Best sites for wave energy resources creating opportunities for low-cost e-fuel production

Rasul Satymov, Dmitrii Bogdanov, George Lavidas, Shona Pennock, Sarah Kluge, Benjamin Lehner and Christian Breyer

Abstract—[1] **The global energy transition is driving an urgent need to defossilise energy-intensive industries and hard-to-abate transport segments, with electricity-based fuels and chemicals emerging as a promising solution. These e-fuels, such as e-methane, e-ammonia, e-methanol, e-kerosene, and e-diesel offer a pathway to reduce greenhouse gas emissions while maintaining high energy density, but their production depends on low-cost renewable electricity. While solar photovoltaics and onshore wind power are widely studied, the potential of ocean energy remains largely untapped. This study shows that wave power can technically support large-scale e-fuels and e-chemicals production and can deliver the lowest cost e-fuels and e-chemicals at the best site in the world situated in the waters around the Kerguelen Islands. However, any of the investigated sites with wave power full load hours below 8100 prioritises onshore renewable energy until it saturates land constraints before installing wave power. These findings challenge the assumption that wave power's high full load hours would inherently lead to economic viability, instead highlighting the critical role of electricity costs in determining the feasibility of energy hubs. Nevertheless, this study identifies wave power as a potential solution for regions with limited land availability.**

Keywords—**energy hub, Kerguelen Islands, point absorber wave energy converter, wave energy.**

I. 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), which offer a pathway to reduce greenhouse gas emissions while maintaining the high energy density required for sectors such as aviation, marine, and chemical and energy-intensive industries [3], [4], [5]. Such synthetic e-fuels and e-chemicals, including e-ammonia [6], e-methanol [7], electricity-based Fischer-Tropsch liquids (e-FTL) [8], [9], and e-methane [10], [11], are produced using electricity and can potentially serve as alternatives to fossil fuels and fossil feedstocks in existing infrastructure, although small modifications or new engines may be required for some of these fuels, such as e-ammonia and e-methanol, to be fully integrated. Additionally, e-fuels can be stored and transported using existing infrastructure, 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 making these energy carriers economically viable.

One of the key challenges in scaling up e-fuel and e-chemical production is the uneven global distribution of renewable energy (RE) resources and the land constraints faced by heavy energy consumers. Regions like Europe and East Asia (South Korea and Japan), which are major energy consumers, lack the land area to generate sufficient renewable electricity domestically. 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 [4], [12].

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 Chile [13], Morocco [14], and Iberia [15] have been highlighted [6] 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_2 and the synthesis of e-fuels, making them attractive for large-scale production. However, while such studies have made significant

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R. Satymov, D. Bogdanov, and C. Breyer is with the School of Energy Systems, LUT University, Yliopistonkatu 34, Lappeenranta, Finland (rasul.satymov@lut.fi, dmitrii.bogdanov@lut.fi, christian.breyer@lut.fi)

G. Lavidas is with Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg, 1, 2628 CN Delft, the Netherlands (G.Lavidas@tudelft.nl)

S. Pennock is with CorPower Ocean, Västberga Allé 60, 126 30 Hägersten, Stockholm, Sweden (shona.pennock@corpowerocean.com)

S. Kluge and B. Lehner are with Dutch Marine Energy Centre, Hellingweg 11 d, 2583 DZ The Hague, Netherlands (sarah@dutchmarineenergy.com, benjamin@dutchmarineenergy.com)

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progress in assessing the potential of onshore RE, the role of ocean energy, particularly wave power, remains underexplored.

Ocean energy, particularly wave power [16], represents a largely untapped resource for e-fuels and e-chemicals production. Waves have the advantage of being more consistent compared to wind power and solar PV resources, offering a stable energy supply profile that, hypothetically, could be ideal for continuous e-fuels production. Despite this potential, most studies on ocean energy focus on offshore wind power [17], [18], [19], while wave power remains largely overlooked. A few notable exceptions, such as [20] on wave power in the United Kingdom and Ireland, [21] on wave power in New Zealand and [22] on Seychelles, have begun to explore the potential of wave power for e-fuels and e-chemicals production. However, these studies are limited in scope, primarily focusing on domestic energy transition, and a significant research gap persists in understanding how wave power can be harnessed at scale for e-fuels and e-chemicals production.

This research gap is particularly relevant in the context of regions with exceptional wave energy resources. One such region is the Kerguelen Islands, located in the southern Indian Ocean, which lie in the epicentre of best wave energy resources globally due to their unique geography, born from winds unobstructed by continents. The islands' remote location and lack of existing infrastructure may be limiting, but they also present an opportunity to develop dedicated energy hubs focused solely on e-fuels and e-chemicals production [18], [23]. Similarly, New Zealand and Chile, which also boast some of the highest full load hours (FLH) for wave power globally [16], offer complementary advantages, including larger land areas and existing populations that could support the development of onsite energy hub infrastructure. 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 the Kerguelen Islands, New Zealand, Chile, and Ireland (Fig. 1), 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 [16], which concluded that wave power can become cost-competitive with offshore wind power by 2030s, which was confirmed for several regions [20], [21]. 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 not only highlights the technical potential of wave power for e-fuels production but also explores economic implications of developing wave power hubs in regions with exceptional resources.

II. METHODS AND DATA

The underlying data for this study comes from [16], that 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 [16] mainly relied on technical and financial assumptions pertaining to a point-absorber wave energy converter (WEC) inspired by CorPower Ocean [24] and the results for global FLH values are presented in Fig. 1.

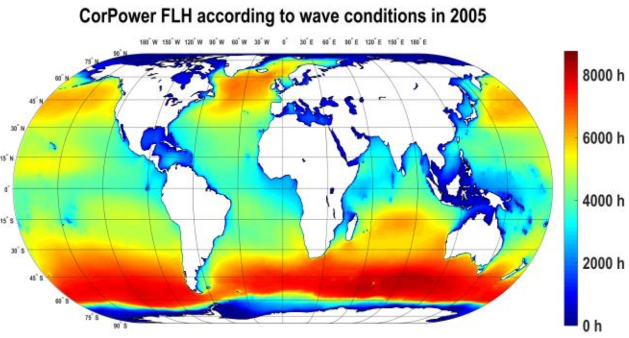

Fig. 1. Global full load hour values for the point absorber WEC.

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

In addition to rich wave energy resources, all four regions 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. The WEC from CorPower demonstrates a wide range of operation and its power matrix is shown in Fig. 2.

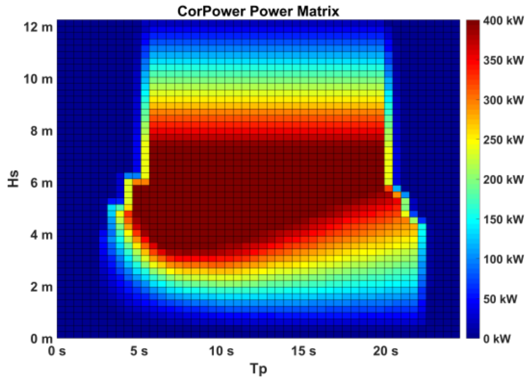

Fig. 2. CorPower WEC's power matrix. Abbreviations: H_s – significant wave height; T_P – peak wave period.

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 [16] sets a rudimentary constraint of 15% area utilisation, allowing 85% of the area to remain unused and enable the wave energy to recuperate.

A. *Demand for e-fuels and e-chemicals*

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

TABLE I DEMAND FOR E-FUELS AND E-CHEMICALS IN 2050.

Region	Europe	East Asia
e-Methane	873 TWh	255 TWh
e-Ammonia	396 TWh	212 TWh
e-Methanol	1340 TWh	871 TWh
e-FTL	1613 TWh	245 TWh

B. *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 100 €/MWh threshold was obtained from [16], considering waters within 300 km from shore, with depths up to 1000 m, excluding protected marine areas and applying a 15% area utilisation 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 II.

TABLE II. INSTALLABLE WAVE POWER CAPACITY AND PRODUCTION POTENTIALS.

Region	Installable capacity	FLH	Share of the demand
Kerguelen Islands	7 GW	8101 h	0.47 %
New Zealand	650 GW	7121 h	39 %
Chile	113 GW	7032 h	6.50 %
Ireland	418 GW	5770 h	20 %

C. *energyHub-LUT*

The simulation was performed on 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, heat pumps, electrolysers, DAC, fuel synthesis units, and fuel storage units. energyHub-LUT is a linear programming optimisation model with a target function to minimise the total annualised system cost (1).

$$min\left(\sum_{t\in tech}(Capex_t \cdot crf_t + Opexfix_t)\cdot instCap_t + rampCost_t \cdot totRamp_t\right) \quad (1)$$

where *tech* and *t* are generation and storage technologies, $Capex_t$, crf_t, $Opexfix_t$, $rampCost_t$ are capital expenditures, capital recovery factor, fixed operational expenditures, and cost of ramping, respectively, for technology *t*; $instCap_t$, and $totRamp_t$ are installed capacity and sum of power ramping values 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.

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

where $E_{gen,t}$ is hourly generation for technology *t*, $E_{s,disch}$ and $E_{s,ch}$ are hourly storage discharge and charge for storage unit *s*, and E_{dem} is hourly energy demand.

First, each region is modelled utilising only wave power, to assess the technical performance of a wave power-only systems and determine the associated costs.

Second, each region is re-modelled with solar PV or onshore wind power instead of wave power. While the e-fuel production targets remained fixed, the capacities of solar PV and wind power were adjusted accordingly to meet these targets. This enables a direct comparison of the costs associated with e-fuels and e-chemicals production in each location. The solar PV profiles were obtained from [25]. Onshore wind power profiles were based on [26].

Third, each region is re-modelled with a combination of solar PV and onshore wind power, following the setup of [7], as these two onshore RE technologies are expected to complement each other with their production profiles.

Finally, each region is re-modelled with an optimal mix of wave power, solar PV and onshore wind power. In this scenario, solar PV, and onshore wind power are limited to 10% of the available land area, which allows to see if there is enough land for the modelled energy hub.

D. *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 takes into account the capital and operational expenditures of liquid fuel synthesis units, methanation units, methanol synthesis units, and ammonia synthesis units, levelised cost of hydrogen ($LCOH_2$), levelised cost of CO_2 ($LCOCO_2$) 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).

$$LCOF_f = \frac{Capex_f \cdot crf_f + Opex_f + LCOH2 \cdot H2_f + LCOCO2 \cdot CO2_f + LCOE \cdot el_f}{Output_f} \tag{3}$$

where *f* denotes the fuel, *Capex* is capital expenditure, *Opex* is operational expenditure for synthesis capacities, *crf* is capital recovery factor, and $Output_f$ is the total annual output of fuel *f*. In case of e-ammonia, $CO2_f$ is zero. $LCOH_2$ is calculated according to (4).

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

where $Capex_{H2}$ and $Opex_{H2}$ are for water electrolysers and hydrogen storage, and wel_{el} is electricity consumed by the water electrolysers, and $Output_{H2}$ is total annual hydrogen production.

$LCOCO_2$ was calculated according to (5).

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

where *DAC* is direct air capture, DAC_{el} and DAC_{el} are electricity and heat consumed by DAC, *LCOH* is levelised cost of heat and $Output_{CO2}$ is total annual captured amount.

LCOE was calculated according to (6).

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

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).

$$LCOH = \frac{Capex_h \cdot crf_h + Opex_h}{Output_{he}} \tag{7}$$

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).

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

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

E. *Techno-economic assumptions*

All techno-economic assumptions were based on values projected for 2050.

The cost assumptions regarding wave power were obtained from [16] and are presented in Fig. 3, which projects a strong decline in Capex with volume-driven cost reduction thanks to economies of scale.

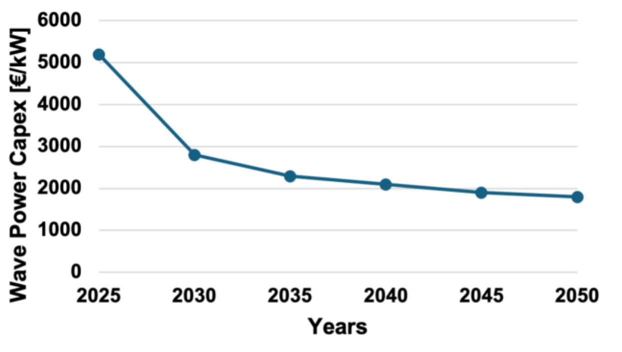

Fig. 3. Wave power Capex projection until 2050.

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 [16]. Best sites were defined as the nodes within the exclusive economic zone (EEZ) of each location with LCOE below 100 €/MWh. The selected sites were then averaged weighting by LCOE. The Capex for each location is given in Table III.

TABLE III. CAPEX OF WAVE POWER PROJECTED FOR 2050.

Region	Capex
Kerguelen Islands	2400 €/kW
New Zealand	2020 €/kW
Chile	1852 €/kW
Ireland	1980 €/kW

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 the Appendix. Two types of solar PV plants were modelled: fixed optimally tilted and single-axis tracking installations. Hydrogen storage costs (H_2 Storage) were taken for a lined rock cavern, assuming the availability of such type of storage in all locations studied.

Batteries are assumed to have 96% efficiency (92.16% round-trip efficiency), water electrolysers 73% (1.426 $kWh_{el}/kWh_{H2,LHV}$), and DAC consume 229 kWh_{el}/t_{CO2} of electricity and 981 kWh_{th}/t_{CO2} of heat in 2050. Heat pumps are assumed to have an average coefficient of performance (COP) of 2.5 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 and Fischer-Tropsch, ammonia and methanol synthesis units have a 50% minimum load requirement. The input assumptions in 2050 for fuel synthesis units are given in Table IV.

TABLE IV. PROJECTED FUEL CONVERSION INPUTS IN 2050.

Technology	H_2 kWh$_{H2}$/kWh	CO_2 kg/kWh	Electricity kWh$_{el}$/kWh
Ammonia	1.138	0	0.141
Methanol	1.189	0.262	0.03
Fischer-Tropsch	1.517	0.26	0.052
Methanation	1.217	0.198	0

III. RESULTS

F. Installed capacities

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

TABLE V. INSTALLED CAPACITIES OF BATTERIES, WATER ELECTROLYSERS AND HYDROGEN STORAGE IN WAVE POWER BASED HUBS.

Technology	Battery	WEL	H_2 Storage
Kerguelen Islands	0 GWh	4.4 GW	20 GWh
New Zealand	0 GWh	417 GW	3089 GWh
Chile	0 GWh	71 GW	573 GWh
Ireland	0 GWh	243 GW	4713 GWh

The energy hub of Ireland installs very large hydrogen storage due to prolonged shortage of wave electricity in the summer period. Notably, none of the sites install battery storage units, largely owing to the consistent power output profile of wave power.

The capacities in the PV energy hub are presented in Table VI, alongside the shares of the land that would be occupied by solar PV plants, assuming installation density of 150 MW/km^2 for solar PV (taking 1000 W/m^2 global horizontal irradiation, assuming 30% PV efficiency by 2050 [27] and 50% ground cover ratio).

TABLE VI. INSTALLED SOLAR PV POWER CAPACITIES IN PV-BASED HUBS.

Technology	Solar PV	% of land
Kerguelen Islands	82 GW	8%
New Zealand	4904 GW	101%
Chile	1045 GW	5%
Ireland	4108 GW	32%

The capacities in the wind power hub are presented in Table VIII, alongside the shares of the land that would be occupied by wind power plants, assuming an installation density of 8.4 MW/km^2 for wind power (taking all turbines from [26] and assuming 7 by 4 rotor diameters between the turbines).

TABLE VIII. INSTALLED WIND POWER CAPACITIES IN WIND-BASED HUBS.

Technology	Wind power	% of land
Kerguelen Islands	7.55 GW	12%
New Zealand	1305 GW	482%
Chile	139 GW	13 %
Ireland	547 GW	77 %

The capacities in the PV-wind energy hub are presented in Table IX.

TABLE IX. INSTALLED SOLAR PV AND ONSHORE WIND POWER CAPACITIES IN PV-WIND BASED HUBS.

Technology	Solar PV	Wind power	% of land
Kerguelen Islands	4.7 GW	7 GW	12%
New Zealand	1900 GW	573 GW	251%
Chile	116 GW	120 GW	11%
Ireland	753 GW	344 GW	54%

The capacities of the batteries, water electrolysers and hydrogen storage were greatly increased in the solar PV and onshore wind power systems due to increased variability of electricity supply as shown in Table VII. Batteries in all locations were assumed to have an energy-to-power ratio of 4 (e.g., 6 GW/24 GWh).

Finally, the installed capacities in the wave-PV-wind energy hubs are presented in Table X. In New Zealand and Ireland, wave power is deployed only when onshore RE limits are saturated. In contrast, wave power contributes to the energy mix in the Kerguelen Islands and Chile, even when onshore RE limits still have available potential.

TABLE X. INSTALLED POWER CAPACITIES IN WAVE-PV-WIND BASED HUBS.

Technology	Wave power	Solar PV	Wind power
Kerguelen Islands	1.3 GW	1.3 GW	5.9 GW
New Zealand	540 GW	468 GW	26 GW
Chile	10 GW	94 GW	110 GW
Ireland	148 GW	1266 GW	71 GW

The capacities of the batteries, electrolysers and hydrogen storage are presented in Table XI. The inclusion of wave power helps to greatly reduce the need for storage units, both batteries and hydrogen storage, in almost all locations.

TABLE XI. INSTALLED CAPACITIES OF BATTERIES, ELECTROLYSERS, AND HYDROGEN STORAGE IN WAVE-PV-WIND BASED HUBS.

Technology	Battery	WEL	H_2 Storage
Kerguelen Islands	7 GWh	4.6 GW	45 GWh
New Zealand	0 GWh	496 GW	3011 GWh
Chile	123 GWh	68 GW	790 GWh
Ireland	853 GWh	325 GW	2980 GWh

TABLE VII. INSTALLED CAPACITIES OF BATTERIES, ELECTROLYSERS, AND HYDROGEN STORAGE IN PV, WIND AND PV-WIND BASED HUBS.

Technology	Battery [GWh]			Electrolyser [GW]			H_2 Storage [GWh]		
Scenario	PV	Wind	PV-wind	PV	Wind	PV-wind	PV	Wind	PV-wind
Kerguelen Islands	104	36	31	5.7	4.5	4.5	216	48	40
New Zealand	5620	11 020	2462	582	432	457	3345	11 510	8458
Chile	1067	291	224	98	70	67	1241	1055	872
Ireland	4104	4683	863	259	208	224	32024	4431	4033

G. Levelised costs

The primary energy supply in all cases is electricity and the entire economic feasibility of the endeavour depends on the LCOE. Kerguelen Islands sits in the epicentre of a RE resource, boasting what may be the highest FLH of any RE resource globally, which would promise low LCOE. However, the water depths around the island lead to relatively high CAPEX, which results in LCOE of 31.1 €/MWh. The lowest wave power LCOE among the investigated locations is observed in Chile at 27.6 €/MWh, possibly thanks to shallower waters and resources closer to the shore, as seen in Fig. 4.

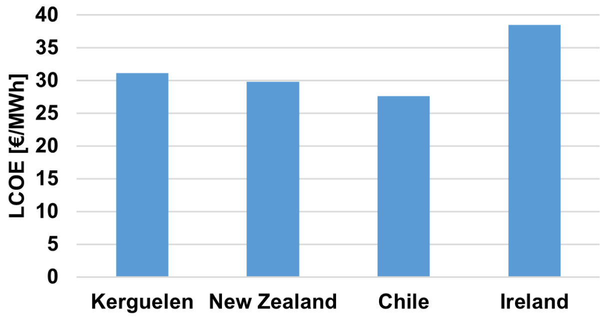

Fig. 4. LCOE of wave power-based energy hubs.

Electricity constitutes 65% of LCOH, 94% of $LCOH_2$ and 30% of $LCOCO_2$ in the wave power-based energy hub on the Kerguelen Islands, with similar proportions for other locations. Consequently, the LCOH, $LCOH_2$ and $LCOCO_2$ follow the LCOE, with lowest values in Chile (17.9 €/MWh_{th}, 42.6 €/MWh_{H2}, 66.5 €/t_{CO2}) and highest in Ireland (23.3 €/MWh_{th}, 58.8 €/MWh_{H2}, 80.3 €/t_{CO2}). With the lowest LCOE, Chile delivers the lowest LCOF e-fuels and e-chemicals, as shown in Fig. 5, with e-methane at 67.6 €/MWh, e-ammonia at 66.7 €/MWh, e-methanol at 76.4 €/MWh, and e-FTL at 95.8 €/MWh.

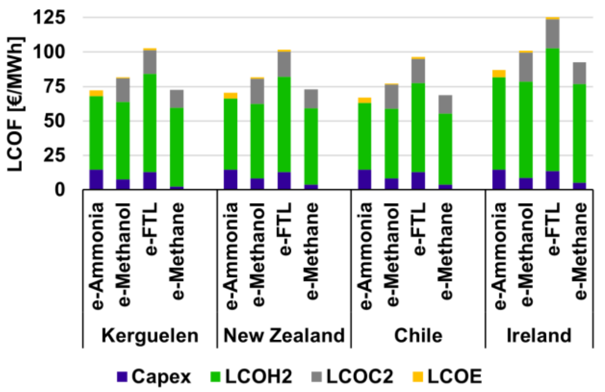

Fig. 5. LCOF of wave power-based energy hubs.

Hydrogen constitutes an outsized share of the LCOF, accounting for 68% in e-methanol to 79% 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 stand out, because ammonia synthesis units in energyHub-LUT are assumed to include nitrogen air separation units.

The solar PV and wind power-based energy hubs demonstrate lower LCOE across all locations, as shown in Fig. 6, except the wind only system in New Zealand, where the optimisation model curtails 30% of electricity in the search of the lowest system cost. The Kerguelen Islands achieve 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 FLH on the island, 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.

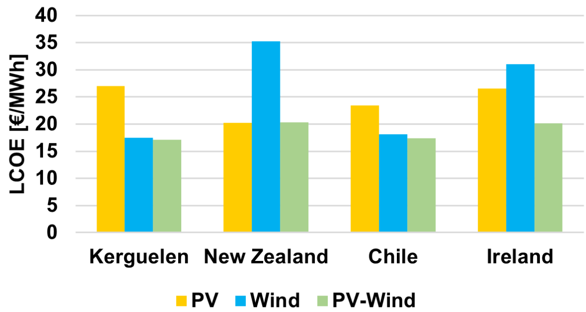

Fig. 6. LCOE of PV-wind power-based energy hubs.

In the PV-wind power-based energy hubs, the LCOF also follows the LCOE trends, despite the need for significantly higher storage and larger electrolyser capacities, with lowest LCOF on the Kerguelen Islands, as shown in Fig. 7, with e-ammonia at 48.1 €/MWh, e-methanol at 55.7 €/MWh, e-FTL at 70.1 €/MWh, and e-methane at 46.9 €/MWh. Electricity remains a major component of LCOH and $LCOH_2$ with 51% and 90%, respectively, but its share drops to 19% for LCOCO2.

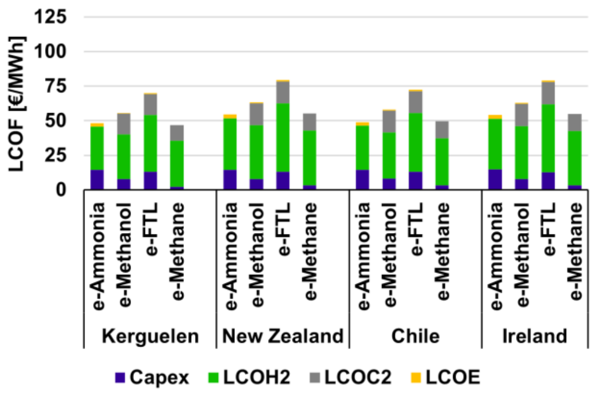

Fig. 7. LCOF of PV-wind power-based energy hubs.

The share of $LCOH_2$ in LCOF is smaller in PV-wind setups, ranging from 57% in e-methanol to 69% in e-methane, due to the very low LCOE. Capex constitutes a slightly larger share of final LCOF in the PV-wind power-based energy hubs attributed to lower utilisation 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 [6] and [7], respectively. Although, reference [6] reports a slightly higher LCOF of e-ammonia, this discrepancy can be partly attributed to that study's higher Capex assumptions for water electrolysers.

Finally, the LCOE in the scenario with an optimised mix of all three technologies with realistic limits on land utilisation are shown in Fig. 8. Notably, Kerguelen Islands reach the lowest LCOE among all scenarios, highlighting the benefit of wave power in this location with extremely high FLH.

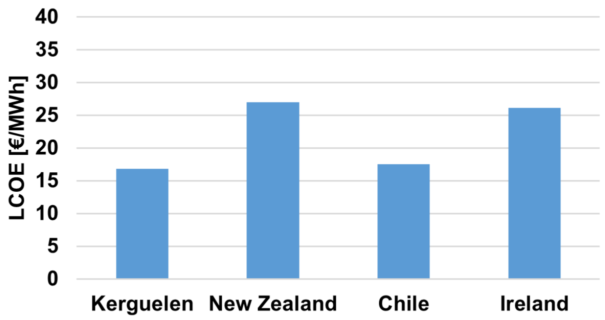

Fig. 8. LCOE of wave-PV-wind power-based energy hubs.

The lowest LCOE enables the Kerguelen Islands to reach the lowest LCOF for all fuels among all locations in all scenarios with e-ammonia at 47.5 €/MWh, e-methanol at 55.2 €/MWh, e-FTL at 69.4 €/MWh and e-methane at 46.4 €/MWh, as shown in Fig. 9.

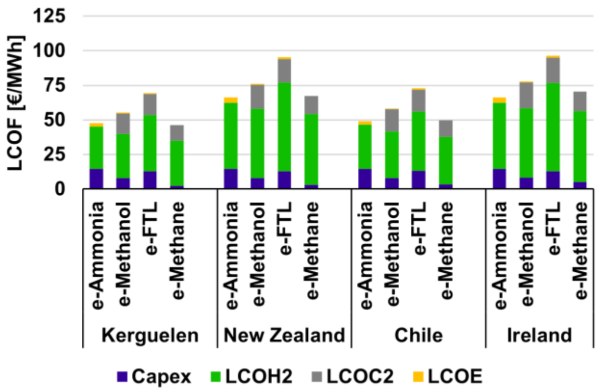

Fig. 9. LCOF of wave-PV-wind power-based energy hubs.

IV. Discussion

H. *Wave power with PV-wind*

The interest in wave power is growing alongside the need to defossilise the global energy systems and the potential of offshore energy hubs. The high FLH of wave power in the southern Indian Ocean presents a potential site for an energy hub 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 also offers the potential for lower energy storage requirements and higher utilisation of water electrolysers, which could hypothetically lead to lower LCOE and LCOF. Notably, wave power-based energy hubs install zero battery energy storage, as the electricity output of wave power is enough to cover the electricity demand of the water electrolysers, heat pumps, 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 an optimal mix of wave, solar PV, and onshore wind power would be the lowest among all scenarios investigated in this study.

In contrast, the other three sites could achieve lower LCOE and LCOF if the energy hubs are based on solar PV and onshore wind power instead. Hybrid PV-wind power-based energy hubs promise 1%-22% lower LCOF compared to the systems that mix wave power, despite requiring 1%-343% larger battery capacities and 10%-220% larger hydrogen storage. The lowest cost e-fuels and e-chemicals from a PV-wind power-based energy hub are found in Chile. Several studies have found Chile, in particular the Atacama Desert and the Patagonia, to host the sites with best solar PV and onshore wind resources, promising the lowest LCOE and LCOF. 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, $LCOH_2$ and $LCOCO_2$ as they simply follow the pattern in LCOE, regardless of the capacities of heat pumps, electrolysers and storage units. However, as shown in Table IX, sites in New Zealand and Ireland would require unrealistically large land areas to produce the same amount of fuel as wave-PV-wind power could deliver at the same locations. Herein lies an advantage in favour of wave power, because not all sites with good RE resources may have the required land area. 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 amount of e-fuels and e-chemicals, onshore RE sources would require 251% of Southland's area.

I. *Shipping e-fuels and e-chemicals*

The challenges associated with the Kerguelen Islands extend to the lack of existing infrastructure, such as ports, roads, and workforce housing, significantly increases the cost and complexity of building and maintaining these systems. Despite lower LCOF of e-fuels produced on Kerguelen Islands, the sites in New Zealand, Chile, and Ireland may prove more practical due to their existing local populations, developed infrastructure, and access to skilled labour.

Another critical factor is the transportation infrastructure of the final e-fuels and e-chemicals to demand centres. As shown in Table XII, estimated shipping distances using online mapping software highlight the advantages of Ireland's proximity to European demand centres, while the Kerguelen Islands, New Zealand, and Chile are located at similar world-spanning distances from demand centres. This proximity not only reduces transportation costs but also aligns with the growing demand for energy sovereignty in Europe, making Ireland a more strategic location for serving the regional markets. 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.

TABLE XII. SHIPPING DISTANCES.

Technology	Hamburg, Germany	South Korea and Japan
Kerguelen Islands	17 000 km	12 000 km
South Port, New Zealand	22 000 km	9 600 km
Punta Arenas, Chile	14 200 km	17 150 km
Ireland	1 500 km	13 000 km

Shipping costs vary significantly depending on the type of fuel. Shipping denser fuels, such as e-FTL and e-methanol, only adds about 2%-9% additional costs per unit of energy on top of production LCOF, depending on distance [15], [28]. Shipping gaseous fuels, such as e-methane, can add up to 52% of additional costs per kWh, as shown in Fig. 10, but the overall order of costs remain the same. Nevertheless, Kerguelen Islands remain the cheapest source of e-fuels and e-chemicals even at a distance of 17 000 km.

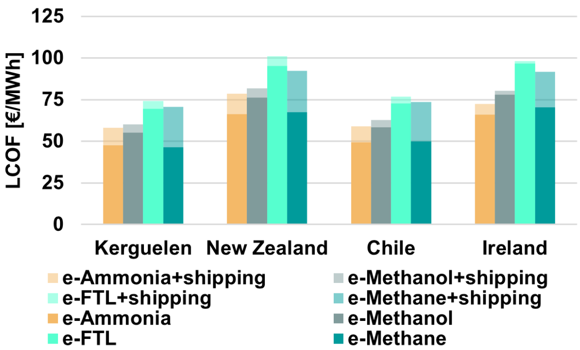

Fig. 10. LCOF of wave-PV-wind power-based energy hubs with shipping to Hamburg, Germany.

Similarly, the order of the lowest cost sources of e-fuels and e-chemicals remains roughly the same in case of PV-wind power-based energy hubs, as shown in Fig. 11, except that Ireland becomes much more competitive with Chile and cheaper than New Zealand.

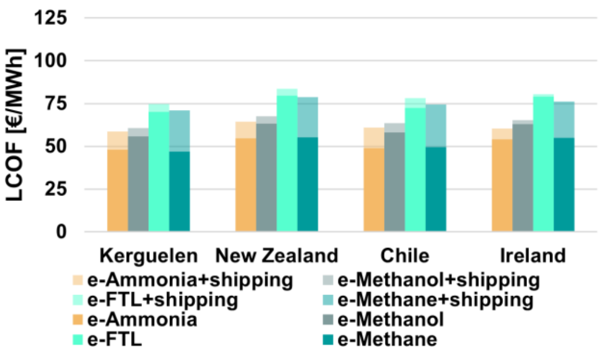

Fig. 11. LCOF of PV-wind power-based energy hubs with shipping to Hamburg, Germany.

J. *Sensitivity analysis*

To reiterate, the economic value of high FLH of wave power is limited to the Kerguelen Islands among all investigated sites in this study. If cost projections come true, the combination of solar PV and onshore wind power offers considerably lower LCOF in most locations, despite requiring larger energy storage capacities. A sensitivity analysis was conducted to evaluate the impact of cost assumptions on the findings, using the Kerguelen Islands 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 290 €/$kW_{H2,LHV}$, or 61% higher than the default assumption. This change raised the LCOF of all fuels in the wave-PV-wind power-based energy hub by ~3.7%. In a surprising twist, the higher electrolyser CAPEX decreased the capacities of wave power by 6% and increased the capacity of solar PV by 25% and batteries by 17%, and the rest of the system remained relatively unchanged.

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 their 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. However, given their technological readiness today and the slow rollout, it is unlikely that their Capex will be significantly lower. Similarly, the costs of the widely deployed solar PV and onshore wind power were held constant, as they are supported by various scientific studies [29], [30], [31], [32] and exhibit lower uncertainty. Additionally, adjusting these costs would require significant increases, given the substantial advantage in LCOE of more than 77%, to have a noticeable impact on the overall findings, which is unlikely given current trends and projections.

K. *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 on remote islands. While wave power is generally considered to have a lower environmental impact than fossil fuels, large-scale deployment could disrupt marine ecosystems, particularly in regions with high biodiversity. However, the underlying data on wave power potential used for the analysis does exclude areas that fall under the World Database on Protected Areas [33].

Lastly, the spatial resolution of the underlying data from [16] 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.

V. CONCLUSION

The study explores the potential of wave power as a promising yet underexplored resource for producing e-fuels and e-chemicals, emphasising the consistency of its electricity production profile compared to solar photovoltaics and onshore wind power. However, the findings reveal significant economic challenges associated with wave power, primarily due to its high capital expenditures (CAPEX) and the resulting high levelised cost of electricity (LCOE). The study demonstrates that while solar photovoltaics and onshore wind power offer substantially lower LCOE and subsequently lower cost of e-fuel in most regions, the extremely high full load hours of wave power in Kerguelen Islands in an optimal mix with onshore renewables enable the lowest cost e-fuels among all investigated scenarios.

The study's findings indicate that the LCOE of wave-PV-wind power in the Kerguelen Islands, New Zealand, Chile, and Ireland reach 16.8 €/MWh, 27.0 €/MWh, 17.5 €/MWh, and 26.1 €/MWh by 2050, respectively, compared to the LCOE of solar photovoltaics and onshore wind power in these regions, which demonstrate 17.1 €/MWh, 20.3 €/MWh, 17.4 €/MWh, and 20.1 €/MWh, respectively.

The lowest levelised cost of fuels are found in Kerguelen Islands with e-ammonia at 47.5 €/MWh, e-methanol at 55.2 €/MWh, e-Fischer-Tropsch liquids at 69.4 €/MWh, and e-methane at 46.4 €/MWh.

The study concludes that the economic benefit of wave power in e-fuel and e-chemicals production only manifests itself when its full load hours are above 8000 hours. Solar photovoltaics and onshore wind power are more economically viable for e-fuels and e-chemicals production in all other investigated regions, despite the lower need for energy storage and water electrolysis 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. However, in regions with limited land availability, the requirement for unrealistically large land areas to support large-scale e-fuels and e-chemicals production using solar photovoltaics or onshore wind power makes wave power an increasingly attractive alternative, as it can be deployed offshore to enable the large-scale production of these products without competing with other land uses.

APPENDIX

TABLE AI. FINANCIAL ASSUMPTIONS PROJECTED FOR 2050.

Technology	Capex	Opex	Lifetime	Ref.
Solar PV fixed-tilt	166 €/kW	2.2%	40 y	[27], [34], [35]
Solar PV single-axis	183 €/kW	2.2%	40 y	
Onshore Wind	900 €/kW	2%	30 y	[36], [37]
Battery energy storage	61 €/kWh	2.8%	20 y	[27], [34], [38]
Battery Interface	30 €/kW	2.8%	20 y	
Heat Pump	846 €/kW	4.4%	20 y	[39]
Electrolyser	180 $€/kW_{H2,LHV}$	3.5%	30 y	[7]
H_2 Storage	1.25 €/kWh	4%	30 y	[40]
DAC	315 €/t	4%	30 y	[7]
CO_2 Storage	3560 €/t	1.2%	30 y	
Ammonia	1053 €/kW	4%	30 y	[6], [7]
Ammonia Storage	0.286 €/kWh	2%	30 y	[28]
Methanation	107 €/kW	4%	30 y	[41]
CH_4 Storage	0.05 €/kWh	2%	50 y	[42]
Methanol	555.55 €/kW	4%	30 y	[7]
Methanol Storage	0.0086 €/kWh	4%	30 y	[43]
Fischer-Tropsch	934 €/kW	4%	30 y	
Liquid Fuel Storage	0.0142 €/kWh	9%	30 y	[44]

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