysers and multi-fuel generators. In 2030, the electrolyser capacity is 0.133 GW (100RE-SI) and 0.047 GW (100RE-PtL), in 2050 they are 0.127 GW (100RE-SI) and 0.144 GW (100RE-PtL). For the multifuel generators, a total capacity of 0.237 GW (100RE-SI) and 0.242 GW (100RE-PtL) are needed in 2030, as well as 0.555 GW (100RE-SI) and 0.547 GW (100RE-PtL) in 2050.

4.2. Transport e-fuel production system of the 100RE-PtL scenario

While all the hydrocarbon e-fuels for the transport sector are imported in the 100RE-SI scenario, the 100RE-PtL scenario system requires local fuel production capacities. EnergyPLAN models the CO_2 DAC and e-fuel synthesis units to run in baseload. For the present demands, in 2030, DAC units with the potential of capturing 0.5 $MtCO_2/a$ are needed. In 2050 the required DAC potential is 0.9 $MtCO_2/a$. The synthesis unit have a capacity of 187 MW_{fuel} output in 2030 and 335 MW_{fuel} output in 2050. The electrolyser and hydrogen storage can be scaled dynamically. Here, an electrolyser capacity of 1.08 GW_{el} and 1.9 GW_{el} is needed in 2030 and 2050, respectively. Hydrogen storage capacities of 25 GWh in 2030 and 80 GWh in 2050 are necessary.

4.3. System cost and emissions

In addition to the technological performance of the energy system, the economic performance is of major relevance. A comparison of the annualised system cost and relative cost per final energy unit is shown in Fig. 7 to evaluate if the 100% renewable energy system options are economically beneficial and to demonstrate which of the future system options is the most viable alternative from an economic point of view.

The reference scenario in 2017 has a total annualised cost of 485 m€ or in relative terms cost of 105.7 €/MWh. Even though the total annualised cost decrease for both scenarios in 2030 to 425 m€ in the 100RE-SI scenario and 467 m€ in the 100RE-PtL scenario, the relative cost per final energy unit increases to 120.3 €/MWh in the 100RE-SI scenario and 132.1 €/MWh in the 100RE-PtL scenario. Without using diesel generators for electricity supply the cost for imported (fossil) diesel is substituted with more efficient RES. However, due to the electrification of the road transportation the final energy demand decreases disproportionately. As a consequence, a fully renewable energy system in 2030 is going to be slightly more expensive on a relative scale. Nevertheless, until 2050 it will be possible to set up a 100% renewable energy system which is economically beneficial. The total annualised system cost for the 100RE-SI scenario is going to increase to 613 m€ with a relative cost of 77.6 €/MWh. Therefore, this option is almost 27% lower in cost per energy unit than the current fossil fuels-based system. In addition, it will be possible to produce e-fuels for the transport sector autonomously in a cost-effective way. The annualised system cost of the 100RE-PtL scenario in 2050 are 732 m€, which is 92.6 €/MWh, which in turn is about 13% lower in cost than the reference system.

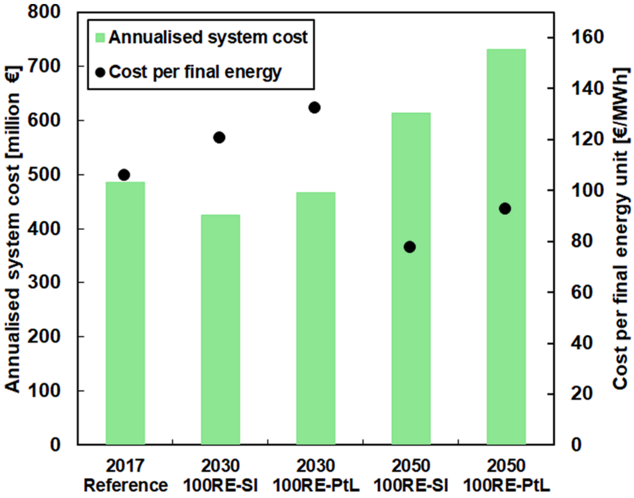


Fig. 7. Comparison of annualised system cost and cost per final energy unit in the 2017 reference scenario, and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

According to the World Bank, the CO_2 emissions of the Maldives in 2017 were about 1.82 $MtCO_2$ [16]. With the assumed emission factors, the reference system of 2017 modelled in EnergyPLAN results in 1.702 $MtCO_2$ emissions. Both scenarios in 2030, as well as in 2050, are able to reduce the CO_2 emissions to a total of 0.01 $MtCO_2$. The residual carbon emissions are due to the waste-to-energy facility.

4.4. Cost advantage of wave power deployment

The role of solar PV and especially the role of solar technologies in providing low-cost and sustainable electricity for the energy transition has been studied earlier [85,94,95]. In order to estimate the role of wave power electricity generation, the present system has been simulated and optimised without the option of wave power. The cost advantage of the system with wave power varies from 1.8% in 2030 to 11% in 2050, both for the 100RE-SI scenario. The cost advantage of the 100RE-PtL scenario is 9.8% in 2030 and 9.5% in 2050. Fig. 8 shows the change of technology capacities for the case when wave power is included in the system versus a system without wave power.

The introduction of wave energy diminishes the need for floating PV, battery storage and offshore wind (down by almost 80% for the latter in 2050 for 100RE-SI). On the contrary, in 2050 both of the scenarios need more hydrogen storage capacities to cover seasonal effects when wave power is included. A consistent change can be noticed for interface components, primarily the electrolyser for charging the hydrogen storage as a flexibility option. This is due to the fact that wave power is more steadily available compared to PV and offshore wind (cf. Figs. A.2–A.4). Therefore, hydrogen can be produced rather continuously with less electrolyser capacity. Additionally, it has to be noted that the capital expenditure (capex) assumptions for wind offshore in this study can be considered as optimistic compared to insights published by Wiser et al. [96] for the 2030′s value (capex projections for 2050 are missing), thus

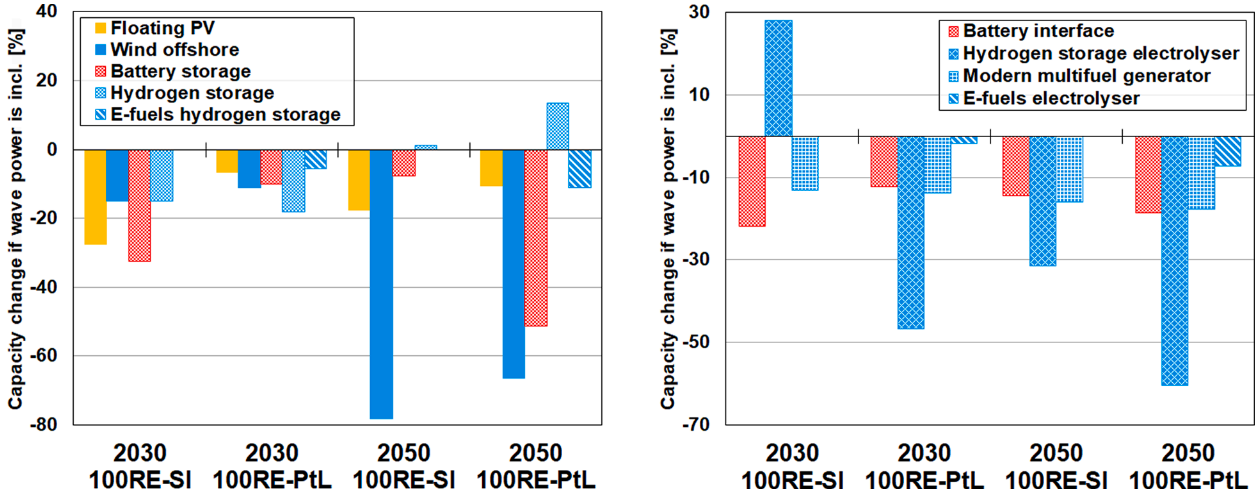


Fig. 8. Change of renewable energy source and storage capacities (left) and storage interface components (right) for the case that wave power is available as an energy source. For rooftop PV no changes are assumed.

creating an even tougher benchmark for wave power in this research.

4.5. Environmental and socio-economic impacts

Many regions worldwide face similar available land area problems as the Maldives, due to similar geographic constraints or high population density. The highest capacity density of the technologies can be found for floating offshore PV with 100–200 MW_p/km^2 [32]. WECs combined in clusters can reach a power density of 25 MW/km^2 [97]. Due to reasons of wake effects and respective spacing, offshore wind farms show the lowest power density of about 10 MW/km^2 [98]. Especially for islands and coastal areas with coral reefs, only a fraction of the available sea area is suitable for floating offshore technology deployment. Taking the Maldives with a total territorial area of 67,000 km^2 as an example, as much as 21,596 km^2 are unsuitable for offshore floating technologies, as it is either land area or atoll reefs [3]. Of the remaining 45,404 km^2 available sea area, only 0.04% and 0.13% for the 100RE-SI scenario or 0.10% and 0.26% for the 100RE-PtL scenario would be needed for energy supply. Therefore, floating PV is a very effective electricity supply option for islands and coastal areas in the Sun Belt, as the technology combines low cost, high electricity yield and low area demand. Moreover, offshore floating technologies have to be designed to withstand extreme weather conditions in order to avoid harmful impacts on the environment, flora, fauna and human life.

The main objective of the energy policy developed by the government in 2016 is the provision of affordable and reliable electricity to the people, while at the same time increasing national energy security [99]. Hence, offshore floating energy technologies investigated in this research have the potential to provide energy security and at the same time can effectively reduce the severe dependency on imported fossil fuels. Nevertheless, fossil fuels are very popular among the locals, due to its perceived efficiency, low storage space, ease of transport, reliability and expected cheap price. However, combustion processes suffer from a substantially lower efficiency as renewable electricity-based solutions [100]. Installations of offshore floating energy technologies will require substantial investments, which in turn lead to lower levelised cost of electricity compared to the present energy system, while in addition some space for battery storage and e-fuel storage is required, the latter similar to the present energy system. Due to these constraints, the public might show hesitancy in choosing floating offshore PV systems as an alternative to fossil fuel. Besides issues already discussed, a fully renewable energy system brings further benefits such as job creation [101], providing a possible benefit in public acceptance. However, with the rise in demand for energy due to progress in standards of living, investments in renewable energies are the best alternative to ensure a secure and affordable energy supply in the long run.

Transition from a fossil fuel-based energy system to a renewable energy system seems very promising for the country due to the profusion of renewable energy sources available in the country. However, this transition may be limited due to high public debt and reduced public sector financing capacity. As a result, SIDS are very much in need of support from multi-lateral development banks, bilateral cooperation with donor countries, private sector participation and foreign investments to carry out large-scale renewable energy projects. If done correctly, renewable energy sources can take over the role of currently used fossil fuels in SIDSs like the Maldives, to move towards a sustainable development pathway in the future. General sustainability issues of the used technologies regarding required materials etc. is considered to be out of scope of this study, as respective research on that topic is already available [56,102–104].

4.6. Opportunities and research advances

Combining different marine renewable energy technologies in offshore power plants is very well feasible [31,32]. Floating technologies can also be used for offshore fuel production plants [105]. Many coastal areas and islands have been proven to be suitable for such facilities. Particularly islands with a substantial tourism sector face the problem of providing enough fuels to supply their demand, e.g. for air transportation. Securing the supply by ramping up vast biofuel production capacities [106] might not be the most sustainable way forward. As this study has shown, deployment of offshore floating technologies provides an opportunity of becoming independent of fuel imports. However, fuel imports are also a suitable way, even though it should be ensured that biofuels are excluded from the imported fuel portfolio due to sustainability limitations [107].

Many islands depend on extensive fuel import to secure their power supply, which includes several risks such as supply change disruption and global fuel shortages [108]. Furthermore, deployment of renewable energy is often driven by the cost of fuel imports, as shown for Pacific Islands [109]. Especially SIDS have highly ambitious renewable energy targets but struggle to increase their renewables share accordingly [8]. Archipelagic countries face technical problems in particular due to a limited possibility of interconnected energy systems. Combining floating offshore technologies as proposed in this study enables to overcome such limitations, as islands are not limited to their available land area anymore.

This study marks a milestone for analysing 100% renewable based island energy systems. As found by Meschede et al. [48], no study of 100% renewable energy system has considered offshore floating PV in their technology portfolio nor the combination of several floating offshore technologies. Therefore, this study provides several advances for future island energy system research:

- Offshore floating PV can be a game changer for island energy transitions, especially in the Sun Belt, if land area is limited and no utility-scale ground-mounted PV plants can be installed. Remaining challenges are expected to be overcome in the near future, considering the huge potential, market growth and planned offshore projects [110]. Offshore floating PV is therefore strongly recommended to be considered in future island studies, as well as when studying countries with limited land area and available sea waters;
- Wave power will also be very important, even if the wave resources are moderate. Constant electricity production over the whole year and very good complementarity with electricity generation from solar PV, wave power will be able to challenge offshore wind until 2050;
- Wave power provides clear added value for powering islands and coastal areas. It was shown that even in 2030, a rather constant electricity generation of the WECs is indispensable for an economic advantage of the energy system. Only 4 out of 11 studies found by Meschede et al. [48] consider wave power in a respective techno-economic optimisation. Yue et al. [111] conclude no benefits of wave power at an investment cost level of more than double of what is assumed in 2050 in this study. A future modelling with respective cost reductions is missing in their work. Alves et al. [112] found only a minor role of wave power until 2050, even though the assumed cost level is comparable to the assumptions in this study. However, the resource potential and modelling are not reported in detail. Gils and Simon [113] also conclude a low potential for wave power until 2050, though referencing to the early development stage and necessary cost reduction of applied WECs. Similar results as in this study with a share of 25% of electricity generation by wave power were found by Loisel and Lemiale [114].

SIDS all over the world not only show similar energy supply characteristics and usually high dependency on fossil fuels, but also are restricted by land area due to geographic limitations or high population density [115]. This problem is not yet sufficiently addressed in 100% renewable energy research for islands or coastal areas [48]. In addition to islands, offshore floating technologies could also solve energy supply problems in coastal areas with high population density. The solar PV roadmap for Singapore already includes offshore floating PV [116], though only for near-shore applications. Another example where the considerable advantage of offshore floating technologies could be proven is Bangladesh, a country with high population density and low available land area for renewable energy deployment [117,118]. The excellent solar resources of the country in combination with available sea area could be very beneficial for covering additional energy demand apart from the power sector [119]. However, also in countries with more moderate solar resources such as the Netherlands, offshore floating PV can play a major role in the country's PV deployment [120]. The present study provides first insights into a suitable solution for the energy needs of island states and coastal areas.

5. Conclusions

The aim of this research was to provide an insight whether offshore floating technologies have the potential to supply a renewable energy system for an archipelago country, either in combination with the import of CO_2 neutral synthetic e-fuels, or for supplying own synthesis units within the country on the example of the transportation intensive context of the Maldives. This study showed that novel technological approaches such as offshore floating PV and wave power are able to secure the energy supply as needed. Additionally, a global e-fuel trade will be an important option for a cost-effective and reliable of transport fuel supply. The example of the Maldives shows that a transport- and fuel-intensive energy system does not necessarily have to be a bottleneck in transitioning to a fully renewable energy system when using available RES technologies. This study reveals that a transition of the Maldivian energy system towards 100% renewable based until 2030 is technically possible with a minor increase in cost per final energy unit.

Novel technology approaches, namely, offshore floating PV and wave power have been verified as potentially main technologies for countries with very limited land area and access to sea areas. Phasing out diesel-based electricity generation will have a positive effect on the countries' cost for final energy in the long-term. In the Maldives, for example, from a starting point of 105.7 €/MWh in 2017, a transitioned system would cost 120.3 €/MWh in 2030 and 77.6 €/MWh in 2050, if the CO_2-neutral e-fuels for the transport sector are imported from the global market. In case of setting up own transport e-fuel production facilities in the country, the cost would account to 132.1 €/MWh in 2030 and 92.6 €/MWh in 2050. Especially wave power with its relatively stable electricity generation over the whole year and especially during the monsoon season will be the backbone of the archipelago's energy system, in particular when energy intensive facilities for transport e-fuel production are set up within the country. Besides the cost advantages, CO_2 emissions drop substantially, or are avoided completely if a sustainable solution for handling waste residues can be found.

However, with an increase of RES, the demand for storage technologies grows, especially short-term battery storage. Not having interconnections available and geographically widespread storage options, the Maldives require a specialised balancing and seasonal storage option. Hydrogen is most qualified to take over this task, not least because of a well distributable nature of the system components, which can be placed on the islands all over the country. Without the domestic transport e-fuel production, more than a third of the electricity in the considered scenario is cycled via storage technologies. If the scenario includes local production facilities for e-fuels, the share of wave power, wind power and directly used solar power increases and less electricity has to be provided via storage options. In 2030, about 25% of the electricity is supplied by storage technologies, whereas in 2050 it is 13.5%.

Many islands and countries are in a similar situation to the Maldives, in that they are dependent on diesel-based electricity generation and have limited land area but have access to sea areas. Floating offshore PV and wave power have the potential to provide suitable solutions for these regions to ensure a sustainable energy transition reaching a 100% renewable energy supply share between 2030 and 2050. Further research is required by implementing these technologies in optimisation models and studying the advantages of the technologies based on a comprehensive techno-economic optimisation. Further research in the necessary efforts and implications for grid connections of the technologies will be necessary. Nevertheless, the present study provides useful insights for the future of offshore floating PV and wave power and their role in the energy transition.

CRediT authorship contribution statement

Dominik Keiner: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Orlando Salcedo-Puerto:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing. **Ekaterina Immonen:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing. **Wilfried G.J.H.M. van Sark:** Validation, Writing – review & editing. **Yoosuf Nizam:** Validation, Writing – review & editing. **Fathmath Shadiya:** Validation, Writing – review & editing, Investigation. **Justine Duval:** Methodology, Validation, Investigation, Resources, Writing – review & editing. **Timur Delahaye:** Methodology, Validation, Investigation, Resources, Writing – review & editing. **Ashish Gulagi:** Validation, Writing – review & editing. **Christian Breyer:** Conceptualization, Methodology, Validation, 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.

Acknowledgements

The authors gratefully acknowledge the public financing of European Union's Horizon 2020 and Green Deal research and innovation programme under grant agreement No 953016 (SERENDI-PV) and No 101036457 (EU-SCORES).

Appendix A

See Figs. A1–A6 and Tables A1 and A2.

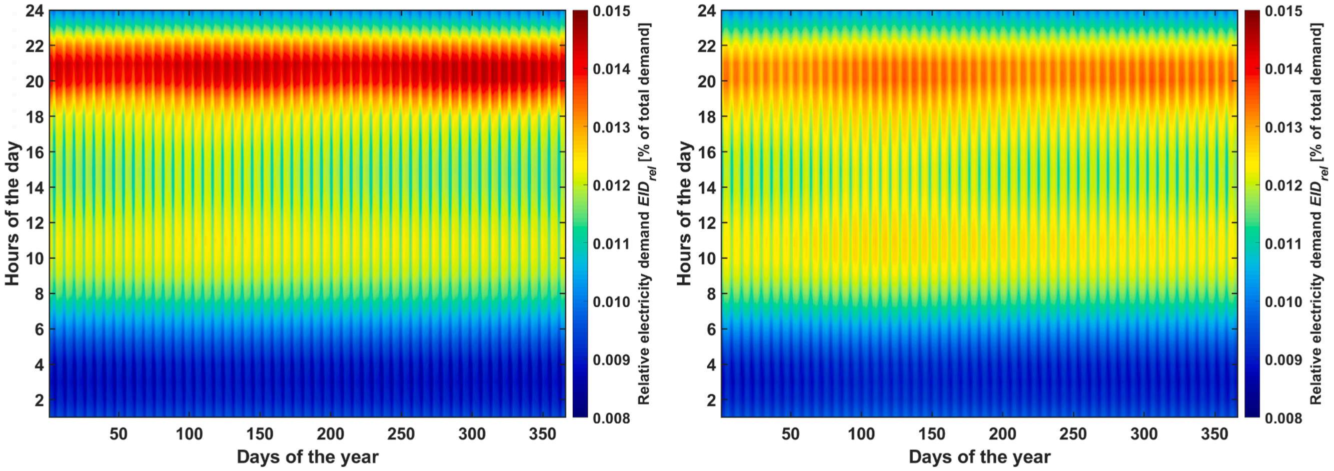


Fig. A1. Electricity load distribution profile used for 2017 and 2030 simulation (left), and profile used for 2050 simulation (right). Based on data from [74].

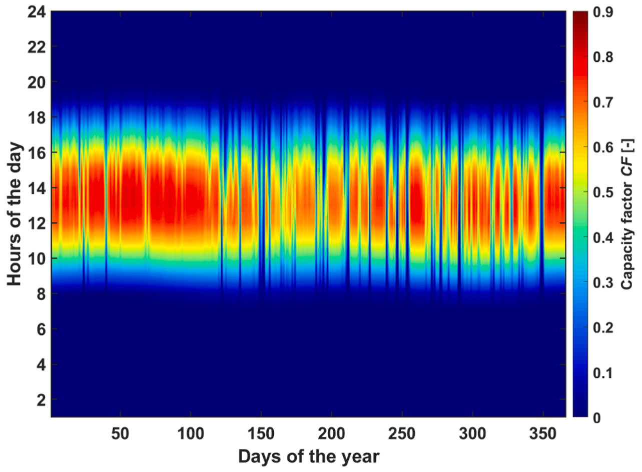


Fig. A2. Capacity factor profile for solar PV in the Maldives without yield correction as applied for floating solar PV.

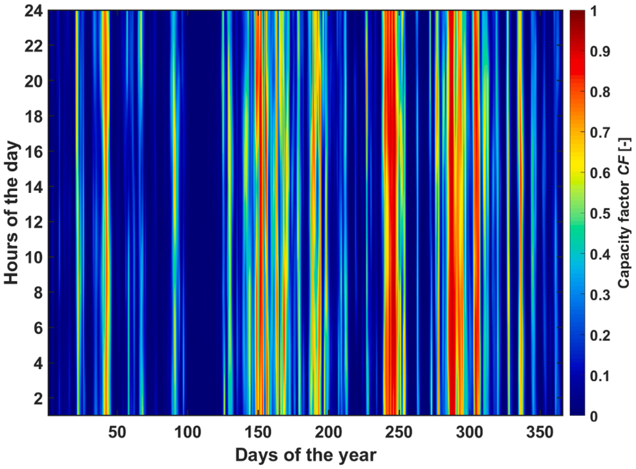


Fig. A3. Capacity factor profile for offshore wind power plants in the Maldives without yield correction.

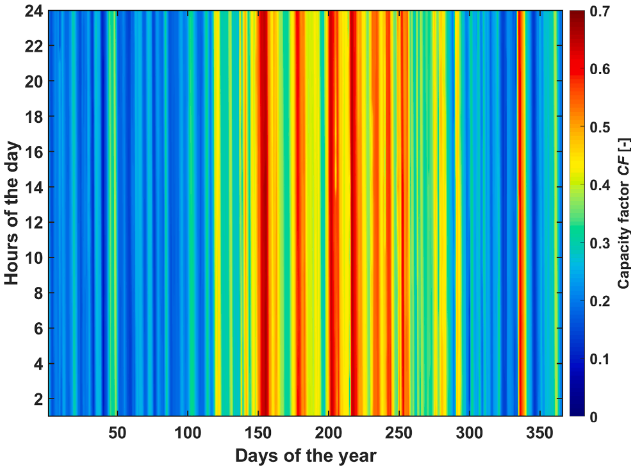
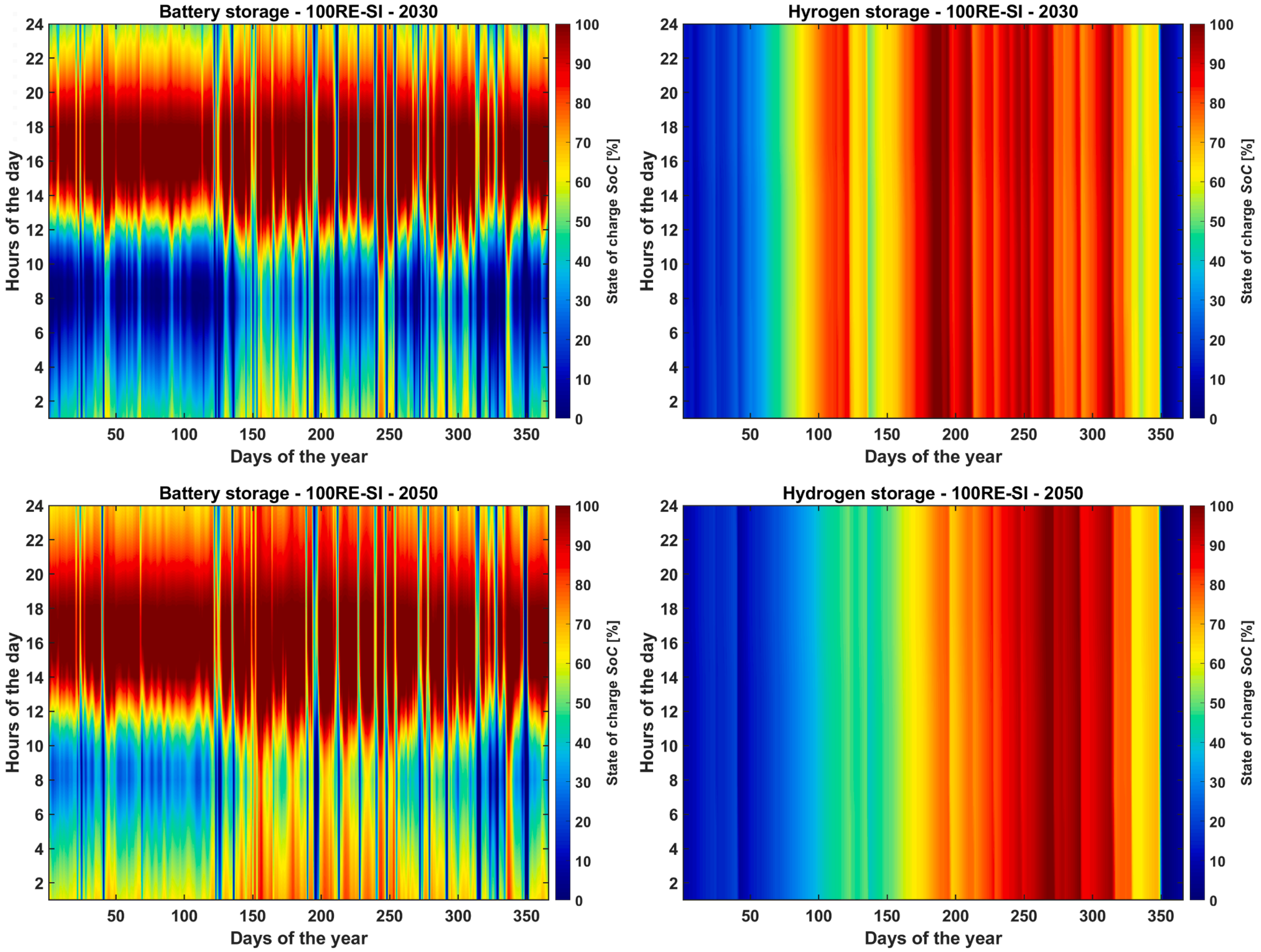


Fig. A4. Capacity factor profile for the wave energy converter system in the Maldives.


Battery storage - 100RE-SI - 2030

Hyrogen storage - 100RE-SI - 2030

Battery storage - 100RE-SI - 2050

Hydrogen storage - 100RE-SI - 2050

Fig. A5. State of charge profiles of the 100RE-SI scenario in 2030 (top) and 2050 (bottom) of the battery storage (left) and hydrogen storage (right).

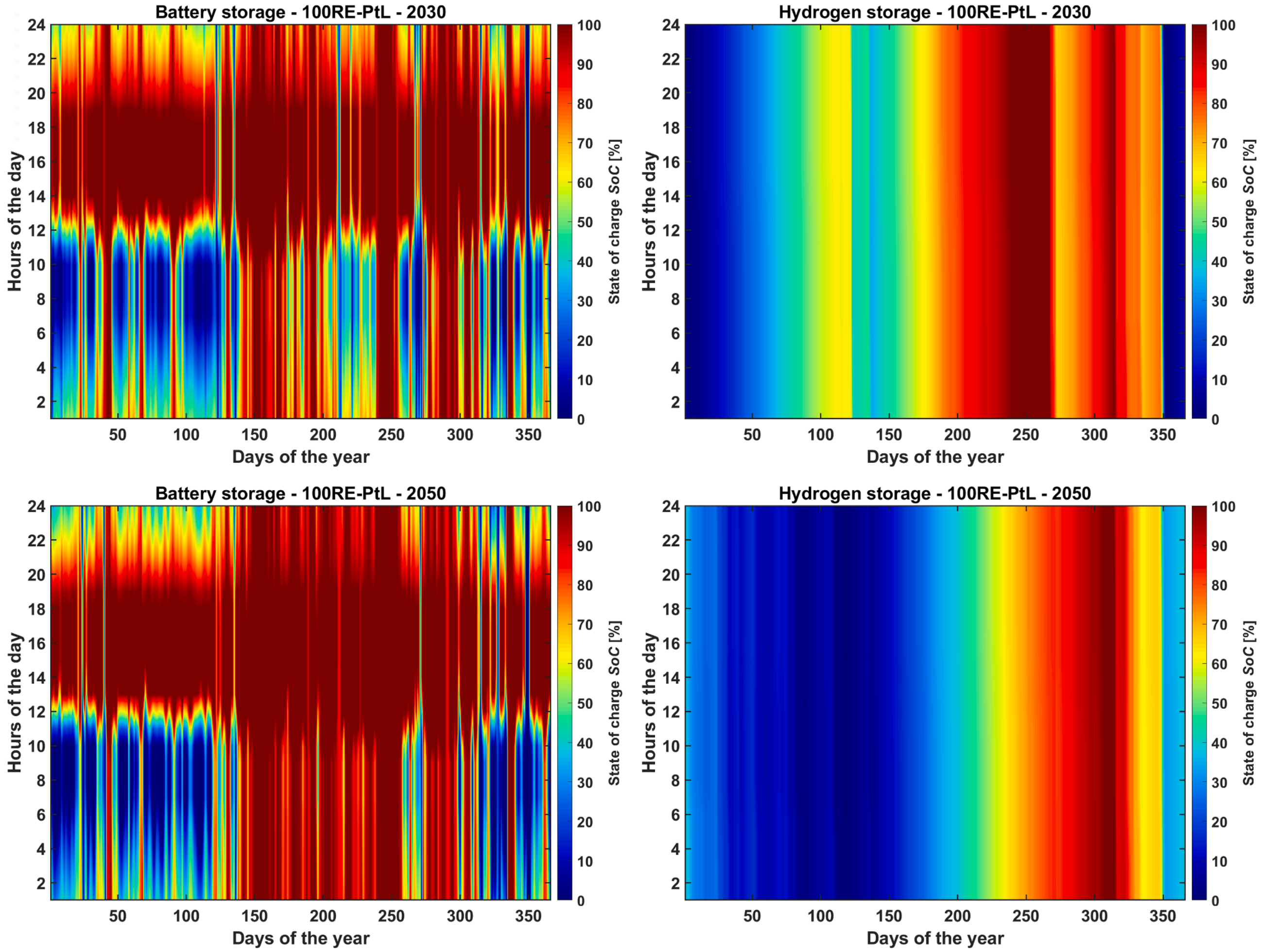


Fig. A6. State of charge profiles of the 100RE-PtL scenario in 2030 (top) and 2050 (bottom) of the battery storage (left) and hydrogen storage (right).

Table A1
Techno-economic input parameters for all applied technologies including power generation, storage, sector coupling, imported fuels and emission prices. Data referenced to the EnergyPLAN model [49] itself refer to the respective EnergyPLAN database available at the model's website.

	Parameter	Unit	2017	2030	2050	Source
PV rooftop[1]	capex	€/kW$_p$	1360	490	300	[54,121]
	opex$_{fix}$	% of capex	1.5	2	2	
	lifetime	years	30	35	40	
	correction factor[2]	–	−0.731	−0.731	−0.731	
	annual capacity factor	–	0.15	0.15	0.15	
PV floating offshore	capex	€/kW$_p$		695	332	INNOSEA, Nantes, 2021, private communication
	opex$_{fix}$	% of capex		2	2	
	lifetime	years		30	30	
	correction factor[2]	–	–	–	–	
	annual capacity factor	–	0.19	0.19	0.19	
Wind offshore	capex	€/kW	2973	2287	2130	[122]
	opex$_{fix}$	% of capex	2.9	2.9	2.9	
	lifetime	years	25	25	25	
	correction factor[2]	–	0.25	0.25	0.25	
	annual capacity factor	–	0.27	0.27	0.27	
Wave power	capex	€/kW		2800	1800	[123]
	opex$_{fix}$	% of capex		2.75	2.4	
	lifetime	years		25	30	
	correction factor[2]	–	–	–	–	
	annual capacity factor	–	0.33	0.33	0.33	
Waste-to-energy	capex	€/kWh (inp.)[3]		0.2156	0.2156	[49]
	lifetime	years		20	20	
	efficiency (el.)	%		80	80	
Internal combustion engine (diesel)	capex	€/kW	385			[124]
	opex$_{fix}$	% of capex	3			
	opex$_{var}$	€/kWh	0.0047			
	lifetime	years	30			
	efficiency (el.)	%	40			
Battery storage[4]	capex	€/kWh		142.5	79.5	[55,56,121]
	opex$_{fix}$	% of capex		1.85	2.55	
	lifetime	years		20	20	
	self-discharge	%/h		0	0	
	round-trip efficiency	%		92.9	95.1	
Battery interface[4]	capex	€/kW		72	39	[121]
	opex$_{fix}$	% of capex		1.9	2.3	
	lifetime	years		20	20	
Balancing H_2 storage	capex	€/kWh		0.374	0.367	[69]
	opex$_{fix}$	% of capex		4	4	
	lifetime	years		30	30	
Balancing electrolyser	capex	€/kW$_{el}$		446	291	[125]
	opex$_{fix}$	% of capex		3.5	3.5	
	lifetime	years		30	30	
	efficiency	%		70	70	
Balancing compressor	capex	€/kW$_{el}$		4.7	4.7	[69]
	opex$_{fix}$	% of capex		4	4	
	lifetime	years		20	20	
	electricity consumption	kWh$_{el}$/kWh$_{H2,LHV}$		0.047	0.047	
Balancing electrolyser-compressor-unit[5]	capex	€/kW$_{el}$		432	282	
	opex$_{fix}$	% of capex		3.5	3.5	
	lifetime	years		30	30	
	efficiency	%		67.8	67.8	
Multi-fuel generator	capex	€/kW$_{el}$		537	475	[66,67]
	opex$_{fix}$	% of capex		1.2	1.3	
	lifetime	years		30	30	
	efficiency	%		47	47	
E-fuels electrolyser	capex	€/kW$_{el}$		446	291	[125]
	opex$_{fix}$	% of capex		3.5	3.5	
	lifetime	years		30	30	
	efficiency	%		70	70	

(*continued on next page*)

Table A1 (*continued*)

	Parameter	Unit	2017	2030	2050	Source
E-fuels synthesis unit (Fischer-Tropsch)	capex	€/kW$_{fuel}$		1017	915	[71]
	opex$_{fix}$	% of capex		3	3	
	lifetime	years		30	30	
	H_2 consumption	kWh$_{H2}$/kWh$_{fuel}$		1.44	1.44	
	CO_2 consumption	kgCO_2/kWh$_{fuel}$		0.305	0.305	
E-fuels CO_2 DAC	capex	€/(tCO_2/a)		338	199	[70]
	opexfix	% of capex		4	4	
	lifetime	years		30	30	
E-fuels H_2 storage	capex	€/kWh		0.28	0.28	[126]
	opex$_{fix}$	% of capex		4	4	
	lifetime	years		30	30	
Diesel storage	capex	€/kWh		0.02	0.02	[49]
	opex$_{fix}$	% of capex		0.63	0.63	
	lifetime	years		50	50	
Petrol/ kerosene storage	capex	€/kWh		0.05	0.05	[49]
	opex$_{fix}$	% of capex		0.63	0.63	
	lifetime	years		50	50	
Fossil diesel import[6]	price	€/MWh	57.6			[49]
	emissions	kgCO_2/MWh	72.9			
Fossil petrol/kerosene import[6]	price	€/MWh	59.04			[49]
	emissions	kgCO_2/MWh	262.44			
Fossil LPG import	price	€/MWh	61.2			[49]
	emissions	kgCO_2/MWh	213.26			
E-fuel import[6]	price	€/MWh		127.51	79.99	[72,73]
	emissions	kgCO_2/MWh		0	0	
Diesel handling	price	€/MWh	13.86	13.86	13.86	[49]
Petrol handling	price	€/MWh	16.81	16.81	16.81	[49]
Kerosene handling	price	€/MWh	1.04	1.04	1.04	[49]
Waste	emissions	kgCO_2/MWh	117	117	117	[49]
CO_2 pricing[7]	price	€/tCO_2	28	61	150	[127]

[1] Assuming a mix of 87.5% commercial- and 12.5% residential-scale rooftop PV.

[2] The correction factor acts as a tool to adapt the electricity production of renewable energy sources to actual numbers in EnergyPLAN. The correction factors here have been validated with given numbers for capacities and electricity production for the reference year 2017.

[3] Waste input.

[4] Assuming a mix of 50% commercial- and 50% utility-scale batteries.

[5] The electrolyser and the compressor for the balancing storage system are modelled in combination as charging technology of the balancing hydrogen system.

[6] Diesel, petrol and kerosene.

[7] Until 2040 from source, then extrapolated.

Table A2
Simulation results of the reference scenario in 2017 and the 100RE-SI and 100RE-PtL scenarios for 2030 and 2050.

	Parameter	Unit	Reference	100RE-SI		100RE-PtL	
			2017	2030	2050	2030	2050
PV rooftop	Capacity	GW_p	0.010	0.34	0.44	0.34	0.44
	Generation[1]	TWh_{el}	0.014	0.34	0.35	0.23	0.23
	Generation share[2]	%	2.1	16.6	6.8	4.2	2.0
PV floating offshore	Capacity	GW		0.67	2.075	2.55	4.795
	Generation	TWh_{el}		1.08	2.88	3.83	6.85
	Generation share[2]	%		52.7	55.7	70.0	60.2
Wave power	Capacity	GW		0.115	0.550	0.15	1.1
	Generation	TWh_{el}		0.34	1.61	0.44	3.21
	Generation share[2]	%		16.6	31.1	8.0	28.2
Wind offshore	Capacity	GW	0.000209	0.085	0.1	0.35	0.4
	Generation	TWh_{el}	0.002	0.22	0.26	0.9	1.02
	Generation share[2]	%	0.3	10.7	5.0	16.5	9.0
Waste-to-energy	Capacity	GWh/a		876	876	876	876
	Generation	TWh_{el}		0.07	0.07	0.07	0.07
	Generation share[2]	%		3.4	1.4	1.3	0.6
Diesel generator	Capacity	GW_{el}	0.266				
	Generation	TWh_{el}	0.64				
	Supply share[2]	%	97.6				
Curtailment	Quantity	TWh_{el}		0.16	0.88	0.73	1.66
	Generation share[2]	%		7.2	14.5	11.8	12.7
Battery storage	Capacity	GWh_{el}		2.7	8.3	2.7	3.9
	Output	TWh_{el}		0.73	1.67	0.45	0.6
	Supply share[3]	%		38.6	33.7	23.8	12.1
Battery interface	Capacity	GW_{el}		0.65	1.61	1.04	1.79
Balancing H_2 storage	Capacity	GWh_{el}		31.5	62.8	20.5	92
	Output[4]	TWh_{el}		0.05	0.05	0.02	0.07
	Supply share[3,4]	%		2.6	1.0	1.1	1.4
Balancing electrolyser	Capacity	GW_{el}		0.133	0.127	0.047	0.144
	Input	TWh_{el}		0.14	0.17	0.06	0.23
Multi-fuel generator	Capacity	GW_{el}		0.237	0.555	0.242	0.547
Fuel storage diesel	Capacity	GWh_{th}	0.88	0.123	0.164	0.123	0.164
Fuel storage Petrol/Kerosene	Capacity	GWh_{th}	0.337	0.287	0.572	0.287	0.572
E-fuels electrolyser	Capacity	GW_{el}				1.08	1.9
E-fuels synthesis unit (Fischer-Tropsch)	Capacity	$GW_{th,out}$				0.187	0.335
E-fuels carbon capture	Capacity	$MtCO_2/a$				0.5	0.9
E-fuels H_2 storage	Capacity	GWh_{th}				25	80
Annualised cost	Cost	M€/a	485	424	612	465	726
Variable fuel cost (import + handling)	Cost	M€/a	406	223	255	14	20
Emission cost	Cost	M€/a	48	2	2	2	2
Cost per final energy	Cost	€/MWh	105.7	120	77.4	131.6	91.9
Emissions	Emissions	$MtCO_2/a$	1.706	0.01	0.01	0.01	0.01

[1] Varies despite same capacities due to demand- and simulation-related curtailment.
[2] Of total electricity generation.
[3] Of total electricity demand; in 100RE-PtL scenario incl. electricity demand for e-fuel production.
[4] Electricity output of modern multi-fuel generator.

References

[1] Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: Cambridge University Press; 2021 [in press].

[2] Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Geneva; 2018.

[3] Stevens GMW, Froman N. The Maldives Archipelago. World Seas and Environ. Eval. Elsevier; 2019. p. 211–36.

[4] Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, et al. Sea level rise and implications for low-lying islands, coasts and communities. IPCC Spec. Rep. Ocean Cryosph. a Chang. Clim., Geneva 2019.

[5] De Falco C, Bracco A, Pasquero C. Climatic and oceanographic controls on coral bleaching conditions in the Maldivian Region. Front Mar Sci 2020;7. https://doi.org/10.3389/fmars.2020.539869.

[6] United Nations Framework Convention on Climate Change (UNFCC). Report of the Conference of the Parties on its Twenty-First Session FCCC/CP/2015/10/Add.1. Paris; 2015.

[7] Mengel M, Nauels A, Rogelj J, Schleussner C-F. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. Nat Commun 2018;9:601. https://doi.org/10.1038/s41467-018-02985-8.

[8] Syauqi A, Pratama YW, Purwanto WW. Sustainable energy system in the archipelagic country: challenges and opportunities; 2021. p. 49–69. https://doi.org/10.1007/978-3-030-67529-5_3.

[9] The World Bank. Maldives: Towards a Sustainable Net-Zero Future 2021. https://www.worldbank.org/en/news/feature/2021/07/12/towards-a-sustainable-net-zero-future-in-maldives [accessed July 15, 2021].

[10] Central Intelligence Agency (CIA). The world factbook - Maldives 2021. https://www.cia.gov/the-world-factbook/countries/maldives/#economy [accessed July 16, 2021].

[11] Asian Development Bank. A Brighter Future for Maldives Powered by Renewables: Manila, Philippines; 2020. https://doi.org/10.22617/TCS200355-2.

[12] Meschede H, Holzapfel P, Kadelbach F, Hesselbach J. Classification of global island regarding the opportunity of using RES. Appl Energy 2016;175:251–8. https://doi.org/10.1016/j.apenergy.2016.05.018.

[13] Blechinger P, Cader C, Bertheau P, Huyskens H, Seguin R, Breyer C. Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands. Energy Policy 2016;98:674–87. https://doi.org/10.1016/j.enpol.2016.03.043.

[14] United Nations Statistics Division (UNSD). UN Data – Energy Statistics Database 2021. http://data.un.org/Search.aspx?q=maldives+datamart%5BEDATA%5D [accessed July 16, 2021].

[15] Ministry of Environment and Energy. Island Electricity Data Book 2018. Malé; 2018.

[16] The World Bank. CO2 emissions (kt) - Maldives 2021. https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?end=2018&locations=MV&start=1960&view=chart [accessed July 20, 2021].

[17] The World Bank. CO2 emissions (metric tons per capita) - Maldives, OECD members 2021. https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2018&locations=MV-OE&start=1960&view=chart [accessed July 20, 2021].

[18] Liu J, Mei C, Wang H, Shao W, Xiang C. Powering an island system by renewable energy—a feasibility analysis in the Maldives. Appl Energy 2018;227:18–27. https://doi.org/10.1016/j.apenergy.2017.10.019.

[19] van Alphen K, van Sark WGJHM, Hekkert MP. Renewable energy technologies in the Maldives—determining the potential. Renew Sustain Energy Rev 2007;11(8): 1650–74. https://doi.org/10.1016/j.rser.2006.02.001.

[20] Wijayatunga P, George L, Lopez A, Aguado JA. Integrating clean energy in small island power systems: Maldives experience. Energy Procedia 2016;103:274–9. https://doi.org/10.1016/j.egypro.2016.11.285.

[21] International Renewable Energy Agency (IRENA). Renewable energy roadmap: The republic of Maldives. Abu Dhabi; 2015.

[22] van Sark WGJHM, Lysen EH, Cocard D, Beutin P, Merlo GF, Mohanty B, et al. The first PV-diesel hybrid system in the Maldives installed at Mandhoo island. Munich: WIP-Renewable Energies; 2006. p. 3039–43.

[23] Contestabile P, Di LE, Galli P, Corselli C, Vicinanza D. Offshore Wind and Wave Energy Assessment around Malè and Magoodhoo Island (Maldives). Sustainability 2017;9:613. https://doi.org/10.3390/su9040613.

[24] Ali I, Shafiullah G, Urmee T. A preliminary feasibility of roof-mounted solar PV systems in the Maldives. Renew Sustain Energy Rev 2018;83:18–32. https://doi.org/10.1016/j.rser.2017.10.019.

[25] The World Bank Group, ESMAP, SERIS. Where Sun Meets Water: Floating Solar Market Report—Executive Summary. Washington, D.C.; 2018.

[26] Farfan J, Breyer C. Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential. Energy Procedia 2018;155:403–11. https://doi.org/10.1016/j.egypro.2018.11.038.

[27] Trapani K, Millar DL. Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. Energy Convers Manag 2013;67:18–26. https://doi.org/10.1016/j.enconman.2012.10.022.

[28] Sahu A, Yadav N, Sudhakar K. Floating photovoltaic power plant: a review. Renew Sustain Energy Rev 2016;66:815–24. https://doi.org/10.1016/j.rser.2016.08.051.

[29] Solanki C, Nagababu G, Kachhwaha SS. Assessment of offshore solar energy along the coast of India. Energy Procedia 2017;138:530–5. https://doi.org/10.1016/j.egypro.2017.10.240.

[30] Liu H, Krishna V, Lun Leung J, Reindl T, Zhao L. Field experience and performance analysis of floating PV technologies in the tropics. Prog Photovoltaics Res Appl 2018;26(12):957–67. https://doi.org/10.1002/pip.v26.1210.1002/pip.3039.

[31] López M, Rodríguez N, Iglesias G. Combined floating offshore wind and solar PV. J Mar Sci Eng 2020;8:576. https://doi.org/10.3390/jmse8080576.

[32] Golroodbari SZM, Vaartjes DF, Meit JBL, van Hoeken AP, Eberveld M, Jonker H, et al. Pooling the cable: a techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park. Sol Energy 2021;219:65–74. https://doi.org/10.1016/j.solener.2020.12.062.

[33] Soukissian TH, Karathanasi FE, Zaragkas DK. Exploiting offshore wind and solar resources in the Mediterranean using ERA5 reanalysis data. Energy Convers Manag 2021;237:114092. https://doi.org/10.1016/j.enconman.2021.114092.

[34] Golroodbari SZ, Sark WGJHM. Simulation of performance differences between offshore and land-based photovoltaic systems. Prog Photovoltaics Res Appl 2020; 28(9):873–86. https://doi.org/10.1002/pip.v28.910.1002/pip.3276.

[35] Langhamer O, Haikonen K, Sundberg J. Wave power—Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. Renew Sustain Energy Rev 2010;14(4):1329–35. https://doi.org/10.1016/j.rser.2009.11.016.

[36] López I, Andreu J, Ceballos S, Martínez de Alegría I, Kortabarria I. Review of wave energy technologies and the necessary power-equipment. Renew Sustain Energy Rev 2013;27:413–34. https://doi.org/10.1016/j.rser.2013.07.009.

[37] Lin Y, Bao J, Liu H, Li W, Tu L, Zhang D. Review of hydraulic transmission technologies for wave power generation. Renew Sustain Energy Rev 2015;50: 194–203. https://doi.org/10.1016/j.rser.2015.04.141.

[38] Uihlein A, Magagna D. Wave and tidal current energy – a review of the current state of research beyond technology. Renew Sustain Energy Rev 2016;58: 1070–81. https://doi.org/10.1016/j.rser.2015.12.284.

[39] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304. https://doi.org/10.1016/j.renene.2012.01.101.

[40] Reguero BG, Losada IJ, Méndez FJ. A global wave power resource and its seasonal, interannual and long-term variability. Appl Energy 2015;148:366–80. https://doi.org/10.1016/j.apenergy.2015.03.114.

[41] Zheng C. Dynamic self-adjusting classification for global wave energy resources under different requirements. Energy 2021;236:121525. https://doi.org/10.1016/j.energy.2021.121525.

[42] Anton I, Nash S. Application of the IEC technical specification for assessment of wave energy resource: a case study from the West Coast of Ireland. Civ Eng Res Irel 2020;2020.

[43] Iglesias G, Carballo R. Wave power for La Isla Bonita. Energy 2010;35(12): 5013–21. https://doi.org/10.1016/j.energy.2010.08.020.

[44] Curto D, Van Doan B, Franzitta V, Montana F, Nguyen NQ, Sanseverino ER. Wave and wind energy systems integration in Vietnam: analysis of energy potential and economic feasibility. In: 2020 IEEE Int. Conf. Environ. Electr. Eng. 2020 IEEE Ind. Commer. Power Syst. Eur. (EEEIC/I&CPS Eur.). IEEE; 2020. p. 1–6. https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160682.

[45] Jahangir MH, Shahsavari A, Vaziri Rad MA. Feasibility study of a zero emission PV/Wind turbine/Wave energy converter hybrid system for stand-alone power supply: a case study. J Clean Prod 2020;262:121250. https://doi.org/10.1016/j.jclepro.2020.121250.

[46] de Oliveira L, dos Santos IFS, Schmidt NL, Tiago Filho GL, Camacho RGR, Barros RM. Economic feasibility study of ocean wave electricity generation in Brazil. Renew Energy 2021;178:1279–90. https://doi.org/10.1016/j.renene.2021.07.009.

[47] Lavidas G, Blok K. Shifting wave energy perceptions: the case for wave energy converter (WEC) feasibility at milder resources. Renew Energy 2021;170: 1143–55. https://doi.org/10.1016/j.renene.2021.02.041.

[48] Meschede H, Bertheau P, Khalili S, Breyer C. A review of 100% renewable energy scenarios on islands; 2021 [submitted for publication].

[49] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, vad Mathiesen B. EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy 2021;1: 100007. https://doi.org/10.1016/j.segy.2021.100007.

[50] Meschede H, Child M, Breyer C. Assessment of sustainable energy system configuration for a small Canary island in 2030. Energy Convers Manag 2018; 165:363–72. https://doi.org/10.1016/j.enconman.2018.03.061.

[51] Meschede H, Hesselbach J, Child M, Breyer C. On the impact of probabilistic weather data on the economically optimal design of renewable energy systems – a case study on La Gomera island. Int J Sustain Energy Plan Manag 2019;23:15–26. https://doi.org/10.5278/ijsepm.3142.

[52] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy Convers Manag 2017;137:49–60. https://doi.org/10.1016/j.enconman.2017.01.039.

[53] Child M, Nordling A, Breyer C. The impacts of high V2G participation in a 100% Renewable Åland Energy System. Energies 2018;11:2206. https://doi.org/10.3390/en11092206.

[54] Mann SA, de Wild-Scholten MJ, Fthenakis VM, van Sark WGJHM, Sinke WC. The energy payback time of advanced crystalline silicon PV modules in 2020: a prospective study. Prog Photovolt Res Appl 2014;22:1180–94. https://doi.org/10.1002/pip.2363.

[55] Spitthoff L, Lamb JJ, Pollet BG, Burheim OS. Lifetime Expectancy of Lithium-Ion Batteries. Micro-Optics and Energy. Cham: Springer International Publishing; 2020. p. 157–80. https://doi.org/10.1007/978-3-030-43676-6_11.

[56] Peters IM, Breyer C, Jaffer SA, Kurtz S, Reindl T, Sinton R, et al. The role of batteries in meeting the PV terawatt challenge. Joule 2021;5(6):1353–70. https://doi.org/10.1016/j.joule.2021.03.023.

[57] CorPower Ocean AB. Technology; 2021. https://www.corpowerocean.com/technology/ [accessed July 22, 2021].

[58] Asian Development Bank. ADB Approves $73 Million Package to Develop Waste-to-Energy Facility in Maldives 2020. https://www.adb.org/news/adb-approves-73-million-package-develop-waste-energy-facility-maldives [accessed July 21, 2021].

[59] Ministry of Environment Climate Change and Technology. Environmental Impact Assessment – MLD: Greater Malé Waste-to-Energy Project – Waste to Energy Plant 2020. https://www.environment.gov.mv/v2/en/download/10368 [accessed July 21, 2021].

[60] Aboobakur S, Samarakoon MB. Solid waste management in Kulhudhuffushi, Maldives; Most suitable solution for the Crisis. Int J Environ Agric Biotechnol 2019;4(6):1853–61.

[61] Ministry of Tourism. Assessment of Solid Waste Management Practices and Its Vulnerability to Climate Risks in Maldives Tourism Sector. Malé; 2015.

[62] Malatesta S, di Friedberg MS, Pecorelli V, Di Pietro A, Cajiao MA. The right place. Solid waste management in the Republic of Maldives: between infrastructural measures and local practices. Misc Geogr 2015;19:25–32. https://doi.org/10.1515/mgrsd-2015-0003.

[63] Ministry of Environment and Energy. Maldives SREP investment plan. Malé 2012.

[64] Swimsol GmbH. Swimsol, Vienna 2019. https://swimsol.com/ [accessed November 17, 2021].

[65] Speckmann FW, Keiner D, Birke KP. Influence of rectifiers on the techno-economic performance of alkaline electrolysis in a smart grid environment. Renew Energy 2020;159:107–16. https://doi.org/10.1016/j.renene.2020.05.115.

[66] Wärtsilä Corporation. Research reveals G20 needs over 3,500 GW of flexibility to enable 100% renewable electricity, as Wärtsilä launches grid balancing technology 2021. https://www.wartsila.com/media/news/31-03-2021-research-reveals-g20-needs-over-3-500-gw-of-flexibility-to-enable-100-renewable-electricity-as-wartsila-launches-grid-balancing-technology-2888430 [accessed August 30, 2021].

[67] Ram M, Gulagi A, Bogdanov D, Breyer C. A 100% renewable power system across India by 2050. White paper on power system optimisation. Lappeentanta, Helsinki. 2021.

[68] Wang J, Wang H, Fan Y. Techno-economic challenges of fuel cell commercialization. Engineering 2018;4(3):352–60. https://doi.org/10.1016/j.eng.2018.05.007.

[69] Fasihi M, Weiss R, Savolainen J, Breyer C. Global potential of green ammonia based on hybrid PV-wind power plants. Appl Energy 2021;294:116170. https://doi.org/10.1016/j.apenergy.2020.116170.

[70] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO2 direct air capture plants. J Clean Prod 2019;224:957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.

[71] Fasihi M, Bogdanov D, Breyer C. Long-term hydrocarbon trade options for the Maghreb region and Europe—renewable energy based synthetic fuels for a net zero emissions world. Sustainability 2017;9:306. https://doi.org/10.3390/su9020306.

[72] Ram M, Galimova T, Bogdanov D, Fasihi M, Gulagi A, Breyer C, et al. Powerfuels in a Renewable Energy World - Global volumes, costs, and trading 2030 to 2050. Lappeenranta, Berlin: LUT University and Deutsche Energie-Agentur GmbH (dena; 2020. https://doi.org/10.13140/RG.2.2.32687.56487.

[73] Galimova T, Ram M, Bogdanov D, Fasihi M, Gulagi A, Khalili S, et al. Role of e-fuels and e-chemicals trading in enabling the global energy transition towards 100% renewable energy across the power, heat, transport and industry sectors by 2050; 2022 [submitted for publication].

[74] Toktarova A, Gruber L, Hlusiak M, Bogdanov D, Breyer C. Long term load projection in high resolution for all countries globally. Int J Electr Power Energy Syst 2019;111:160–81. https://doi.org/10.1016/j.ijepes.2019.03.055.

[75] United Nations Department of Economic and Social Affairs. World Population Prospects 2019. Washington, D.C.; 2019. https://population.un.org/wpp/Download/Standard/Population/ [accessed June 23, 2020].

[76] Khalili S, Rantanen E, Bogdanov D, Breyer C. Global transportation demand development with impacts on the energy demand and greenhouse gas emissions in a climate-constrained world. Energies 2019;12:3870. https://doi.org/10.3390/en12203870.

[77] National Bureau of Statistics. Statistical yearbook of Maldives 2019; Table 11.3: REGISTERED AND NEWLY REGISTERED VEHICLES ACCORDING TO TYPE, 2010 - 2018. Malé; 2019. http://statisticsmaldives.gov.mv/yearbook/2019/ [accessed July 20, 2021].

[78] Leary J, Menyeh B, Chapungu V, Troncoso K. eCooking: challenges and opportunities from a consumer behaviour perspective. Energies 2021;14:4345. https://doi.org/10.3390/en14144345.

[79] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90. https://doi.org/10.1016/j.enconman.2016.01.019.

[80] Stackhouse PW, Whitlock CH. Surface meteorology and solar energy (SSE) release 6.0, NASA SSE 6.0; Langley; 2008. https://searchworks.stanford.edu/catalog?q=%22NASA+Langley+Atmospheric+Sciences+Data+Center%22&search_field=search_author.

[81] Stackhouse PW, Whitlock CH. Surface meteorology and solar energy (SSE) release 6.0 Methodology, NASA SSE 6.0. Langley 2009. https://power.larc.nasa.gov/docs/methodology/.

[82] Stetter D. Enhancement of the REMix energy system model: global renewable energy potentials, optimized power plant siting and scenario validation. Faculty of energy-, process- and bio-engineering. University of Stuttgart; 2012.

[83] Abdulhadi WAA, Golroodbari SZ, van Sark WGJHM. Worldwide Offshore Floating Photovoltaic Yield Assessment: Finding Yield Advantages. In Preparation; 2021.

[84] Killinger S, Lingfors D, Saint-Drenan Y-M, Moraitis P, van Sark WGJHM, Taylor J, et al. On the search for representative characteristics of PV systems: data collection and analysis of PV system azimuth, tilt, capacity, yield and shading. Sol Energy 2018;173:1087–106. https://doi.org/10.1016/j.solener.2018.08.051.

[85] Vartiainen E, Masson G, Breyer C, Moser D, Román Medina E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. Prog Photovoltaics Res Appl 2020;28(6):439–53. https://doi.org/10.1002/pip.v28.610.1002/pip.3189.

[86] Q Cells. Q.PEAK DUO XL-G9 2021. https://www.q-cells.com/en/main/products/solar_panels/G9/Q.PEAK-DUO-XL-G9.html [accessed August 2, 2021].

[87] Global Monitoring and Forecasting Center. WAVERYS – global ocean waves reanalysis Product, E.U. Copernicus Marine Service Information; 2018. https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_WAV_001_032 [accessed June 17, 2021].

[88] Law-Chune S, Aouf L, Bruno L, Dalphinet A. CMEMS-GLO-QUID-001-032, E.U. Copernicus Marine Service Information; 2020. https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-032.pdf [accessed June 21, 2021].

[89] Cheung KF. WaveWatch III (WW3) Global Wave Model. [Indicate temporal subset used.] Distributed by the Pacific Islands Ocean Observing System (PacIOOS) http://pacioos.org/metadata/ww3_global.html [accessed via NOAA's ERDDAP data servers]; 2010. https://coastwatch.pfeg.noaa.gov/erddap/index.html [accessed June 17, 2021].

[90] CorPower Ocean AB. Wave Energy product roadmap. Stockholm; 2021.

[91] Google LLC. Google Earth Version 9.143.0.0 - WebAssembly, Data SIO, NOAA, U. S. Navy, NGA, GEBCO Landsat/Copernicus 2021. https://earth.google.com/web/ [accessed August 23, 2021].

[92] Gulagi A, Choudhary P, Bogdanov D, Breyer C, Merk B. Electricity system based on 100% renewable energy for India and SAARC. PLoS ONE 2017;12(7): e0180611. https://doi.org/10.1371/journal.pone.0180611.

[93] Bogdanov D, Ram M, Aghahosseini A, Gulagi A, Oyewo AS, Child M, et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy 2021;227:120467. https://doi.org/10.1016/j.energy.2021.120467.

[94] Breyer C, Gerlach A. Global overview on grid-parity. Prog Photovoltaics Res Appl 2013;21(1):121–36. https://doi.org/10.1002/pip.v21.110.1002/pip.1254.

[95] Breyer C, Bogdanov D, Gulagi A, Aghahosseini A, Barbosa LSNS, Koskinen O, et al. On the role of solar photovoltaics in global energy transition scenarios. Prog Photovoltaics Res Appl 2017;25(8):727–45. https://doi.org/10.1002/pip.v25.810.1002/pip.2885.

[96] Wiser R, Rand J, Seel J, Beiter P, Baker E, Lantz E, et al. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. Nat Energy 2021;6(5):555–65. https://doi.org/10.1038/s41560-021-00810-z.

[97] DNV GL. CorPower: Wave energy converter questionaire. Høvik, Norway; 2021.

[98] Borrmann R, Rehfeldt K, Wallasch A-K, Lüers S. Capacity densities of European offshore wind farms. Varel: Deutsche WindGuard GmbH; 2018. https://vasab.org/10564-2/.

[99] Ministry of Environment and Energy. Maldives Energy Policy and Strategy 2016. Malé; 2016.

[100] Brown TW, Bischof-Niemz T, Blok K, Breyer C, Lund H, Mathiesen BV. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. Renew Sustain Energy Rev 2018;92:834–47. https://doi.org/10.1016/j.rser.2018.04.113.

[101] Ram M, Osorio-Aravena JC, Aghahosseini A, Bogdanov D, Breyer C. Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. Energy 2022;238:121690. https://doi.org/10.1016/j.energy.2021.121690.

[102] Victoria M, Haegel N, Peters IM, Sinton R, Jäger-Waldau A, del Cañizo C, et al. Solar photovoltaics is ready to power a sustainable future. Joule 2021;5(5): 1041–56. https://doi.org/10.1016/j.joule.2021.03.005.

[103] Breyer C, Bogdanov D, Khalili S, Keiner D. Solar Photovoltaics in 100% Renewable Energy Systems. In: Meyers R, editor. Encycl Sustain Sci Technol. New York: Springer; 2021. https://doi.org/10.1007/978-1-4939-2493-6_1071-1.

[104] Greim P, Solomon AA, Breyer C. Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. Nat Commun 2020;11:4570. https://doi.org/10.1038/s41467-020-18402-y.

[105] Patterson BD, Mo F, Borgschulte A, Hillestad M, Joos F, Kristiansen T, et al. Renewable CO 2 recycling and synthetic fuel production in a marine environment. Proc Natl Acad Sci 2019;116(25):12212–9. https://doi.org/10.1073/pnas.1902335116.

[106] Hong Y, Cui H, Dai J, Ge Q. Estimating the cost of biofuel use to mitigate international air transport emissions: a case study in Palau and Seychelles. Sustainability 2019;11:3545. https://doi.org/10.3390/su11133545.

[107] Jeswani HK, Chilvers A, Azapagic A. Environmental sustainability of biofuels: a review. Proc R Soc A Math Phys Eng Sci 2020;476(2243):20200351. https://doi.org/10.1098/rspa.2020.0351.

[108] Daw JA, Stout SR. Building Island Resilience through the Energy, Water, Food Nexus. Golden, CO (United States: National Renewable Energy Laboratory; 2019. https://doi.org/10.2172/1569216.

[109] Weir T. Renewable energy in the Pacific Islands: Its role and status. Renew Sustain Energy Rev 2018;94:762–71. https://doi.org/10.1016/j.rser.2018.05.069.

[110] Liu H, Kumar A, Reindl T. The Dawn of Floating Solar—Technology, Benefits, and Challenges. Springer Singapore; 2020. p. 373–83. https://doi.org/10.1007/978-981-13-8743-2_21.

[111] Yue C-D, Chen C-S, Lee Y-C. Integration of optimal combinations of renewable energy sources into the energy supply of Wang-An Island. Renew Energy 2016;86: 930–42. https://doi.org/10.1016/j.renene.2015.08.073.

[112] Alves M, Segurado R, Costa M. On the road to 100% renewable energy systems in isolated islands. Energy 2020;198:117321. https://doi.org/10.1016/j.energy.2020.117321.

[113] Gils HC, Simon S. Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands. Appl Energy 2017;188:342–55. https://doi.org/10.1016/j.apenergy.2016.12.023.

[114] Loisel R, Lemiale L. Comparative energy scenarios: solving the capacity sizing problem on the French Atlantic Island of Yeu. Renew Sustain Energy Rev 2018;88: 54–67. https://doi.org/10.1016/j.rser.2018.02.017.

[115] Cross S, Padfield D, Ant-Wuorinen R, King P, Syri S. Benchmarking island power systems: results, challenges, and solutions for long term sustainability. Renew Sustain Energy Rev 2017;80:1269–91. https://doi.org/10.1016/j.rser.2017.05.126.

[116] Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS). UPDATE of the Solar Photovoltaic (PV) Roadmap for Singapore. Singapore; 2020.

[117] Sustainable & Renewable Energy Development Authority. Scaling Up Renewable Energy in Low Income Countries (SREP). Investment Plan for Bangladesh. Dhaka: Ministry of Power, Energy & Mineral Resources; 2015.

[118] Das A, Halder A, Mazumder R, Saini VK, Parikh J, Parikh KS. Bangladesh power supply scenarios on renewables and electricity import. Energy 2018;155:651–67. https://doi.org/10.1016/j.energy.2018.04.169.

[119] Gulagi A, Ram M, Solomon AA, Khan M, Breyer C. Current energy policies and possible transition scenarios adopting renewable energy: a case study for Bangladesh. Renew Energy 2020;155:899–920. https://doi.org/10.1016/j.renene.2020.03.119.

[120] Folkerts W, van Sark WGJHM, de Keizer C, van Hooff W, van den Donker M. Roadmap PV systemen en toepassingen. Ondernemend Nederland (RVO). TKI Urban Energy 2017. https://www.uu.nl/sites/default/files/roadmap-pv-systemen-en-toepassingen-final.pdf.

[121] European Technology and Innovation Platform for Photovoltaics (ETIP-PV). Photovoltaic Solar Energy: Big and Beyond. Sustainable Energy to Limit Global Warming to 1.5 Degrees. Brussels; 2019.

[122] European Commission (Directorate General for Energy), E3 Modelling, Ecofys, Tractebel. Technology pathways in decarbonisation scenarios. Luxembourg; 2020. https://doi.org/10.2833/994817.

[123] CorPower Ocean AB. Wave energy converter questionnaire. Stockholm; 2021.

[124] Lazard Ltd. Lazard's Levelized Cost of Energy Analysis 10.0. New York; 2016. https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf.

[125] Farfan J, Breyer C. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. J Clean Prod 2017;141:370–84. https://doi.org/10.1016/j.jclepro.2016.09.068.

[126] Michalski J, Bünger U, Crotogino F, Donadei S, Schneider G-S, Pregger T, et al. Hydrogen generation by electrolysis and storage in salt caverns: potentials, economics and systems aspects with regard to the German energy transition. Int J Hydrogen Energy 2017;42(19):13427–43. https://doi.org/10.1016/j.ijhydene.2017.02.102.

[127] Bloomberg New Finance. New Energy Outlook 2015 - Long-term projections of the global energy sector. London; 2015.