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# Wave power for e-fuels and e-chemicals production: technical feasibility, economic viability, and regional opportunities

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## ABSTRACT

The global energy transition necessitates the defossilisation of the energy-intensive industry and hard-to-abate transport sectors, where direct electrification falls short due to limitations in energy density. Electricity-based fuels and chemicals (e-fuels and e-chemicals) emerge as a viable alternative, offering high energy density and compatibility with existing infrastructure. However, their production hinges on access to vast amounts of low-cost renewable electricity, a challenge for regions with limited land. This study explores wave power as an underexplored source for e-fuel production, focusing on regions with exceptional wave energy: New Zealand, Chile, and Ireland. Using energyHub-LUT, a newly developed optimisation model, the research evaluates the techno-economics of wave power, alongside solar photovoltaics and wind power, for producing e-fuels and e-chemicals. The results show that wave power supplies more stable power for e-fuel production compared to onshore wind power and solar photovoltaics, cutting the need for batteries by 25-100%, depending on location. Chile produces the lowest cost e-fuels when wave power is integrated alongside solar photovoltaics and onshore wind power, thanks to over 7000 full load hours, but its higher capital expenditures render it less competitive than onshore renewable energy. The study concludes that wave power's economic viability is limited even in regions with very high full load hours but also highlights its potential as an alternative where land scarcity hinders large-scale renewable energy projects or in cases of near baseload direct electricity need.

## 1. Introduction

The global energy transition is driving an urgent need to defossilise energy-intensive industries and hard-to-abate transport segments [1]. While battery-electric solutions are viable for road vehicles and short-haul transport, they face significant limitations in segments requiring high energy density and long-range capabilities [2]. Among the most promising approaches are electricity-based fuels and chemicals (e-fuels and e-chemicals) [3], [4], [5], which offer a pathway to reduce greenhouse gas emissions while maintaining the high energy density required for sectors such as aviation [6], [7], marine [8], [9], chemical [10], [11], and energy-intensive industries [12], [13]. Such synthetic e-fuels and e-chemicals, including electricity-based Fischer-Tropsch liquids (e-FTL) [14], [15], e-methane [16], [17], e-ammonia [18], [19], and e-methanol [20], [21], are produced using electricity, synthesised

through a multi-step process involving the electrolytic production of hydrogen from water using renewable electricity, followed by the catalytic reaction of this hydrogen with CO<sub>2</sub> to generate a liquid or gaseous hydrocarbon fuels or with N<sub>2</sub> for e-ammonia. CO<sub>2</sub> is often assumed to be captured directly from the air, but it can also be captured from point-sources [22], thus making e-fuels and e-chemicals environmentally sustainable in terms of net greenhouse gas emissions. e-Fuels and e-chemicals can potentially serve as alternatives to fossil fuels and fossil feedstocks in existing infrastructure [23], [24], although small modifications or new engines may be required for some of these fuels, such as e-ammonia [19] and e-methanol, to be fully integrated. Additionally, e-fuels can be stored and transported using existing infrastructure [5], making them a practical solution for global energy systems. However, the production of these e-fuels and e-chemicals is highly dependent on the availability of low-cost renewable electricity, which is essential for

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making these energy carriers economically viable [14], [16], [18], [20].

One of the key challenges in scaling up e-fuels and e-chemicals production is the uneven global distribution of renewable energy (RE) resources and land constraints faced by heavy energy consumers. Regions such as Europe and East Asia, in particular South Korea, Japan, and Taiwan, which are major energy consumers, lack land area to domestically generate sufficient renewable electricity for e-fuels production in a cost-optimal way [25]. This imbalance underscores the need for strategic locations that can serve as hubs for e-fuels and e-chemicals production with abundant RE resources to export these energy carriers to regions with high demand [3], [26], [27].

Recent studies have identified several regions around the world with the potential to become global hubs for low-cost e-fuels and e-chemicals production. Countries such as Australia [27], Chile [28], [29], Egypt [30], Morocco and Namibia [31], [32], Kenya, Tanzania, and Somalia [32], and Iberia [23] have been highlighted [18], [20] as promising locations due to their abundant RE resources, such as solar photovoltaics (PV) and onshore wind power. These regions can provide the low-cost electricity required to power the electrolysis of water, direct air capture (DAC) of CO<sub>2</sub>, and the synthesis of e-fuels, making them attractive for large-scale production. However, while such studies have made significant progress in assessing the potential of onshore RE, the role of ocean energy, particularly wave power, remains underexplored.

Ocean energy [33], particularly wave power [34], [35], represents a largely untapped resource for e-fuels and e-chemicals production. Wave energy has the advantage of being more consistent compared to wind and solar energy resources, offering a stable energy supply profile [36] that could be ideal for continuous e-fuels production. Despite this potential, most studies on ocean energy hubs focus on offshore wind power [37], [38], [39], while wave power remains largely overlooked. A few notable exceptions have begun to explore the potential of wave power for e-fuels and e-chemicals production, such as in the United Kingdom and Ireland [40], New Zealand [41], Hawai'i [42], Maldives [43], and Seychelles [44]. However, these studies primarily focus on domestic energy transition, and a research gap persists in understanding how wave power can be harnessed at scale for e-fuels and e-chemicals production in dedicated off-grid energy hubs.

This research gap is particularly relevant in the context of regions with exceptional wave energy resources. Such regions include the Southland, New Zealand, and Magallanes, Chile, which have access to the best wave energy resources globally due to their unique geography, born from winds unobstructed by continents [45], [46]. Both Chile and New Zealand have demonstrated a proactive interest in the development of RE [47], [48], positioning these specific regions as strategic focal points for innovation. The remote location and lack of existing infrastructure in these regions may present significant logistical and financial barriers. However, the absence of legacy systems presents a “greenfield” opportunity to develop dedicated energy hubs focused solely on e-fuels and e-chemicals production [38], [49], [50]. Alternatively, Ireland presents a strong case for wave power energy hubs, offering proximity to the demand centre in Europe.

The current lack of studies on wave power for e-fuels and e-chemicals production hubs highlights a research gap that this study aims to address. Furthermore, there is a lack of studies that focus on the sites with the best wave energy resources globally. By focusing on New Zealand, Chile, and Ireland, this study seeks to fill this gap and assesses the feasibility of wave power for large-scale e-fuel production.

In terms of novelty, this research builds on the latest study on wave power [34], which concluded that wave power can become cost-competitive with offshore wind power during the late 2030s, which was confirmed for several regions [40], [41]. By integrating the latest research on wave power with the growing body of literature on e-fuels, this study provides a novel perspective on how ocean energy can contribute to the global energy transition. The study highlights the technical potential of wave power for e-fuels production and explores economic implications of developing wave power hubs in regions with

exceptional resources.

## 2. Methods and data

The underlying data for this study comes from Ref. [34], which assessed the global techno-economic potential of wave energy resources within 300 km of distance from the shore, 1000 m of water depth and excluding protected marine areas. That study [34] mainly relied on technical and financial assumptions pertaining to a point-absorber wave energy converter (WEC) inspired by CorPower Ocean [51] and the results for global FLH values are presented in Fig. 1.

The southern hemisphere stands out thanks to the waves born from the winds unobstructed by continents, in contrast to the northern hemisphere. The southern tips of New Zealand and Chile have access to rich wave energy resources. Ireland presents an alternative option with high wave resources closer to continental Europe.

In addition to rich wave energy resources, all three regions, New Zealand, Chile, and Ireland, offer high geopolitical attractiveness, being members of the Organisation for Economic Co-operation and Development (OECD) and located outside of geopolitically challenging regions, such as South China Sea, Middle East, or North America.

The point-absorber WEC from CorPower is a buoy-like device connected to the seabed by a mooring line, which generates electricity by oscillating in resonance with the waves [51], [52], [53]. The WEC from CorPower demonstrates a wide range of operation and its power matrix [34] is shown in Fig. 2.

CorPower's WECs are rated at 400 kW and are designed to be operated in clusters with a total power output of 10-30 MW. Deploying multiple WEC arrays in close proximity can lead to a decrease in wave energy quality, which may negatively impact the performance of downstream arrays. To mitigate this issue, the underlying data in Ref. [34] sets a rudimentary constraint of 15% area usage, related to sea area limitation analyses of Taminiau and van der Zwaan [54], allowing 85% of the area to remain unused and enable the wave energy to recuperate.

### 2.1. Demand for e-fuels and e-chemicals

The analysis looked at the future e-fuel and e-chemicals demand in Europe and East Asia (Japan and South Korea) in 2050, assuming they have transitioned to 100% RE systems but need to import e-fuels and e-chemicals, following [55]. The values, presented in Table 1, were obtained from Ref. [3]. Only a portion of these fuels and chemicals demands can be supplied by the investigated regions.

### 2.2. Potential for e-fuel and e-chemicals production

To estimate the potential production of e-fuels and e-chemicals, the wave power potential under a 50 €/MWh threshold was obtained from Ref. [34], considering waters within 300 km from shore, with depths up to 1000 m, excluding protected marine areas and applying a 15% area usage rate to allow for wave energy recuperation. By multiplying the installable capacity by the FLH in each region, the potential electricity generation was calculated. This potential was then used to estimate the production of e-fuels and e-chemicals and what share of the demand for these fuels in Europe and East Asia in 2050 could be satisfied, as shown in Table 2.

The installable potential of onshore RE sources was calculated using a rudimentary assumption of 10% land area usage, assuming an installation density of 150 MW/km<sup>2</sup> for solar PV (taking 1000 W/m<sup>2</sup> global horizontal irradiation, assuming 30% PV efficiency by 2050 [50,56]% ground cover ratio [57]) and 8.4 MW/km<sup>2</sup> for wind power (taking all turbines from Ref. [58] and assuming 7 by 4 rotor diameters between the turbines). Emerging research suggests that PV module efficiencies exceeding 30% may become feasible by 2050 [59], [60], potentially reducing future land use requirements. The area demand for wind power

### CorPower FLH according to wave conditions in 2005

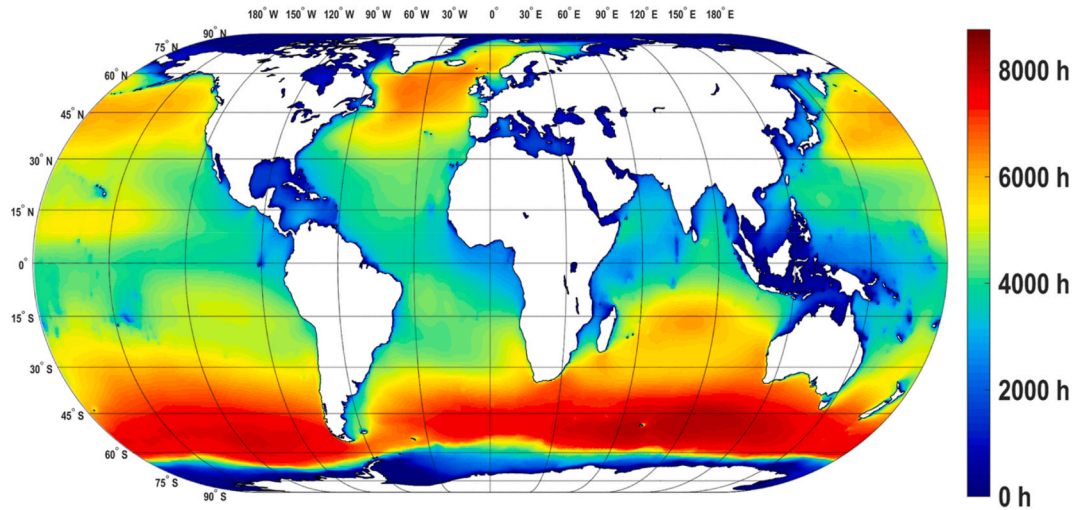


Fig. 1. Global full load hours for the point-absorber WEC. Note: h – hours.

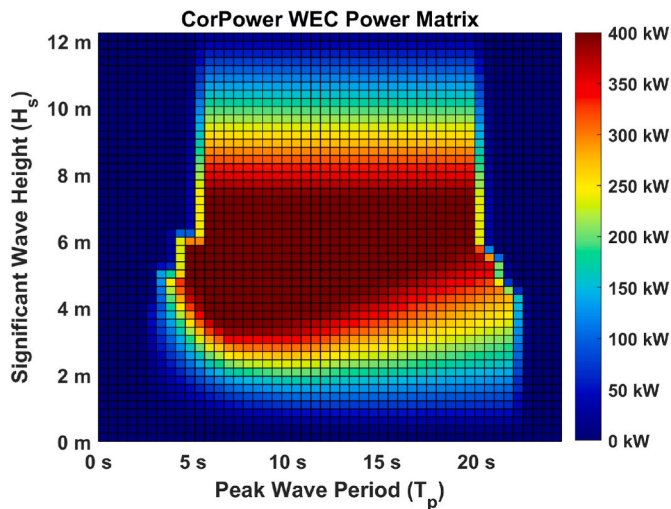


Fig. 2. CorPower WEC's power matrix. Note: m – meters; s – seconds.

**Table 1**  
Demand for e-fuels and e-chemicals in 2050 in TWh<sub>LHV</sub>.

Region	Europe	East Asia
e-Ammonia	396	212
e-Methanol	1340	871
e-FTL	1613	245
e-Methane	873	255
<b>Total</b>	<b>4222</b>	<b>1581</b>

**Table 2**  
Installable wave power capacity, full load hours, and electricity potential.

Region	Installable capacity [GW]	FLH	Electricity potential [TWh]	Share of the demand
New Zealand	646	7098 h	4586	39.0%
Chile	112	7016 h	786	6.7%
Ireland	393	5753 h	2261	19.0%

is gross area, while the net area demand is about 1% of the gross area [61]. The solar PV profiles were obtained from Ref. [62]. Onshore wind power profiles were based on [58].

### 2.3. energyHub-LUT

The simulation was performed with a newly developed optimisation model named “energyHub-LUT”, dedicated purely for the techno-economic modelling of off-grid e-fuels and e-chemicals production, powered by RE sources, batteries, multi-fuel internal combustion engines (ICE), heat pumps, electric heaters, thermal energy storage, electrolyzers, DAC, fuel/chemicals synthesis units, fuel/chemicals storage units, and waste heat utilisation [63]. EnergyHub-LUT is a linear programming optimisation model with a target function to minimise the total annualised system cost (1).

$$\min \left( \sum_{t \in \text{tech}} (Capex_t \cdot crf_t + Opexfix_t) \cdot instCap_t + Opexvar_t \cdot E_{gen,t} \right) \quad (1)$$

where *tech* and *t* are generation and storage technologies, *Capex<sub>t</sub>*, *crf<sub>t</sub>*, *Opexfix<sub>t</sub>*, *Opexvar<sub>t</sub>* are capital expenditures, capital recovery factor, and fixed and variable operational expenditures, respectively, for technology *t*; *instCap<sub>t</sub>* is installed capacity and *E<sub>gen,t</sub>* is total generation for technology *t*.

The model ensures the balance of hourly energy supply and demand according to (2), subject to constraints, such as minimum permissible load for fuel synthesis units.

$$\forall h \in [1, 8760] \sum_{t \in \text{tech}} E_{gen,t} + \sum_{s \in \text{st}} E_{s,disch} \geq \sum_{e \in \text{energy}} E_{dem,e} + \sum_{s \in \text{st}} E_{s,ch} \quad (2)$$

where *E<sub>gen,t</sub>* is hourly generation for technology *t*, *E<sub>s,disch</sub>* and *E<sub>s,ch</sub>* are hourly storage discharge and charge for storage unit *s*, and *E<sub>dem,e</sub>* is hourly energy demand for energy use *e*.

The model schematic is illustrated in Fig. 3, which shows exogenous inputs on the left representing RE capacity factor profiles and on the right final fuel demands. All parameters enclosed within the black square are subject to optimisation.

EnergyHub-LUT was developed entirely with Matlab (created and tested on version R2024b) [64], relying on the “solve” function within the Optimisation Toolbox, using the “linprog” solver and “interior-point” algorithm. One optimisation run requires approximately 20 min on a Windows 11 machine with an Intel Core i5-10210U processor, and 16 GB of memory. The underlying source code is openly available in a code repository, alongside the input files [65].

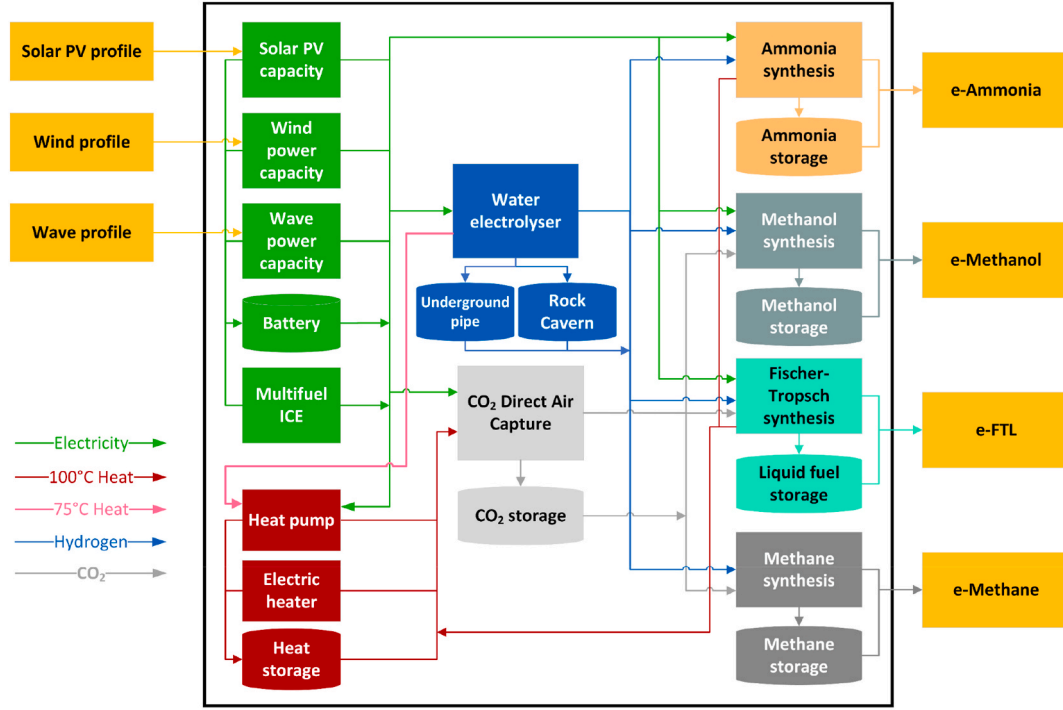


Fig. 3. Schematic diagram of energyHub-LUT linear optimisation model.

2.4. Scenarios

First, each region is modelled using only wave power, to assess the technical performance of wave power-only systems and determine the associated costs. Second, each region is re-modelled with an onshore hybrid solar PV and wind power plant instead of wave power. While the e-fuel production targets remained fixed, the capacities of solar PV and wind power were optimised accordingly to meet these targets, following the setup of [18], [20]. This enables a direct comparison of the costs associated with e-fuels and e-chemicals production in each location. Finally, each region is re-modelled with an optimal mix of wave power, solar PV, and onshore wind power as hybrid energy hub system. In this scenario, solar PV, and onshore wind power are limited to 10% of the available land area to determine if there is enough land for the modelled energy hub. An overview of the scenarios is available in Table 3.

2.5. Levelised cost of fuels

Levelised cost of fuels (LCOF) was calculated for each fuel to assess the economic attractiveness of wave power in each location. LCOF considers the capital and operational expenditures of liquid fuel synthesis units, methanation units, methanol synthesis units, and ammonia synthesis units, levelised cost of hydrogen (LCOH<sub>2</sub>), levelised cost of CO<sub>2</sub> (LCOCO<sub>2</sub>) and levelised cost of electricity (LCOE) that is fed into all fuel synthesis units. The equation for the calculation of LCOF is shown in (3).

$$LCOF_f = \frac{Capex_f \cdot crf_f + Opex_f + LCOH_2 \cdot H2_f + LCOCO_2 \cdot CO2_f + LCOE \cdot el_f}{Output_f} \quad (3)$$

where *f* denotes the fuel, *Capex* is capital expenditure, *Opex* is operational expenditure for synthesis capacities, *crf* is capital recovery factor, and *Output<sub>f</sub>* is the total annual output of fuel *f*. For e-ammonia, CO<sub>2f</sub> is zero. LCOH<sub>2</sub> is calculated according to (4).

$$LCOH_2 = \frac{Capex_{H2} \cdot crf_{H2} + Opex_{H2} + LCOE \cdot wel_{el}}{Output_{H2}} \quad (4)$$

where *Capex<sub>H2</sub>* and *Opex<sub>H2</sub>* are for water electrolyzers and hydrogen storage, and *wel<sub>el</sub>* is electricity consumed by the water electrolyzers, and *Output<sub>H2</sub>* is total annual hydrogen production.

LCOCO<sub>2</sub> was calculated according to (5).

$$LCOCO_2 = \frac{Capex_{DAC} \cdot crf_{DAC} + Opex_{DAC} + LCOE \cdot DAC_{el} + LCOH \cdot DAC_{he}}{Output_{CO2}} \quad (5)$$

where *DAC* is direct air capture, *DAC<sub>el</sub>* and *DAC<sub>he</sub>* are electricity and heat consumed by DAC, *LCOH* is levelised cost of heat and *Output<sub>CO2</sub>* is total annual captured amount.

LCOE was calculated according to (6).

$$LCOE = \frac{\sum_{p \in power} (capex_p \cdot crf_p + Opex_p)}{Output_{el}} \quad (6)$$

Table 3

Overview of the scenarios and their upper limits for RE technologies. Entries shown as Inf denote infinite (unbounded) upper limit for solar PV and wind power in the PV-wind scenario.

Scenarios	New Zealand			Chile			Ireland		
	Wave	PV	Wind	Wave	PV	Wind	Wave	PV	Wind
Wave	646	0	0	112	0	0	393	0	0
PV-wind	0	Inf	Inf	0	Inf	Inf	0	Inf	Inf
Wave-PV-wind	646	468	26	112	1984	111	393	1266	71

where  $p$  denotes the power units (wave power, wind power, solar PV, battery) and  $Output_{el}$  is total annual electricity generation.

LCOH was calculated according to (7).

$$LCOH = \frac{Capex_h \cdot crf_h + Opex_h}{Output_{he}} \quad (7)$$

where  $h$  denotes the heat producing units (heat pumps) and  $Output_{he}$  is total annual heat production.

Capital recovery factors were calculated according to (8).

$$crf = \frac{WACC \cdot (1 + WACC)^n}{(1 + WACC)^n - 1} \quad (8)$$

where WACC is the weighted average cost of capital, set at 7%, and  $n$  is the lifetime.

Additionally, shipping costs were calculated to be able to compare the cost of e-fuels and e-chemicals at the final destination. The shipping costs of e-ammonia and e-methanol were based on [23], [24], with adjustments made for e-FTL and e-methane based on the same studies. The parameters for e-FTL and e-methane shipping are given in Table 4.

### 2.6. Technical and financial assumptions

All techno-economic assumptions were based on values projected for 2050. The cost assumptions regarding wave power were obtained from Ref. [34] and are presented in Fig. 4, which projects a strong decline in capex with volume-driven cost reduction thanks to economies of scale.

The capex of wave power was tailored for each location adjusting for water depths and distances to shore of the best sites, based on data from Ref. [34]. Best sites were defined as the nodes within the exclusive economic zone (EEZ) of each location with LCOE below 50 €/MWh. The selected sites were then averaged weighting by LCOE. The capex for each location is given in Table 5.

The opex of wave power was assumed 2.4% of capex and lifetime of 30 years. The capex and opex of solar PV, onshore wind power, batteries, and fuel synthesis units were assumed the same for all locations and are presented in Table 6. Two types of solar PV plants were modelled: fixed optimally tilted and single-axis tracking installations. Hydrogen storage costs were taken for a lined rock cavern [18], [66], assuming the

**Table 4**  
Technical and financial assumptions of shipping e-ammonia, e-methanol, e-FTL and e-methane.

Parameter	e-ammonia	e-methanol	e-FTL	e-methane	Units
Export terminal capex	10.6	0.75	0.41	4.63	€/kW <sub>th,LHV</sub>
Export terminal opex	2%	2%	2%	3%	%
Export terminal lifetime	30	30	30	25	Years
Export terminal load time	12	12	18.14	12.92	Hours
Export terminal energy	15	14	6.8	5.8	kWh/MWh
Export terminal FLH	3000	3000	3000	3000	Hours
Ship size	304	670	879	863	GW <sub>h,LHV</sub>
Speed	22	22	22	30	km/h
Charge/discharge time	4	2	2	2	days
Ship capex	270	107	63	192	€/MWh <sub>th,LHV</sub>
Ship opex	4%	4%	3%	4%	%
Ship lifetime	30	30	25	35	Years
Boil-off	0.04%	0%	0%	0.1%	%/day
Fuel consumption (laden)	1.64	1.4	2.1	1.6	kWh/GWh
Fuel consumption (ballast)	1.42	1.2	1.8	1.3	kWh/GWh
Import terminal capex	6.5	0.75	0.41	20.62	€/kW <sub>th,LHV</sub>
Import terminal opex	2%	2%	2%	3%	%
Import terminal lifetime	30	30	30	30	Years
Import terminal unload time	12	12	18.14	12.5	Hours
Import terminal energy	15	14	6.8	7.8	kWh/MWh
Import terminal FLH	6000	6000	6000	6000	Hours

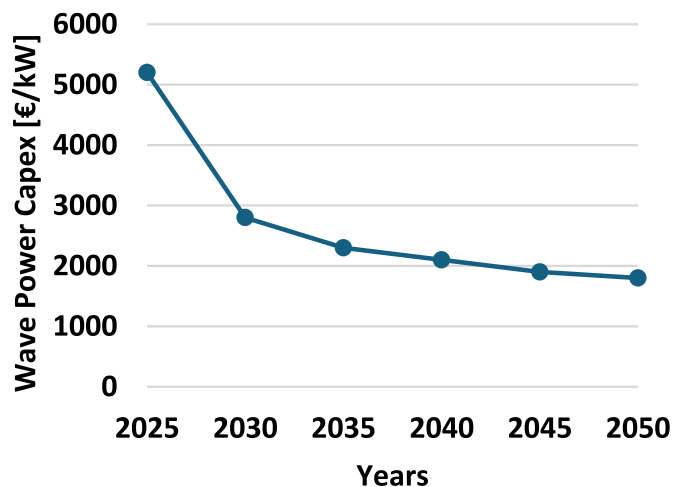


Fig. 4. Wave power capex projection until 2050.

**Table 5**  
Capex of wave power projected for 2050.

Region	Capex [€/kW]
New Zealand	2020
Chile	1852
Ireland	1970

availability of such type of storage in all locations studied [18], [67] and an underground pipe storage [68]. The associated energy-to-power (E/P) ratio of storage units reflect the rate of charging and discharging the storage.

Batteries are assumed to have 96% efficiency (92.16% round-trip efficiency) [75], water electrolyzers 70% (1.426 kWh<sub>el</sub>/kWh<sub>H2,LHV</sub>)

**Table 6**  
Financial assumptions projected for 2050. All units for the fuels relate to LHV.

Technology	Capex	Opex	Lifetime	E/P ratio	Ref.
Solar PV fixed-tilted	166 €/kW	2.2%	40 y		[56], [69], [70]
Solar PV single-axis	183 €/kW	2.2%	40 y		[71], [72]
Wind power onshore	900 €/kW	2%	30 y		[73]
Multi-fuel ICE	475 €/kW	1.3%	30 y		[74], [75]
Battery energy storage	41.7 €/kWh <sub>cap</sub>	2.8%	20 y	6	[56], [69], [74], [75]
Battery interface	30 €/kW	2.8%	20 y		[76]
Heat pump	530 €/kW <sub>th</sub>	2%	25 y		[1]
Electric heater	75 €/kW	2%	35 y		[77]
Thermal energy storage	13 €/kWh	2.3%	30 y	1	[20]
Electrolyser	148 €/kW <sub>el</sub>	3.5%	30 y		[68]
H <sub>2</sub> rock cavern storage	1.48 €/kWh	4%	30 y	240	[20]
H <sub>2</sub> underground pipe storage	14.5 €/kWh	1%	30 y	6	[20]
DAC	315 €/tCO <sub>2</sub>	4%	30 y		[20]
CO <sub>2</sub> storage	3560 €/tCO <sub>2</sub>	1.2%	30 y	6	[18], [20]
Ammonia synthesis	1053 €/kW	4%	30 y		[24]
Ammonia storage	286 €/MWh	2%	30 y	23.8	[78]
Methanol synthesis	107 €/kW	4%	30 y		[79]
CH <sub>4</sub> storage	50 €/MWh	2%	50 y	50	[20]
Methanol storage	556 €/kW	4%	30 y	168	[80]
Methanol storage	8.6 €/MWh	4%	30 y		[81]
Fischer-Tropsch synthesis	934 €/kW	4%	30 y		
Liquid Fuel storage	14.2 €/MWh	4%	30 y	1	

**Table 7**  
Projected fuel conversion inputs in 2050.

Technology	H <sub>2</sub> [kWh <sub>H2</sub> /kWh]	CO <sub>2</sub> [kg/kWh]	Electricity [kWh <sub>el</sub> /kWh]	References
Ammonia	1.138	0	0.141	[18]
Methanol	1.189	0.262	0.03	[20]
Fischer-Tropsch	1.517	0.26	0.052	[83]
Methane	1.217	0.198	0	[83]

[82], and DAC consume 229 kWh<sub>el</sub>/tCO<sub>2</sub> of electricity and 981 kWh<sub>th</sub>/tCO<sub>2</sub> of heat [82] in 2050. *Heat pumps* are assumed to have an average coefficient of performance (COP) of 1.5 reflecting the lower efficiency to reach the temperature required for the DAC units of around 100 °C. Electrolysers are assumed to have a 20% minimum load requirement, methanation units 40%, and ammonia, methanol, and Fischer-Tropsch synthesis units have a 50% minimum load requirement [20]. Minimum load requirements are primarily driven by safety limits (preventing explosive gas mixtures) and mechanical constraints (preventing equipment damage such as compressor surge or catalyst quenching). These thresholds ensure the system maintains the precise pressure and temperature needed for chemical reactions to remain stable and efficient. For similar reasons, ramping limits are also set to ensure gradual transition between production output rates. The input assumptions in 2050 for fuel synthesis units are given in Table 7.

### 3. Results

The results section first presents the installed capacities deemed the most cost-optimal by the energyHub-LUT tool in each scenario. The levelised costs of electricity and e-fuels are presented afterwards.

#### 3.1. Installed capacities

The installed wave power capacities in wave power-based energy hubs are predefined and already provided in Table 2. The model is constrained to install the maximum wave power potential, but free to optimise the capacities of the batteries, water electrolysers, hydrogen storage, and multi-fuel ICEs, which are presented in Table 8.

The energy hub of Ireland installs large battery and hydrogen storage

**Table 8**  
Installed capacities of batteries, water electrolysers, and hydrogen storage in wave power-based hubs.

Technology	Battery [GWh <sub>cap</sub> ]	Electrolyser [GW <sub>el</sub> ]	H <sub>2</sub> storage [GWh <sub>H2,LHV</sub> ]	ICE [GW]
New Zealand	0	590	3350	0
Chile	0	103	462	0
Ireland	146	352	6000	24

**Table 9**  
Installed capacities in the hybrid PV-wind based hubs.

Technology	Solar PV [GW]	Wind power [GW]	% of land	Battery [GWh <sub>cap</sub> ]	Electrolyser [GW <sub>el</sub> ]	H <sub>2</sub> storage [GWh <sub>H2,LHV</sub> ]	ICE [GW]
New Zealand	1523	601	254%	1973	686	20 577	33
Chile	163	102	10%	152	115	2000	7
Ireland	569	319	49%	612	329	9630	18

**Table 10**  
Installed power capacities in wave-PV-wind based hubs.

Technology	Wave power [GW]	Solar PV [GW]	Wind power [GW]	Battery [GWh <sub>cap</sub> ]	Electrolyser [GW <sub>el</sub> ]	H <sub>2</sub> storage [GWh <sub>H2,LHV</sub> ]	ICE [GW]
New Zealand	541	468	0	0	672	512	0
Chile	6.6	94	106	114	110	2350	4.9
Ireland	249	600	37	385	347	2580	0

alongside ICEs due to prolonged shortage of wave electricity in the summer period. Notably, other sites install zero battery storage units largely owing to the consistent power output profile of wave power.

The capacities in the hybrid PV-wind energy hubs are presented in Table 9, alongside the shares of the land that would be occupied by solar PV and onshore wind power plants. The onshore RE installations would require unrealistically high shares of land area to produce the amount of fuel that wave power installations could produce. New Zealand and Chile install large battery and balancing ICE capacities to cope with the variability of solar PV and onshore wind power.

Finally, the installed capacities in the hybrid wave-PV-wind energy hubs are presented in Table 10. In all locations, wave power is deployed only when onshore RE limits are saturated. There is little or zero ICE capacities in this scenario with wave power in the mix. However, there is a larger reliance on underground pipe H<sub>2</sub> storage, which can be operated more flexibly than rock cavern H<sub>2</sub> storage. For instance, the H<sub>2</sub> storage in New Zealand switches from 20 260 GWh rock caverns to 512 GWh underground pipes. Interestingly, New Zealand and Ireland rely more on the combination of wave power and solar PV systems, rather than wind power. This preference can be attributed to the strong complementary nature of wave and solar resources, as illustrated in Figs. S1 and S7 of the Supplementary Material 1.

#### 3.2. Levelised costs

The primary energy supply in all cases is electricity, and the entire economic feasibility of the endeavour depends on the LCOE. Southland and Magallanes have access to wave energy resource with very high FLH, higher than of any variable RE resource globally, which would promise high use of fuel conversion capacities and maybe low LCOF. The lowest wave power LCOE among the investigated locations is observed in Chile at 27.7 €/MWh, also thanks to shallower waters and resources closer to the shore, as seen in Fig. 5.

The onshore hybrid PV-wind based energy hubs demonstrate lower LCOE across all locations. Chile achieves the lowest LCOE of 17.1 €/MWh in the hybrid PV-wind system thanks to high FLH of onshore wind power. The very same winds that create consistent waves in that region of the world also enable high wind power FLH, and coupled with significantly lower capex, onshore wind power generates electricity far cheaper than wave power. Solar PV complements the wind power with higher FLH in summer time in the southern hemisphere, as seen in the Supplementary Material Fig. S4.

In a hybrid wave-PV-wind power plant energy hub setup, with realistic limits on land usage, Chile reaches the lowest LCOE among all locations, only slightly higher than the PV-wind LCOE.

Electricity constitutes 44% of LCOH, 93% of LCOH<sub>2</sub>, and 18% of LCOCO<sub>2</sub> in the wave power-based energy hub in New Zealand, with similar proportions for other locations. Consequently, the LCOH, LCOH<sub>2</sub>, and LCOCO<sub>2</sub> follow the LCOE, with lowest values in Chile (12.8 €/MWh<sub>th</sub>, 43.2 €/MWh<sub>H2,LHV</sub>, 58.8 €/tCO<sub>2</sub>) and highest in Ireland (15.5

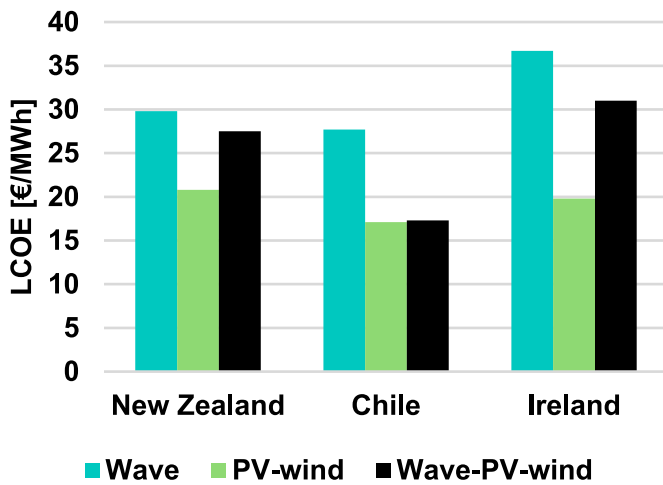


Fig. 5. LCOE of energy hubs based on wave power, hybrid PV-wind, and hybrid wave-PV-wind power plants for New Zealand, Chile, and Ireland. Note: The PV-wind scenario does not set land use constraints, while the Wave-PV-wind scenario sets 10% land use limits for the PV and wind power resources so that additional wave power is required.

€/MWh<sub>th</sub>, 57.3 €/MWh<sub>H<sub>2</sub>LHV</sub>, 69.2 €/t<sub>CO<sub>2</sub></sub>). With the lowest LCOE in the wave power scenario, Chile delivers the lowest LCOF e-fuels and e-chemicals, as shown in Fig. 6, with e-ammonia at 68.5 €/MWh<sub>LHV</sub>, e-methanol at 75.9 €/MWh<sub>LHV</sub>, e-FTL at 98.4 €/MWh<sub>LHV</sub>, and e-methane at 69.6 €/MWh<sub>LHV</sub>.

Hydrogen constitutes an outsized share of the LCOF, accounting for 68% in e-methanol and 78% in e-methane, which in itself mostly consist of electricity costs, providing another piece of evidence that the endeavour’s feasibility mostly depends on LCOE. The share of electricity in e-ammonia costs is driven by nitrogen air separation units supplying the ammonia synthesis units.

In the hybrid PV-wind power-based energy hubs, the LCOF also follows the LCOE trends, with lowest LCOF in Chile, as shown in Fig. 7, with e-ammonia at 51.1 €/MWh<sub>LHV</sub>, e-methanol at 58.7 €/MWh<sub>LHV</sub>, e-FTL at 76.6 €/MWh<sub>LHV</sub>, and e-methane at 54.4 €/MWh<sub>LHV</sub>. Electricity remains a major component of LCOH and LCOH<sub>2</sub> with 40% and 85%, respectively, but its share drops to 14% for LCOCO<sub>2</sub>.

The share of LCOH<sub>2</sub> in LCOF is smaller in hybrid PV-wind setups, ranging from 58% in e-methanol to 73% in e-methane, due to the very

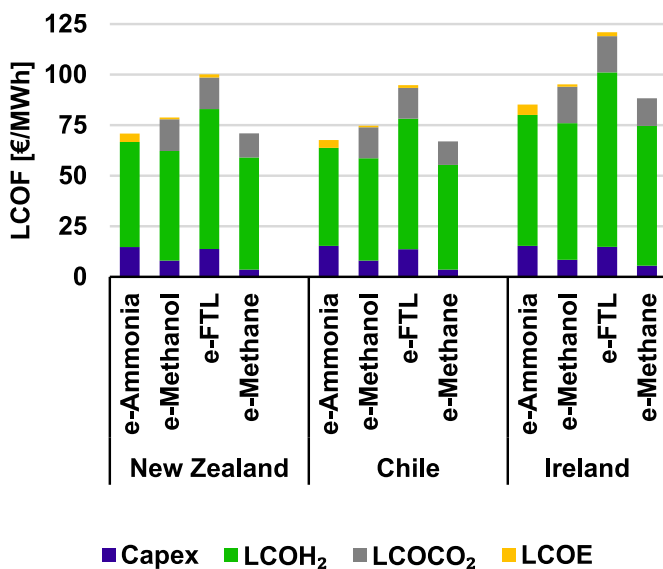


Fig. 6. LCOF of wave power-based energy hubs.

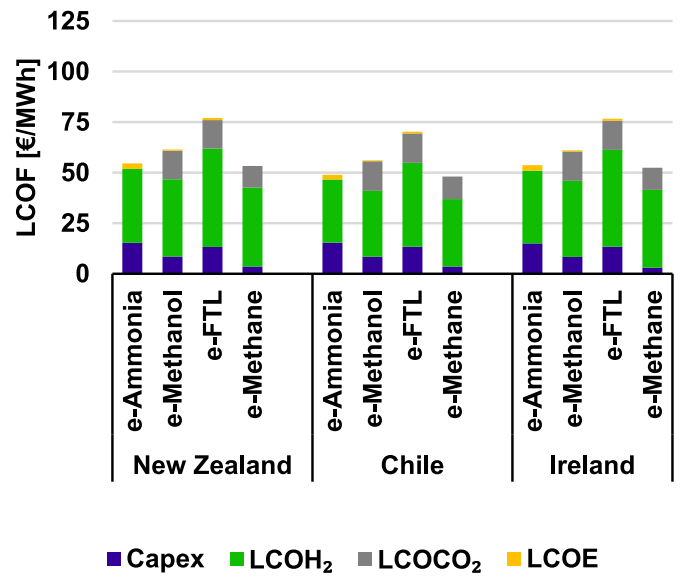


Fig. 7. LCOF of hybrid PV-wind power-based energy hubs.

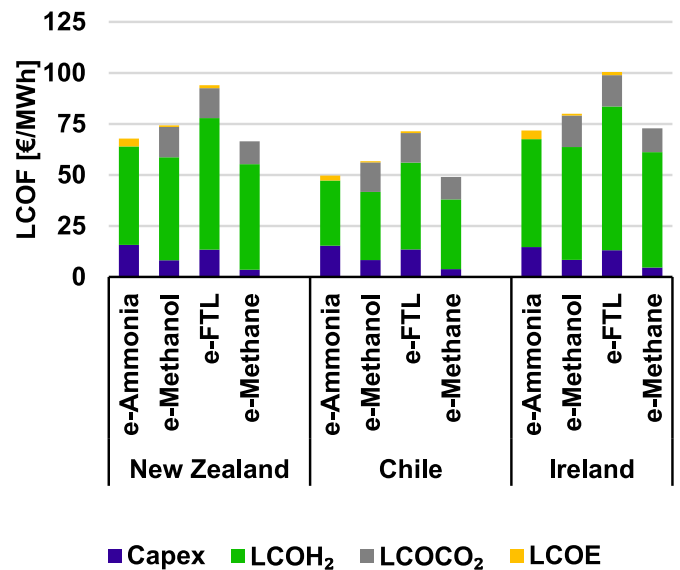


Fig. 8. LCOF of hybrid wave-PV-wind power-based energy hubs.

low LCOE. Capex and opex constitute slightly larger share of final LCOF in the hybrid PV-wind power-based energy hubs attributed to lower use rate than in the wave power-based hubs. The new energyHub-LUT model is supported by evidence that its estimated costs for e-ammonia and e-methanol align with those reported in [18] and [20], respectively.

Finally, the LCOF in the wave-PV-wind scenario is presented in Fig. 8. The LCOF in all locations end up costing more than in the PV-wind only scenario, as the model first saturates the 10% land area usage constraint for low-cost onshore RE and then installs more costly wave power capacities.

The Supplementary Material contains hourly profiles for RE resources, state of charge of storage units and water electrolyser output in all locations for wave and wave-PV-wind scenarios.

#### 4. Discussion

This study addresses a research gap by examining the role of wave power in large-scale energy hubs. The existing literature has largely overlooked wave power, focusing instead on solar PV and wind power.

Using the energyHub-LUT model, this research evaluates the techno-economic feasibility of wave power alongside other RE sources, providing insights into optimal energy mixes for e-fuels and e-chemicals hubs.

#### 4.1. Wave power enhanced energy hubs

The interest in wave power is growing [84] alongside the need to decarbonise the global energy systems and the potential of offshore energy hubs [37], [38], [85]. The findings reveal a compelling tension: while solar PV and onshore wind power offer the lowest LCOE and LCOF, wave power presents unique advantages that challenge a singular focus on cost.

The high FLH of wave power in the southern hemisphere presents potential sites for energy hubs to produce e-fuel and e-chemicals and ship to demand centres in Europe and East Asia. The relatively consistent electricity yield profile of wave power [34] offers the potential for lower energy storage requirements and higher use of water electrolyzers, which could lead to lower LCOE and LCOF. Wave power-based energy hubs do not need battery energy storage, except Ireland, as the electricity output of wave power is sufficient to cover the electricity demand of the water electrolyzers, heat units, DAC units, and fuel synthesis units at every hour of a year.

The findings of this study indicate that the LCOE and LCOF of e-fuels produced from an energy hub based on solar PV and onshore wind power would be the lowest among all scenarios investigated in this study, assuming no land area limitations. Hybrid PV-wind power-based energy hubs promise 1-28% lower LCOF compared to the systems that also use wave power, despite requiring large ICE and battery storage capacities. The lowest cost e-fuels and e-chemicals from a hybrid PV-wind power-based energy hub are found in Chile. This aligns with several studies that have identified Chile, in particular the Atacama Desert and Patagonia, to host the sites with best solar PV and onshore wind power resources, promising the lowest LCOE and LCOF [18], [20], [29], [86]. This underscores the advantages of solar PV and onshore wind power, as extremely low LCOE can outweigh the high FLH offered by wave power at most sites. It can also be seen in LCOH, LCOH<sub>2</sub>, and LCOCO<sub>2</sub> as they simply follow the pattern in LCOE, regardless of the capacities of heat pumps, electrolyzers, ICE, and storage units.

However, as shown in Table 9, sites in New Zealand and Ireland would require unrealistically large land area to produce the same amount of fuel as hybrid wave-PV-wind power systems could deliver at the same locations. Herein lies an advantage in favour of wave power, because not all sites with good RE resources may possess the required land area for solar PV and onshore wind power farms. The wave power potential in the EEZ of the Southland of New Zealand is substantial, with an abundance of sea area with relatively shallow waters, which enables it to meet 39% of the e-fuels and e-chemicals demand in Europe and East Asia. To produce the same quantity of e-fuels and e-chemicals, onshore RE sources would require 254% of Southland's area.

#### 4.2. Shipping e-fuels and e-chemicals

A critical factor in determining the economic attractiveness of energy hubs is the transportation infrastructure for delivering the final e-fuels and e-chemicals to demand centres. As shown in Table 11, estimated shipping distances using online mapping software highlight the advantages of Ireland's proximity to European demand centres, while New Zealand and Chile are situated at similar world-spanning distances from demand centres. This proximity both reduces transportation costs and aligns with the growing demand for energy sovereignty in Europe [87], making Ireland a more strategic location for serving the regional markets and enhancing European energy security. The shipping distance from Ireland to East Asia is estimated via the North Pole, assuming new shipping routes will become available by 2050 due to climate change [55], [88].

**Table 11**  
Shipping distances in kilometres.

Technology	Hamburg, Germany	South Korea and Japan
South Port, New Zealand	22000	9600
Punta Arenas, Chile	14200	17150
Ireland	1500	13000

Shipping costs vary significantly depending on the type of fuel. Shipping denser fuels, such as e-FTL and e-methanol, only adds about 1-6% additional costs per unit of energy on top of production LCOF, depending on distance. Shipping gaseous fuels, such as e-methane, can add up to 13% of additional costs per MWh, as shown in Fig. 9, making Ireland more competitive with New Zealand.

Similarly, the order of the lowest cost sources of e-fuels and e-chemicals remains roughly the same in case of hybrid PV-wind power-based energy hubs, as shown in Fig. 10, except that Ireland becomes much more competitive with Chile and 3-8% cheaper than New Zealand. These findings provide crucial insights for regional energy strategies, suggesting that geographical advantages can significantly influence the viability of e-fuel supply chains and foster international collaborations focused on regional energy security.

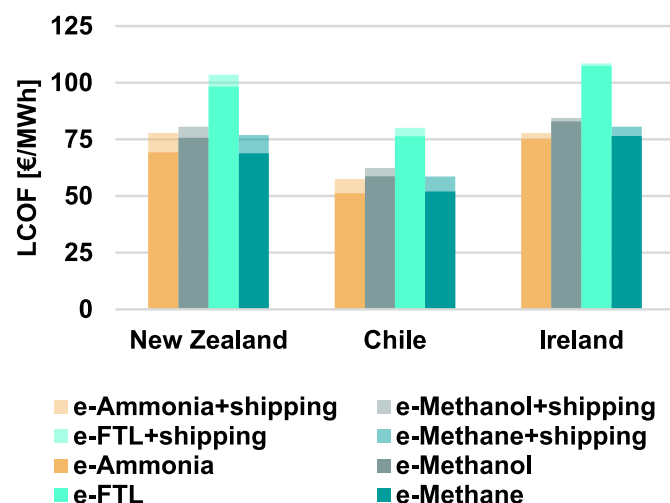


Fig. 9. LCOF of hybrid wave-PV-wind power-based energy hubs with shipping to Hamburg, Germany.

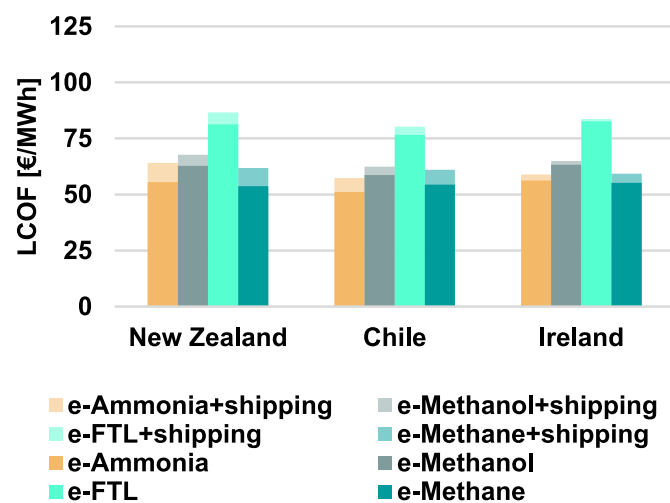


Fig. 10. LCOF of hybrid PV-wind power-based energy hubs with shipping to Hamburg, Germany.

### 4.3. Sensitivity analysis

To reiterate, the economic value of high FLH of wave power is limited. If cost projections come true, the combination of solar PV and onshore wind power offers considerably lower LCOF in all locations, despite requiring larger balancing capacities. A sensitivity analysis was conducted to evaluate the impact of cost assumptions on the findings, using Chile as a case study. The analysis focused on electrolyser costs, as hydrogen is a critical input for all e-fuels and e-chemicals, and gigawatt-scale electrolysers are not yet widely deployed, leading to higher uncertainty in their 2050 cost projections. Electrolyser capex was increased to 1113 €/kW<sub>el</sub>, or 523% higher than the default assumption, based on estimates by BloombergNEF for less mature early markets often based on publicly funded demonstration projects [89]. This change led to lower LCOF in the wave-PV-wind scenario than PV-wind, by around 0.2-2%. The value of high FLH of wave power came to the forefront as the CAPEX of electrolysers went up over 5 times, as the optimisation model prioritised to install fewer electrolysers but utilise them with higher capacity factor in the wave-PV-wind. However, this increase in CAPEX lead to a substantial rise in total LCOF by over 30% in both scenarios, compared to the scenarios with default electrolyser CAPEX, casting strong doubts on the competitiveness of such e-fuels with fossil fuels. The high CAPEX projection from BloombergNEF, which reflects the costs of electrolyser manufacturers outside of China, represents a pessimistic future where the development of electrolysers and the hydrogen economy never truly materialised and e-fuels remain prohibitively expensive. In contrast, market data from China supports the default electrolyser cost assumptions in this study [90]. To create viable markets for e-hydrogen-to-X products, an electrolyser CAPEX level similar to the default assumption is required. International markets outside of China are likely to be established based on Chinese electrolyser technology and cost levels, with respective quality, while higher-cost technology from other countries will most likely struggle to achieve cost competitiveness.

Wave power costs were not varied in the sensitivity analysis because their LCOE is already relatively high in the base case and increasing them further would not meaningfully alter the study's conclusions. It is possible that its capex will be lower than projected here, for example with shared infrastructure with other offshore energy resources, such as offshore wind power and offshore floating solar PV [42], [43]. However, given their technological readiness today and the slow rollout, it is unlikely that its capex will be significantly lower by 2050. Similarly, the costs of the widely deployed solar PV and onshore wind power were held constant, as they are supported by various scientific studies [91], [92],

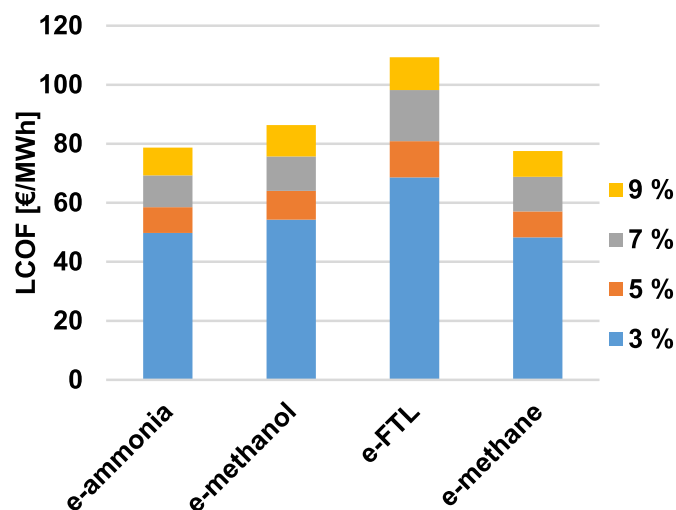


Fig. 11. LCOF with varied WACC values in the wave-PV-wind power-based energy hub in New Zealand.

[93], [94] and exhibit lower uncertainty.

Additionally, a sensitivity analysis was performed by varying the WACC, which affects all technologies, on the case of the hybrid wave-PV-wind energy hub in New Zealand. WACC was varied from the default 7% to 3%, 5%, and 9% and the resulting LCOF values are shown in Fig. 11. WACC variation does not demonstrate drastic changes in LCOF values, with linear increases with higher WACC values. The system configurations do not change either, as the model slightly adjusts the installed capacities of fuel storage units to find the lowest system cost.

### 4.4. The best wave energy site in the world

One unexplored region omitted in this study is the Kerguelen Islands, situated in the epicentre of the best wave energy resources worldwide with over 8000 FLH. Located on the Kerguelen Plateau, the islands are characterised with relatively shallow waters, which would facilitate the installation of up to 426 GW of wave power within their EEZ, at depths up to 1000 m, assuming 15% area usage. Theoretically, the Kerguelen Islands could supply 29% of the e-fuels and e-chemicals demand in Europe and East Asia by 2050.

Nevertheless, despite their high FLH, the LCOF on the Kerguelen Islands would still be higher than the LCOF in Chile in this study, with 64.0 €/MWh<sub>LHV</sub> for e-ammonia, 70.4 €/MWh<sub>LHV</sub> for e-methanol, 89.3 €/MWh<sub>LHV</sub> for e-FTL, and 61.9 €/MWh<sub>LHV</sub> for e-methane. These finding highlights that even the world's highest variable RE resource FLH do not automatically guarantee economic viability, underscoring the complex interplay of resource quality and technology-driven capex. The reason that the islands were omitted from the analysis is that all of the islands, including the EEZ, fall within the French national reserve and World Heritage Site protections [95].

### 4.5. Inflexible baseload electricity consumers

The results of the energy hub optimisation demonstrate that if the final energy demand can be met flexibly with inexpensive fuel storage units, the system prioritises low-cost onshore RE sources first, despite their variability. In this study, all fuels were assumed to have a baseload demand profile; however, the optimisation model finds it more cost-effective to install fuel storage units to balance supply and demand. To assess the potential of wave power in meeting truly inflexible energy demand, a scenario was simulated for New Zealand, where a data centre's power demand was assumed instead of e-fuels and e-chemicals. Data centres have been gaining increasing attention in the energy domain due to their growing electricity requirements [96], [97], [98], [99], [100]. Moreover, high-capex data centres operate 24/7, requiring an uninterrupted power supply throughout the year [97], which often leads data centre operators to seek nuclear power [101], while this may ignore the high LCOE of that technology [102], [103]. This presents an opportunity for wave power, given its high FLH and lower variability compared to other RE sources as shown in Fig. 12.

The annual electricity demand of the data centre was assumed to be 8.8 TWh, which translates to 1 GW instantaneous demand every hour, in line with hyperscale data centres being built today [104], [105]. The operation of the system in an exemplary winter period in the southern hemisphere, thus in mid-year, is illustrated in Fig. 13.

The results of this scenario show that the model installs wave power even before saturating the onshore RE potential. The model meets the data centre's baseload demand with a supply of electricity from a mix of wave power (22%), solar PV (57%), and wind power (21%), supplemented by balancing options in the form of batteries and ICE running mostly on e-methane. The LCOE in this system equals 29.3 €/MWh, well below the price Microsoft purportedly agreed to pay for nuclear power under the power purchasing agreement with Constellation Energy over 100 €/MWh [106].

This scenario highlights the potential of wave power in a cost-optimised system with direct electricity supply for inflexible power

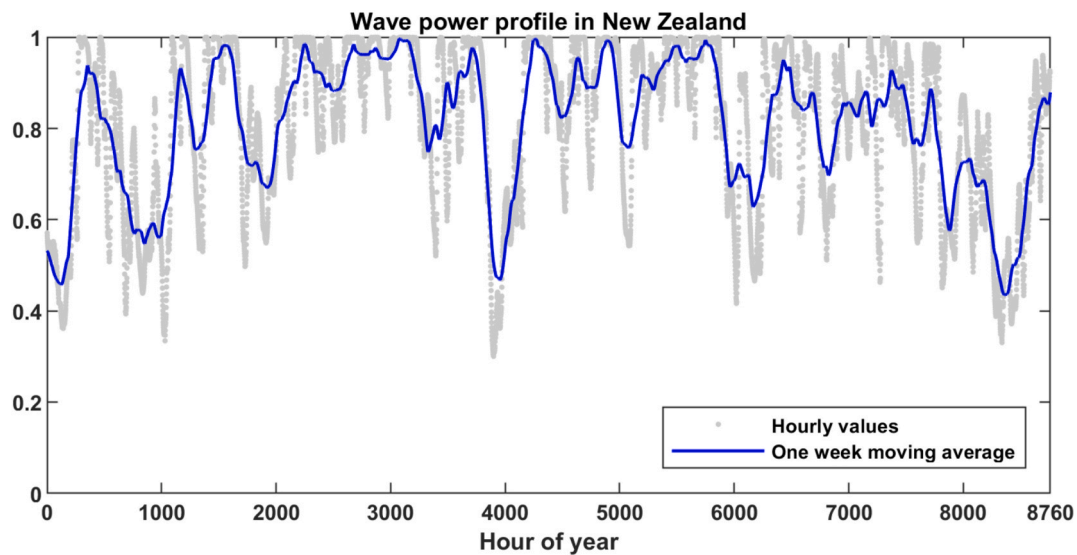


Fig. 12. Wave power profile in Southland, New Zealand.

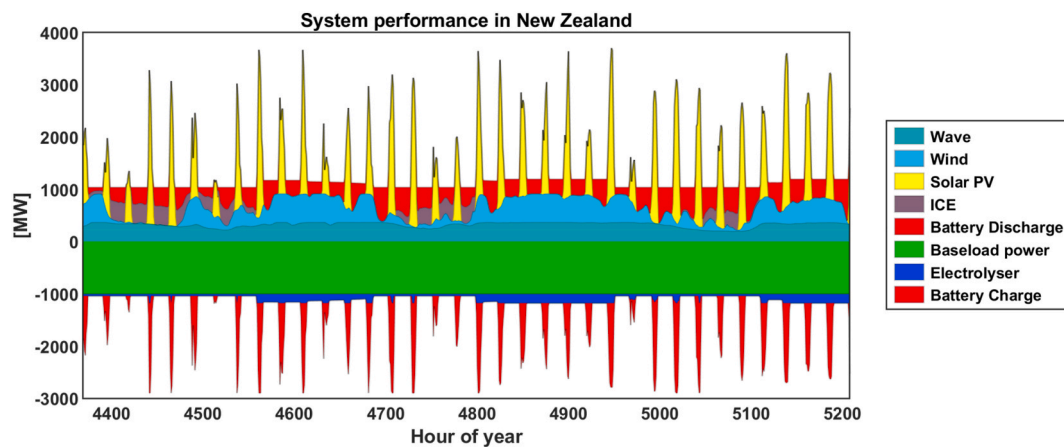


Fig. 13. System operation with a baseload data centre power demand in summer in New Zealand.

consumers. In other words, if flexibility is limited and the electricity is needed directly, then wave power's high FLH becomes a key factor in cost optimisation. A future study considering offshore floating energy hubs [37], [107], [108], which inherently lack access to underground caverns for fuel storage, may find similar benefits in incorporating wave power. Another application of interest may be seawater desalination, which also requires near baseload supply for financial reasons [109], [110]. The location of desalination plants at the shore further supports the integration with wave power.

The results of this scenario are supported by an earlier study by Fasihi and Breyer [86], who assessed a baseload electricity supply based on hybrid PV-wind power plants showing the feasibility of RE sources in providing reliable and cost-effective electricity. Their research demonstrates that baseload electricity can be generated at 33 €/MWh by 2050 using cost-optimised configurations of variable solar PV, onshore wind power, and balancing technologies. The addition of wave power in this study was able to provide baseload electricity at a lower LCOE of 29.3 €/MWh. It is important to note that techno-economic assumptions differ between the two studies, with the present study projecting lower costs for onshore RE technologies and batteries.

#### 4.6. Limitations

A significant limitation of this study is its dependence on projected

future costs, which, despite being grounded in scientific literature, inherently carry uncertainty.

Another limitation of this study is the lack of consideration of environmental impacts of large deployment of wave power. Although wave power is generally considered to have a lower environmental impact than fossil fuels [53], with a global warming potential of 25.1 to 46.0 gCO<sub>2</sub>e/kWh, or 23-43 times lower than fossil fuel electricity generation, large-scale deployment could disrupt marine ecosystems, particularly in regions with high biodiversity. Such disruptions might include changes in sediment transport, noise pollution affecting marine mammals, or impacts on fish migration patterns.

Evidence from global ocean energy projects [111], [112] suggests additional risks such as temporary habitat disturbance, visual impacts, and interference with fisheries. However, these effects are typically more localised and less severe than those of offshore wind power [113], [114]. To ensure sustainable deployment, these risks must be managed through proactive site selection, adaptive design, and participatory planning processes.

Nonetheless, the underlying data on wave power potential used for the analysis does exclude areas that fall under the World Database on Protected Areas [95].

The spatial resolution of the underlying data from Ref. [34] is 0.45°, which translates to roughly 50 km by 50 km at the equator, and wave conditions and water depth can vary significantly within 50 km.

Lastly, this study positions wave power as a solution to land-constrained regions, but it is important to note that other more mature technologies, such as offshore wind power or even floating offshore solar PV, may be more suited for such cases.

## 5. Conclusion

The study explores the potential of wave power as a promising yet underexplored resource for producing e-fuels and e-chemicals, emphasizing the consistency of its electricity production profile compared to solar photovoltaics and onshore wind power. The results highlight the value of wave power's consistent output, which significantly reduces the need for energy storage and enables higher utilisation of balancing and fuel conversion units, allowing them to operate at higher full load hours. However, the findings reveal significant economic challenges associated with wave power, primarily due to its higher capital expenditures and the resulting higher levelised cost of electricity (LCOE). The study demonstrates that solar photovoltaics and onshore wind power offer lower LCOE and subsequently lower cost of e-fuel in all regions.

The study's findings indicate that the LCOE of hybrid wave-PV-wind power systems in New Zealand, Chile, and Ireland reach 27.5 €/MWh, 17.3 €/MWh, and 31.0 €/MWh by 2050, respectively, compared to the LCOE of solar photovoltaics and onshore wind power in these regions, which demonstrate 20.8 €/MWh, 17.1 €/MWh, and 19.8 €/MWh, respectively.

The lowest levelised cost of fuels are found in Chile in the PV-wind scenario with e-ammonia at 51.1 €/MWh<sub>LHV</sub>, e-methanol at 58.7 €/MWh<sub>LHV</sub>, e-Fischer-Tropsch liquids at 76.6 €/MWh<sub>LHV</sub>, and e-methane at 54.4 €/MWh<sub>LHV</sub>. These findings depend on projected future costs which, despite being grounded in scientific literature, inherently carry uncertainty.

The study concludes that, purely economically, wave power-based energy hubs for e-fuels and e-chemicals production cannot compete with lower cost onshore renewable energy resources even when its full load hours are above 7000 h. Solar photovoltaics and onshore wind power are more economically viable for e-fuels and e-chemicals production in all investigated regions, despite the larger balancing capacities. The lower LCOE of these technologies, combined with their faster deployment timelines and lower technological risks, makes them more attractive for large-scale production.

Nevertheless, the economic disadvantage of wave power is partially offset by its spatial advantages. In regions where land availability is a critical constraint, the massive geographic footprint required for large-scale solar photovoltaics or wind power installations often proves unrealistic. In such scenarios, wave power serves as an increasingly attractive alternative by enabling large-scale offshore production without competing for terrestrial land use. However, it still faces competition from more mature offshore technologies, such as offshore wind power and floating offshore solar photovoltaics, which may be better optimised for land-constrained environments.

Furthermore, when flexibility is limited, the consistent power output of wave power emerges as a significant advantage. However, a comprehensive assessment of wave power's suitability for inflexible demand remains an area for future research.

## CRedit authorship contribution statement

**Rasul Satymov:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dmitrii Bogdanov:** Writing – review & editing, Validation. **George Lavidas:** Writing – review & editing, Validation. **Shona Pennock:** Writing – review & editing, Validation, Investigation, Conceptualization. **Sarah Kluge:** Writing – review & editing, Validation. **Benjamin Lehner:** Writing – review & editing, Validation. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding

acquisition, Conceptualization.

## Declaration of generative AI use

During the preparation of this work the corresponding author used Llama (large language model from Meta AI) in order to proofread and improve the reading comprehension of the manuscript. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

## Declaration of competing interest

The authors declare no conflict of interest.

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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.2026.141252>.

## Data availability

More data is available in the Supplementary Material.

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