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Future role of wave power in Seychelles: A structured sensitivity analysis empowered by a novel EnergyPLAN-based optimisation tool

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ABSTRACT

Mitigating climate change requires a variety of energy technologies and energy simulation approaches to evaluate the best possible system structures. Screening whether novel technologies are a viable solution for a particular country within a cost-optimised system setup is usually simulation- and time-intensive. This study introduces the novel add-on optimisation tool EP-ALISON-LUT for use in combination with EnergyPLAN applied to the test case of wave power in the case of Seychelles in 2030 and 2050 within a structured sensitivity analysis. The tool enables a high number of possible system setups and scenarios, including the import and domestic production of electricity-based fuels, to be modelled, allowing for an in-depth view of the system impacts of integrating wave power. The results indicate a limited role for wave power due to its relatively low yield, especially in 2030. However, in 2050, up to 500 MW of wave power capacity is possible with a lower or similar levelised cost of final energy compared to the reference scenario in 2019, which can benefit the diversification of the power generation portfolio. Thus, this novel tool is fast and effective in technology screening studies requiring a fast optimisation algorithm.

1. Introduction

Rising global average temperatures induced by climate change are an existential threat to humankind [1]. Regions in the Sunbelt and sub-Saharan Africa are expected to be most vulnerable, with significant impacts on food security, livelihoods [2]. Social repercussions are to be expected as well [3]. In the case of island nations, rising sea levels are another, if not the biggest existential threat [4]. To mitigate climate change and counter-act its adverse developments, almost 200 nations, including the Seychelles, signed the Paris Agreement in 2015 [5] to limit global warming to well below 2°C and making efforts to limit it to 1.5°C until the end of this century. A defossilisation of the energy system towards 100% renewable energy (RE) sources is the number one priority to fight climate change [6] and is also envisioned by the Seychelles [7]. A broad electrification of the energy system opens the door for the two leading RE technologies: solar photovoltaics (PV) and wind power [8]. However, island nations have the disadvantage of limited land area, and alternative RE sources [9], such as ocean energy technologies, may be a game changer for restricted countries, as shown in the cases of the Maldives [10] and the Caribbean [11].

Such analyses require a fast and flexible modelling tool to determine the future role of specific non-conventional RE technologies. EnergyPLAN [12] is a reliable and most suitable modelling tool for studying the impacts of such technology. It has already been used in a great number of scientific assessments [13], in particular for islands [9,14]. As a simulation tool, EnergyPLAN requires either a broad knowledge of the user, or add-on tools to acquire an optimisation or near-optimal solutions of the studied system [15]. However, an iterative optimisation algorithm usually depends on many function calls, which is time-intensive. This study aims to introduce a novel EnergyPLAN add-on tool combining the proven advantages of the EnergyPLAN modelling software with the benefits of fast and accurate linear optimisation. As a

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case study of the tool, the analysis is done for wave power sensitivity in Seychelles as a representative test case for Indian Ocean islands.

The Seychelles is an archipelagic country located Northeast of Madagascar in the Indian Ocean. It consists of approximately 115 islands, which are grouped into the Inner Islands, where almost the entire population is located, and the Outer Islands [16]. The location of the Seychelles is shown in Fig. 1.

The Seychelles have the aim of reaching 15% RE in the power sector by 2030 [17,18], the ambition for 100% RE in the long term [7], and the first respective analyses [19]. The location far off the coast and unavailability of local resources makes the Seychelles dependent on liquid fuel imports for the transport sector, especially as Seychelles is a popular destination for international tourists. Tourism and fisheries are the main economic drivers in the country [20]. The import or production of electricity-based fuels (e-fuels) for the hard-to-electrify marine transport and aviation sections of the transport sector [21] is a crucial topic for island nations in the Indian Ocean and worldwide.

This study aims to assess the future role of the non-conventional RE technology wave power in Seychelles introducing a novel optimisation add-on tool for EnergyPLAN. The main aims and novelties of the current study are:

- Introducing a novel add-on tool for the EnergyPLAN simulation software, enabling a techno-economic optimisation of RE scaling and energy storage use.
- Applying a structured sensitivity analysis to implement wave power in the Seychelles' energy system for the years 2030 and 2050 with a total of 110 optimised scenarios into the future.
- Applying different power and heat sector transition goals for the year 2030.
- Assessing two main scenarios for the import and domestic production of e-fuels for marine transport and aviation.

The new EnergyPLAN add-on is designed for this purpose to enable a fast and extensive optimisation of the power and hydrogen system while maintaining a strong connection to the EnergyPLAN software itself, combining the advantages of both approaches. The novel modelling tool and its documentation are available in an open-access repository (https://doi.org/10.5281/zenodo.10066771).

2. Literature review

Research on 100% RE systems is still in its early stages for this region [22], with most articles published in 2018. A total of 24 peer-reviewed articles have been published on 100% RE systems for islands in the Indian Ocean (IOCE), including country, regional, and global studies (see supplementary material 1, note 1).

Sector-wise, the power sector is the most researched in energy system terms. There are eleven cross-sector analyses for the entire region; the power sector tops the list with 13 articles, representing over 50% of the articles reviewed. In terms of the most used energy system models (ESMs), TIMES [23–27] is followed by OSeMOSYS [28–30] and HOMER [31,32]. The most used ESM for 100% RE systems on islands is EnergyPLAN [9,12]. In terms of temporal resolution, time slices dominate with seven articles, followed by hourly-resolved analyses in four studies, and one study uses annual time resolution. A pathway towards 100% RE integration is largely lacking, as 17 studies used an overnight approach, while five present analyses on transition pathways, and two remain unspecified. Studies have discussed that an overnight approach may not provide sufficient insights to make decisions about transitioning to a fully RE system in a timely manner [6,22,33,34]. Across the articles reviewed, technology-wise, a mix of RE technologies, such as solar PV, wind power, bioenergy, hydropower, geothermal, ocean thermal energy conversion (OTEC), tidal, and wave power, were integrated as part of 100% RE-based systems. Due to the limited land area, offshore RE technologies present an exciting opportunity for the energy transition on these islands (see Fig. 2, left). The most common ocean energy technologies in the articles reviewed are wave power and OTEC, with twelve and seven articles, respectively.

Three articles explore other ocean energy technologies, especially offshore floating solar PV, wave power, and wind offshore in fully defossilised energy systems: offshore floating solar PV and wave power by Keiner et al. [10] for the Maldives, Timmons et al. [28] for Mauritius, and offshore wind power by Flessa et al. [35] for Mayotte. Geographically, the French overseas department of La Réunion is the most studied island, as depicted in Fig. 2 (right). A similar result was reported recently by Oyewo et al. [34] from a pan-African perspective. To fill existing research gaps, several islands in the Indian Ocean require in-depth research. This review shows that the transition towards 100% RE has not been well-researched for IOCE islands, confirming earlier findings [9]. Even larger islands do not have dedicated studies, such as Madagascar, or require more research, such as Sri Lanka [36]. However, at least regional studies covered both larger islands [37–39]. One article on 100% RE systems for Seychelles [19], and three non-peer-reviewed reports [40–42] were found, however, none of the studies considers ocean energy technologies. Fittingly, Surroop and Raghoo [43] mention the lack of studies focusing on the feasibility of ocean energy in African Island states. In this context, this study presents the structural impact of

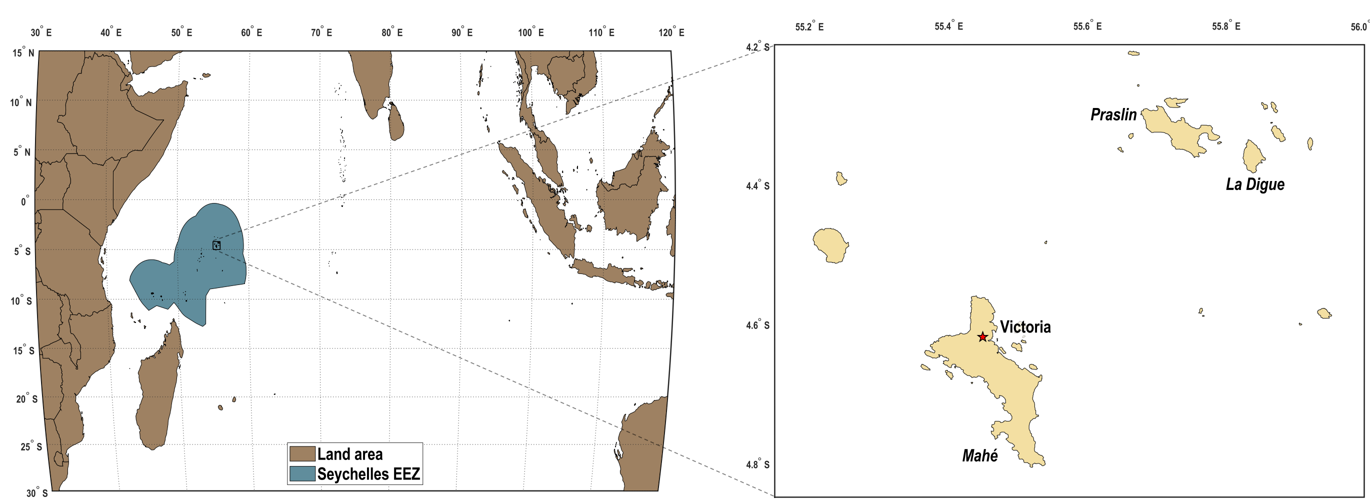

Fig. 1. Location of Seychelles represented by its exclusive economic zone (EEZ) in the Indian Ocean (left) and focus map on the three main Inner Islands - Mahé, Praslin, and La Digue (right).

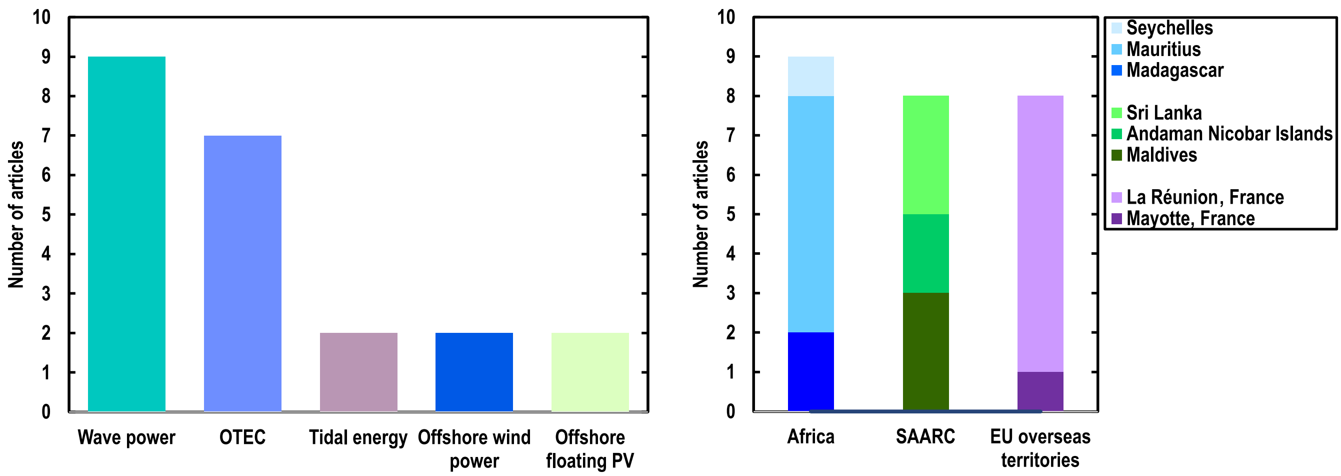

Fig. 2. Ocean energy technologies applied in 100% RE studies for Indian Ocean Islands (left) and the number of 100% RE system articles per island aggregated into different regions, including Africa, South Asian Association for Regional Cooperation (SAARC), and European Union (EU) overseas territories (right).

wave power on a fully defossilised energy system for Seychelles, covering the demands of the power, heat, transport, and industry sectors.

3. Methods and data

The energy system optimisation is based on the EnergyPLAN model version 16.0 [12]. An EnergyPLAN add-on for linear system optimisation by LUT University (EP-ALISON-LUT) is applied to enable a fast and accurate system optimisation. An overview of the techno-economic input data used for the reference system and scenarios for 2030 and 2050 for all technologies and fuels can be found in the supplementary file 1, note 2. All system simulations in this study apply a 7% discount rate, cf. Eq. (2).

3.1. Reference energy system

The year 2019 is chosen as the reference for future scenarios with comprehensive available data and without distortions in demand and supply. Fig. 3 shows the primary energy mix of Seychelles in the year 2019.

The energy system of Seychelles in 2019 is almost solely dependent on oil imports. Due to its relatively isolated location in the Indian Ocean and flourishing tourism, the transport sector consumed 2.41 TWh, or more than half of the country's total oil imports. This also includes international marine and aviation transportation (international bunkers). Another 1.42 TWh was used for electricity generation. Except for minor shares of wind power and solar PV, electricity is primarily generated from fossil oil (heavy oil) or oil products. About 0.06 TWh of oil was used in households, most probably for heating. Furthermore, minor amounts of liquified petroleum gas (LPG), as well as some biomass (charcoal for barbecue) [45], have been used in households mainly for cooking.

The installed capacity for thermal electricity generators running on oil was 147 MW_{el}, while 6 MW of wind power and 4 MW_p of solar PV complete all electricity generation capacity [44]. The total annual cost of the reference system modelled with EnergyPLAN amounts to 293 m€, of which the major share of 240 m€ is due to fuel imports. Therefore, the reference energy system is vulnerable to price fluctuations for imported fossil fuels. As a result of the heavy dependency on fossil fuels, the total

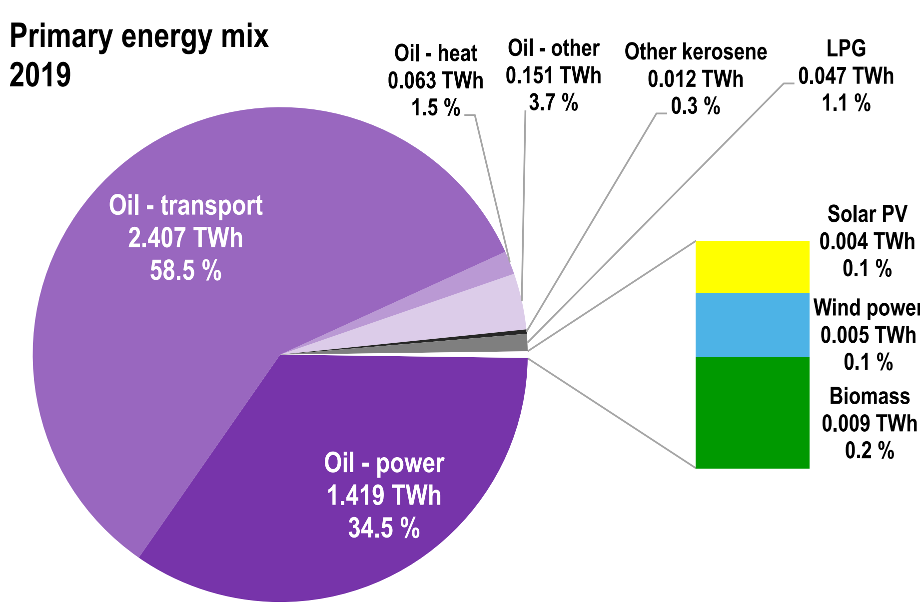

Fig. 3. Primary energy mix of the Seychelles in 2019. Data source: [44].

energy-related CO_2 emissions accumulate to 1.1 $MtCO_2$ or about 11.3 tCO_2/capita, which is about 27% higher than the average of OECD members in 2018 of 8.8 tCO_2/capita [46]. Numeric results for the reference system modelling are provided in the supplementary material 1, note 5, with numeric results of the future scenarios. For some numbers a respective uncertainty has to be allowed due to rounding of EnergyPLAN, resource profiles, and demand profiles, as presented later.

3.2. Applied scenarios

Similar to previous work done for an island state in the case of the Maldives [10], two main scenarios are applied: The e-fuels import (eF-I) scenario cluster for importing e-fuels for transportation from the global market, and the e-fuels domestic production (eF-DP) via power-to-liquid (PtL). In addition to a free cost optimisation (FCO), the role of wave power in the system is analysed by gradually increasing the installed capacity in 50 MW increments up to 500 MW for each of the two main scenarios in 2030 and in 100 MW increments up to 1000 MW in 2050 in order to study wave power as a sensitivity for the energy system. The step sizes are chosen with respect to typical cluster sizes of wave power [47] and final energy demand, allowing for a detailed impact analysis, while limiting the number of scenarios. Fig. 4 gives an overview of the structure of the scenario definition.

In 2030, four different transition options are considered for the power and heat sectors. The slow, medium, and fast transition paths use the transition functions introduced by Keiner et al. [48,49]. The slow path means 18% of the power generation and heat fuel switch to RE sources are done by 2030, which is close to the set target of 15% renewable electricity in the power sector [17,18]. The medium path relates to a 71% switch and the fast path to 83%. The full power and heat transition case relates to a 100% RE system. The transition paths influence the remaining diesel electricity generation capacity using fossil diesel fuel and the remaining fuel oil used for heating. The remaining diesel power generation capacities are estimated using Eq. (1):

$$Cap_{gen,diesel} = \frac{El_{power} + El_{transport} + El_{heat}}{8784\ \text{h}} \tag{1}$$

wherein $Cap_{gen,diesel}$ – Capacity of (fossil) diesel and fuel oil internal combustion power generators, El_{power} – power electricity demand, $El_{transport}$ – transport electricity demand, and El_{heat} – heat sector electricity demand.

The power and heat electricity demand depends on the future demand estimation, as well as the above-mentioned transition rates. The electricity demand for the transport sector solely depends on the future demand estimation, as explained in the next section. Additional electricity demand to produce hydrogen or e-fuels is excluded since producing those energy carriers only makes sense if powered by renewable electricity. By dividing the electricity demand by 8784 h, the temporal resolution of EnergyPLAN, it is assumed the diesel generator runs in baseload, except when the electricity load is higher than the available diesel generator capacity within the EnergyPLAN simulation part. This estimation leads to a remaining fossil diesel or fuel oil generation capacity of 81.2 MW_{el} for the slow, 30.0 MW_{el} for the medium, and 17.1 MW_{el} for the fast transition path in 2030. The full transition path assumes a full phase-out of fossil generation, which is also true in all 2050 scenarios. The baseload characteristics of remaining diesel generators are due to the fact that conventional power production and renewable power production are separately modelled in EnergyPLAN and EP-ALISON-LUT, as explained in subsection 3.6.

3.3. Future energy demand estimation

Future energy demand is based on the LUT-DEMAND model [48,49] using the delayed economic equality scenario (LUT-DEES) in combination with the UN medium population projection. Electricity demand is directly taken as calculated in the model. Transportation fuel demand has to be adapted to the unique structure of an island region far off the continental coast in the Indian Ocean. Final transport fuel demand is

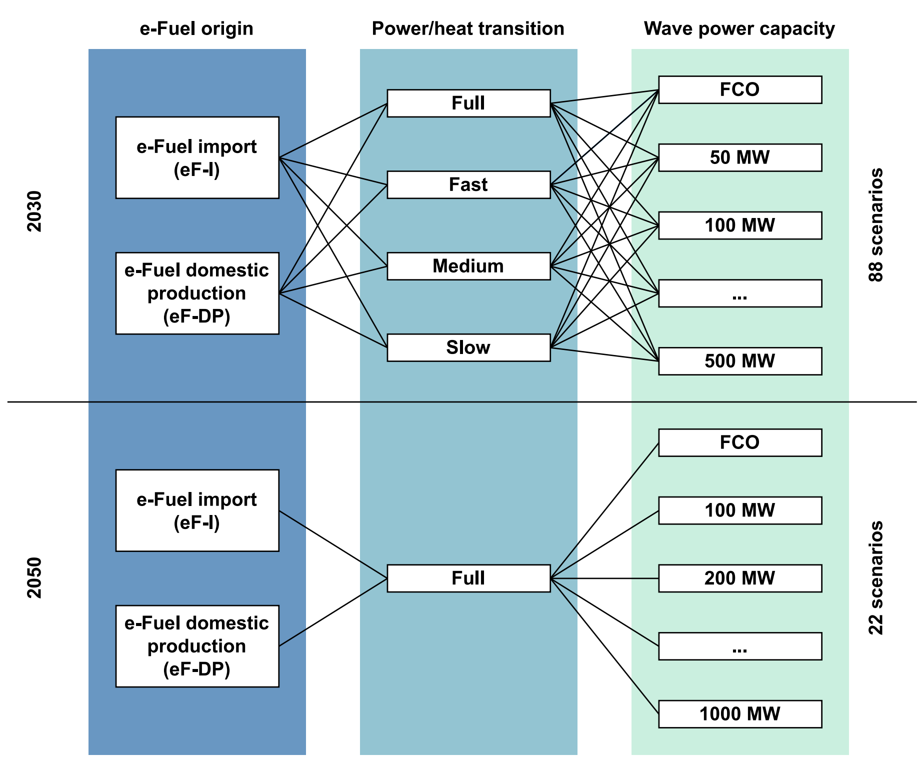

Fig. 4. Overview of the applied scenario structure for Seychelles. The free cost optimisation (FCO) allows the tool to find the optimal wave power for the system without any preset capacity limitations.

taken from LUT-DEMAND for road and non-road transportation (marine and aviation). The fuel demand per capita for the transport modes is then corrected to the per capita fuel demand of the reference system, and future fuel demand for each type is calculated according to the modelled fuel demand in LUT-DEMAND and the respective correction. Fossil fuels and e-fuels are also disaggregated according to a phase-in function. The total fuel demand is subsequently calculated via the per capita values and the population projection. In the final step, the liquid fuel demand is disaggregated into diesel, petrol, and kerosene jet fuel. While for road transportation, the diesel and petrol shares are assumed to stay equal, the share of diesel and kerosene is estimated using the fuel switch phase-in functions for marine transport and aviation. A complete description of the calculation can be found in supplementary material 1, note 3.

In 2019, the demand for transport fuel was dominated by fossil liquid fuels. By 2030, e-fuels are expected to be ramped up, and electrification will begin. By 2050, all liquid fuel demand will be covered by e-fuels. In addition, a modern transport fuel for marine transportation, namely electricity-based methanol (e-methanol), covers large parts of marine transportation [50,51]. Direct use of electricity in battery-electric vehicles dominate road transportation.

Despite having year-round warm temperatures, some fossil liquid fuels are used in heating, most likely for providing domestic hot water (DHW). Other fossil liquid fuels like kerosene, liquified petroleum gas, and biomass are assumed to be fully substituted by electric cooking by 2030, and this is added to the power demand [52,53]. Depending on the transition speed, it is not expected that all oil boilers will be phased out by 2030. By 2050, all domestic heating demand is assumed to be substituted by direct electric heating.

There is no heavy industry located in Seychelles, so no specific energy demand for the industry sector is included in this study. A visualisation of the heat and transport demand structure as well as an overview of the total final energy demand, can be found in the supplementary material 1, note 3. The total final energy demand increases from 2.63 TWh in 2019 to 4.63–4.64 TWh in 2030 depending on the transition speed, and 6.76 TWh in 2050.

3.4. Renewable energy resource modelling and potentials

In addition to wave power, solar PV and wind power are modelled as RE options. Solar PV is further divided into rooftop PV and utility-scale PV and wind power into onshore and offshore wind power. In this case, the utility-scale solar PV option is offshore floating PV, as a typical bottleneck for small island states is the scarcity of available land. While the main three islands of the Seychelles are comparably big and of solid granite compared to small coral islands, they also have a mountainous structure. Therefore, no onshore utility-scale solar PV installations are assumed to be feasible in this study.

The profiles for solar and wind resources are calculated according to Bogdanov et al. [54], based on exemplary global weather data for 2005 from NASA [55,56] and reprocessed by the German Aerospace Centre [57]. In the case of wind power, onshore wind capacity factor profiles are calculated according to Ref. [58], assuming a relatively small Enercon E−53 wind turbine [59] with a hub height of 73 m, as it is assumed that at the Seychelles no infrastructure for bigger wind turbines will be available. As Seychelles do not have a large geographic extension of the land mass, wind flows are not affected significantly. Thus, the same wind resource profiles are used to calculate the offshore wind capacity factor profiles using a Siemens SWT-3.6-120 [60] wind turbine with 90 m hub height. No efficiency improvements for offshore floating PV installations are assumed due to high water temperatures similar to those in Maldives [10].

The total resource potential for offshore floating solar PV is assumed to be unlimited, as sea area is abundantly available. Rooftop PV is extrapolated from a proxy potential of 0.655 kW_p/cap in 2030 and 0.751 kW_p/cap in 2050 [10]. In total, 67 MW_p of rooftop PV potential in 2030 and 78 MW_p in 2050 can be obtained in the Seychelles. For the potential for onshore wind power, protected areas have to be considered, as they are blocked for wind turbine installations. Onshore wind power is assumed to be limited to the inner islands of the Seychelles, where about 99% of the population is located. Within the inner islands, only the three main islands of Mahé, Praslin and La Digue are considered for onshore wind turbine installations. Excluded are inhabited areas and protected areas [61], estimated based on the population density of the capital Victoria. If 4% of the uninhabited and unprotected land area is available for wind turbines [54] and a power density of 8.4 MW/km^2 [58] for onshore wind turbines is assumed, the total calculated potential of onshore wind turbines is 56.3 MW. Offshore wind power is assumed to be equal to offshore floating PV without limitations due to the vast available sea area. Details on protected areas, onshore wind power potential, and rooftop solar PV potential, estimations can be found in supplementary material 1, note 4.

The potential for wave power is assessed based on Satymov et al. [47], which utilised the exclusive economic zone (EEZ) to determine the total capacity potential for installing wave power, using ERA5 wave data [62] and bathymetry information from GEBCO [63]. Specifically for the Seychelles, calculations are confined to an area within a radius of 300 km of the capital, Victoria (cf. Fig. 1), considering a power density of 14.8 MW/km^2 for the CorPower C4 wave energy converter [47] installations. Likewise, the potential for offshore wind power is evaluated within the same 300 km radius of the capital, assuming a power density of 10 MW/km^2 for offshore wind turbine installations. To obtain the capacity factor profile for wave power, the analysis focuses on sites with the highest FLH, deriving a weighted average. This involves assigning weights of 0.3 to the top 20% of sites, 0.2 to the next 10% (from the top 20% to the top 30%), and 0.1 to the subsequent 20% (from the top 30% to the top 50%). Similarly, the profile for offshore wind power is computed using sites with the lowest levelised cost of electricity (LCOE) and employing the same weight distribution. Both wave power and offshore wind power capacity factors are constrained to sites with LCOE under 100 €/MWh. A visualisation of the resource profiles and resource potential maps can also be found in the supplementary file 1, note 4. As it can be seen, the assigning of weights for floating solar PV is not required due to the homogenous solar PV yield over the whole area of the Seychelles.

3.5. Storage options and vehicle-to-grid potential

For short-term energy storage, batteries are included. Despite the mountainous terrain of the inner islands in the Seychelles, no potential for a second electricity storage system such as pumped hydro energy storage is assumed, as the topography constrains access of heavy machinery [64]. For seasonal balancing, e-hydrogen is used as a storage medium. Depending on the scenario, hydrogen storage serves two purposes in seasonal storage: As a direct balancing option for re-electrification via a gas turbine [65], and as a storage of hydrogen for e-fuel production.

Vehicle-to-grid (V2G) [66] has been shown to be able to play a major role as flexibility provider and storage options in energy systems [67,68]. The available potential of V2G storage and interface capacity is estimated based on the share of vehicles using smart charging, the share of vehicles using smart charging and having V2G enabled, an estimation on registered vehicles, the phase-in of powertrains, and estimations of average battery capacities and interface capacities per vehicle type (cf. supplementary material 1, note 3).

3.6. EnergyPLAN-based optimisation tool

This subsection gives a general overview on the optimisation tool. Specifics are available in the supplementary material 2. EP-ALISON-LUT has multiple purposes:

- Allow for an accurate optimisation of renewable electricity generation capacities and electricity storage capacities in addition to energy system modelling with EnergyPLAN.
- Provide an add-on to the EnergyPLAN software including the option for seasonal energy storage and a variety of related electricity generation options without the need for cumulative cost consideration (e.g., utility-scale solar PV and rooftop PV can be considered with their specific costs and optimised, respectively).
- Allow for a fast screening of different system setups by an automated optimisation algorithm without the need for manual system optimisation or iterative optimisation requiring extensive and repetitive system simulation, which allows for structured sensitivity analyses of single technologies in an energy system.

Fig. 5 shows the schematics of the EnergyPLAN and ALISON-LUT interaction and energy and information flows.

The add-on is based on energy flows and information given by the EnergyPLAN model. Similar to EnergyPLAN, ALISON-LUT works in hourly resolution. The power and hydrogen balances have to be satisfied for every hour of the year.

The objective function of the linear optimisation applied in ALISON-LUT is the annual total costs of energy (Eq. (2)) of the system components included in the optimisation process. The remaining cost of the system parts modelled in EnergyPLAN are read from the EnergyPLAN results file and added to the annual costs obtained from the ALISON-LUT optimisation afterward.

$$\min\left(\sum_{t=1}^{tech}\left(\frac{Cap_t \cdot CAPEX_t}{1-(1+i)^{-N}} + OPEXfix_t \cdot Cap_t + OPEXvar_t \cdot E_{gen,disch,t}\right)\right.$$
$$\left. + E_{import} \cdot cost_{import} - E_{export} \cdot rev_{export} + \sum_{f=1}^{efuel}\left(eLF_{import,f} \cdot cost_{eLF,import,f}\right)\right) \qquad (2)$$

wherein t – technology, $CAPEX$ – capital expenditures, i – interest rate, N – lifetime, $OPEXfix$ – fixed operational expenditures, $OPEXvar$ – variable operational expenditures, $E_{gen,disch}$ – generated or discharged electricity of technology, E_{import} – imported electricity, $cost_{import}$ – cost of imported electricity, E_{export} – exported electricity, rev_{export} – revenue for exported electricity, f – fuel, eLF_{import} – imported liquid e-fuel, $cost_{eLF,import}$ – cost of imported e-fuel.

The add-on tool allows for a variety of settings. For example, the capacities of the RE technologies can be optimised without limitation, limited with lower and upper boundaries, or preset, as done in this study in the case of wave power. For the two electricity storage options, the energy-to-power ratio can be preset or freely optimised by the tool. Furthermore, hydrogen can be used for flexible balancing of the electricity system. Import and export capacities can be limited via boundaries as well. The documentation is available for the current version as

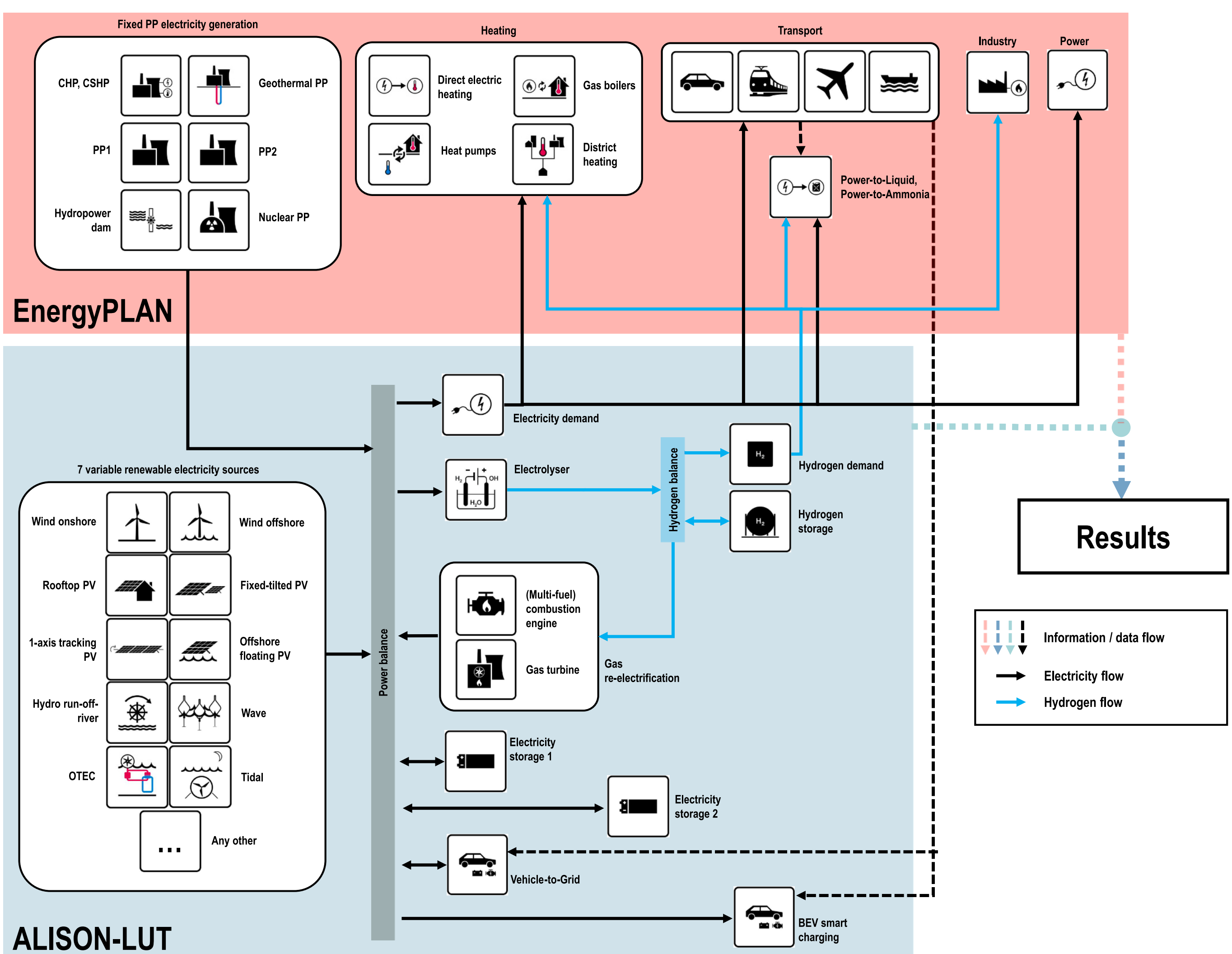

Fig. 5. Schematic overview on the structure of ALISON-LUT and interconnection with EnergyPLAN as the basic modelling platform.

supplementary material 2 or in an online repository of the tool that includes a thorough description of all options.

EP-ALISON-LUT, due to its strong link to EnergyPLAN, only allows for overnight transition analyses of energy systems. However, since capacity limitations can be defined for the optimisation, the characteristics of a transition approach can be reflected. The tool does not include an option for flexible operation of conventional power plants, which might be an option for later model versions.

4. Results

The results of the structured sensitivity analyses are shown for the slow transition path compliant with the 15% RE share aim of Seychelles, and the full transition paths in 2030, and the full transition in 2050. The results for the medium and fast transition paths can be found in the supplementary file 1, note 5.

4.1. Power generation capacities and electricity generation

The capacities of the power generation are either set manually for the case of the diesel power generators (cf. subsection 3.2), preset for the cases of rooftop PV and wave power except the FCO scenario, or the result of the cost optimisation. Fig. 6 shows the installed capacity of power generation technologies and the annual electricity generation.

The total installed power generation capacity increases in all cases. Compared to the reference scenario, the capacity of the diesel generators decreases according to the above-mentioned estimation. In the FCO, about 13.5 MW_p of floating solar PV and 12.8 MW of onshore wind power are installed in addition to the 81.2 MW_{el} of installed diesel generators and 67 MW_p rooftop PV if the e-fuels for the transport sector are imported, and the slow transition path is assumed. In the case of domestic e-fuel production, the significantly higher required capacities are clearly noticeable. Even for the slow transition pathway, 1822.1 MW_p of floating solar PV is installed, and the full 56.3 MW onshore wind potential is used. If a full phase-out of the diesel generation capacities is assumed, the installed capacities for floating solar PV increase to 287.1 MW_p and 2111.0 MW_p for e-fuel import and domestic production, respectively, for the FCO. In both cases, the full 56.3 MW onshore wind potential is used. Wave power is not part of any of the FCO scenarios. While forcing wave power into the system, floating solar PV and wind onshore are pushed out of the system. In the case of slow transition and e-fuel import, the already installed 50 MW wave power capacity is enough to make floating solar PV and onshore wind obsolete. For domestic e-fuel production, the significantly increased electricity demand

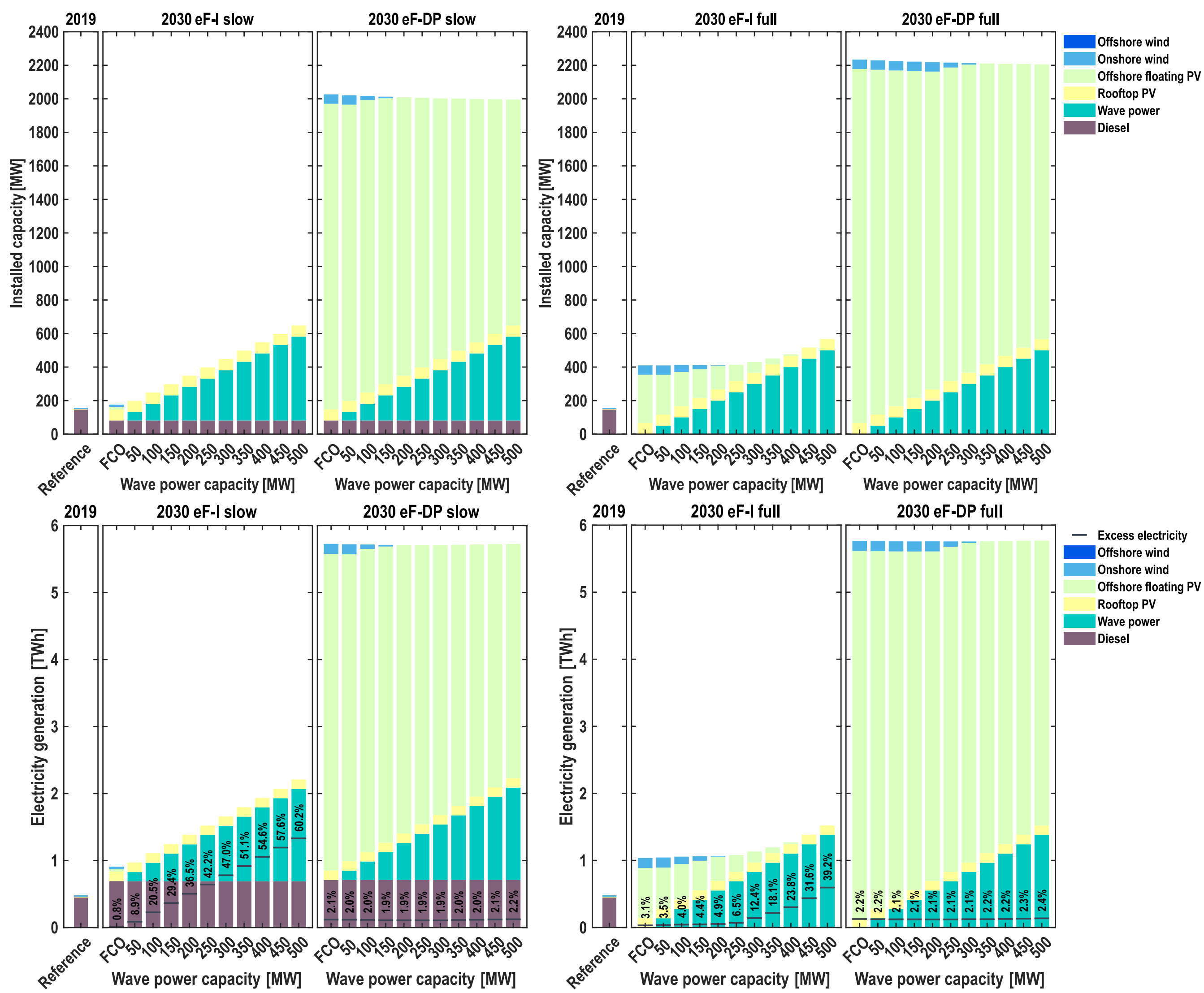

Fig. 6. Installed capacity (top) and electricity generation (bottom) for the slow transition path (left) and full transition path (right) in 2030. Each panel compares the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

would require wave power on a multi-GW scale to obtain the same result. However, offshore wind power is already pushed out with 200 MW of wave power capacity. If no diesel power generation is available, onshore wind power is pushed out at 250 MW wave power capacity in the case of e-fuel import and at 350 MW wave power capacity in the case of domestic production.

For the slow transition pathway, diesel remains the primary power generation source. Even though the capacity has been assumed to be reduced, the higher electricity demand, even without domestic e-fuel production, results in higher utilisation of diesel generators, entailing increased electricity generation. Interesting is the excess share or curtailment of electricity. Already, 50 MW wave power installations result in about 8.9% excess electricity in the system, compared to 0.8% in the FCO in the slow transition. The relatively high excess share is a sign that, with the high diesel generation capacity, 50 MW of wave power means there is already an overcapacity of electricity generation for the system. For domestic e-fuel production, this value stays relatively stable at 1.9%–2.2%. For the full transition path, the excess share increases from 3.1% for the FCO to 4.9% at 200 MW wave power capacity. After that, when onshore wind is not part of the solution anymore, the excess share increases significantly, indicating significant overcapacity. For domestic e-fuel production, the value is again relatively stable, though slightly higher at 2.1%–2.4%. A similar situation for the full transition in 2030 can be seen in the case of 2050, as shown in Fig. 7.

Based on the 2050 cost assumptions, wind onshore plays less of a role than in 2030, and floating PV is the main electricity supplier for the FCO. With e-fuel import, 921 MW_p of floating PV and 26.3 MW wind onshore capacity are chosen by the optimisation. With domestic e-fuel production, these values increase to 5084 MW_p and 56.3 MW. Wind onshore is already phased out, with 100 MW of wave power capacity in the eF-I scenario and 200 MW of wave power capacity in the eF-DP scenario. However, for up to 1000 MW of wave power capacity, floating PV is part of the solution in all investigated scenarios. The higher floating PV share, in general, leads to about 3.6% excess electricity for the slow path FCO and increases afterward with additional electricity generation from wind power. In the case of domestic e-fuel production, the excess electricity share stays between 3.0% and 3.3%.

4.2. *Energy storage capacities and energy discharge*

The capacity results for the three available types of energy storage are shown in Fig. 8. The V2G storage is preset according to the methods described in subsection 3.5, while both stationary battery capacity and hydrogen storage are part of the optimisation.

With low variable RE in the system, the storage requirement is relatively low as well. The slow transition path and eF-I scenario require some hydrogen storage of about 10.8 $GWh_{H2,LHV}$ which can be linked to some solar PV and wind electricity in the FCO. Even without the production of e-fuels in the system, it is assumed that all hydrogen demand for the transport sector is produced locally. The hydrogen storage demand rapidly decreases until 350 MW of wave power is installed, after which no hydrogen storage is required. The stationary battery requirement of 0.06 GWh_{cap} for the FCO also decreases, until a wave power capacity of 300 MW, after which rooftop PV and waver power would be able to operate without short-term energy storage. If local e-fuel production is included, the hydrogen storage demand is significantly higher, as wave power does not provide stable electricity production either. In case of the full transition scenarios, the hydrogen storage is significantly higher compared to the slow transition case. However, the capacity increases from about 55.5 $GWh_{H2,LHV}$ in the case of the FCO to 104.5 $GWh_{H2,LHV}$ at 250 MW of installed wave power capacity and subsequently decreases again. For both eF-DP scenarios cluster, the hydrogen storage capacity first slightly increases from 118.1 $GWh_{H2,LHV}$ (slow) and 136.9 $GWh_{H2,LHV}$ (full) for the FCO to a certain wave power capacity of about 200–300 MW and then increases more strongly. This point can be linked to the point when wave power dominates the variability of electricity generation, as solar PV is rather stable throughout the year, and the wave energy converter assumed in this study has a higher limit of surviving extreme wave heights in the region, thus showing increased power production during the monsoon season. The stationary battery capacity in the eF-DP scenarios is comparably small, with about 0.18 GWh_{cap} capacity for the slow transition in the FCO case. Again, the stationary battery requirement decreases strongly, though it still plays a role throughout all investigated wave power capacities. The full transition case requires about 1.16 GWh_{cap} capacity with the same trajectory.

Despite the dominating role of hydrogen storage capacity, the re-electrification of hydrogen plays a minor role, indicating that hydrogen from storage is mainly used for further use in transport or e-fuel production in the eF-DP scenario cluster cases. About 73%, or 22.8 GWh, of the electricity cycled through all energy storage technologies is supplied by stationary batteries in the slow transition eF-I/FCO case. This share is slightly higher at 82% for the forced wave power capacities, though it decreases with the phase-out of stationary batteries until V2G batteries take over the main role as energy storage. Re-electrification of hydrogen is the second important storage option for small wave power capacities and the FCO; however, it is obsolete before the stationary batteries are pushed out of the system. For more than 300 MW of wave

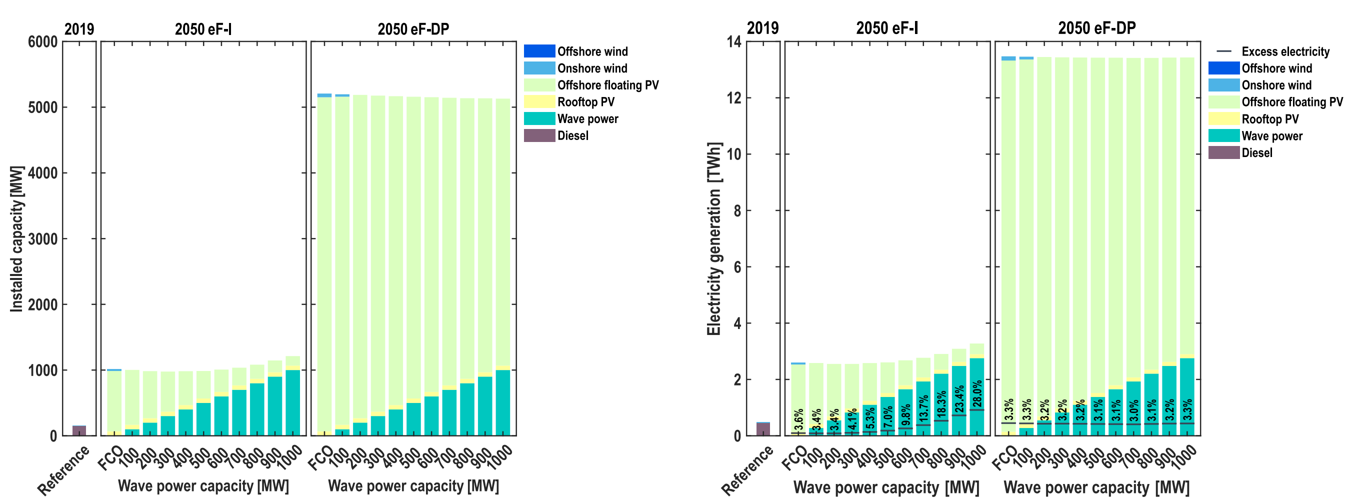

Fig. 7. Installed capacity (left) and electricity generation (right) in 2050 comparing the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

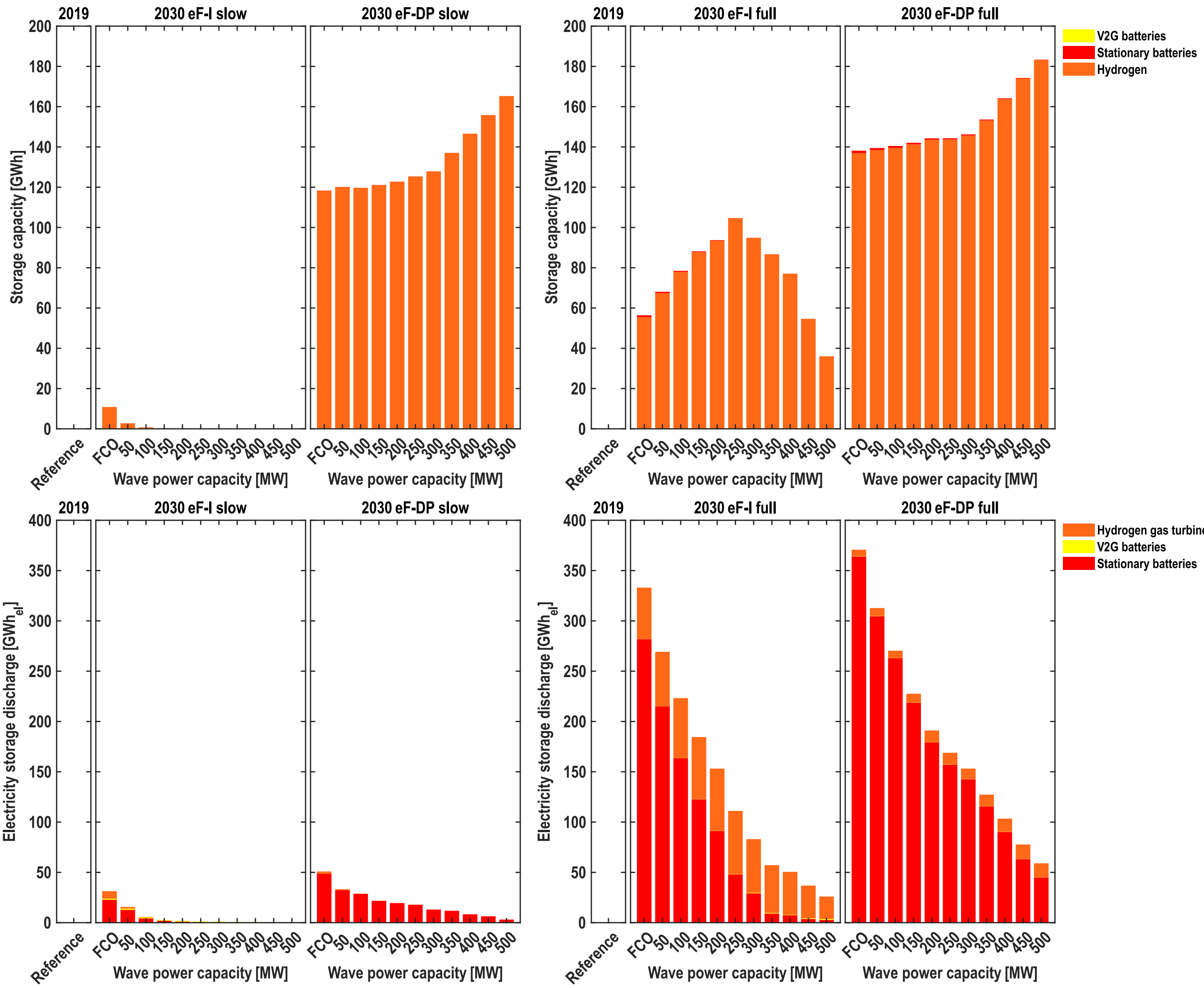

Fig. 8. Storage capacity (top) and electricity discharge (bottom) for the slow transition path (left) and full transition path (right) in 2030. Each panel compares the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

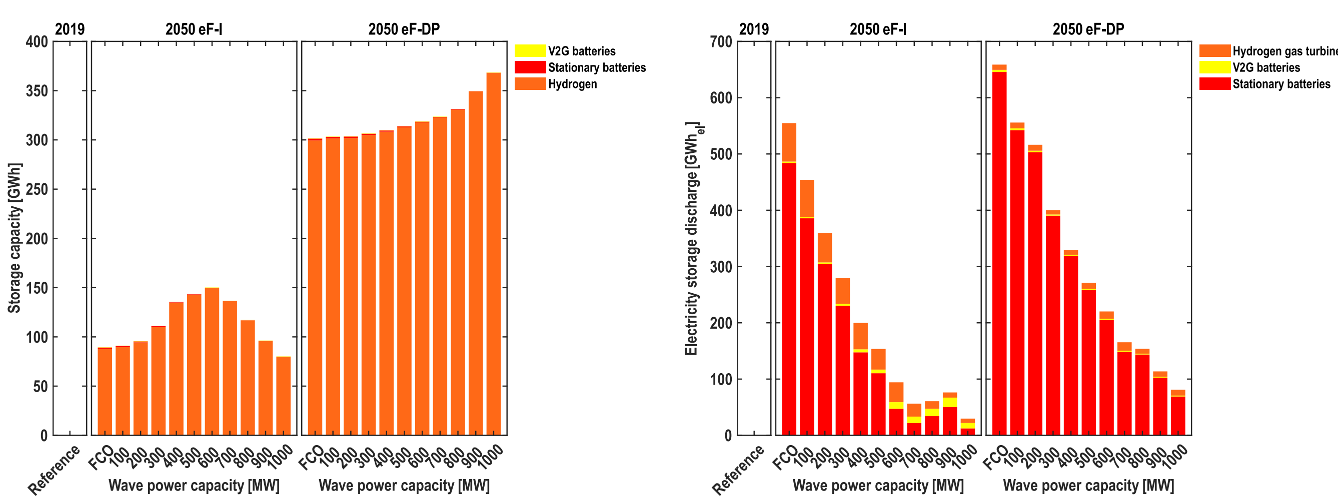

Fig. 9. Storage capacity (left) and electricity discharge (right) in 2050 comparing the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

power capacity, no hydrogen re-electrification is required anymore. The share of stationary batteries as electricity storage is even more eminent in the eF-DP case of the slow transition path, as batteries, utilised as short-term storage are usually linked to solar PV capacity. Here, the FCO results in a 95.9% or 48.8 GWh, electricity supply share for stationary batteries of all storage technology options.

While hydrogen re-electrification is used less with increasing wave power capacity, the share increases to a maximum of almost 100%, until gradually stationary batteries are less relevant and V2G batteries, for which no cost for the energy system are assumed, are used favourably. However, within the investigated wave power capacities, this effect is rather insignificant. If the full transition is assumed by 2030, the share of stationary batteries without e-fuel production can be accounted to about 84.6% or 281.8 GWh, for the FCO, with a decreasing trend for increasing wave power capacity. Again, the higher share of RE, and especially solar PV requires more electricity cycled via energy storage technologies. Therefore, the re-electrification of hydrogen is also significantly higher in absolute numbers. In the eF-DP scenarios of the full transition, the situation is quite similar. However, the stationary batteries again show a higher supply share of 98.2% or 364.0 GWh. In this case, increasing the wave power capacity does not result in an increasing share of stationary batteries, and the relevance of stationary batteries decreases. Fig. 9 shows the situation of energy technology capacities and electricity discharge in 2050.

Overall, the energy storage capacity requirement in 2050 over the set wave power capacities is very similar to the full transition path in 2030. The required hydrogen storage for the eF-I scenario cluster first increases with more wave power added to the system and then decreases. For the eF-DP scenario cluster, the increasing hydrogen energy storage over the investigated wave power capacities can be seen. It can be assumed that if the wave power capacity would be increased to a multiple of the upper limit of 1000 MW in this study, the same trajectory over wave power capacities could be seen for the eF-DP scenario cluster as for the eF-I scenario cluster. If e-fuels are imported, the stationary battery shows similar electricity supply shares of all storage technologies as in 2030, with about 87.2% at 484 GWh for the FCO and a decreasing trend. The second most important is hydrogen re-electrification.

Interestingly, the system chooses the V2G battery capacity as an energy storage option to support the phase-out of stationary batteries with increasing wave power capacities in the system. While V2G batteries play only a minor role in the FCO at 0.4%, despite not being assigned any additional cost for their use in the system. Their electricity

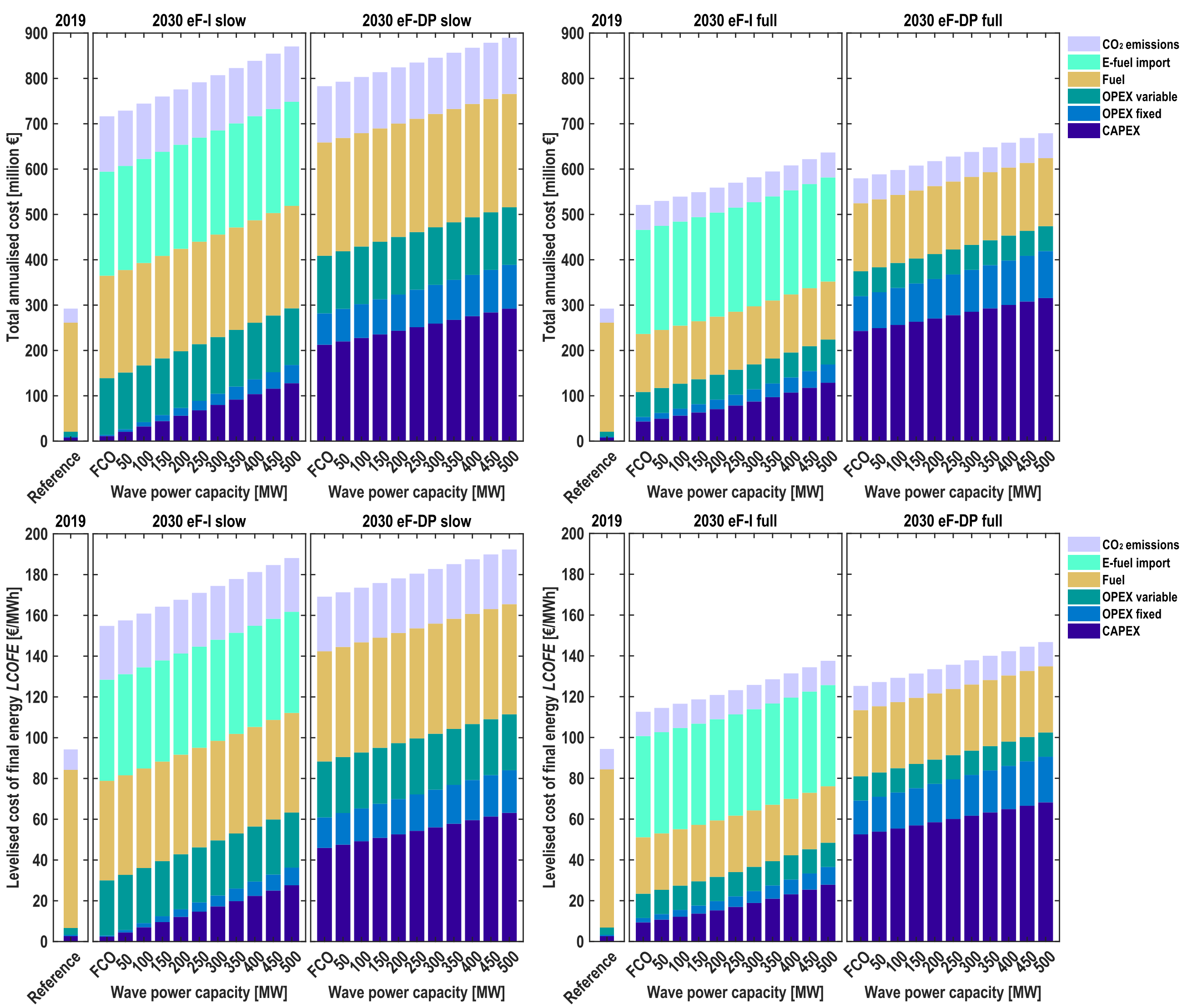

Fig. 10. Total annual system cost (top) and levelised cost of final energy (bottom) for the slow transition path (left) and full transition path (right) in 2030. Each panel compares the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

supply share among the energy storage technologies rises up to 32.2% if 1000 MW wave power would be installed in the system. Especially noteworthy in this case is that the composition of mainly solar PV and wave power reaches a local minimum for total energy storage required at 700 MW installed wave power capacity, after which it shortly rises only to plunge to the lowest value within the investigated capacity limitations. The significantly higher electricity demand and, therefore, significantly higher floating PV capacity mainly trigger the requirement of stationary batteries for domestic e-fuel production. Stationary batteries have a supply share of 98.0% at 645.7 GWh for the FCO and also show decreasing characteristics, though not as significant. Even though the V2G batteries are also able to gain share in this scenario cluster, the maximum share for the 1000 MW of installed wave power capacity merely reaches 2.0%. However, it seems that the availability of V2G in the system is more favourable with wave power than with floating PV as the main variable RE in the system.

4.3. Total system cost and levelised cost of final energy

The total annualised system cost of a future energy system must be evaluated keeping in mind that higher total costs compared to the reference case are naturally evident in countries with increasing energy demand, since additional energy demand requires either additional fuel imports or additional generation technologies, driving up the total cost. Fig. 10 shows the total annualised system cost, as well as the levelised cost of final energy (LCOFE) that puts the total annualised system cost in relation to the total final energy demand of the system. In the supplementary material, note 5, additional information on the calculation of LCOFE and levelised cost of electricity (LCOE) can be found.

As mentioned in subsection 3.1, the total cost of the reference system in 2019 stands at 293 m€, of which the majority of 240 m€ can be assigned to fuel costs. CAPEX and fixed OPEX for mainly diesel-based power generation are almost very low. CO_2 emission costs account for another 31 m€. The total cost increase significantly already by 2030. In the slow transition FCO case, the total cost increase by a factor of 2.5–716 m€ if e-fuels are imported and by a factor of 2.7–783 m€ if e-fuels are produced domestically. The fuel for the remaining diesel-based power generation and transport still has a significant share, as well as the e-fuel import cost. In case of the eF-DP scenario cluster, the e-fuel import cost does not play a role, however, the required e-fuel production facilities result in a substantially higher portion of CAPEX. By increasing the wave power capacity, the total cost increases as well, which means that reduced solar PV, wind power, and energy storage requirements do not have a positive effect. This in turn means that the system optimum can be found with the least wave power capacity in the system. In the case of the total annualised system cost, the situation is similar if a full transition is assumed. Though the fuel cost portion is noticeably smaller due to no fuel oil or diesel demand for power generation, the high cost share of e-fuel imports or high CAPEX for e-fuel production facilities increase the total system cost compared to the reference year. The FCO of the full transition eF-I case has an increased cost factor of 1.8–521 m€, and the eF-DP FCO case results in an almost doubling of the reference case total cost to 580 m€.

However, if the total annual system cost is put into perspective with the total final energy demand of the system, a significant difference between the two shown transition paths can be noticed. While for the slow transition path, the LCOFE increases by a factor of 1.6 from 94.3 €/MWh in 2019 to 154.8 €/MWh for the FCO of the eF-I scenario, and by a factor of 1.8–169.2 €/MWh for the FCO of the eF-DP scenario, the LCOFE increase less significantly for the full transition path. Though the LCOFE is higher than for the reference system, the eF-I FCO LCOFE increased to 112.6 €/MWh by a factor of 1.2, and for the PtL case, by a factor of 1.3–125.3 €/MWh. Therefore, a full transition away from diesel-based power generation and oil-based heating to a fully renewable power and heating system by 2030 has a most positive effect on the relative final energy cost. The main reason is the improved efficiency of the power generation. The low combustion efficiency of diesel generators leads to a high fuel input to provide the required electricity to the system, which is a common problem for small island states that are dependent on diesel for power generation. The low efficiency drives the energy system cost as the fuel demand is the main cost factor of the power system, as can be seen for the reference system. RE can diminish this problem in a more cost-effective way. With further cost reduction of RE technologies by 2050, the cost structure also changes significantly, as can be seen in Fig. 11.

Again, the highest system benefit comes with the lowest wave power capacity in the system. Compared to the reference system, the total cost increases by a factor of 1.3–369 m€ if e-fuels are imported and by a factor of 1.5 with domestic e-fuel production to 448 m€. The remaining fuel costs in the eF-DP scenario cluster are for handling the produced e-fuels, which are assumed to be part of the e-fuel price in the import scenario. Even though wave power benefits from a major cost reduction by 2050, increasing the wave power capacity does not bring any benefit in terms of total system cost. The high e-fuel demand in 2050 will be the main driver for the energy system cost in the Seychelles by mid-century, either due to their import cost, or due to the significant production capacities required.

Nevertheless, if the total costs are put in correlation with the final energy demand, it is possible to achieve lower LCOFE if e-fuels are imported for the optimised system. The LCOFE of the eF-I cluster FCO is 79.8 €/MWh and, therefore, about 15% lower compared to the reference system. In fact, the LCOFE is lower for the import scenarios for installed wave power capacities of up to 500 MW. The domestic e-fuel production scenario cluster is not able to achieve lower LCOFE however, the cost-optimised FCO case can be assumed to be cost-neutral compared to the reference system at 96.8 €/MWh. By 2050, the Seychelles will, therefore, most probably remain a fuel-importing country, as the economic prospects are more beneficial than the domestic production of e-fuels.

5. Discussion

One crucial factor of 100% RE systems apart from mere cost optimisation is the issue of diversification of the power generation portfolio. Often, the issue of diversification of power generation is discussed in light of economic growth, as done, for example, by Gozgor and Paramati [69] for various countries and regions and by Ahmed et al. [70] for the Nordic countries, while the analyses are mainly based on the concern that diversification in terms of energy transition could have a negative economic impact. Apart from that, diversification of power generation should be discussed in light of 100% RE systems. A study by Aslani et al. [71] discusses the aspect of diversification of the RE portfolio in the context of the Finnish energy system. Relying on one energy source is a major threat to energy security in terms of availability and cost, however, other findings indicate that more diversification may imply higher costs [72], primarily due to the availability of very low-cost solar PV. However, the general results of this study are in line with former research on ocean energy for 100% RE systems on islands [9], showing positive prospects for the future. While wave power may not be part of the least cost solution in Seychelles, considering the diversification of the generation portfolio and consequent enhancement of energy security, it can contribute substantially without excessively raising the cost of the energy system. Investing in different technologies, e.g., floating solar PV and wave power, might also secure a fast transition by 2050 or earlier with a lower risk of bottlenecks.

Currently, the Seychelles depends on imported oil as its primary source of electricity. However, this study showed that by 2050, the system could be fully defossilised. The FCO chooses almost entirely floating solar PV as the source of electricity, which is consistent with the findings for the role of solar PV in Sunbelt countries [8] but also for tropical islands [11]. However, it would not change the situation of a low diversity in power generation. The results for 2050 showed that if

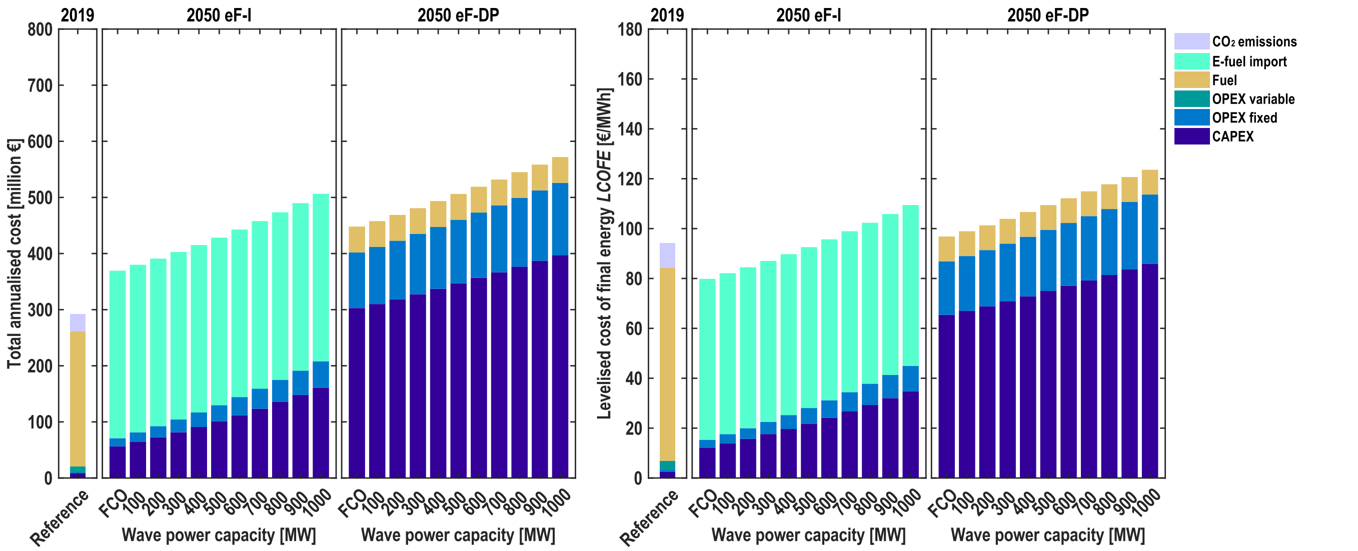

Fig. 11. Total annual system cost (left) and levelised cost of final energy (right) in 2050 comparing the 2019 reference system with the assessed wave power capacity scenarios for the e-fuel import (eF-I) and e-fuel domestic production (eF-DP) scenario cluster.

e-fuels are imported, up to 500 MW of wave power can be installed in the system while maintaining a cheaper or neutral cost structure compared to the reference system for LCOFE. Wave power's higher CAPEX is balanced by its higher FLH and complementary generation profile with solar PV [47], reducing the necessity for extensive energy storage. The structured sensitivity analyses applied in this study enabled this insight, and it can be concluded from such results that a cost-neutral energy system with higher power generation diversity might be superior to a lower-cost energy system relying on a single technology as the main provider of electricity. The relatively low FLH of wave power, as typical for Indian Ocean islands near the equator, does not allow for domestic e-fuel production to become the superior option. Installing the floating PV capacities of the 2030 cases in an order of cumulative 0.4–2.2 GW_p might be challenging to achieve. Though solar PV installations of 1–2 GW_p are not a problem in the global context, regarding the state of energy transition in Seychelles as of now it can be assumed to be challenging. However, it might not be impossible as the majority of the needed capacity is solar PV technology. Wave power as a relatively new option might be more restricted to possibly slower ramp-up constraints. Nevertheless, the dependence of Indian Ocean islands on fossil fuels from abroad gives these countries a strong incentive for transitioning to 100% RE as fast as possible. Signs of such dynamics are currently noticeable after the COVID-19 pandemic and Russia's invasion of Ukraine [73].

As opposed to the claim made by Cole and Banks [74], ocean energy has become a real alternative already, even though cost competitiveness may still be an issue. Compared to the solution for a 100% RE system provided by Wehner et al. [19] of 140–188 MW_p solar PV and 56 MW wind power capacity, the FCO scenario of this study finds a higher required solar PV capacity of 354.1 MW_p, of which 67 MW_p is assigned to rooftop PV and 287.1 MW_p to floating solar PV. Interestingly, the total required wind power capacity matches exactly the wind power potential estimated by this study. Wehner et al. [19] assume additional balancing generation of 25 GWh/a based on biodiesel, and based on Hohmeyer [40,41] 1 GWh of pumped hydro energy storage. Assuming a long-term exchange rate of 1.2 USD/€ and applying a conversion factor of ca. 0.6142 barrel of oil equivalent per MWh, the biofuel cost given by Hong et al. [75] can be estimated between 101.8 €/MWh and 356.3 €/MWh in 2030 and between 174.0 €/MWh and 609.6 €/MWh by 2050. Therefore, biofuels seem not to be an economically attractive solution to be used in combustion processes in addition to local air pollution [76]. As the biomass potential on Indian Ocean islands are usually rather limited due to limited land area, biofuels would be subject to import, however, the import of biofuels may trigger several environmental issues in the region of production [77]. An alternative would be sea-grown biomass such as algae [78]. However, large-scale cultivation of sea-grown biomass rather comes with high risk for the environment and possible negative effects on the already vulnerable marine life [79]. Considering the extensive protected areas on the main islands, the realisation of pumped hydro energy storage in the Seychelles might have to be discussed further. Other Indian Ocean islands might lack the required elevation for such solutions. The dominating role of solar PV found in this study for low wave power capacities will have to be checked for grid integration limitations [80]. Furthermore, the significantly higher capacity density of floating solar PV of 100–200 MW/km^2 [81] compared to 14.8 MW/km^2 [47] of wave power reduces the environmental impact and ocean area demand.

The new add-on tool for EnergyPLAN, EP-ALISON-LUT, has proven to be effective in providing highly detailed insights for the role of wave power in the future energy system of the Seychelles. The additional options that can be used in the tool, such as using a mix of fossil fuels modelled in EnergyPLAN, e-fuel imports, conventional power production, and optimisation of RE generation and storage technologies in EP-ALISON-LUT enabled the investigation of several transition paths for the year 2030. The structured sensitivity analysis allowed for the identification of non-optimal solutions that may still be within acceptable cost margins if other benefits justify the higher costs. Near-optimal solutions, either done with EnergyPLAN [15], or in several instances with PyPSA [82–84] are valuable to identify alternative system designs. EP-ALISON-LUT adds an option for analysing near-optimal solutions in the EnergyPLAN framework based on a structured sensitivity of certain technologies. The otherwise comparable study by Keiner et al. [10], done only using EnergyPLAN, relied on a single transition path option. However, EP-ALISON-LUT is limited in using conventional power generation technologies in a more flexible way due to two-fold modelling in EnergyPLAN and EP-ALISON-LUT, as it was done in this study with a required baseload operation of diesel generators in the slow, medium, and fast transition cases. Therefore, EP-ALISON-LUT is best used for 100% RE system simulation and optimisation. Furthermore, the re-electrification is limited to hydrogen, as the production of electricity-based methane (e-methane) as an alternative option is interwoven in the EnergyPLAN model. Another limitation is the availability of the tool to users of Matlab, including the optimisation toolbox. The elimination of this limitation, however, could be subject to future improvements to the tool.

EnergyPLAN has been coupled to optimisation algorithms by a variety of studies, either for multi-objective optimisation [85], near-optimal solutions [15], or to obtain marginal abatement cost curves [86]. These approaches usually require multiple simulations of EnergyPLAN, with different inputs. Comparing computation time would not improve the discussion, and each tool does have its advantages depending on the type of study and application case. However, EP-ALISON-LUT can be used for parallel optimisation of energy systems which can improve computation time significantly if respective computation resources are available. The time for a system optimisation using EP-ALISON-LUT varies depending on the system structure, between a few minutes and up to approximately 30 min. While one system simulation of EnergyPLAN takes up to ca. 10 s, a system optimisation done by hand, i.e., the iterative adaptation of the EnergyPLAN system parameters to find a working, cost-optimised solution, can take several hours to several days. This again depends on the skills of the user and the complexity of the system. As a comparison, the 110 scenario simulations of this study done with 28 simulations in parallel required approximately 2 h of computation time.

6. Conclusions

This study used a novel optimisation add-on tool for EnergyPLAN to evaluate the future role and impact of wave power on the future energy system structure in Seychelles via a structured sensitivity analysis. Scenarios varying the power and heat transition progress in 2030 and the source of the required e-fuels, either imported or produced domestically, have been evaluated.

The results indicate a limited role for wave power if only techno-economic factors from the simulation are used for the evaluation. Due to the location of the Seychelles in the Earth's Sunbelt, floating solar photovoltaics will emerge as the leading electricity generation technology in the future, complemented by onshore wind power. Stationary batteries are the most critical electricity storage technology, followed by hydrogen storage and vehicle-to-grid batteries. With increasing wave power capacity, the role of stationary batteries decreases, and vehicle-to-grid capacities become more important. Hydrogen energy storage is essential for hydrogen used directly in the transport sector or that is further converted into e-fuels.

The cost results showed that it is difficult to achieve an energy system lower in cost compared to the reference system in 2019. High import costs for e-fuels or production costs will increase the total annual system cost and the levelised cost of final energy in 2030. However, by 2050, it is possible to lower the levelised cost of final energy compared to the reference scenario with up to 500 MW of installed wave power capacity if e-fuels are imported. Additionally, even though wave power increases the levelised cost of final energy, diversification of the power generation portfolio is possible with a lower cost or similar cost to the reference system.

The newly designed optimisation add-on tool for EnergyPLAN proved to be a valuable instrument to assess the role of wave power in the future energy system of Seychelles and its impact on the energy system design throughout a wide variety of scenarios. The fast and accurate techno-economic optimisation of the capacities of renewable energy sources, energy storage technologies, hydrogen re-electrification, and the possibility to include e-fuel imports and preset or limit capacities enabled an in-depth structured sensitivity analysis of wave power in the energy system of Seychelles. It will improve technology screening studies of various regions and countries in the future. The open-access software adds a valuable EnergyPLAN-based optimisation tool to the EnergyPLAN optimisation tool family.

CRediT authorship contribution statement

Dominik Keiner: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Conceptualization. **Ashish Gulagi:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Rasul Satymov:** Writing – review & editing, Resources, Methodology. **Daniel Etongo:** Writing – review & editing, Validation. **George Lavidas:** Writing – review & editing, Validation. **Ayobami S. Oyewo:** Writing – review & editing, Formal analysis. **Siavash Khalili:** Writing – review & editing, Formal analysis. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data, model software, and model documentation are available in the supplementary material and in an online open access repository (https://doi.org/10.5281/zenodo.10066771).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.131905.

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