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Ocean energy enabling a sustainable energy-industry transition for Hawai‘i

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ABSTRACT

Global transitions to highly sustainable energy-industry systems imply shifts to high shares of variable renewable energy sources. While onshore solar photovoltaics and wind power can be expected to be the lowest cost electricity sources around the world, land-constrained regions and islands may have limited onshore renewable potential. Thus, offshore energy technologies, including floating solar photovoltaics, offshore wind turbines, and wave power, may become essential. Furthermore, for Hawai‘i, offshore energy may provide increased supply diversity and avoid land conflicts as electricity generation is expected to increase. The LUT Energy System Transition Model was employed to investigate the techno-economic implications of high technological diversity through integration of offshore energy technologies compared to full cost-optimisation under both self-supply and electricity-based fuel import scenarios. Limiting solar electricity leads to 0–2.3 GW of offshore electricity and 0–4.1 GW of wave power by 2050, but at 3.5–28.0% increased system costs. Under self-supply conditions and an 80% solar photovoltaics limit, a novel interaction between the key offshore technologies was identified with 0.6–1.1 GW of offshore floating photovoltaics, which contribute 12.3% of all electricity generation by 2050. Due to the limited land availability in Hawai‘i and island regions, ocean energy technologies may significantly contribute to energy-industry system defossilisation.

1. Introduction

As a response to increasing effects to climate change caused by anthropogenic greenhouse gas emissions, renewables are increasingly being used to decouple fossil fuels from energy-industry systems. Indeed, in recent years, solar photovoltaics (PV) and onshore wind turbines have comprised the most significant new capacity installations in many regions of the world [1,2]. For islands and land-constrained regions, however, available land area may be limited, thus reducing the potential for these key onshore technologies in defossilising their energy-industry systems. Energy transitions for island regions also encounter challenges to maintain supply reliability, which, for islands, can be achieved mainly through supply variability and energy storage. Combinations of solar PV, wind power, and energy storage through batteries of pumped hydro energy storage have been found to provide stable electricity supplies for small islands in the Philippines [3] and Hong Kong [4]. The variability of RE resources, though, may lead to high curtailment levels if sector coupling is not considered throughout the transition that can effectively utilise excess renewable electricity [5]. Hydrogen may also be used for long-term energy storage to manage seasonality of resources [6], but may be less relevant for tropical island regions. Nevertheless, the closed nature of island regions may make them the regions that can most rapidly transition to 100% renewable energy (RE) systems [5,7]. Research on 100% RE systems [8] has identified a strong evidence of the technical feasibility and economic viability for the energy-industry system transition. The U.S. state of Hawai’i is one such region that is currently heavily reliant on energy imports, particularly of oil [9,10], and, as such, has some of the highest electricity prices in the U.S [11]. Thus, Hawai‘i took a key step in 2022 by becoming the first state to set ambitious targets to reach net-zero emissions across the entire energy system by 2045 [12].

1.1. Ocean energy for Hawai‘i

Existing projections for the Hawaiian transition from the Hawaiian state electricity company [13] and provided to the state legislature [14] emphasise an increasing role of offshore wind power, especially for the island of O‘ahu, which is the largest island by population but the second smallest island by area. Integration of ocean energy in Hawai‘i has been a particular topic of interest, the world’s first ocean thermal energy conversion (OTEC) plant was researched and deployed in 1979 with a

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Abbreviations

BEV	Battery Electric Vehicle
BPS	Best Policy Scenario
CAPEX	Capital Expenditure
CCS	Carbon Capture and Sequestration
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DHW	Domestic Hot Water
e-Ammonia	Electricity-Based Ammonia
e-Fuel	Electricity-Based Fuel
e-Methanol	Electricity-Based Methanol
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FED	Final Energy Demand
FTL	Fischer-Tropsch Liquids
HI	Hawaiʻi
ICE	Internal Combustion Engine
IHD	Industrial Heating Demand
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Heat
LCOFE	Levelised Cost of Final Energy and non-energy use
LCOS	Levelised Cost of Storage
LNG	Liquefied Natural Gas
LUT-ESTM	LUT Energy System Transition Model
OPEX	Operational Expenditure
OTEC	Ocean Thermal Energy Conversion
PHEV	Plug-in Hybrid Electric Vehicle
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
RPS	Renewable Portfolio Standard
SHD	Space Heating Demand
SM	Supplementary Material
SoC	State-of-Charge
TPED	Total Primary Energy Demand
WACC	Weighted Average Cost of Capital

capacity of 50 kW in Hawaiʻi [15]. In 2009, a 500 kW OTEC project by Oceanlinx off the northern coast of Maui was granted a permit by the U. S. Federal Energy Regulatory Commission [16]. Furthermore, in 2011, the U.S. government established a cooperation between Bureau of Ocean Energy Management, Regulation and Enforcement and the Hawaiʻi Outer Continental Shelf Renewable Energy Program to identify opportunities for research and commercial renewable energy leasing on the Outer Continental Shelf off Hawaiʻi [17].

Interest at the local and federal government levels for ocean energy as well as Hawaiʻi's ambitious targets have driven research into Hawaiʻi's ocean energy resources. Stopa et al. [18] investigated the year-round wave energy resources along the Hawaiian islands, finding peak power potential of 60 kW/m due to swell events and consistent energy resources of 15–25 kW/m from wind waves throughout the year. A similar methodology is applied by Ref. [19] to identify potential wave energy sites, highlighting the potential for small-scale wave power farms to provide electricity to remote communities. Li et al. [20,21] further evaluate Hawaiʻi's wave energy resources by applying a hindcast method. In total, wave energy resources in Hawaiʻi have been estimated to be around 380 TWh/a according to Ref. [22], with peak wave power supply occurring in January. Satymov et al. [23] find a wave power potential of 50 TWh that would be able to supply electricity at or below 70 €/MWh in Hawaii by 2050. Despite increased research attention in wave power [24], wave energy converters have not reached sufficiently high technology readiness levels, which may in part be due to a lack of funding, especially compared to other RE projects.

Vella et al. [25] propose a design for an OTEC plant to power observational buoys in Hawaiʻi. Research in the techno-economic potential of OTEC has advanced further, as Langer et al. [26] and Langer and Blok [27] respectively investigate the state of OTEC on their economics and the global techno-economic potential of OTEC. Offshore wind resources across the U.S. were investigated by Ref. [28], finding that Hawaiʻi has available area of 718,600 km^2 for offshore wind installations, corresponding to a potential nameplate capacity of 5.4 TW_{el}, though the expected cost value is among the highest in the U.S. due to water depth, which would require floating structures. Anchoring limitations may limit the available depths for floating turbines, thus depth limits between 700 and 1300 m are generally assumed [29]. Analysis of the technological development of offshore wind power [30,31] indicates that accelerating offshore wind power projects may lead to significant cost reductions and expansion of offshore wind power outside of Europe, where the majority of current offshore wind power installations are located. More recently, floating solar PV has gained research attention as a means through which low-cost solar electricity can be scaled in regions with limited land availability [32,33].

Energy system research has additionally found roles for offshore energy resources in the Hawaiian energy transition. Phillips et al. [34], in the first energy transition research for Hawaiʻi in 1992, developed a net-zero emissions transition scenario to 2100 with electricity coming from a combination of geothermal, OTEC, wind power, and solar PV and liquid fuel requirements being satisfied by biomass-based methanol. Jacobson et al. [35,36] find roles for offshore wind and tidal power, reaching 12% and 1% of total electricity generation in 2050, respectively. The self-supply scenarios developed in Ref. [37] find a role of floating offshore PV when the onshore solar PV limit is reached, corresponding to 1% of land area, with floating PV having a 21.5% electricity generation share under best policy conditions. Projections prepared by Hawaiian Electric using the RESOLVE model [13] find a significant role for offshore wind power starting in 2035, where it reaches 17.5% of electricity generation before slightly decreasing to 16.2% in 2045. Similarly, results prepared by the Hawaiʻi State Energy Office using the PATHWAYS model [14] found that offshore wind power would supply an average of 12% of generated electricity by 2045.

1.2. Growing role of ocean energy in island energy transitions

Offshore energy solutions have increasingly been found in energy systems literature, particularly for island regions. Energy systems for the British Isles [38], Åland Islands [39,40], the island of Pantelleria in Italy [41], Japan [42,43], and Reunion Island [44] have found solutions including offshore wind power. Furthermore, research has found roles for offshore floating PV in the Caribbean [45], and a combination of offshore floating PV, offshore wind power, and wave power for the Maldives [46]. However, the review from Icaza et al. [7] indicates that research for 100% RE in American islands remains lacking, despite pledges from these countries to increase their contributions of RE. The relevance of offshore energy solutions, especially for island regions such as Hawaiʻi, suggests that these technologies may have a role in the Hawaiian energy transition.

Previous analysis using the LUT Energy System Transition Model for Hawaiʻi [37] has found that, under cost-optimal conditions, the future Hawaiian energy-industry system will be solar PV dominated, with onshore technologies capable of supplying all demand under conditions where electricity-based fuels (e-fuels) are imported. However, a research gap remains for Hawaii, and similarly for island regions around the world, as to the potential of the integration of the main ocean energy technologies of offshore floating PV, offshore wind power, and wave power, considering important constraints including sustainable fuel import, land area restrictions, and system diversity. Thus, the aim of this paper is to identify conditions under which offshore wind power and wave power may be part of a cost-optimal solution, and to determine the effects on overall system performance as well as on the levelised costs of electricity (LCOE), levelised cost of final energy (LCOFE), and total annualised system costs of increased system supply diversity. Furthermore, the novelty of the research is the full integration of three major ocean energy technologies in hourly resolved energy-industry system transition optimisation.

The methods section describes the functionality of the LUT Energy System Transition Model, utilised as the energy system modelling platform in this research, the resource profiles and potentials of offshore energy sources in Hawai'i, the assumptions, and scenarios applied. The results section presents the simulation results with a particular focus on system performance when offshore energy sources are integrated, followed by a discussion of the results. Conclusions are then drawn based on the main findings of the research.

2. Methods

This research utilises the LUT Energy System Transition Model (LUT-ESTM) [47] to model the energy-industry transition of Hawai'i covering the integrated and coupled power, heat, transport, industry, and desalination sectors. LUT-ESTM considers energy, including electricity, heat, fossil, bio-, and electricity-based fuel flows to satisfy energy and non-energy demands throughout the year. Energy demands are divided between residential, commercial, and industrial segments. The cost-optimised modelling was done in 5-year time steps in hourly resolution to ensure that supply and demand are balanced for all hours of the year. Notably, as shown in Fig. 1, the target of the model is the minimisation of annualised system costs for the simulated year considering the legacy system and techno-economic inputs for each technology. Fig. 2 shows the technologies included within LUT-ESTM and their interactions across sectors, with strong considerations for all Power-to-X routes [48,49] including heat, fuels, chemicals, materials, and CO_2.

2.1. Renewable energy resource modelling

To determine the potentials of these resources, profiles for sustainable resource potentials were developed using NASA weather data from 2005 [50] that had been reprocessed by the German Aerospace Centre [51]. Resource potentials are then determined at a 0.45° × 0.45° resolution for Hawai'i's land resources and exclusive economic zone. Given the limited land availability in Hawai'i, similar to other island regions, a 1% and 2% area limit was applied for the onshore RE resources of solar PV and wind power, respectively. For solar PV, installation density was assumed to increase from 91.0 to 136.6 MW/km^2, 62.4–93.6 MW/km^2, and 90.0–134.9 MW/km^2 for fixed-tilted PV, single-axis tracking PV, and floating PV, respectively, assuming PV module efficiency increase from 18% in 2020 to 30% in 2050 [52] and trends in the PV ground cover ratio [53]. The annual offshore floating PV full load hours (FLH), defined in Eq. (1), assuming a fixed-tilted structure within Hawai'i's Exclusive Economic Zone are shown in Fig. 3. Onshore and offshore wind power are assumed to have a constant power density throughout the transition, at 8.4 and 10 MW/km^2, respectively [54,55]. Similarly, the power density of wave power is assumed to remain constant at 14.8 MW/km^2 [23].

$$FLH = \frac{E_t}{P_t} \tag{1}$$

where E_t is the annual electricity generation by technology t and P_t is the rated power capacity of technology t. The FLH indicate the amount of hours a power plant would produce electricity at maximum capacity.

An offshore wind profile was constructed by taking the weighted average of the grid cells with the lowest LCOE, considering depth and distance to shore. For depths below 100 m, bottom-fixed turbine foundations are applied, with floating foundations being applied for deeper waters up to 1000 m [56]. The 20% of sites with the most favourable LCOE were assigned a weight of 3, followed by a weight of 2 for the subsequent 10%, and a weight of 1 for the next 20%. The remaining 50% of sites, representing the highest cost options, were assigned a weight of zero. The CAPEX within the corresponding cells were used as the cost input in the model and the area of the corresponding cells were used to

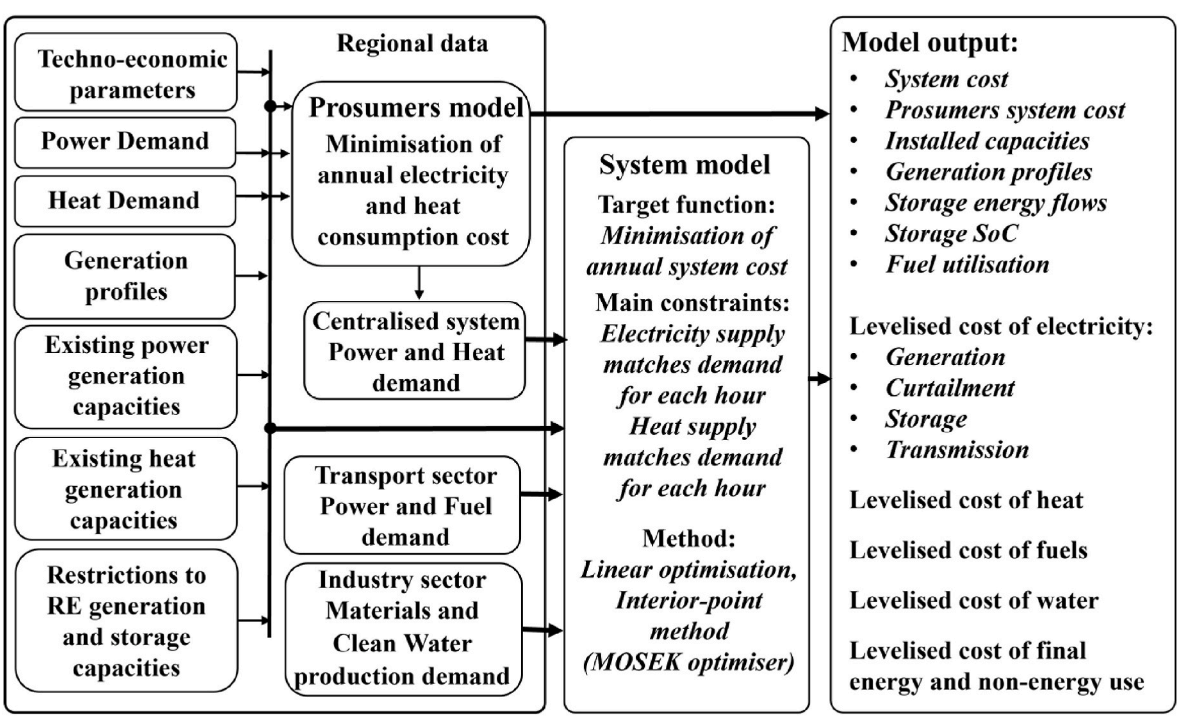

Fig. 1. LUT Energy System Transition Model flowchart.

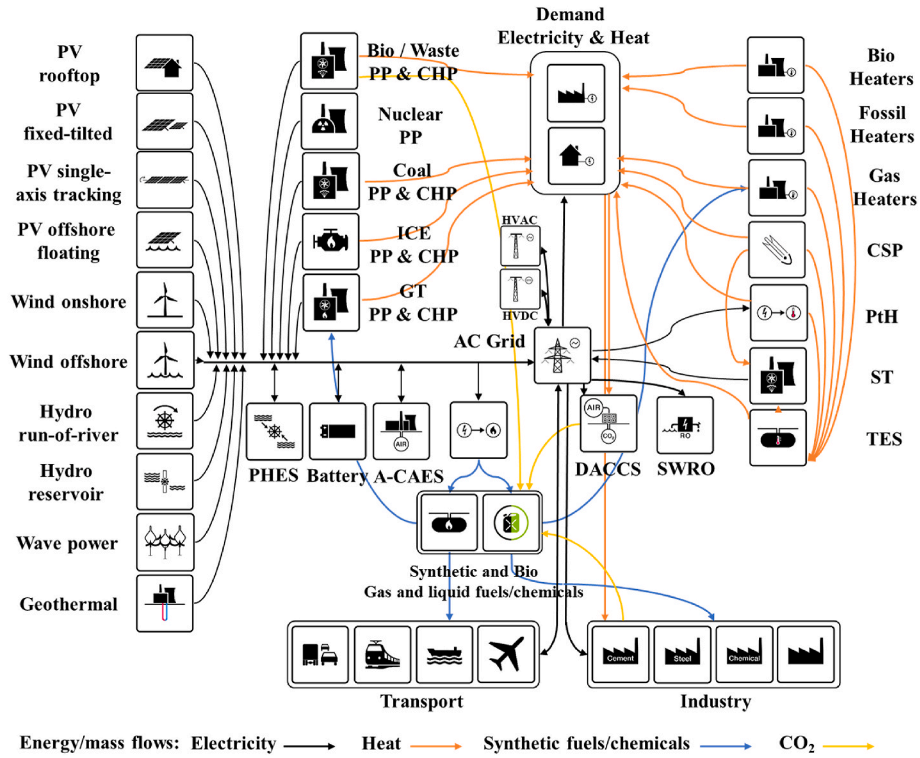

Fig. 2. Schematic of the LUT-ESTM for the power, heat, transport, industry, and desalination sectors [47].

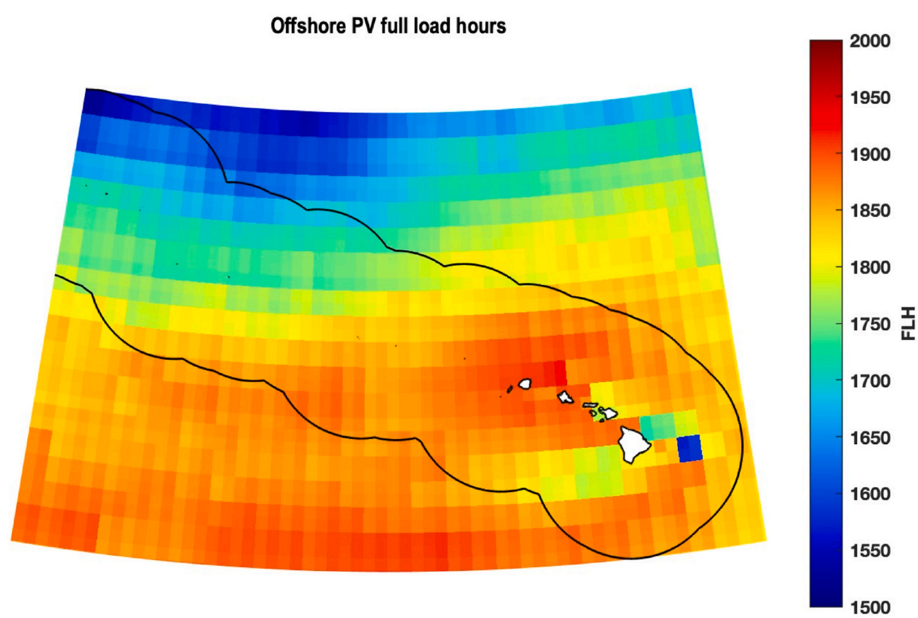

Fig. 3. Offshore floating solar PV resources for Hawaiʻi's Exclusive Economic Zone.

estimate the upper limit for offshore wind power potential, which is shown in Table 1. The CAPEX values are determined relative to a reference CAPEX considering depth and distance from the shore, along with grid and installation costs [56]. This weighted averaging approach simulates a prioritization of development for the most cost-effective sites, capitalising on their high FLH and consequently lower LCOE. Offshore wind FLH within the territorial waters of Hawaiʻi are shown in Fig. 4.

Table 1
Lower and upper capacity limits of renewable energy in Hawaiʻi [23,54,57].

Lower and upper capacity limits – Renewable energy		
Solar PV floating offshore [GW]	Wind offshore [GW]	Wave power [GW]
0–37121	0–37.1	0–25.9

A wave profile was generated employing a methodology analogous to that used for the offshore wind profile, using an LCOE cutoff of 100 €/MWh. However, in this case, grid cells were sorted by FLH. Hourly capacity factors were obtained from Ref. [20], where wave energy resources were assessed using the CorPower point-absorber wave energy

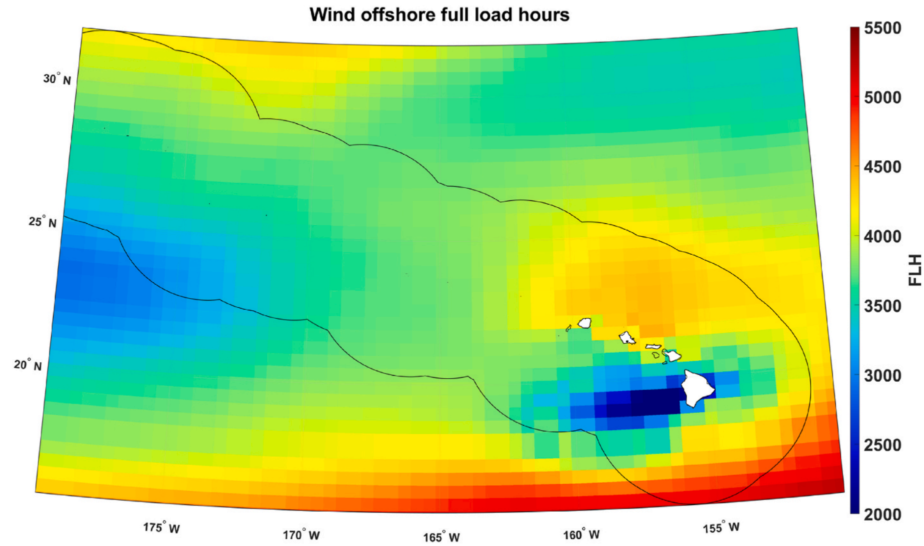

Fig. 4. Offshore wind power resources for Hawai'i's Exclusive Economic Zone.

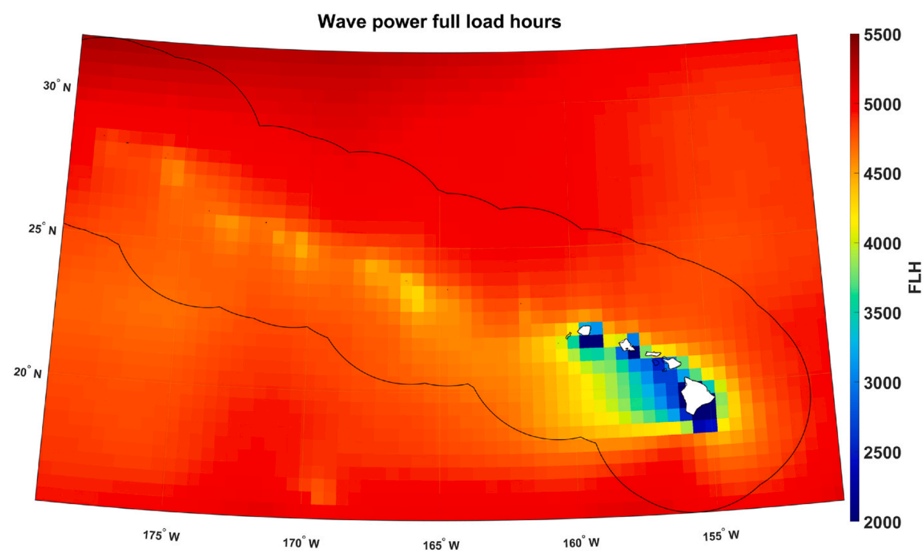

Fig. 5. Offshore wave power resources for Hawai'i's Exclusive Economic Zone.

converter. Mirroring the approach for offshore wind, the model incorporated CAPEX values within corresponding cells, which account for depth and grid connection costs as a function of the distance from shore. The area of each cell was used to estimate the upper limit of wave power potential, limiting the area utilisation to 15% due to the strict depth requirements and possible interference between wave power farms and shared uses of maritime space [23], shown in Table 1. A depiction of wave FLH within Hawaiian territorial waters is provided in Fig. 5.

Offshore energy economic potentials are summarised in Table 1.

2.2. Input data and assumptions

The input data for simulations follow those presented in Ref. [37] for the power, heat, transport, industry, and desalination sectors, with a detailed description of demand assumptions available in SM1 Section 1.1. Electricity demands were taken from the State Energy Data System [58] for 2020, and a compound annual growth rate of 0.68% was used for projections from 2020 to 2050. Power demand profiles were then developed based on the methodology of [59] (see Fig. 6), and electricity price projections for individual users were synthetically generated from Refs. [60,61]. Individual heating demands, including space heating, domestic hot water, and industrial heating demands were estimated for 2020 based on US Energy Information Administration data for 2020 [62, 63], and profiles developed from Keiner et al. [64] for the 'US-HI' region. Passenger and freight transport demands are developed from Khalili et al. [65] after being rebalanced to 2019 as the reference year to avoid influence from the COVID-19 crisis, with all assumptions for the transport sector in Tables S2–S6. Additional demands for aluminium and desalination demands are similarly available in Tables S7–S8.

Techno-economic assumptions for the main ocean energy technologies integrated in this research and described in Section 2.1 are presented in Table 2.

Similar to Ref. [37], both e-fuel import and self-supply scenarios are investigated. The reference scenarios are the BPS-Imp and BPS-noImp, representing fully cost optimised transitions to 100% RE by 2050 across all sectors. The findings of that research, with solar electricity

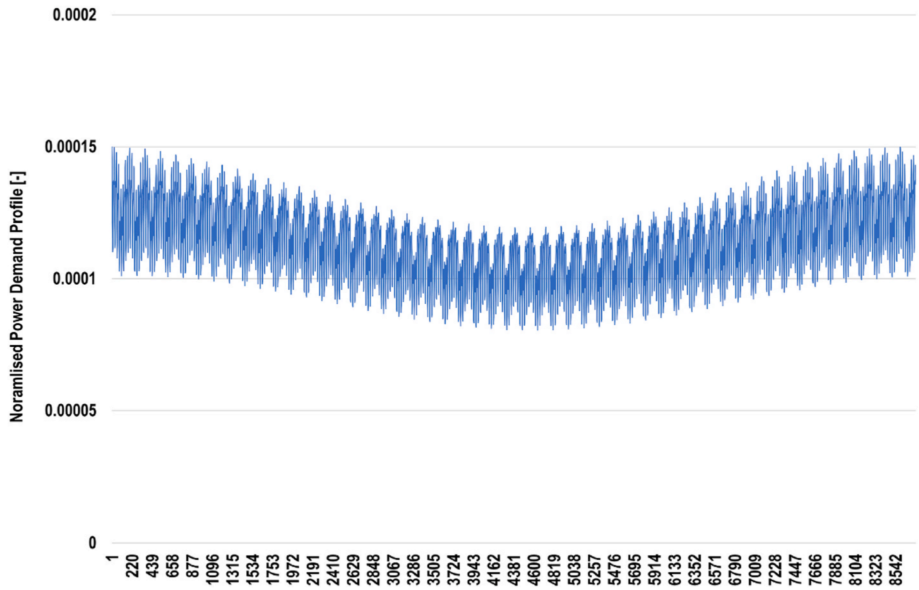

Fig. 6. Normalised power demand applied for Hawaiʻi time-shifted to UTC-10.

Table 2
Techno-economic assumptions for key offshore energy technologies.

Technologies	Parameter	Unit	2020	2025	2030	2035	2040	2045	2050	Ref
PV floating	Capex	€/kW$_{el}$	1425	1110	765	474	414	368	332	[46]
	Opex fix	€/(kW$_{el}$•a)	28.5	22.2	15.3	9.48	8.28	7.36	6.64	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	Years	20	25	25	25	30	30	30	
Wind offshore	Capex	€/kW$_{el}$	2973	2561	2287	2216	2168	2145	2130	[66,67]
	Opex fix	€/(kW$_{el}$•a)	85.0	73.0	65.9	64.0	62.0	61.0	60.7	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	Years	25	25	25	25	25	25	25	
Wave power	Capex	€/kW$_{el}$	21420	6326	2777	2247	2012	1819	1731	[23]
	Opex fix	€/(kW$_{el}$•a)	1050	367	75	56	48	45	42	
	Opex var	€/kWh$_{el}$	0	0	0	0	0	0	0	
	Lifetime	years	20	20	25	25	30	30	30	

Table 3
Characteristics of the applied energy transition scenarios.

Scenario	Electricity Generation Limits	Imports allowed?	CO_2 emissions cost [€/tCO_2]	Fischer-Tropsch liquids
BPS-Imp [37]	None	Yes	2020: 50 2025: 82 2030: 114 2035: 147 2040: 180 2045: 200 2050: 220	Yes; 100% of liquid hydrocarbons demand by 2050
BPS-noImp [37]	None	No	Same as BPS-Imp	Same as BPS-Imp
BPS-60Imp	60% Solar PV	No	Same as BPS-Imp	Same as BPS-Imp
BPS-60noImp	60% Solar PV	Yes	Same as BPS-Imp	Same as BPS-Imp
BPS-80Imp	80% Solar PV	Yes	Same as BPS-Imp	Same as BPS-Imp
BPS-80noImp	80% Solar PV	No	Same as BPS-Imp	Same as BPS-Imp
BPS-80ImpWf	80% Solar PV 10% Wave power minimum in 2050	Yes	Same as BPS-Imp	Same as BPS-Imp
BPS-80noImpWf	80% Solar PV 10% Wave power minimum in 2050	No	Same as BPS-Imp	Same as BPS-Imp

generation shares above 98%, are then compared with scenarios designed to force system diversity, as solar electricity is limited to 60–80% of electricity generation share, depending on scenario. Additionally, scenarios that gradually force wave power to 10% of all electricity generation by 2050 are investigated to understand the system performance when wave power is integrated into the Hawaiian energy-industry system. For all scenarios, available land for solar PV and onshore wind power is limited to 1% and 2%, respectively. The eight scenarios considered in this research are described in Table 3, and further description of the scenarios can be found in Section 1.3 in the SM1.

The wide range of scenarios investigating penetration of various offshore energy technologies will provide the basis for assessing the performance of 100% RE systems under high system diversity compared to the cost-optimal reference. Furthermore, the relative increase in costs for high system diversity can be quantified for the case of Hawaiʻi, especially in the context of current state government plans to incorporate significant shares of offshore wind power [13,14]. The investigation of wave power integration can further determine the potential role of this technology in Hawai'i's energy transition.

3. Results

The results of the eight-scenario analysis for Hawai'i are shown in the following subsections first describing the structure of primary energy demand, followed by the effects of varying system structure on supply structures and flexibility options through storage and PtX. The impacts of these supply structures are then investigated for their cost structures. Additional results by sector, energy flow diagrams, and system costs by sector are available in the SM1. All data for installed power, heat, storage, and PtX capacities, their generation/throughput, and system costs and emissions trajectories can be found in the SM2.

3.1. Impact on primary energy demand

Increases in electrification throughout the energy-industry system have a noticeable effect on the overall system efficiency, with the final energy demand for Hawai'i decreasing from 69.7 TWh in 2020 to 55.5 TWh in 2050, as shown in Fig. 7.

However, the first effects of limiting the share of solar PV can be observed in the primary energy demand structure, as shown in Fig. 8. During the transition, the power sector is first defossilised with the high availability of low-cost electricity, followed by the heat sector through direct electric heating, heat pumps, and solar thermal heating. The transport and industry sectors are the last to be defossilised as e-fuels are required along with increased direct electrification, which only begin to be economically viable in the late 2030s and 2040s. While the supply structure for all scenarios in 2030 and 2050 are near identical, 2040 shows a notable outlier in the BPS-60noImp. In the other self-supply scenarios, fossil fuels are found to compose 27% of the total primary energy demand (TPED) in 2040; however, in the BPS-60noImp, fossil fuels still compose 48% of the TPED. The import scenario counterpart, the BPS-60Imp, though, does not experience a similar effect, which suggests that offshore electricity costs of wind power and wave power in 2040 in the BPS-60noImp are not sufficiently low to replace fossil hydrogen, as hydrogen is required for Fischer-Tropsch liquid (FTL) fuel synthesis. The limited sustainable bioenergy potential in Hawai'i, which is fully utilised in all scenarios, additionally limits the possibility of biofuels to substitute fossil fuels. In 2040, FTL fuels reach 23% of the total final transport energy demand, at 9.4 $TWh_{th,LHV}$. As will be seen in Section 3.5, while the general trend for FTL synthesis is through significant installation of electrolysers, significant steam methane reformer capacities are installed in the BPS-60noImp and supply the majority of hydrogen for fuel synthesis processes. The effect of self-supply and e-fuel import scenarios can be observed in the TPED in 2040 and 2050, as the TPED for the e-fuel import scenarios are, on average, 22.6% and 28.6% lower than the self-supply scenarios, respectively.

3.2. Impact on power sector structure

Limiting solar electricity opens the window for alternative electricity generation technologies to emerge in Hawai'i's 100% renewable electricity supply. While the reference scenarios find solar PV generation shares of 95.6–98.7% in 2050, these shares are limited to 60–80% in the scenarios investigated in this research. The limitations on solar PV introduce increasing shares of wind power in particular during the transition years, with wave power having some introduction during the later years of the transition. When solar PV is limited to 60%, onshore wind power gains significant shares as early as 2030, at 20.5–20.6% of electricity generation compared to 5.4–7.1% in the reference cases. This share increases to 24.0–31.9% in 2040 before decreasing to 10.3–19.0% in 2050 due to the limited onshore wind power potential and growing electricity generation required to meet demand. Reaching this limited potential leads to the introduction of offshore wind starting in 2040, at 4.5–15.1% of electricity generation. Interestingly, however, this share decreases by 2050, at 3.4–11.7%, as wave power is introduced to the system, leading to installed capacities of 1.2–4.1 GW_{el}, which corresponds to 11.8–17.8% of total electricity generation. Significant capital expenditure (CAPEX) reductions for wave power from 6942 €/kW_{el} in 2030 to 1989 €/kW_{el} in 2050 result in the model opting for significant installation of wave power in the 2050 time-step over increasing offshore wind capacity. Thus, offshore capacities are responsible for 15.2% and 29.4% of generated electricity in the BPS-60Imp and BPS-60noImp, respectively.

In the 80% solar PV limit scenarios, offshore technologies expectedly have a less significant role. In the BPS-80Imp, no offshore capacities are required, as the sustainable onshore wind power potential is sufficiently large to contribute 19.0% of electricity generation by 2050. In the BPS-80ImpWf, the share of wind power is reduced to 10.3% in 2050 as wave power contributes 10%. The BPS-80noImp, similar to the BPS-60noImp, require offshore power capacities, but at lower shares, as offshore wind and wave power contribute 7.7% and 1.8% in 2050. Furthermore, with the increase in the allowed solar PV share, floating PV has a 2.8% generation share in 2050, being the only scenario with a significant interaction between offshore wind power, wave power, and floating PV. When wave power is forced to a 10% share, offshore wind power has no electricity generation in the import case, and only a 0.7% generation share in 2050.

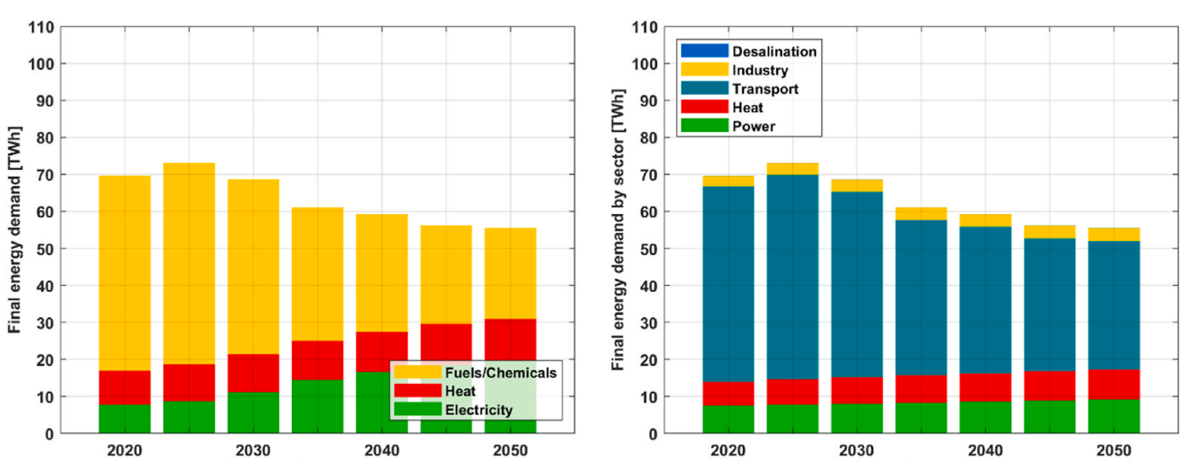

Fig. 7. Final energy demand by energy type (left) and by sector (right) for all investigated scenarios from 2020 to 2050.

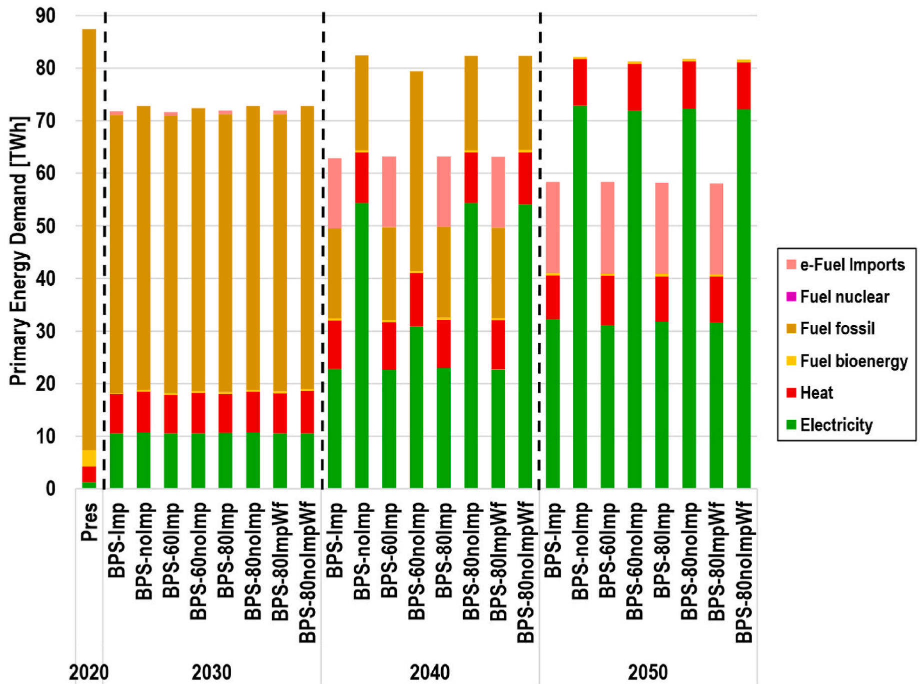

Fig. 8. TPED across all scenarios by energy source in 2020, 2030, 2040, and 2050.

The increased system supply diversity additionally leads to reductions in overall capacity required, which are at 20.6 and 40.9 GW_{el} in 2050 for the BPS-Imp and BPS-noImp, respectively, as onshore and offshore wind power and wave power have higher full load hours compared to solar PV. Thus, the scenarios limiting solar PV to 60% lead to the lowest capacities for the self-supply and e-fuel import scenario variations by 2050, at 17.7 and 33.5 GW, for the BPS-60Imp and BPS-60noImp, respectively. The results for the BPS-60noImp especially stand out, as the total installed capacity is 45% lower than in the BPS-noImp in 2040, and 18% lower in 2050. The 80% PV limit scenarios see lower reductions, ranging from 6 to 9% in 2050.

3.3. Impact on heat sector structure

While the overall heat supply structure remains relatively consistent throughout the transition, variations can particularly be observed in the shares of electricity-based and solar heating. The reference BPSs have heat generation shares of 18.5–25.1% and 69.3–75.8% for heat pumps and solar thermal heating, respectively. The absence of waste heat from electrolysis in the BPS-60noImp in 2040 leads to the highest heat generation of all scenarios at 13.3 TWh, 5.4% higher than the BPS-noImp, as shown in Fig. 10.

In the scenarios analysed in this research, the share of solar thermal heating increases in all scenarios compared to the reference scenarios, with heat generation shares from solar thermal increasing by 2.1–6.9% and 0.3–0.7% in 2050 in the e-fuel import and self-supply scenarios, respectively. Correspondingly, the share of electric-based heating through heat pumps and direct electric heating decrease by 2.2–6.9% and 0.3–0.6%, respectively. This effect is largely caused by increased electricity costs associated with higher system diversity, and the reduced effect in the self-supply scenarios occurs as higher quantities of electricity are available, even if it is at a higher cost compared to the reference scenarios. The availability of waste heat from PtX processes in the self-supply scenarios leads lower heat generation than the e-fuel import scenarios; however, the difference ranges from 0.46 to 0.91% by 2050.

3.4. Impact on storage

Increased system diversity implies that supply will cover more hours of the year, indicating that electricity storage requirements should be reduced. The installed electricity storage capacity, shown in Fig. 11 (left), confirms this expected trend, as, in 2040, installed electric storage capacity is 3.3–16.3% lower in the self-supply scenarios compared to the BPS-noImp, and 12.8–26.9% lower in the e-fuel import scenarios compared to the BPS-Imp. In 2050, this range slightly increases to 5.2–18.7% for the self-supply scenarios and decreases to 2.4–21.9% for the e-fuel import scenarios.

The disparity between storage throughout between the reference scenarios and the solar PV limiting scenarios is more noticeable when comparing the electricity storage throughput (Fig. 9 (left)), as increased supply complementarity leads to decreased storage requirements. By 2050, limiting solar PV to a 60% generation share reduces the total electricity storage throughput by 43.7% and 43.6% for the BPS-60Imp and BPS-60noImp, respectively, with the BPS-noImp having the lowest throughput of all scenarios at 4.4 TWh_{el}. The 80% solar PV share scenarios, thus, act as a middle ground with 11.7–21.8% reduced storage throughput. Forcing wave power appears to have an effect of reducing storage requirements, which indicates improved supply complementarity between solar PV and wave power. Interestingly, when supply diversity is increased, the electricity storage throughput decreases in the self-supply scenarios compared to the import scenarios, which is the inverse trend of that observed in the reference scenarios. Increased supply availability as well as increased avenues for electricity usage through PtX processes in the self-supply scenarios thus allows for the system to operate more flexibly without high electricity storage requirements.

In the reference scenarios, heat storage is required to balance solar- and electricity-based heat, and, to varying levels, store low temperature waste heat from PtX processes, which corresponds to the thermal energy storage (TES) district heat capacities and throughout shown in Fig. 12. The rapid integration of solar thermal heating, especially for medium temperature heat, leads to significant thermal energy storage as early as 2030 (Fig. 12 (left)), with capacities ranging from 4.5 to 5.7 GWh_{th}. In the self-supply scenarios, the integration of PtX processes, especially

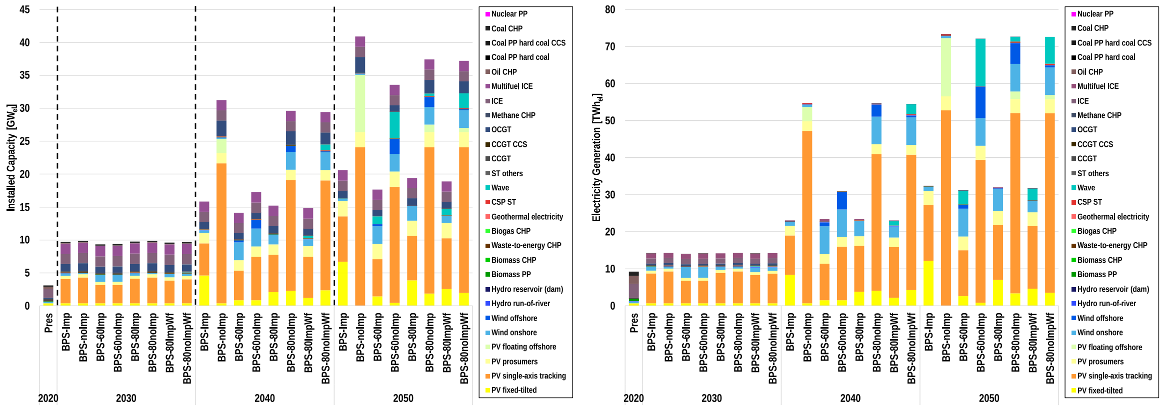

Fig. 9. Electricity generation capacity (left) and electricity generation (right) for all scenarios in 2020, 2030, 2040, and 2050. Abbreviations: CHP – combined heat and power; ST – steam turbine.

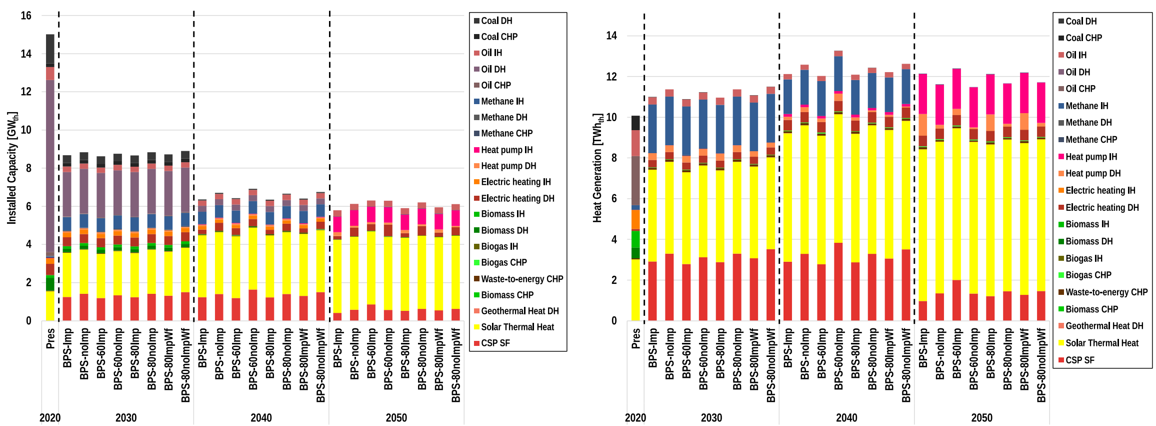

Fig. 10. Installed heat capacity (left) and heat generation (right) for all scenarios in 2020, 2030, 2040, and 2050. Abbreviations: DH – district heat; IH – individual heat.

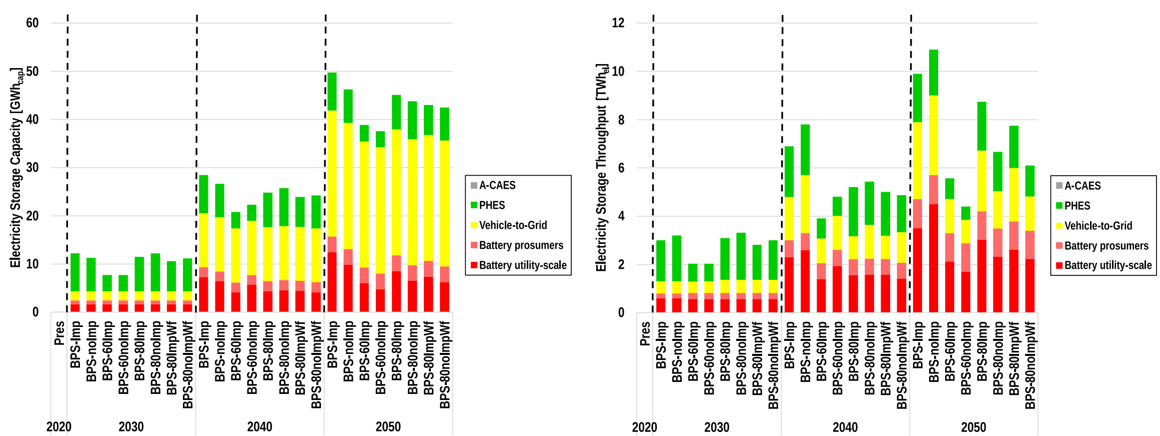

Fig. 11. Installed electricity storage capacity (left) and throughput (right) for all scenarios in 2020, 2030, 2040, and 2050. Abbreviations: A-CAES: adiabatic compressed air energy storage; PHES – pumped hydro energy storage.

water electrolysis, dictate the levels of low temperature heat storage capacity and throughput, which is evident in 2040, as the BPS-60noImp, with the low penetration of water electrolysis, leads to the lowest TES capacity of all self-supply scenarios, and 25.2% lower than the BPS-noImp, followed by the BPS-80noImp (12.3% lower) and the BPS-80noImpWf (6.0% lower). This trend extends to 2050, as the self-supply scenarios investigated in this study have 2.3–28.6% lower capacity than the BPS-noImp. In the e-fuel import scenarios, the capacities in 2050 do not vary significantly in absolute value, however, increased medium temperature TES is required to balance increased solar heating, leading to 2.7–37.2% higher TES capacity compared to the BPS-Imp.

The trends in the TES throughput (Fig. 12 (right)) largely follow those of the capacity, especially for the e-fuel import scenarios, as the

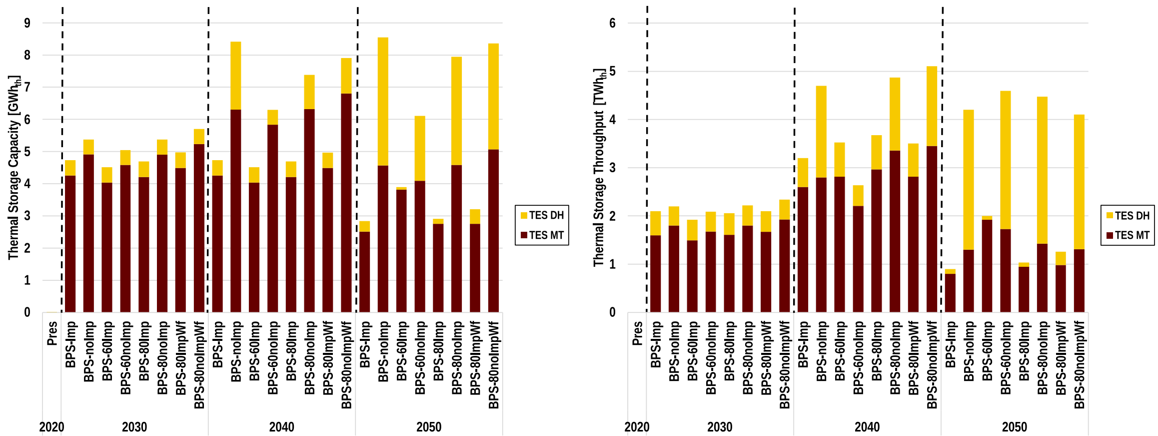

Fig. 12. Installed heat storage capacity (left) and throughput (right) for all scenarios in 2020, 2030, 2040, and 2050. Abbreviations: DH – district heat; MT – medium temperature.

throughput increases by 6.5–122% in 2050 compared to the BPS-Imp. However, while the TES capacities in 2050 are lower in the self-supply scenarios than the reference BPS-noImp, the throughputs see more variance, with the BPS-60noImp and BPS-80noImp having 9.3% and 6.5% increased throughput, respectively, and the BPS-noImpWf having a 2.4% reduction in throughput. The increase may be more attributed to medium temperature TES, which has higher utilisation due to increased solar heating shares. In the BPS-60noImp, the utilisation of low temperature TES is the highest, which corresponds to high full load hours for electrolysis compared to the higher solar PV share scenarios.

In terms of gaseous storage, it does not begin to play a role in the Hawaiian energy system until 2040, especially in the self-supply scenarios, where PtX begins to be installed on a large scale, with capacities in the hundreds of $GWh_{H2,LHV}$ (Fig. 13 (left)). As such, the difference in gas storage, especially the throughput, as shown in Fig. 13 (right), is significant between the e-fuel import and self-supply scenarios, as the e-fuel import scenarios only balance e-hydrogen produced for direct uses. The strong coupling of solar PV and water electrolysis in the BPS-noImp leads to the highest gas storage throughput of all scenarios at 16.1 $TWh_{H2,LHV}$. Similar to the characteristics of low temperature TES, the increased operational profile for water electrolysis in the 60% and 80% solar PV limit scenarios leads to reduced gas storage throughput, as e-hydrogen is directly produced for more hours of the year. Thus, the storage throughputs of these scenarios have gas storage throughput reductions ranging from 16.5% to 44.1%. In the e-fuel import scenarios, a similar trend can be observed as gas storage throughput decreases by 44.1%, 41.0%, and 20.0% in the BPS-60Imp, BPS-80Imp, and BPS-80ImpWf, respectively, compared to the BPS-Imp.

3.5. Impact on power-to-X

As indicated in previous results, the increased supply diversity affects the penetration of fuel conversion capacities, particularly of PtX, as well as the total capacities required to meet e-fuel demands. In terms of overall system flexibility, the component most affected is water electrolyser capacity, which is operated according to the availability of renewable electricity in excess to inelastic electricity demand. In the reference BPSs, electrolysers are exclusively operated as excess solar electricity is available; however, with increased supply diversity, excess electricity from onshore wind, offshore wind, and wave power become available and influence the operational profile of electrolysers. Other PtX capacities, including e-FTL, e-methanol, and e-ammonia synthesis units, which have less flexible operation, experience lower variation on capacity installed, as shown in Fig. 14. With the introduction of e-fuels in the system starting in 2035, PtX capacities are rapidly introduced in the self-supply scenarios. An exception is the BPS-60noImp, where electrolysers are installed simultaneously with steam methane reforming with carbon capture and sequestration (CCS), indicating that electricity prices during the 2040 and 2045 time steps are not sufficiently low when restricting solar PV to a 60% share. The result in 2050 is 2.3 $GW_{H2,LHV}$ of stranded steam methane reforming and CCS assets as fossil fuels are fully phased out, compared to the other self-supply scenarios that only have 0.16–0.25 $GW_{H2,LHV}$ of steam methane reforming and CCS.

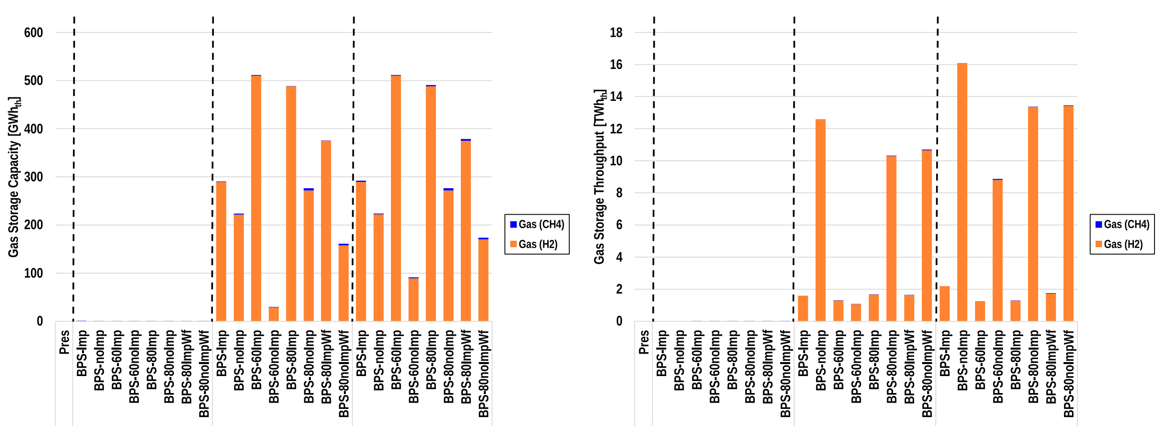

Fig. 13. Installed gas storage capacity (left) and throughput (right) for all scenarios in 2020, 2030, 2040, and 2050.

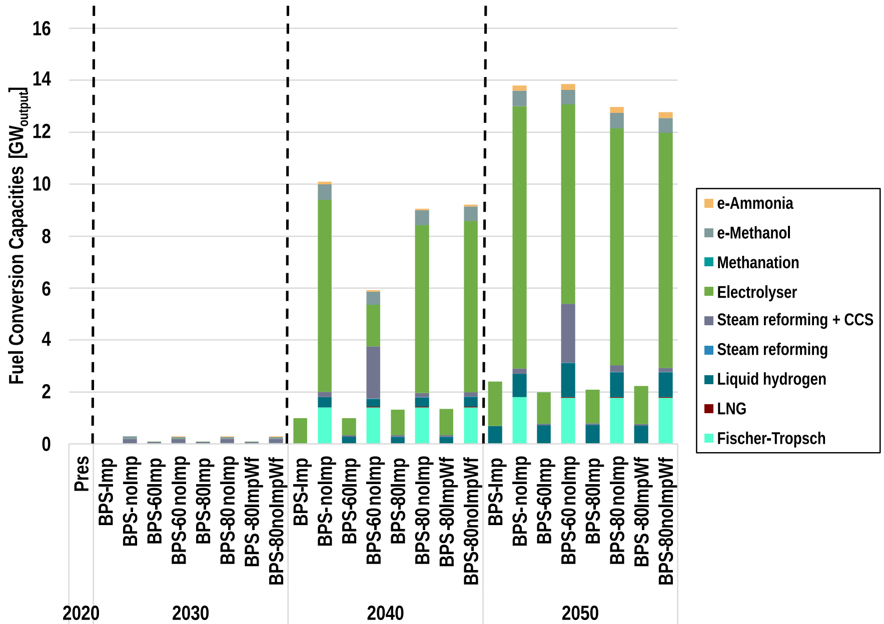

Fig. 14. Installed fuel conversion capacities for all scenarios in 2020, 2030, 2040, and 2050.

Nevertheless, by 2050, all scenarios have lower electrolyser capacities than the reference scenarios. In the e-fuel import scenarios, this range is 14–29%, and, in the self-supply scenarios, 10–29%, with the BPS-60 scenarios having the lowest capacities at 1.7 and 10.9 GW_{el} for the BPS-60Imp and BPS-60noImp, respectively. Forcing wave power in the 80% solar PV self-supply scenarios causes a slight decrease in electrolyser capacity, with the BPS-80noImpWf having an electrolyser capacity of 12.8 GW_{el} compared to the 13.0 GW_{el} installed in the BPS-80noImp. However, when examining the operational profiles for electrolysis in Fig. S32 there is not a significant difference in the solar-dominated operation of electrolysis, except for some higher capacity factors in the winter months, likely due to the increased penetration of wave power. The influence of supply diversity on electrolyser operation is more noticeable in the e-fuel import scenarios due to the reduced quantity of electricity required, though the primary high capacity factors are during the hours of available solar electricity. Wind power appears to contribute primarily from spring to autumn with electrolysers largely experiencing low capacity factors in the winter months.

3.6. *Impact on system costs*

While increased supply diversity is expected to be associated with higher costs, the relative increase in costs is not yet known as LUT-ESTM provides a singular cost-optimal solution. Although electricity prices

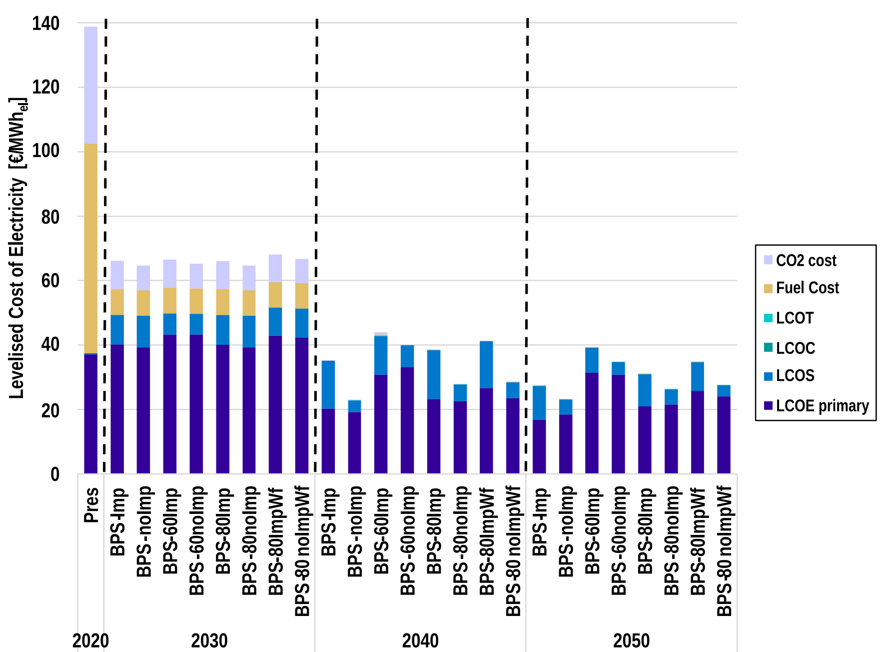

Fig. 15. Levelised cost of electricity for all scenarios in 2020, 2030, 2040, and 2050. Abbreviations: LCOS – Levelised cost of storage; LCOC – Levelised cost of curtailment; LCOT – Levelised cost of transmission.

may increase, the system has been shown to have operational benefits with reduced capacities across the entire energy-industry system due to increased supply complementarity. Thus, the overall increase in costs may only be marginal. Examining the LCOE, shown in Fig. 15, provides a first indication of the financial implications of supply diversity. During the early transition years, the LCOEs do not differ significantly as the solar PV supply share limits are not yet reached; however, in 2040, the difference becomes significantly more noticeable. Compared to the BPS-Imp, at 35.2 €/MWh$_{el}$, and the BPS-noImp, at 22.9 €/MWh$_{el}$, the self-supply and e-fuel import scenarios have LCOEs that are 9.5–24.9% and 21.7–74.9% higher, respectively. By 2050, the LCOEs of the self-supply and e-fuel import scenarios range from 31.3 to 39.3 €/MWh$_{el}$ and 26.3–39.3 €/MWh$_{el}$, respectively, which correspond to increases of 13.2–50.5% and 13.2–50.4% compared to the BPS-Imp and BPS-noImp, respectively.

In the reference scenarios, the trend that increases in system flexibility through self-supply and decreases in relative share of storage leads to reductions in LCOE compared to the e-fuel import scenario. This trend continues in the scenarios investigated in this study, as reductions in the share of the levelised cost of storage (LCOS) in the total LCOS can be observed. While the role of the LCOS in the LCOE structure decreases, the increases in primary LCOE from more capex-intensive technologies of wind and wave power lead to overall growth in LCOE when solar PV is limited.

Despite noticeable increases in the LCOE across scenarios investigated in this research, the general growth in LCOFE is less significant. By 2050, the BPS-60noImp has the highest LCOFE of all scenarios at 72.9 €/MWh, representing a 28.0% increase compared to the BPS-noImp. The 80% solar PV limit self-supply scenarios, conversely, are only higher in LCOFE by 5.6% and 7.9% for the BPS-80noImp and BPS-80noImpWf, respectively. The high variance in LCOFE in the self-supply scenarios primarily relates to the increased electricity required to produce e-fuels required to defossilise all sectors. The e-fuel import scenarios, however, experience lower variance in LCOFE as all e-fuels are imported, thus, the high fuel cost in the LCOFE structure of Fig. 16. Indeed, the e-fuel import scenario with the highest LCOFE, the BPS-60Imp (55.8 €/MWh), has a lower LCOFE than the lowest self-supply scenario, the BPS-noImp (57.0 €/MWh). Compared to the scenario with the lowest LCOFE, the BPS-Imp (49.9 €/MWh), the e-fuel import scenarios investigated in this research have LCOFEs that are 3.5–11.8% higher. Thus, increased supply diversity can be understood to have a relatively minor effect on total final energy costs if future e-fuel demands are covered by imports.

In terms of total annualised costs, which follow the same trends the LCOFE, indicate that most scenarios lead to annualised costs lower than in 2020, further indicating the viability of highly renewable energy-industry systems in Hawaiʻi. Indeed, the only scenario that leads to higher annualised costs relative to the 4.0 b€ in 2020 is the BPS-60noImp, which has total annualised costs of 4.1 b€ in 2050. By 2050, the annualised costs of the self-supply and e-fuel import scenarios, shown in Fig. 17, are 5.6–28.0% and 3.5–11.8% higher than the BPS-noImp and BPS-Imp references, respectively. However, in terms of cumulative annualised costs, the differences are not as significant, as the respective increases from higher supply diversity are 2.3–6.5% and 0.9–2.8% for the self-supply and e-fuel import scenarios. Nevertheless, increased cost of RE integration may lead to a delayed transition, especially for the self-supply scenarios where low-cost electricity is essential for competitive e-fuels. Compared to the cumulative emissions reference BPS-noImp, at 0.43 GtCO_2, the BPS-60Imp has 17.3% higher cumulative emissions, whereas the BPS-80noImp and BPS-80noImpWf only see increases of 0.5% and 0.3%, respectively. The differences across the e-fuel import scenarios compared to the BPS-Imp, at 0.41 MtCO_2, are much smaller, ranging from 0.2 to 0.8%.

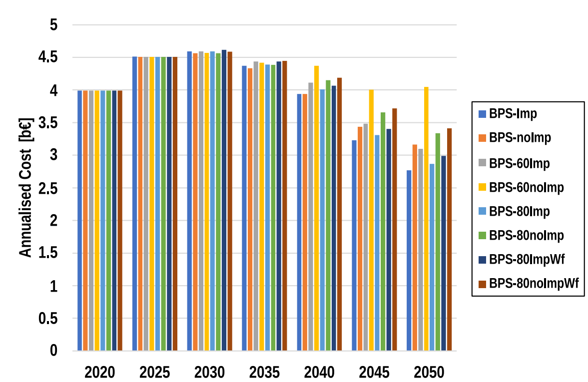

Fig. 17. Annualised system costs through the transition for all scenarios.

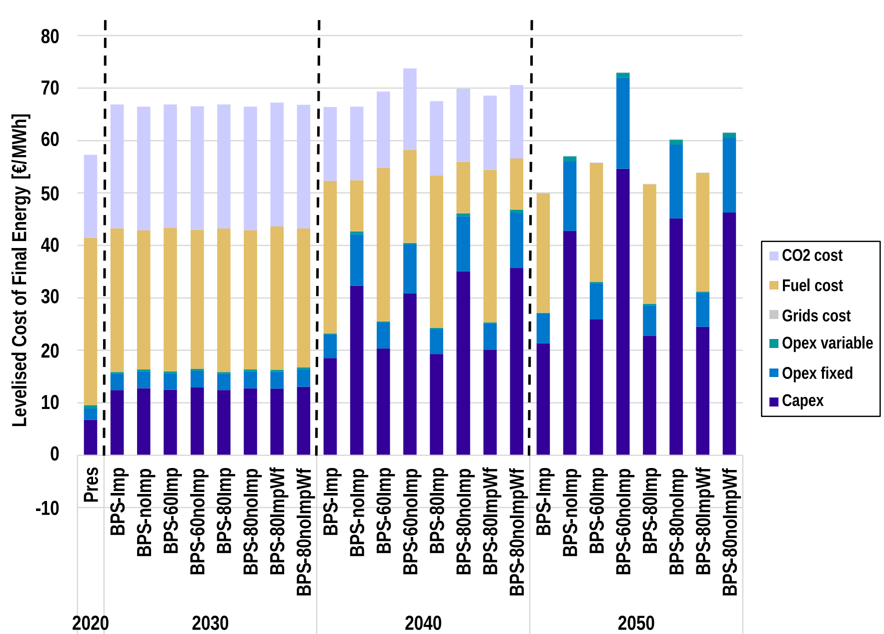

Fig. 16. Levelised cost of final energy for all scenarios in 2020, 2030, 2040, and 2050.

4. Discussion

The results of this research indicate that high system diversity is techno-economically feasible for Hawaiʻi's energy-industry transition reaching 100% RE by 2050 compared to the cost-optimal solution dominated by solar PV. The remaining sections discuss the fundamental characteristics of the systems described across scenarios and the implications of increased system diversity, followed by a discussion on the potential for ocean energy resources to play a significant role in the energy-industry transition of island regions throughout the world.

4.1. Implications of high system diversity

The overall structure in terms of the TPED in Hawaiʻi's defossilised energy system by 2050 does not significantly vary across scenarios, as renewable electricity is the dominant energy carrier in the system. With e-fuel imports, the TPED can be reduced noticeably due to efficiency gains throughout the system due to widespread electrification. Even with increased electricity supply diversity, solar energy still dominates the energy-industry system, as, in the self-supply scenarios, solar PV and solar heating contribute 64–82% of the TPED, compared to 99% in the reference BPS-noImp. Thus, the defossilised energy-industry system of Hawaiʻi may be best described as a Solar-to-X Economy [49].

When solar PV is limited, the results indicate several technologies emerge to contribute to Hawaiʻi's electricity supply. The first technology that is expanded after the solar PV limit is reached is onshore wind power, and, in the BPS-80Imp, only onshore technologies are required to supply local energy demands, indicating that less than 3% of Hawaiʻi's available land area would be required for solar PV and onshore wind power installations. The area needed for wind power is gross area demand, and 99% of the gross area demand of wind power is not needed directly [68]. Conversely, the area for solar PV cannot be significantly used for other purposes, though a substantial support for biodiversity can be enabled for low cost given proper regulation [69,70]. Forcing wave power in the BPS-80ImpWf leads to a 1.1 GW reduction in onshore wind power capacity, which reduces the land impact of the transition but leads to a 13% increased LCOE. When solar PV is further limited to 60% in the BPS-Imp, offshore energy installations begin to be required as the onshore PV limit is reached in 2040, corresponding to 7.5 TWh_{el} of offshore electricity. In 2040, the cost-optimal choice is to install offshore wind power, which has a LCOE of 66.8 €/MWh, compared to the 77.3 €/MWh LCOE of wave power. Floating PV has an LCOE of 23.0 €/MWh, but due to solar PV constraints, it cannot be chosen; nevertheless, the results of the reference BPS-noImp show that when onshore energy limits are reached, offshore floating PV would be the next choice. Although offshore wind grows significantly in 2040, it does not receive new capacity in 2045 and 2050, as wave power begins to emerge by reducing the overall system costs, despite having LCOEs of 69.8 and 65.8 €/MWh, which is 5.8 and 0.4% higher than offshore wind power, respectively. Thus, the effect of wave power on the system can be observed to be a higher resource complementarity than offshore wind power, reducing storage requirements in the system [71]. Indeed, compared to the reference BPS-Imp, electricity storage throughput decreases by 44%.

In the self-supply scenarios, a similar effect can be observed, and the quantities of offshore electricity increase significantly as electricity is required for e-fuel production. Incorporating wave power in the BPS-80noImp and BPS-80noImpWf leads to a novel offshore energy configurations where offshore floating PV, offshore wind, and wave power interact and collectively supply 12.3% of electricity in 2050. Similar to the e-fuel import case, when wave power reaches near cost parity in 2050, new offshore wind power is not installed and wave power is preferred, though at a relatively low share as offshore floating PV is ramped more significantly. When wave power is gradually forced in the BPS-80noImpWf, the role of offshore wind power and offshore floating PV are reduced. Despite a reduction in the levelised cost of storage component in the LCOE compared to the BPS-80noImp, the installation of capex-intensive wave power leads to slight increase in LCOE of 1.2 €/MWh. In the BPS-60Imp, wave power is massively ramped in 2050 to supply 12.8 TWh, 17% of all generated electricity. The operational complementarity of solar PV and wave power, also identified in Refs. [23,71,72], can be further observed in the operational profile of electrolysers under a self-supply strategy, as electrolysers have full load hours of 4340 compared to 3212 in the reference BPS-noImp. Although higher full load hours for electrolyser operation are not known to necessarily decrease costs [73], higher electricity availability can be especially important in reducing electricity and hydrogen storage required to supply inflexible PtX processes.

Despite the observed cost-competitiveness and strong resource availability [22,74] of wave power for Hawaiʻi, only Jacobson et al. [36] have identified wave power as having a role in Hawaiʻi's 100% renewable electricity supply, as other literature investigating the Hawaiian transition [75,76] have not found a role for wave power. However, this share is still quite limited at 1%, whereas offshore wind power plays a much larger role supplying 16% of electricity generation. As observed in this research, wave power can achieve competitive LCOEs to offshore wind power starting in 2045. Current government projections in Hawaiʻi expect a 66% onshore solar PV share and a 12% offshore wind power share by 2045 [14], with capacities in the range of those in the e-fuel import scenarios. These costs may be acceptable for an e-fuel import strategy, as low-cost e-fuel imports keep total energy system costs low and Hawaiʻi's existing fossil oil suppliers are expected to be emerging suppliers of e-fuels on the global market [77–79]. However, if a self-supply route is chosen, energy costs may increase compared to today's levels. In terms of a local electricity supply under an e-fuel import strategy, a 60% solar PV share indicates a 43.2% increase in LCOE compared to the reference BPS-Imp, which has an LCOE of 27.5 €/MWh, whereas the BPS-80Imp and BPS-80ImpWf have increases of 13.2 and 26.7%, respectively. Increased supply diversity may lead to increased system resiliency, and such increases in costs may be acceptable. Conversely, system diversity under a self-supply scenario may lead to a delayed transition due to high energy system costs, especially for e-fuels.

4.2. Near cost-optimal solution space

While not outperforming the reference BPSs in terms of system costs, the scenarios investigated in this research are representative of near-optimal system structures. Recent literature has suggested that the presentation of singular optimal solutions are not sufficient for long-term energy planning, as near-optimal solutions may ultimately be socially acceptable, and can indicate what components may be absolutely required, and what may be considered as a choice by decisionmakers [80,81]. Research for the power sector in Europe has demonstrated that the space of near-optimal solutions in terms of total system cost, within 15% of the cost optimal solution, is flat, indicating that a wide range of solutions may be feasible in reaching 100% renewable electricity supply for Europe [82]. This trend is largely supported by the results, as most scenarios investigated fit within a 15% system cost limit despite wide variation in the system electricity supply structure. Furthermore, a strong correlation between solar PV and battery storage is similarly identified.

Providing a wide range of solutions may additionally provide technically feasible and financially viable solutions that may be weighed by additional non-cost criteria, such as e.g., security of supply [83]. Prina et al. [84] investigate near cost-optimal solutions for the Italian power sector as a bridge between traditional energy system modelling and multi-objective optimisation by clustering near-optimal solutions by emissions, annualised costs, diversity of supply, land use, and jobs created. While such a high number of scenarios for analysis may not be feasible for full energy-industry system transition models, the scenario variations in this analysis may be viewed as adding exogenous optimisation criteria of land use and diversity of supply [83], the former of which is particularly relevant for island regions [5,7], in addition to the cost optimisation towards 100% RE. Such variation may also be feasible in terms of financial variations, as performed by Neumann and Brown [85] for a 100% renewable power sector in Europe, which may identify specific system trade-offs between technologies. The results of this research suggest that an operational trade-off exists between solar PV and offshore wind and wave power, where reduced storage across the energy-industry system is required, but at higher electricity, and thus system, costs.

4.3. Offshore energy for island energy transitions

For many island regions, land resource availability for large-scale onshore RE systems is limited [5]; thus, offshore energy resources may be essential to achieve full defossilisation of local energy-industry systems. The results of the e-fuel import scenarios indicate that high direct electrification of local energy demands only leads to minor increases in total LCOE and LCOFE compared to the purely cost-optimal reference scenario. However, without additional flexibility from power-to-X processes, high levels of storage are required to balance renewable electricity supply and demand. Much of this flexibility may come from distributed vehicle-to-grid connections; thus, electrification of the transport sector, especially of road transportation, can lead to increased flexibility and allow for increased penetration of RE [86]. Furthermore, electric vehicles can play an important balancing role through distributed vehicle-to-grid storage [40,87] and reduce the land impact of large-scale storage systems. Nevertheless, the relevance of battery storage systems of an American Pacific island is consistent with the trends of 100% RE literature findings [7]. Buoyancy energy storage systems have additionally been suggested as a form of offshore energy storage for air or hydrogen [88], which may be able to be installed only a few kilometres from the island due to the short continental plates of islands.

To better facilitate the introduction of offshore energy resources, hybrid and co-located plants have increasingly been suggested as options. Cipolletta et al. [89] investigate a hybrid power supply using wave power and backup gas turbines to increase the dispatchability of wave power. In the short term, as evidenced by the electricity storage throughput of the e-fuel import scenarios in 2035 and 2040, this gas-to-power route may be relevant for using existing fossil infrastructure to balance the integration of high renewable electricity shares. The offshore wind and wave resources in Hawaiʻi indicate that the resource availability improves in deeper sea waters, which may require floating support structures for offshore wind power installations [90], but they may be susceptible to wave motions that may affect performance. Dampening systems can improve the stability of the system, but the integration of wave energy converters can both stabilise the system and increase the electricity generation of the system [91]. Furthermore, a combined wind-wave farm has been found to increase the smoothness of the output power curve [92] and reduce curtailment compared to a standalone offshore wind farm, and may additionally reduce the cost of wave energy converters [93]. However, the results appear to indicate that offshore floating PV may be preferable for islands with strong solar resources such as Hawaiʻi, and large market growth may be expected [94]. Indeed, from the perspective of balancing high solar PV shares, the results indicate that wave power may be better suited than offshore wind power. The observed operational synergy between solar PV and wave power may be due to the smoothing of the power profile that occurs when wind energy is transferred to wave energy that additionally can lead to power production even during times of low coastal winds [95].

Although offshore resources have higher technical potentials due to vast ocean areas, considerations must be made regarding the integration of offshore energy. Given the reliance of Hawaiʻi, as well as other island regions, on imported goods via shipping, ocean energy installations should be planned such that they do not pose potential collision risks with ships [96]. Additionally, Hawaiʻi's economy is heavily dependent on tourism [11], which is similarly the case for many island regions, so offshore energy installations should not interfere with popular tourist areas. The regions of strong wave and offshore wind resources may coincide with regions with the best surfing conditions or with Hawaiʻi's coral reefs [97], which are excluded in the offshore resource assumptions in this research. However, given Hawaiʻi's significant exclusive economic zone, such area constraints may not be significant, as the BPS-60noImp, which has the highest capacity of offshore energy technologies, would only require 2.4% and 0.9% of Hawaiʻi's exclusive economic zone of 2,474,715 km^2 for wave and offshore wind power, respectively, assuming a power density of 14.79 and 10 MW/km^2 for the respective technologies [23,54]. von Krauland et al. [28] finds that the available area for offshore wind power developments in Hawaiʻi alone could be as high as 718,600 km^2 with a total capacity potential of 6068 TW. The power density of floating PV can be much higher, ranging from 100 to 200 MW_p/km^2 [98], which may make floating PV an especially relevant technology for islands as a source of low-cost electricity [99]. Researchers increasingly investigate the environmental impacts of floating solar PV in marine applications, especially their effects on hydrodynamics [100], fouling [101], and sensitive ecosystems [102]. The co-location of wave power and offshore wind, and wave power and floating PV may be possible to further reduce the area impact of offshore RE. Nevertheless, the social, economic, and environmental effects of large-scale offshore RE should be considered [96].

4.4. Limitations and future works recommendation

Though the results of this research indicate viability of wave power in conjunction with solar PV, there is still high uncertainty regarding the cost developments of wave power, as well as the feasibility of hybrid solar PV-wave power systems [71]. As such, wave power has been found to have little to no role in island energy transitions [103–105], or to not have electricity generation shares above 25% [46,106]. Thus, additional sensitivity may be required as the cost reduction potential for wave power is better understood. Furthermore, while a 1-h time resolution is standard for energy system modelling, wave power can have sub-hour and sub-minute differences [107], which may affect the power yield. Dedicated resource profiles for floating PV systems may also better capture the operational FLH of future flat east-west oriented arrays. As Hawaiʻi is considered as one node in this research, island specific siting and potential transmission capacities required are not considered. Although the islands of Hawaiʻi have no existing transmission capacities between islands [108,109], research has been conducted to investigate a potential undersea transmission cable that would provide onshore wind power from the less-inhabited Lānaʻi and Molokaʻi islands to the densely populated Oʻahu island [110,111]. Reductions in electricity costs through undersea transmission cables have been identified for the islands of the Canary archipelago [112] the Philippine islands [113], and islands in the Caribbean [114,115]. Future research may therefore model Hawaiʻi at the island or county level to understand additional bottlenecks that may occur with regards to land resources, which may lead to higher shares of offshore RE, and to investigate the potential of inter-island electricity transmission.

An additional limitation involved is the lack of data regarding OTEC technologies. While this resource has been researched for Hawaiʻi [15,116,117] and globally [26,27], proper resource and techno-economic data have not been integrated into the LUT-ESTM framework. The expected role of OTEC may be expected to be low; however, proper integration may identify opportunities for this technology in Hawaiʻi. Combining OTEC with seawater desalination capabilities may be a feasible means by which the low thermal efficiency of OTEC can be compensated, and contribute to a sustainable water supply for Hawaiʻi [118]. Tidal energy [119] may similarly be integrated for a full integration of major ocean energy technologies and their potential to contribute to the defossilisation of the Hawaiian energy-industry system.

5. Conclusions

Increasing system diversity in 100% renewable energy systems can lead to reduced storage requirements across the energy-industry system and increase system resiliency, which may be particularly relevant for island regions such as Hawai'i that do not have access to large country-wide electricity transmission infrastructure. The lack of inclusion of the major ocean energy technologies of floating solar photovoltaics, offshore wind power, and wave power in energy system modelling has remained a research gap. This research closes this gap and demonstrates the impacts on energy system structure and costs from higher system diversity through limits on solar photovoltaics electricity generation compared to a purely cost-optimal solution leading to >95% electricity generation shares from solar PV. Furthermore, the results of the BPS-80noImp and BPS-80noImpWf show the viability of a novel cost-optimised combination of the main ocean energy technologies of offshore floating PV, offshore wind, and wave power, which collectively supply 12.3% of electricity by 2050. The resource complementarity between solar PV and offshore wind and wave power leads to reductions in storage requirements across the energy-industry system, especially for electricity storage, which is reduced by up to 44% in the BPS-60Imp compared to the BPS-Imp. Under an e-fuel self-supply strategy, gaseous storage can be reduced by up to 45% compared to the BPS-noImp as the electrolyser operational profile has increased overlap with near baseload power-to-X processes.

Given the high share of the transport sector in the final energy demand structure, system costs are heavily dependent on the price of electricity-based fuels. Such fuels may be imported by many island regions with limited land availability to expand local electricity-based fuel production, and the availability of low-cost sustainable fuels on the global market will be essential. While the reference BPS-noImp leads to reduced energy-industry system costs by 2050 compared to 2020, the self-supply scenarios investigated in this research lead to costs increases ranging from 5 to 27%. With low-cost supplies of e-fuel imports from emerging global markets, the effect of increased system diversity leads to a lower variance in system costs. Indeed, all investigated scenarios lead to a lower cost energy-industry system compared to 2020, with reductions ranging from 2.7 to 9.9% in 2050, compared to a 12.9% decrease in the reference BPS-Imp. Thus, high system diversity may be economically viable despite increases in electricity generation costs, which may be desirable to reduce the land impact of onshore renewable energy. Furthermore, wave power may be co-located with offshore wind power or offshore floating PV to reduce the ocean area utilised for electricity generation in island exclusive economic zones.

Thus, ocean energy technologies may play a key role in supporting onshore solar PV to defossilise Hawai'i's energy-industry system, along with the availability of low-cost e-fuels and high shares of solar thermal heating. Future research may investigate specific siting of ocean energy installations and grid connections to islands. While the outlook for Hawai'i and islands around the world may be the development of a Solar-to-X Economy given the high relevance of solar energy for electricity and heat, the potential for ocean energy sources to provide a complimentary electricity supply should be considered for island energy transitions.

CRediT authorship contribution statement

Gabriel Lopez: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Rasul Satymov:** Writing – original draft, Methodology. **Arman Aghahosseini:** Methodology, Investigation, Data curation. **Dmitrii Bogdanov:** Writing – review & editing, Validation, Methodology. **Ayobami Solomon Oyewo:** Writing – review & editing, Methodology. **Christian Breyer:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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