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Future costs of key emerging offshore renewable energy technologies

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ABSTRACT

A detailed understanding of the technological development pathways of energy technologies will reduce the risks of public energy policy and private investment actions. However, such assessments for emerging technologies, critical for achieving global decarbonization targets, face numerous shortcomings. These shortcomings include limited information at an early development stage, uncertainty in design convergence and performance improvements, and the application of aggregated methodologies in projecting their cost developments fails to explain underlying cost drivers and foresee potential radical changes. This study applies an improved methodology leveraging the merits of quantitative and qualitative methods and shows the technological progress expected for the tidal stream, wave technology, and biofuel production from seaweed in a detailed manner. Tidal stream LCOE declines from 264 €/MWh at 0.1 GW to 61 €/MWh at 50 GW cumulative capacity, with CAPEX, capacity factor, and OPEX contributing to 38 %, 33 %, and 16 % of LCOE reductions. Wave technology LCOE declines from 365 €/MWh at 0.1 GW to 54 €/MWh at 50 GW, with CAPEX, capacity factor, and OPEX contributing 28 %, 59 %, and 7 % of LCOE reductions. For grid connection costs, we assessed several integration choices for both technologies and concluded that sharing grid connection capacity among several installations would lower the transmission costs and serve as a policy incentive for the uptake of such emerging technologies. Further, the bioethanol production cost from seaweed declines from 17.1 €/*l* at 0.1-million *l* cumulative output to 4.5 €/*l* at 50 million *l*, a 73 % cost reduction in 9 doublings of cumulative output. Identifying fermenting organisms capable of converting the heterogenous monomeric sugars in seaweed is a major limiting factor, resulting in a wide variation in bioethanol yields. Lastly, we also summarized the uncertainties involved in the assessment, their causes, and their impacts on results to improve the understanding of potential development pathways of these technologies.

1. Introduction

Deploying renewable energy technologies at a large scale is vital to reduce CO_2 emissions and mitigate adverse climatic events [1,2]. IEA's net-zero pathway towards 2050 states that CO_2 emission reductions through 2030 will come from renewable energy technologies readily available today. However, in 2050, almost half of the emission reductions are expected from technologies currently in the demonstration or prototype phase [2]. Besides well-established technologies like solar and wind in the electricity sector, the IEA expects 293 GW of ocean energy globally by 2050 [3]. Ocean energy technologies refer to tidal, wave, Ocean Thermal Energy Conversion (OTEC), and other low-TRL technologies that harness the energy available in the ocean. The EU alone aims to reach 1 GW of ocean energy by 2030 and 40 GW by 2050 [4].

Low-carbon fuels are also critical to decarbonizing sectors considered harder to abate, including long-distance transport and heavy industries. IEA's net-zero pathway towards 2050 states that supply accelerates sharply for liquid biofuels by a factor of four. However, the current biofuel supply is significantly dependent (93 %) on conventional feedstocks such as sugarcane, corn, and soybeans, which compete with arable land, limiting the potential for further expansion. Therefore, developing advanced feedstocks that do not compete with arable land and food production is crucial, e.g., seaweed [2,5].

Technologies discussed above are considered emerging technologies due to their limited commercial deployments and high production costs. However, they are crucial for meeting 2050 emission targets and their technological learning process or cost reduction can be stimulated by increased public and private R&D investments, demonstration activities, and the building of enabling infrastructure (e.g., transmission lines for electricity supply technologies) [6]. Most energy strategies and policies

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Abbreviations

AEP	Annual Energy Production
CAPEX	Capital Expenditures
CfD	Contracts for Difference
DECOM	Decommissioning Expenditures
DEVEX	Development Expenditure
DW	Dry Weight
EU	European Union
FEED	Front End Engineering Design
FW	Fresh Weight or Wet Weight
GW	GigaWatt
HAT	Horizontal-Axis Turbine
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
LCoE	Levelized Cost of Energy
LCoT	Levelized Cost of Transmission
LR	Learning Rate
MWh	Megawatt hour
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
OREC	Offshore Renewable Energy Catapult
OTEC	Ocean Thermal Energy Conversion
PA	Point Absorber
SGAB	Sub-group on Advance Biofuels
TRL	Technology Readiness Level
UK	United Kingdom
WACC	Weighted Average Cost of Capital
WTIV	Wind Turbine Installation Vessels

Symbols

M€	Million Euros
$	US Dollars
i	Discount rate
t	Project lifetime in years
t_{dw}	Tonnes Dry Weight
X_n	Cumulative capacity of the component at time n
Ha	Hectares
kV	Kilovolt
kt	Kilo tonnes
E_n	Experience parameter of component n
kg_{dw}	Kilogram dry weight
kg_{FW}	Kilogram fresh weight or wet weight
δ	Share of debt in project capital structure
$Cost_{component\ n}$	Cost of component n
X_0	Initial cumulative capacity of the component

designed to support energy technologies, only to a limited extent, are based on a rational and detailed understanding of learning mechanisms and technology development pathways, as argued by Junginger and Louwen [7]. By thoroughly analyzing specific technologies, including their potential performance improvements, long-term decision-making can be improved, and the risks of public and private investment actions can be reduced. Nevertheless, such assessments for emerging technologies often face numerous shortcomings. The major ones are, 1) limited information about emerging technologies at an early stage necessitates using aggregated Learning Rates (LR)[1] from analogous technologies to extrapolate cost developments. However, aggregated LRs do not underpin the cost drivers and provide no basis for understanding the similarities and differences in cost drivers among technologies. Hence, such applications generally lead to cost projections with high uncertainties (see the case of offshore wind in Ref. [8]). 2) the lack of design convergence at an early stage, uncertainties in future design improvements, and significant variations in site conditions (resource variations) make it difficult to assess the performance improvements achievable by the technology in the long term. 3) most prominent methodologies applied in technology cost assessments fail to foresee radical changes, including technical and market types [9,10]. Such radical changes introduce a step-change in cost development, and not reflecting these changes has historically underestimated the progress of technologies [11]. Overcoming these shortcomings through an improved approach, deriving technology cost forecasts with high certainty and explaining the underlying cost drivers remains a critical gap in literature, as these forecasts play an influential role in long-term energy policy and investment decisions. Santhakumar et al. [12] reviewed these shortcomings and proposed a coherent framework that leverages the merits of quantitative and qualitative methods and means to explain the technological progress and underlying drivers. This study applies the said framework to quantify the long-term cost reduction opportunities of three low-TRL offshore renewables: tidal stream technology,[2] wave energy technology, and biofuel production from marine macroalgae (commonly referred to as seaweed).

Tidal streams are high-velocity sea currents created by the ocean's periodic movement caused by the moon's gravitational pull and, to a lesser extent, by the sun. The kinetic energy in those periodic movements is used to power turbines, referred to as tidal stream generators. Similarly, waves are energy passing through water, causing it to move in a circular motion (e.g., caused by wind blowing along the water's surface). The energy available in the ocean waves' periodic up-and-down movement can be used to power devices, referred to as wave energy generators [13]. Seaweeds are marine algae with little lignin, and high growth and carbon dioxide fixation rates. They do not compete with land and freshwater resources and do not require fertilizers to grow (like 1G and 2G biomass feedstocks). As a result, seaweed is receiving increased attention for producing value-added products (e.g., food, hydrocolloids, medicine) and biofuels [14,15]. Moreover, both tidal stream and wave energy technology are electricity generation technologies. On the other hand, biofuel production from seaweed involves a value chain that can deliver a range of fuels, including biogas and ethanol [16] (see Section 2.1). The cost developments of these three technologies discussed in the literature are reviewed below.

Fig. 1 shows cost development trends for tidal stream and wave technology from the past literature. For the tidal stream, the SI Ocean project reported that LCoE would reduce from around 350 €/MWh at 0.01 GW cumulative installed capacity to 100 €/MWh by 10 GW [17]. The analysis carried out by Ocean Energy Systems, an IEA technology initiative, stated that the SI Ocean study might be optimistic, and the LCoE is expected to reduce to only 122 €/MWh by 10 GW [18]. Nevertheless, OREC in 2018 reported a more optimistic development trend where the LCoE of tidal stream projects is expected to reduce from 372 €/MWh at 0.01 GW cumulative installed capacity to 186 €/MWh by 0.1 GW and then to 111 €/MWh by 1 GW itself. The study argued that initial accelerated reductions were expected to largely arise from the move to utility-scale arrays, similar to trends observed in offshore wind, i.e., economies of volume and scale [19].

For wave energy technology, there are significant differences in the current LCoE as the sector has only single-device prototypes in

[1] LR refers to the percentage increase or decrease in technology cost for each doubling of its cumulative output. Single-Factor Experience Curve (SFEC) uses cumulative output of technology as an aggregate proxy for experience gain and quantifies the development in a single parameter. This approach poses with potential omitted variable bias and also provide limited information on underlying cost drivers.

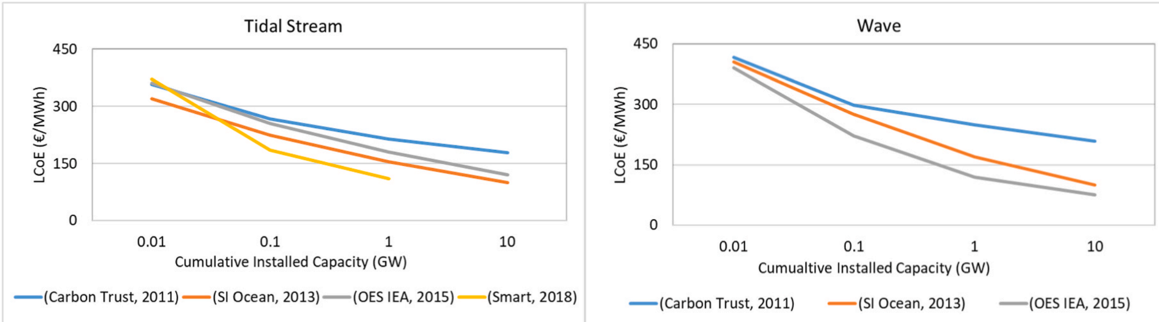

Fig. 1. Summary of notable cost development trends in literature for tidal stream and wave energy technology. Cost reduction assumptions like LRs applied in each projection are detailed further in Appendix A.

deployments, and the technology design convergence has not commenced yet [18]. The OREC study raised similar concerns about the lack of technology design convergence and data availability, making it difficult to accurately estimate current and future costs. Nevertheless, the study indicated that the LCoE of wave energy in 2018 was more than 372 €/MWh and concluded that the current focus should be on gaining confidence in technology designs and performance rather than cost reduction [19]. A more detailed summary of cost reduction estimations and their assumptions for tidal stream and wave technology can be found in Refs. [18,20,21].

Bioethanol production through fermentation from seaweed feedstock is particularly an attractive conversion pathway, as bioethanol is a direct alternative to fossil fuels in transportation and industries, often considered harder to abate. For biofuels from seaweed, the literature dealing with the economics of biofuel production from seaweed is scarce compared to the technical conversion process due to its nascent status [16,22]. The available studies applied bottom-up engineering cost modeling to explore the economic feasibility of producing biofuels from seaweed. Burg et al. [23] reviewed the developments of seaweed and concluded that commercial seaweed production in the North Sea is limited but economically viable seaweed production is possible if high-value products can be obtained. Over the past decade, seaweed cultivation trails have been conducted using different cultivation concepts in the Atlantic region. However, the production cost range reported from those trials was broad (differing roughly by a factor of 100), and little consensus was found [24]. Roesijadi et al. [25] stated that the maximum allowable seaweed feedstock price for ethanol fermentation is approximately 23 €/t_{dw} (1 $ = 0.82 €). Soleymani et al. [26] performed a techno-economic analysis on producing biogas and bioethanol from seaweed. They concluded that the ethanol fermentation process is competitive compared to biogas production from seaweed due to the value of the by-products in the market.

The above literature review shows that the tidal stream and wave energy cost reductions were commonly estimated using the experience curve approach. However, the applied LRs were aggregated and estimated based on expert opinions or extrapolation from analogous technologies. On the other hand, bottom-up engineering cost modeling tools are available to design and optimize large-scale commercial arrays of tidal stream and wave energy technology, providing insights into the technology cost structure and influence of design factors [27–32]. Nevertheless, such studies do not account for long-term cost decline through increased experience gain [33]. For biofuel production from seaweed, techno-economic analyses were available in the literature estimating the conditions for seaweed to become viable feedstock for biofuel production. Moreover, the literature review found no experience curve applications or other approaches to analyze long-term biofuel production costs from seaweed or discuss the cost drivers. From the summary, it is clear that available technology forecasts face the shortcomings and uncertainties discussed above, i.e., costs forecasts are aggregated extrapolations based on analogous technologies' developments, which doesn't consider the underlying characteristics of technology in the context nor quantify the potential cost drivers and their contributions. This study differs from those existing work and fills the above-mentioned knowledge gap in scientific literature. The improved approach applied in this study combines the component-based experience curve approach and bottom-up cost calculations based on expected developments of technologies' technical and economic design factors. Component-based experience curve disaggregates total technology costs into component costs and overcomes the shortcoming of extrapolating technology costs in an aggregated manner. Bottom-up cost modeling provides knowledge on the underlying technical design factors and drivers that bring cost reduction to the technology.

This article is structured as follows. First, the theory on technology designs, advantages and limitations, and cost structures are discussed and compared in Sections 2.1 and 2.2. Second, the theory of energy technology innovation process and methodology to estimate the Capital Expenditure (CAPEX) and Levelized Cost of Energy (LCoE) developments are detailed in Sections 2.3 and 2.4. Third, the assumptions applied in the cost estimations are summarized in Section. 3. Fourth, the results and uncertainties of the technology cost assessments are discussed in Section. 4. Lastly, the quantified outcomes of this study are translated into targeted recommendations for researchers, policymakers, and industry (Section 5).

2. Theory and methodology

2.1. Technology designs

The three emerging technologies discussed in this study have characteristic differences, including end-uses and processes [12]. Tidal stream and wave energy technology produce electricity directly, while biofuel from seaweed involves a value chain of processes in delivering the end product; see Fig. 2.

2.1.1. Tidal stream

As emerging technologies, both tidal stream and wave have multiple designs in development [34,35]. The working principle of these individual designs can be found in Ref. [36], and the focus of technology developers on each design is summarized in Fig. 3. During the initial experimentation phase of the development process, radical designs are tested on a small scale to determine the technology's technical and economic viability in the market. As a result of the experimentation, a dominant design emerges in the market. Once the dominant design of the technology achieves a series of successful demonstrations, commercial deployments are initiated [37,38]. The Horizontal-Axis Turbine (HAT) design of the tidal stream is at this stage, as it has exhibited increased testing and a series of successful demonstration arrays [21,39,40]. The working principle of the HAT design of the tidal stream is similar to a wind turbine, as HAT rotor blades convert the tidal current kinetic energy into mechanical energy, and a generator converts this

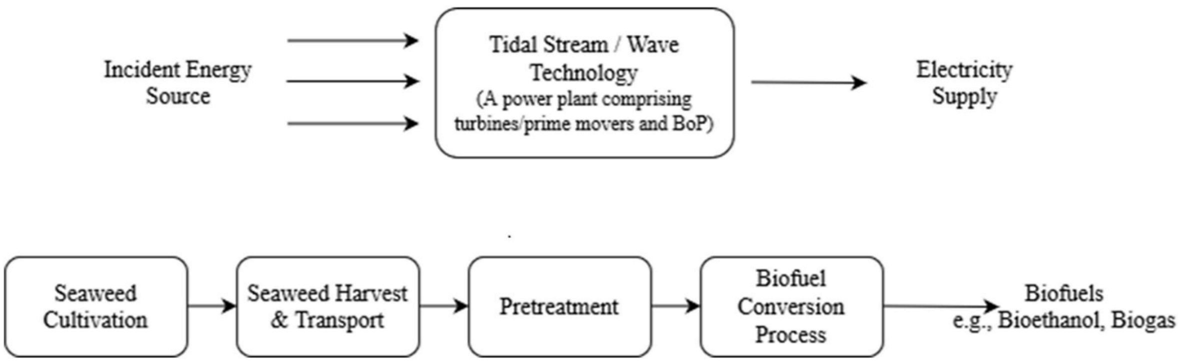

Fig. 2. Description of differences in the process involved in the technologies studied.

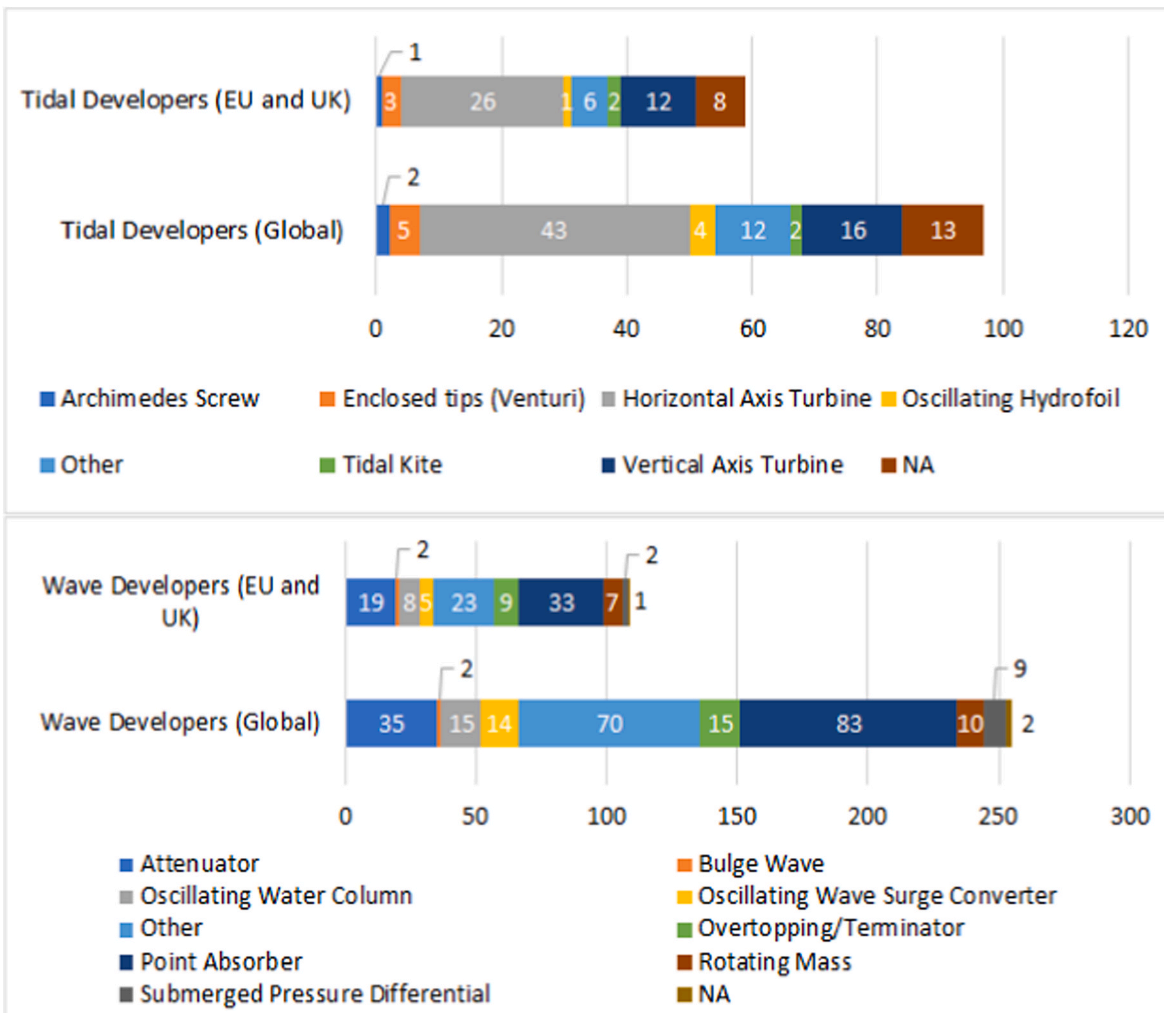

Fig. 3. Tidal stream and wave energy technology developers are categorized according to their focus on technology design. Data source [44].

mechanical energy into electricity. Most developers globally and within the EU and UK align with HAT design (Fig. 3), indicating high confidence in commercialization of this design. The HAT design of a tidal stream has two alternative foundation options, fixed-bottom (gravity-based, monopiles) or floating (mooring and anchor configuration) [41]. Floating tidal stream devices can unlock deep-water sites and pose easier accessibility (i.e., reduced installation and OPEX). However, the fixed-bottom type alone will be considered here due to the maturity of this design in testing and deployment plans [39,42]. Other tidal stream technology designs have also progressed considerably, including enclosed tips and tidal kite devices [21]. In 2018, Minesto, a tidal kite developer, commissioned two grid-connected generator units (Deep Green, DG100 model) in the Faroe Islands [43]. Nevertheless, they are excluded from this analysis due to their low TRL status; refer to IRENA analysis of ocean energy technologies' TRL status [40].

2.1.2. *Wave energy*

In contrast to the tidal stream, the current development of wave energy designs is limited to single-device prototypes or demonstrations. Hence, wave energy is considered a level behind the tidal stream's

Table 1
Summary of advantages and limitations of energy resources (tidal and wave).

	Advantages	Disadvantages
Tidal Stream	• Highly predictable generation pattern. Thus, it can provide value to future energy systems by limiting energy storage requirements [52] • Water is about 800 times denser than air. Thus, farms capture more energy (than wind), take up less space, and can be arranged densely. • Best resource sites (high-velocity tides) are concentrated closer to shore due to tidal streaming around headlands, islands, or through channels [53] • HAT is the leading technology design for tidal stream technology. Thus, spillover effects from the wind industry can be realized.	• Water depth at a site restricts expanding the rotor-swept area freely, which improves energy capture (e.g., onshore and offshore wind) [54]. • Multiple rotors can be placed in a foundation to improve energy capture. Such design will also scale economies. However, wake effects need to be minimized (e.g., HydroWing technology [55]) • High design sensitivity to local circumstances (seabed type, water depth) can introduce high design costs and hamper product standardization, limiting manufacturing scale economies. • As the technology matures and the nearshore spatial constraint increases, far offshore sites can be accessed. However, increased grid connection costs, cost installation, and access to maintenance can outweigh the advantages of far offshore sites
Wave energy	• More predictable than solar and wind [56] • Wave energy generation pattern compensates wind energy generation, leading to reduced reserve and balancing requirements [57] • PA is the leading design of wave energy. Increased market confidence and deployment potential indicate that product standardization can be achieved faster	• The wavelength of the energy resource (wave) limits the device upscaling. Hence, most technology designs are expected to be modular [58] • As energy capture through upscaling is limited, the total annual energy production of the device will largely depend on the site characteristics and availability • Lower rated power from modular devices mean decreased installed power density (kW/km^2) for the technology, i.e., spatial conflicts can arise in nearshore installations • As the technology matures and the nearshore spatial constraint increases, far offshore sites can be accessed. However, increased grid connection costs, cost installation, and access to maintenance can outweigh the advantages of far offshore sites
Biofuel from seaweed	• Seaweed has a high content of carbohydrates and little lignin. Hence, highly suitable for the fermentation process. • It does not compete for land and freshwater resources and does not require fertilizers to grow. • Seaweed cultivation is an emerging practice. However, the transfer of experience from biofuel conversion technologies is immense. • Bioethanol from seaweed can be a direct alternative to fossil fuels.	• Carbohydrate contents vary significantly due to seasonal and geographic variations. E.g., kelp harvested during autumn has higher glucose and ethanol yield, while the winter and spring months have the lowest. • Seaweed has high water content (80–90 %), and drying can be very energy-intensive. Hence, aqueous biorefinery techniques are preferred. • Chloride-containing salt fluxes present after pretreatment could inhibit fermentation and corrode common alloys used in the fermentation vessels.

development [12]. Between 2010 and 2016, the wave energy sector experienced several technological setbacks, and prominent companies went into administration (e.g., Pelamis in 2014). Since 2016, the market has been recovering and focusing on improving the reliability of technology [21]. Two designs, Point Absorber and Oscillating Water Column, have been extensively tested at higher TRL levels [13,21,40]. Here, the development prospects of the Point Absorber (PB) design of wave energy technology alone will be analyzed for two reasons. First, PB converters can convert incident wave energy from any direction (i.e., directional independence) and are fully axisymmetric [45,46], an advantage over other design types. Second, most developers globally and within the EU and UK seem aligned towards point absorber design, indicating increasing market confidence and potential of this technology design [47], see Fig. 3.

2.1.3. *Seaweed*

The low lignin and high carbohydrate content make seaweed an attractive feedstock for anaerobic digestion or fermentation [48]. In 2019, 287 *kt* of seaweed production were recorded in Europe (0.8 % of the global share). Of this, only 4 % was cultivated, and the rest was wild harvesting [49]. Such a low share of cultivation in total production indicates the nascent status of the European sector. Some of the seaweed species that are native to the North Sea region are Laminaria Digitata (Pigment: brown), Saccharina Latissima (brown), Palmaria Palmata (red), Ulva Lactuca (green) [50]. Studies have reviewed seaweed's potential conversion pathways, opportunities, and challenges [5,23,48,51]. This study will discuss the fermentation of Laminaria Digitata into ethanol for the following reasons. First, Laminaria Digitata, also referred to as finger kelp, is a robust seaweed species and has already been cultivated under North Sea conditions [23,49]. Second, bioethanol is a direct alternative to fossil fuels in sectors including transportation and industries, which are often considered harder to abate.

2.2. *Characteristics of technology designs*

Table 1 compares the advantages and limitations of tidal stream, wave energy and bioethanol from seaweed technologies.

2.3. *Theoretical background on energy technology development process*

The energy technology innovation process informing the development stages is briefly explained here, providing a conceptual basis that guides the forecasting process. A more detailed discussion of the process can be referred in Refs. [59,60]. Technological progress happens in sequential stages, as shown in Fig. 4. An innovative technology is a product of fundamental and applied research involving laboratory experiments, prototype testing, and demonstration projects. In most cases, it is also a product of existing technologies combined in innovative ways, referred to as combinatorial evolution [59]. As a first step towards commercialization, the technology undergoes an initial experimentation phase, where radical designs and solutions are demonstrated and tested to prove technology viability, resulting in a dominant design. Second, commercial-scale deployments are initiated once a series of demonstrations of the dominant design is completed. These early-stage deployments provide learning opportunities for technology, supply chain development, and market creation. The new technology competes with market-established solutions at this stage, although incentives are often necessary to compensate for the price gap. Third, after successful early commercial deployments, the upscaling of the technology begins, either unit- or industry-scaling, or both, depending on technology-specific characteristics [61,62]. Later, widespread deployments in the market continue to yield incremental improvements as the new technology becomes competitive. Finally, the development potential of technology saturates or is commonly replaced by new, improved technology. In this sequential process, the role of distinct learning mechanisms, like learning-by-doing, learning-by-searching, and unit-scale economies, and their impacts change as technology develops from emerging to

[2] Tidal stream technologies make direct use of the incoming and outgoing flow in open water. These technologies are different from tidal range, which make use of the height difference between high and low tide range.

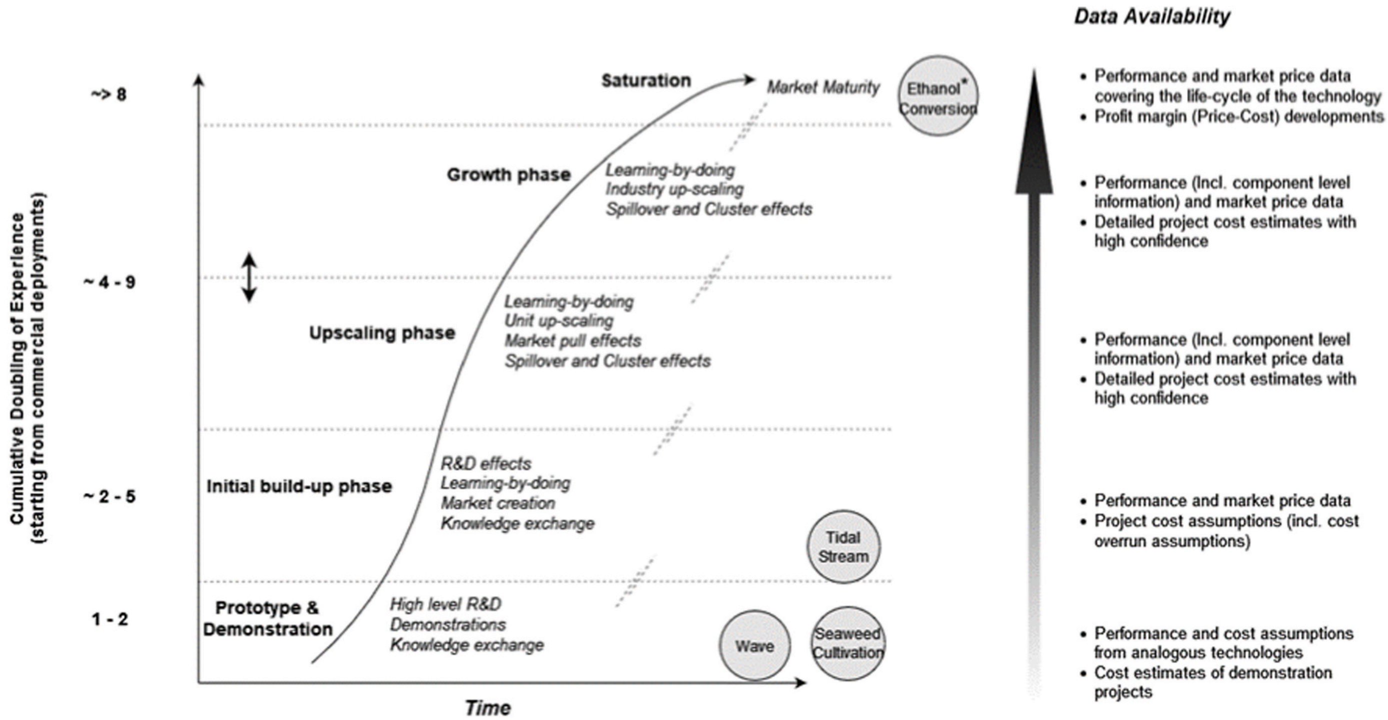

Fig. 4. Illustration of the technology development process and expected data availability across each development stage. Source: Modified from [12].

well-established status [6].

Section 2.1 describes the development status of each technology by summarizing its current deployments and trends in technology design convergence. Using this summary, the technologies have been marked in Fig. 4 to illustrate where they stand in the development process and how they are expected to develop further. The bioethanol conversion process (fermentation) from seaweed poses technical limitations, including identifying fermenting organisms suitable for seaweed and tackling salinity content to avoid lower ethanol yields. However, the process is relatively mature in the market to rapidly optimize bioethanol yields on a commercial scale. Hence, in Fig. 4, the ethanol conversion process is marked as mature technology, while seaweed cultivation is marked as an emerging practice.

In literature, methodologies, including the experience curve approach, bottom-up engineering cost modeling, and expert elicitations, were commonly applied to derive future cost developments of energy technologies. Such approaches, in individual applications, are commonly aggregated or fail to account for radical changes and potential technological improvements, as mentioned in Section 1. The shortcomings are particularly severe for emerging technologies as the availability of information is limited, and the future market potential is highly uncertain (Fig. 4). Nevertheless, the experience curve approach has been extensively used in literature to forecast technology cost developments, and the predictions have been observed closer to the realized outcomes than other methods [11,63].

It is vital to acknowledge emerging technologies' limitations. So, their long-term cost assessments and understanding of the uncertainties can be improved. Santhakumar et al. [12] concluded that disaggregating the technology cost to the component levels before extrapolating future costs is more desired, especially when the empirical information related to the technology is limited. Further, in a disaggregated approach, potential improvements in technology designs and their impact on performance and external market effects can also be considered to provide a detailed account of their impacts. Following the coherent framework described in Ref. [12], the component-based experience curve approach and bottom-up cost calculations are combined. The methodological steps involved are further detailed in the following sub-section.

2.4. CAPEX and LCoE

The LCoE metric holistically covers expenditures over a lifetime that goes into the production of an energy unit, and is considered a functional unit in this study to assess technology development. The LCoE is estimated as shown in Eqn. (1) and is also a critical metric that significantly impacts investment and policy actions and enables comparison between technologies in the market; however, neglecting system-level values [64,65].

$$LCoE = \frac{CAPEX + \left(\sum_{n=1}^{t} \frac{OPEX}{(1+i)^t}\right)}{\sum_{n=1}^{t} \frac{AEP}{(1+i)^t}} \tag{1}$$

In Eqn. (1), CAPEX, OPEX, and AEP represent Capital Expenditure, Operational Expenditure, and Annual Energy Production. i and t represent the discount rate and the project lifetime. For bioethanol production from seaweed, the Levelized cost is presented per liter of ethanol. Hence, AEP in Eqn. (1) will be the total liters of ethanol produced. OPEX comprises operation expenditure of the ethanol conversion step and the feedstock cost, i.e., seaweed cultivation cost; refer to Section 3.1.2 for more details.

First, the total CAPEX of the technologies is expressed as the sum of its components' costs, see Eqn. (2). The sub-components of the technologies analyzed in this study are briefly discussed in Section 3.1. The long-term CAPEX developments of these technologies are derived by applying component-level LRs to each technology component and summing them, as shown in Eqn. (3). The LRs are based on experience from similar industries or components utilized in analogous technologies (Sections 3.2 and 3.3).

$$CAPEX_{technology} = Cost_{component\ 1} + Cost_{component\ 2} + \ldots + Cost_{component\ n} \tag{2}$$

$$CAPEX_t = \sum_{i=1}^{n} Component\ Cost_{0,n} * \left(\frac{X_{n,t}}{X_0}\right)^{-E_n} \tag{3}$$

Where n in Eqn. (2) represents the n number of technology components, $Component\ Cost_{0,n}$ refers to the initial cost of the technology component

n, $X_{n,t}$ refers to the cumulative output of the technology component n at time t (or experience level), E_n refers to the experience parameter[3] for the component n. X_0 refers to the cumulative output of the technology at time $t = 0$, not technology component n (as in $X_{n,0}$) due to the experience of well-established components being dispersed across multiple sectors and geographies, i.e., challenging to consolidate the cumulative experience at a component level. Refer to Section 4.3 for more details.

Second, after deriving the CAPEX, the LCoE is estimated by assuming OPEX, AEP/Annual Yield, and discount rate, as shown in Eqn. (1). The OPEX and AEP development depend on the technology design (impacting accessibility), O&M strategies, site characteristics, and feedstock costs (if applicable). The discount rate of the technologies depends on the project development and investment risk pertinent to these technologies and exogenous factors like risk-free interest rates. The influencing factors and assumptions applied in this study are briefly discussed in Section 3.4. Moreover, the decommissioning expenditures (DECOM) are excluded from the assessment. Decommissioning practices, regulations, and costs are highly uncertain for these technologies at the current stage of development. Besides, in the LCoE estimation, the DECOM expenditure is discounted after the end of the project lifetime, resulting in a negligible impact on LCoE [33].

Fig. 5 describes the steps taken in deriving the LCOE forecasts for tidal stream, wave and bioethanol from seaweed technologies.

3. Data and assumptions

3.1. Capital Expenditure (CAPEX)

CAPEX refers to all the expenditures incurred in developing, constructing, and commissioning the project into operation. The CAPEX assumptions made for the tidal stream, wave technology, and biofuel production from seaweed are discussed in this section.

3.1.1. Tidal stream and wave technology

For tidal stream (HAT design) and wave technology (PA design), the total CAPEX is a sum of six sub-components costs, including DEVEX, Turbine/Prime mover, Foundation/Mooring, Installation costs, Electrical infrastructure, and Other CAPEX. The activities involved in each sub-category are referred from Ref. [66], and the definitions can be found in Appendix A.

The Electrical infrastructure costs exclude the connection cost from the offshore substation/collection point to the onshore connection point/substation. This connection cost is excluded because the distance to shore is expected to negatively impact the total costs of tidal stream and wave energy, and it varies significantly across different distances, similar to offshore wind [67]. Hence, this influence is captured by separating the technology cost into two components. First, the CAPEX and LCoE of the technology until the offshore substation/collection point is estimated. Second, the grid connection cost from offshore substation/collection point to onshore grid station is estimated separately in terms of Levelized Cost of Transmission (LCoT)[4]; refer to Section 4.1.1. The same approach is also followed for wave energy.

Tidal Stream CAPEX: Black & Veatch Ltd [68] reported lessons learned from the MeyGen Phase 1A project, a 6 MW (4 * 1.5 MW) demonstration tidal stream array in the Inner Sound of Scotland's Pentland Firth, and also a detailed CAPEX breakdown of the project (excl. costs incurred prior to financial close). This cost breakdown structure is assumed, but the costs prior to the financial close were included to normalize the cost breakdown. As a starting investment cost for experience curve projections, the average investment cost reported for initial commercial-scale projects from the previous literature (6 M€/MW) was considered. For validation, this estimate was compared to the expected CAPEX of the MeyGen Phase 1C project (500 M€ or 6.80 M€/MW, excl. connection to grid), the first large-scale commercial tidal stream array of 73.5 MW capacity (49*1.5 MW) [69]. This expected investment cost was reported in 2018. Since then, several technological developments have occurred. These include 1) the MeyGen Phase 1C project will use a monopile instead of a gravity-based foundation (Phase 1A), as the developer found it extremely difficult and expensive to satisfy the seabed requirements of gravity foundations [70]; 2) the larger scale of commercial projects mean procurements and fixed costs involved in project activities are distributed among multiple units, and 3) improved technology options have emerged in recent years (e.g., turbine upscaling[5]) and spillovers from offshore wind sector, resulting in cost reductions. This comparison provides confidence in the starting CAPEX assumption made in this study (Fig. 6).

The current cumulative installed capacity for tidal stream technology globally is around 31 MW (18.75 MW from the UK and 11.91 MW from the rest) [39]. In 2021, the UK government announced a ~24 M€ per year ringfenced subsidy for tidal stream technology under the Contracts for Differences (CfD) scheme [71,72], providing a route for commercial deployments. Through this support, the cumulative installed capacity of the tidal stream could reach above 100 MW [39]. Hence, 6 M€/MW and 100 MW will be used as a starting CAPEX and cumulative installed capacity for tidal stream experience curve projections.

Wave Energy CAPEX: Sandberg et al. analyzed the critical factors influencing the viability of wave energy in off-grid locations [73]. The study also provides a cost breakdown scaled from a 40-unit commercial wave farm (40*250 kW = 10 MW), estimated by the wave energy developer CorPower Ocean AB (PA design) [74]. The company states that their technology design is optimized for 10 MW clusters, i.e., each 10 MW hub will deliver electricity through standard 33/66 kV cable commonly used in offshore wind. Hence, the investment cost and cost breakdown estimations were used as a starting CAPEX for a commercial-scale wave energy power plant (7.50 M€/MW incl. onshore grid connection, 6.74 M€/MW excl. onshore grid connection).[6] The installation cost forms a significant portion of the total CAPEX (Fig. 6), potentially due to the expensive tension-leg mooring system design [74]. As discussed in Section 2.1, the technology design convergence has not commenced with wave energy, and the current cumulative installed capacity globally stands at 23.3 MW [75]. Further deployment iterations are required for the technology to develop into the pre-commercial status and converge technology design. Hence, 100 MW, similar to the tidal stream, was used as a starting cumulative installed capacity for CAPEX projections. The started CAPEX cost for wave energy is 6.74 M€/MW.

3.1.2. Bioethanol production from seaweed (fermentation)

The bioethanol production process from the seaweed is described in two steps: seaweed supply and conversion process.

Seaweed supply: The seaweed supply step involves cultivation, harvest, and transportation to the processing site. Bak et al. [76] reported production cost of seaweed of about 24.4 €/kg_{dw} from their cultivation trails in the Faroe islands (15 % dry matter assumed). They also stated

[3] $LR = 1 - 2^{-E_n}$

[4] The LCoT is defined as the €/MWh amount the TSO must charge the electricity generator to cover the cost of developing and operating an offshore grid connection system to the shore. LCoT can be added to the LCoE described in Section 4.1 to estimate final LCoE.

[5] The developments from offshore wind sector in terms of installation practices, vessels and electrical infrastructures are being adapted in tidal stream and wave energy sector. Besides, tidal turbines are also being upscaled from 2 MW to 3 MW (Raz Blanchard Pilot array project, a 12 MW array comprising four 3 MW turbines).

[6] The cost assumptions and breakdown mentioned for Lanzarote case study (0.5 MW plant capacity, 2 units) was chosen here for further assessment. The Bora Bora case (1 MW plant capacity, 4 units) seemed to have unrealistic scaling assumptions, i.e., underestimation in cable costs.

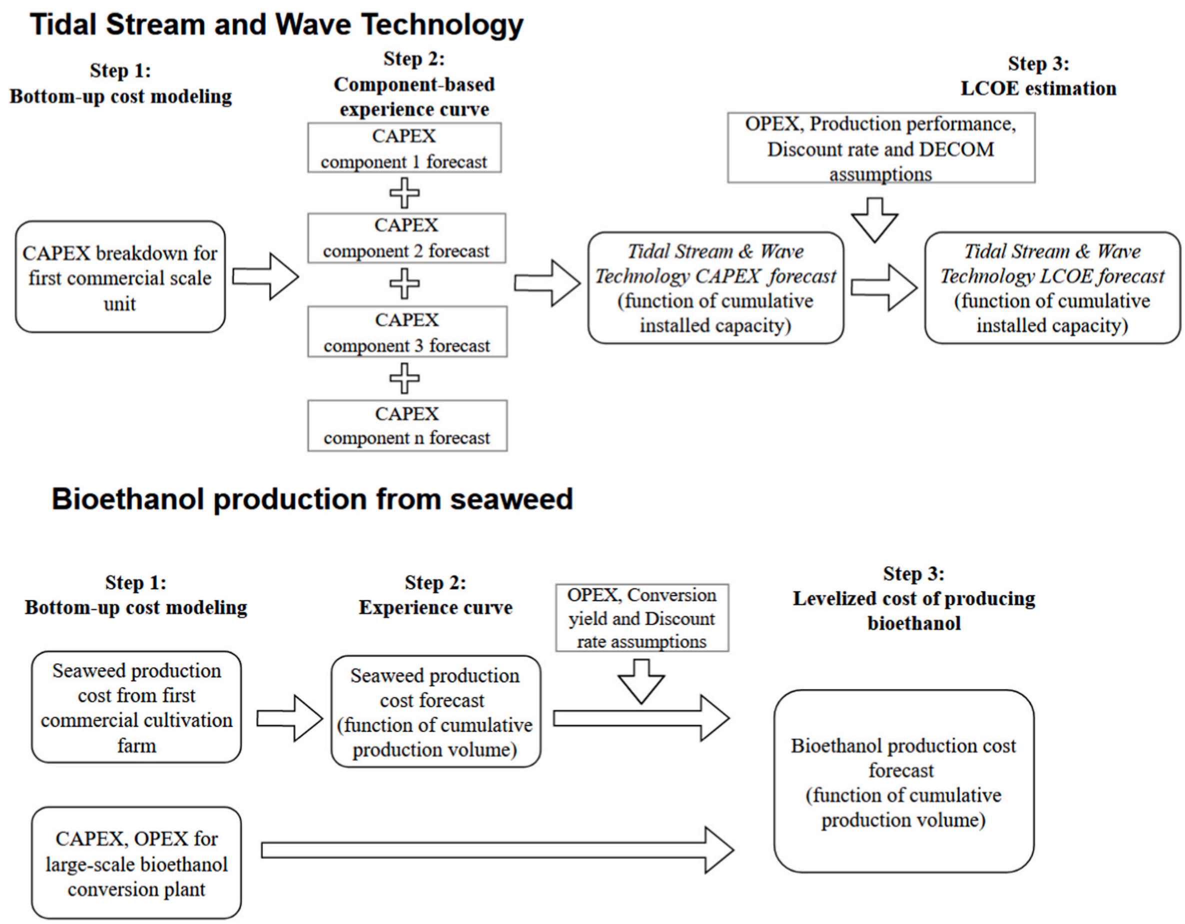

Fig. 5. Flowchart describing the steps followed in estimating the LCOE forecasts of three emerging offshore renewable energy technologies.

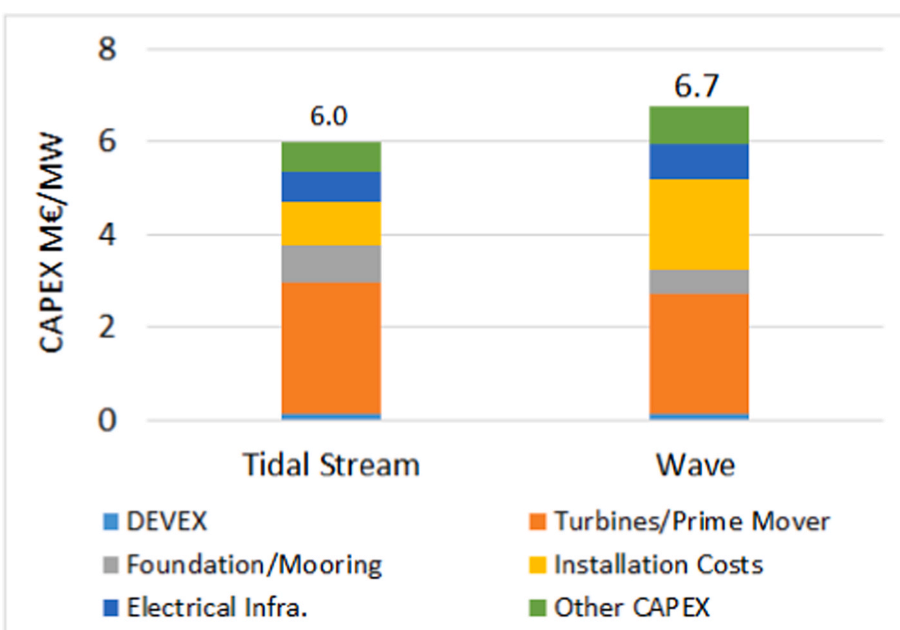

Fig. 6. CAPEX breakdown assumptions for tidal stream and wave energy technology at 100 MW cumulative installed capacity.

that by increasing the number of harvests to six per growth line, the cost reduced to 6.1 €/kg_{dw}, a 75 % reduction. The European project, Energetic Algae, has been carried out to develop sustainable algal biomass technologies and commercializing them [77]. An excel-based cost model was developed to estimate the seaweed cultivation cost by utilizing the data from the pilot setups and interactions with commercial project

Table 2
Assumptions taken to estimate the seaweed cultivation cost using the EnAlgae cost model. Source [79].

Characteristics	Assumptions	Comment
Seaweed Species	Laminaria Digitata	From Section 2.1
Region	North-Western Europe	
Cultivation system	Longline (Direct seeding of zoospores)	Seaweed is hung to a long rope and is suspended by floaters.
Number of longlines	5000	The distance between the longlines is 10m, resulting in cultivation area of 500 ha or 5 km^2.
Length of seeded string needed	1 m/m of longline	
Distance from the harbor to the processing site	50 km	
Boat lease	400 €/day	
Dry weight of seaweed	15 %	Seaweed contains 80–90 % of water
Yield	20 kg_{FW}/m longline	This assumption leads to total cultivation yield of about 1500 t_{dw}
Scaling factor	0.75	Scaling factors between 0.7 and 0.8 are commonly used to estimate plant costs at different sizes/capacities [80]
Interest rate (for capital goods)	8 %	

partners [78]. Burg et al. used the model to estimate the production cost of Sachharina Latissima and reported an estimate of 5.2 €/kg_{dw} in a base case small scale cultivation scenario (1000 longline units). The study also added that by upscaling cultivation, reducing the cost of plant material, increasing the yield and combined use of space, the production costs can be reduced up to 1.2 €/kg_{dw}. Here, we have used the same model to estimate the seaweed production cost at a commercial scale in the North-Western European region, as it provides a detailed bottom-up cost estimation for seaweed cultivation. The main inputs assumed in the model are summarized in Table 2. Component cost assumptions were scaled and other assumptions were kept unchanged [78]. These assumptions result in a CAPEX investment of about 1.6 M€ or 413 k€ per year (annualized estimate) for seaweed cultivation. This estimate leads to seaweed cultivation cost of 1.48 €/kg_{dw}, upon considering the seeding cost, boat lease, labor expenditures,[7] Other Costs, and potential yield; see the cost breakdown in Fig. 7. This estimate is used as the starting feedstock supply cost for the experience curve projections; (see Table 3 for assumptions on discount rate, capacity factor and OPEX).

Fermentation Process (ethanol): The conversion process involved in bioethanol production from seaweed include feedstock pretreatment (e.g., removing foreign objects, chopping or milling to reduce particle size and increase the surface area), hydrolysis/saccharification, fermentation, distillation, and dehydration [25]. Regarding conversion costs, the Sub-group on Advanced Biofuels (SGAB) was established to assist the EU Sustainable Transport Forum by providing recommendations for the scale-up of alternative fuels at the EU level [81]. This study reviewed the bioethanol conversion cost estimates in the literature and information received from SGAB expert stakeholders through interviews to present the overall economics for the production of various advanced biofuels [82]. The CAPEX estimate reported by the study for the fermentation process (ethanol production from lignocellulosic sugar) was referred to, and the costs were scaled to the output capacity of the seaweed cultivation plant discussed above (a scaling factor of 0.75 was assumed). The total CAPEX (overnight investment cost) was 1.9 M€ or 232 k€ per year, annualized by assuming an interest rate of 8 % and a project lifetime of 15 years. This estimate was used as a starting CAPEX cost for bioethanol conversion process. The LRs assumed for tidal stream and wave technology CAPEX forecasts can be found in Appendix B. The LR assumed for seaweed production cost forecasts can be found in Appendix C.

[7] The labor expenditure inputs in the model have been updated with average hourly minimum wage of the Netherlands in the year 2022 [111]. The factors used in the model to scale the expenses for different tasks remains unchanged.

Table 3
Summary of inputs for LCoE estimations of tidal stream and wave technology.

Cumulative Installed Capacity	Discount Rate (%)	Capacity Factor (%)		OPEX (k€ per MW per year)	
	Tidal Stream & Wave	Tidal Stream	Wave	Tidal Stream	Wave
At 0.1 GW	8.5	34	25	200	140
At 0.5 GW	8.0	40	30	156	109
At 2.5 GW	7.5	45	35	121	85
At 10 GW	5.0	45	40	98	69
At 20 GW	4.5	45	45	88	62
At 40 GW	4.0	45	50	79	56
At 50 GW	4.0	45	50	77	54

3.2. Other inputs for LCoE estimation

3.2.1. OPEX

OPEX refers to the annual expenditure necessary for operating and maintaining the energy systems to achieve optimum economic performance, considering necessary downtime for annual maintenance. OPEX for offshore is generally higher than onshore energy systems as the marine environment is harsher and the cost of accessing offshore sites is higher [83]. The accessibility of offshore sites, in turn, is heavily impacted by the weather conditions, availability of specialized vessels and human personnel, and also by the intended maintenance tasks. Besides, due to the nascent status of the technologies considered, the OPEX estimates for commercial-scale deployments should be regarded as highly uncertain [18], i.e., true component failure rates and cost of maintenance activities are limited to assume OPEX with high certainty.

Tidal Stream OPEX: The literature review shows a wide range of initial OPEX estimates, 0.07–0.81 M€ per MW per year; refer to Appendix C for a detailed summary. More than two-thirds of the literature reviewed were between 0.07 and 0.37 M€ per MW per year. MeyGen Phase 1A, a 6 MW tidal stream array, reported OPEX spending of 0.28 M€ per MW per year [68], which falls within the above range. In this study, the starting OPEX estimate is 0.20 M€ per MW per year, which is the average value reported by leading developers of tidal stream technology for initial commercial-scale projects [18].

Wave Technology OPEX: The literature review shows the initial OPEX estimates between 0.06 and 0.38 M€ per MW per year. The lack of technological design convergence introduces differences in O&M strategies, resulting in varied OPEX estimates. Nevertheless, the floating devices is expected to have lower OPEX than bottom-fixed devices, due to its easier accessibility. IEA OES study on ocean energy developments stated that the expected OPEX cost for the first commercial arrays in the literature is 0.14–0.32 M€ per MW per year [18]. The leading developers of wave energy were more optimistic about the OPEX values in the range of 0.06–0.14 M€ per MW per year [18], similar to offshore wind status around 2010. Here, the starting OPEX assumed is 0.14 M€ per MW per year.

The long-term OPEX development is driven by O&M strategies, learning in O&M activities, vessel capabilities improvements, and innovations that improve accessibility and operational reliability. For example, upscaling of turbine capacity, e.g., 3–4 MW in 2010 to 6–8 MW in 2020, has decreased the OPEX for offshore wind farms [84]. Similar upscaling trends could be unlikely for tidal stream and wave technology designs considered in this study, as both technologies face limitations, as

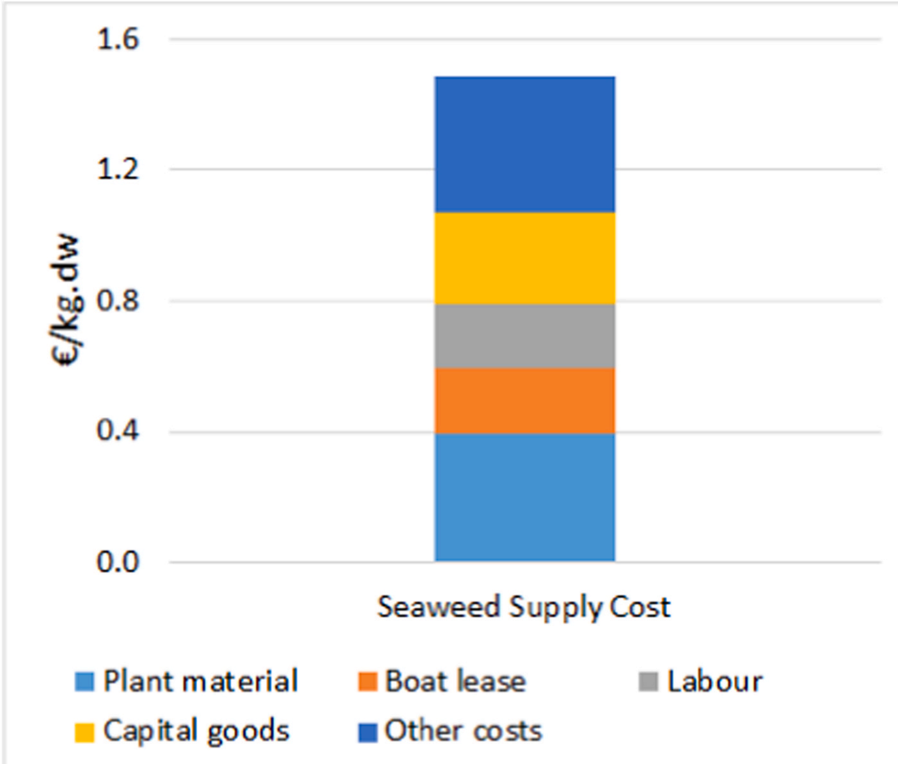

Fig. 7. Illustration of seaweed production cost breakdown, estimated using EnAlgae Model. Other costs include transport costs, licensing, and diving expenses.

mentioned in Table 1. Empirical LR's observed for offshore wind OPEX could be applied here to extrapolate OPEX developments due to similarities in the operational environment, intended activities, and components involved. However, such estimates are not available in literature due to the lack of data, i.e., offshore wind O&M contracts are customized to the projects and not publicly disclosed. Hence, the LR observed for onshore wind OPEX is referred [85]. Steffen et al. [85] reported 9.2 % LR for maintenance and repairs costs and 12.7 % LR for operations costs for onshore wind in Germany, with cumulative electricity production as an experience parameter. Assuming a similar OPEX cost breakdown, the same LRs were applied to extrapolate tidal stream and wave technology OPEX with cumulative installed capacity as an experience parameter.

For bioethanol production from seaweed: OPEX for bioethanol production from seaweed involves seaweed supply costs (feedstock) and O&M costs of the fermentation plant. The input to the seaweed supply costs comes from the experience curve projections discussed in section 3.3. Annual OPEX excluding feedstock cost, is assumed to be 4 % of the CAPEX, as suggested in the literature [82]. This assumption comprises expenses related to co-feeds, labor, feedstock associated costs on the site, maintenance and by-product disposal.

3.2.2. Annual Energy Production (AEP)/Annual Yield

The AEP of the tidal stream and wave technology is based on the gross capacity factor and availability [18]. The gross capacity factor depends on system efficiency (e.g., energy lost in cables), energy capture potential (depends on resource characteristics, device power curve/-matrix), and wake efficiency. The availability is a measure of the potential for an energy device or power plant to generate electrical power given appropriate weather and grid connections, as used in the wind industry [86].

Past studies have estimated the capacity factor of tidal stream and wave technology at different site conditions by assuming a standard device design. Such assessments were made to understand their economic competitiveness, and the outcomes are discussed below to derive capacity factor assumptions for the LCoE outlook.

Tidal Stream Capacity Factor: [68] reported a 34 % capacity factor for the MeyGen Phase 1A project (1.5 MW turbine) based on 25-year project life and 95 % availability. Black & Veatch [87] estimated the capacity factor at the low resource, base case, and high resource site conditions to report technology cost differences among different sites. The corresponding capacity factors were 24 %, 35 %, and 49 %. Iyer et al. [88] investigated tidal stream sites in the UK alone and reported capacity factors ranging between 23.3 % and 43.6 %, assuming a 0.5 MW tidal device. Robins et al. [53] calculated the potential capacity factor across the northwest European shelf seas and reported that 96 % of the potential tidal-stream sites have a capacity factor below 50 %, assuming the Seagen-S twin 600 kW device (net 1.2 MW).

Wave Technology: Sandberg et al. [73] estimated the capacity factor of Corpower Ocean's PA device at three islands, Maldives (Average wave resource: 10–20 kW/m), Bora Bora (20–30 kW/m), and Lanzarote (29 kW/m), and reported capacity factor of about 25 %, 40 % and 50 % accordingly (90 % availability). Lavidas [89] analyzed the wave resource in the North Sea region and the performance of 14 devices in the region. The study reported that the region has a mean wave resource of 15 kW/m, with higher magnitude resources concentrated towards the region's north part. The highest mean capacity factor was 25–32 %, depending on the device design. Rusu and Onea [46] also assessed the potential of wave technology by selecting 15 reference points representing geographical regions with the highest wave power and arrived at similar estimates.

Although the above-discussed studies provide a good indication of potential capacity factors across different site conditions, the limitations should be recognized, i.e., the future design improvements and their impacts on technology performance were not considered in the assessment [33]. For example, due to developments in blade materials, larger rotor blades were manufactured and attached to the onshore wind turbines to increase the energy capture at low-wind sites [90]. Similarly, design improvements and innovations could improve the economics of the tidal stream and wave technology [91]. discusses that the availability of technology improves with operational experience, and also, design advancements and the ability to access farther sites with stronger resources will improve the energy capture performance of the technology as cumulative experience increases.

The ethanol conversion yield improvements for the fermentation process with seaweed as a feedstock is discussed in Section 4.2.

3.2.3. Discount rate or cost of capital

The discount rate or the private cost of capital refers to the expected rate of return that market participants require to attract funds to a particular investment. Steffen [92] summarized three factors with which the cost of capital varies mainly, 1) the country where investment takes place and its local policy regulations, 2) investment risks related to the technology and expected revenue streams, 3) how factors 1 and 2 will vary over time or with experience. The private cost of capital is generally estimated as the Weighted Average Cost of Capital (WACC), where the debt and equity component in the capital structure is proportionally weighted, as shown in Eqn. (4).

$$WACC = \delta * cost\ of\ debt + (1 - \delta) * cost\ of\ equity \tag{4}$$

δ refer to the debt share in the total capital. Both cost of debt and the cost of equity in the WACC entails a risk-free component and a risk premium component [67]. First, the risk-free component of the investment is influenced by the macroeconomic factors in the country where the investment would take place. The macroeconomic factors include monetary policies, inflation, and political uncertainties and are often regarded as exogenous factors influencing the cost of financing. Second, the risk premiums component directly relates to a particular technology's maturity, the future role of technology in the market, the government's support, and regulatory settings, including incentives and permitting procedures. Emerging technologies initially pose higher risks for investors. However, as the technology develops and becomes more reliable with experience, the investment risks decrease, resulting in lower expected returns [93].

Currently, there are no standard subsidy forms and regulatory support (e.g., permitting procedures) for the three Low-TRL technologies considered in this study [94]. Generally, these actions are realized once the technology enters the pre-commercial stage of development, e.g., CfD contracts announced for tidal stream in the UK [72]. Such initiatives are not present for wave and seaweed cultivation yet, making it challenging to estimate the cost of capital developments accurately. Hence, the cost of capital development trend from analogous technologies was considered. The debt margins of solar PV and onshore wind in Germany have decreased by 11 % for every doubling of cumulative investments [93]. Support schemes that provide fixed revenue for project developers improve the chances of accessing cheaper capital (debt), e.g., the CfD scheme, thereby reducing the overall cost of capital [95]. Previously, Santhakumar et al. [67] estimated the cost of capital developments for floating offshore wind technology as a function of cumulative installed capacity. Those estimates were used for tidal stream and wave technology due to the similarities in technology characteristics and investment risks.

3.2.4. Summary of other inputs for LCoE estimations

The following table provides the summary of inputs that were made in estimating the LCOE of tidal stream and wave technology, based on the inputs discussed between Section 3.2.1 and 3.2.3.

4. Results and discussion

As mentioned in section 2.4, the CAPEX development pathway was first derived by applying component level LR to the technology CAPEX cost breakdown. Second, the CAPEX outlook was translated into the LCoE outlook by considering each technology's OPEX, discount rate, and AEP/Annual Yield developments.

4.1. Wave and tidal stream cost reduction

CAPEX Developments: Fig. 8 shows the resulting CAPEX development pathway and cost breakdown for both tidal stream and wave technology as a function of cumulative installed capacity. Tidal stream CAPEX reduces from 6.0 M€ per MW at 0.1 GW to 3.0 M€ per MW by 50 GW. Wave technology CAPEX reduces from 6.7 M€ per MW at 0.1 GW to 2.9 M€ per MW by 50 GW. The similarities and differences in developments between the tidal stream and wave technology are discussed here. Also, the relative contribution of a component's cost in total CAPEX is noted, i.e., to differentiate the development of established technology components from the new ones and emphasize the technology components that remain of critical importance. First, the contribution of DEVEX remains 2–3% of the total CAPEX until 50 GW for both technologies. The scale of the project is expected as a primary driver, similar to offshore wind, as fixed costs involving site and resource surveys and legal services costs remain relatively at the same amount [66].

Second, the cost developments for turbines/prime movers are based on their technology's inherent design characteristics, i.e., unit-upscaling or modular tech (Table 1). For the tidal stream, the unit-upscaling of the turbine is expected to bring cost reduction to the turbine, i.e., reduces the material needs per device, thereby reducing specific costs. The turbine supply cost remains the significant cost component of the installation, i.e., about 45–47 % of total CAPEX until 50 GW. For wave technology, on the other hand, the unit-upscaling is limited, and the device is expected to be modular (Table 1), which will drive rapid cost reduction through the manufacturing scale of economies. The cost contribution of the prime mover reduces from 38 % of total CAPEX at 0.1 GW to 23 % of total CAPEX at 50 GW. Third, for foundation/mooring, the cost reduction potentials are limited as the fabrication processes for these components are well established in the market. Fourth, for the installation cost, the extent of activities involved between the offshore and onshore areas will impact the potential of cost reduction. Most of the installation activities for the tidal stream are handled offshore and are subsea operations (e.g., offshore lifting, piling, commissioning). Thus, providing cost reduction opportunities through learning-by-doing, e.g., optimized scheduling of offshore tasks, improved installation procedures, and reduced contingencies [70]. The cost contribution of installation reduces from 16 % of total CAPEX at 0.1 GW to 10 % of total CAPEX at 50 GW. For wave technology, on the other hand, major assembly activities of floating foundations can be handled onshore and then towed to the commissioning site, limiting the risky offshore activities. PA design assumes a tension leg mooring system for station-keeping, which requires specialized vessels to pre-tension the mooring system before connection and commissioning of the device [96, 97]. Hence, installation remains the major cost component in total CAPEX (29–32 %) up to 50 GW. Fifth, for cables, considerable similarities exist between both technologies, including dynamic cables and connectors. However, limited learning opportunities are available, as these components will be built on the experience of well-established fixed-bottom and emerging floating wind sectors. Lastly, the other CAPEX involves insurance, project management, and contingency costs, for which cost reduction depends on the cumulative experience gained in the industry, i.e., minimizing development, construction, and commissioning risks.

The projected CAPEX development shown in Fig. 8 was then fitted in a single-factor experience curve model to estimate aggregated LRs for the technologies, resulting in 7.6 % LR for tidal stream CAPEX and 9.0 % for wave technology. The LR applied for CAPEX forecasts in the literature (see Fig. 1) was more optimistic (12–17 % LR) than observed in this assessment, indicating an overestimated CAPEX cost reduction in past literature.

LCoE Developments: Fig. 9 shows the resulting LCoE development pathway for tidal stream and wave technology as a function of cumulative installed capacity. Tidal stream LCoE reduces from 264 €/MWh at 0.1 GW to 61 €/MWh at 50 GW. Recent UK CfD allocation 4 auction

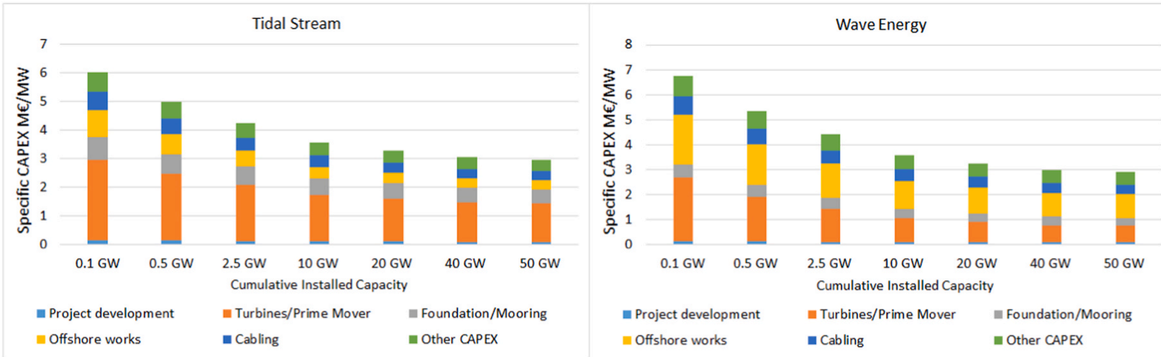

Fig. 8. CAPEX developments for tidal stream and wave energy technology.

results in contract revenue of 214 €/MWh for a period of 15 years [98]. Considering 20 or 25 years of project lifetime will bring the target LCOE of these projects close to the estimation we provided in this study here, acknowledging the certainty of our cost assumptions and estimation. Wave technology LCoE reduces from 365 €/MWh at 0.1 GW to 54 €/MWh at 50 GW. The drivers behind the LCoE reduction are categorized into three, 1) *Technology costs (CAPEX, OPEX)*: For tidal stream, the CAPEX and OPEX contribute about 38 % and 16 % to LCoE reduction from 0.1 GW to 50 GW. For wave technology, CAPEX and OPEX contribute about 28 % and 7 % to LCoE reduction from 0.1 GW to 50 GW. CAPEX and OPEX developments and their contributing factors are discussed above. 2) *Annual Energy production*: AEP improvements contribute to 33 % of LCoE reduction for the tidal stream from 0.1 GW to 50 GW. Besides utilizing higher resource sites, fixed-bottom tidal stream devices can improve their AEP by increasing their hub heights (e.g., 2 % increase in yield for a meter increase in hub height [39]), rotor diameter, and reducing their downtime. In a typical tidal stream site, 75 % of the energy is available in the upper 50 % water column [39]. Therefore, floating devices pose advantages in maximizing energy yield, as they directly position their rotors in this higher energy region (e.g., Orbital O2 turbine [99]). For wave technology, the AEP improvements contribute significantly, 59 % of LCoE reduction from 0.1 GW to 50 GW. As the PA designs are expected to be modular, attaining higher capacity will be based on accessing higher resource sites and improving the energy capture of devices towards their theoretical limits. For example, advanced control strategies effectively expand the range of resonant-power absorption for PA designs, i.e., knowledge of oncoming waves to tune the operating frequency of the wave device [45]. 3) *Discount rate*: The improvements in financing conditions contribute 13 % and 7 % LCoE reduction for tidal stream and wave technology from 0.1 GW to 50 GW. Subsidy instruments and permitting procedures are not yet clear for tidal stream and wave technologies due to their nascent status. Project development risks can be reduced through streamlining permitting procedures, and the revenue risks for developers can be reduced through fixed revenue contracts (e.g., CfD mechanism) [100].

Finally, the reference LCoE of 40 €/MWh, reflecting the wholesale electricity price developments in European electricity markets between 2017 and 2020 [101], is used to benchmark the development. Both technologies did not break even in the assessments made here. Nevertheless, tidal stream generation is predictable, and wave technology generation complements the wind generation profile (see Table 1). Hence, both technologies are expected to provide value to the energy system in terms of flexibility and balance, i.e., factors excluded in the LCoE assessment, which need further research.

4.1.1. Grid connection cost

The grid connection cost of tidal stream and wave technology are discussed separately to illustrate the influence of varying site characteristics and technology choices on the final LCoE. At the early stage of technology development, the capacity of installations is expected to be small (<30–75 MW) and are deployed closer to shore, as evidenced in offshore wind, i.e., to minimize the risks of investment and enable learning opportunities. In such cases, direct connections are preferred, where the electrical energy generated offshore is collected and transferred to shore via an export cable. As the technology matures, the deployment capacity of installations will increase to capture economies of scale and be deployed further from shore to overcome nearshore spatial constraints. In such cases, direct cable connections become more expensive, and offshore substations[8] are preferred.

Fig. 10 illustrates the LCoT of four technology choices, two direct cable connections and two choices of offshore substations. All configurations considered in this study are radial connections, i.e., a direct single-point connection between the offshore power plant and an onshore connection point. The LCoT of direct cable connections for distances below 50 km varies between 3 and 29 €/MWh (single 33 kV export cable) and 2–13 €/MWh (single 66 kV export cable). The LCoT of offshore substation connections for the same distance range varies between 4 and 10 €/MWh (a 200 MW offshore substation) and 5–9 €/MWh (a 350 MW offshore substation). A 33 kV export cable's connection cost increases steeply with distance due to its lower capacity, higher material, and installation costs. Hence, this configuration is preferred for small-scale installations (<50 MW) deployed less than 10 km from the shore, i.e., the pre-commercial demonstrations. The 66 kV export cable connection is competitive compared to 33 kV due to its larger capacity and lower material costs. This configuration remains competitive for installations of 40–100 MW capacity and within 25 km, i.e., early commercial stage. After that, offshore substation choices become competitive, i.e., full commercial stage. The breakeven distance, where offshore substations become competitive, is around 25 km. Before 25 km, utilizing offshore substations for small-scale installations will remain expensive due to higher fixed costs, including substation platforms, offshore foundations, and transformers. Nevertheless, when grid connection capacity is shared among power plants, i.e., hub-type connection, offshore substation choices can lower the net social cost even at farther distances.

4.2. Biofuel production from seaweed cost developments

Seaweed Cultivation Cost: Fig. 11 shows the seaweed production cost development from 1.48 €/kg_{dw} at 1.5 kt_{dw} of cumulative output to 0.2 €/kg_{dw} at 500 kt_{dw} of cumulative seaweed capacity. 500 kt_{dw} of cumulative capacity represents roughly more than eight doublings of cumulative output.

Here, three significant factors expected to reduce the seaweed pro-

[8] The electrical energy generated by the devices are collected at an offshore substation and transformed into a higher voltage level before exporting to shore, i.e., higher transmission voltage level reduces export cable requirements and transmission losses.

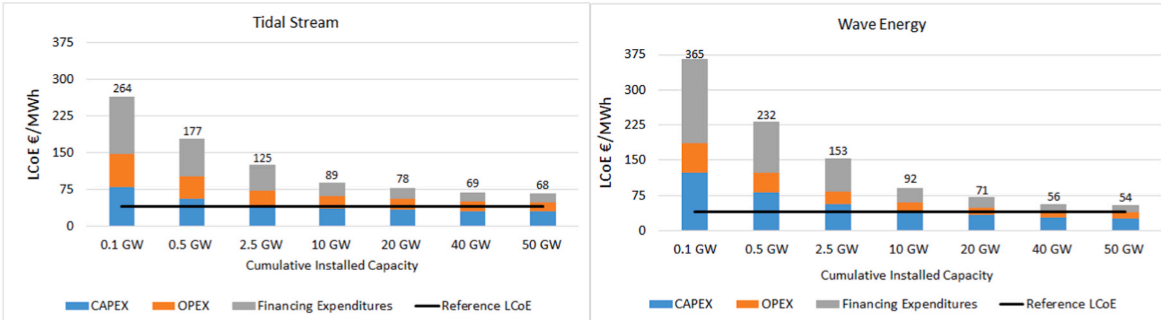

Fig. 9. LCoE developments for tidal stream and wave energy technology, excluding grid connection costs.

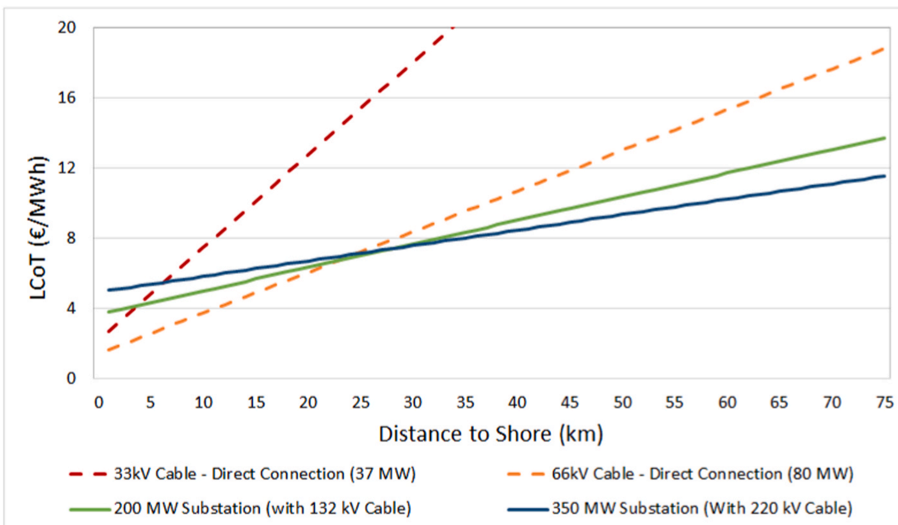

Fig. 10. Grid connection cost for tidal stream and wave energy technology at 40 % utilization factor, described in Levelized Cost of Transmission. Transmission loss with export cables at different distances was not considered.

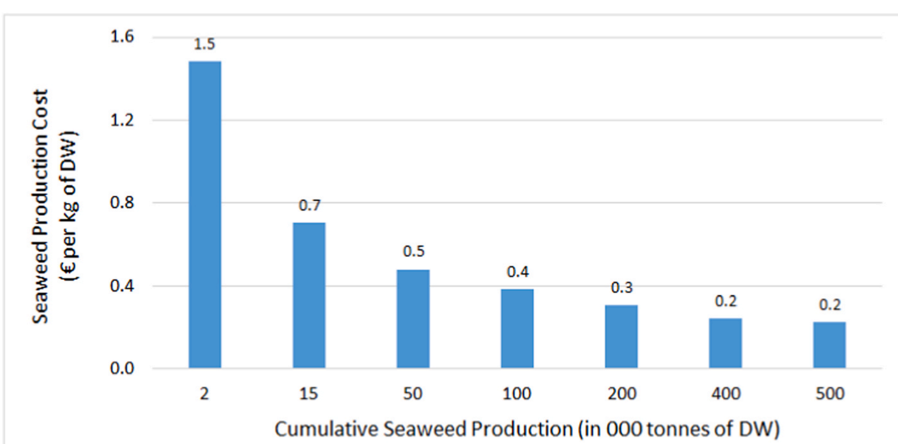

Fig. 11. Seaweed production cost development as a function of cumulative output.

duction cost are discussed, 1) *Cultivation technology and harvesting:* Typically, longlines - a network of floating ropes anchored to the seabed, are used in seaweed cultivation, i.e., referred to as the 1-D substrate [78]. Designs that can increase the seaweed growth per given area in the setup are commonly preferred, as it increases the overall output per given area and reduces the specific fixed costs (CAPEX). Such design type includes mesh-type, using V-droppers in the longlines. For example, using V-droppers in the longline increased the seaweed output by 2.7 times, reducing the seaweed production cost to 1.03 €/ kg_{dw} from 1.48 €/ kg_{dw} in the longline case, i.e., a 30 % reduction. Specifically, the capital goods cost component of seaweed production cost saw a significant reduction to 0.10 €/kg_{dw} (longline + V-dropper) from 0.28 €/ kg_{dw} (longline); see Fig. 6. Similarly, introducing an advanced 2-D substrate would reduce the cost further and improve the overall production [102], e.g., 2-D AlgaeSheet by AtseaNova company [103], Submerged pod structures at diameters ranging between 20m and 200m from SeatechEnergy company [104]. Besides substrate design innovations, multiannual harvest and selective breeding (to improve the yield of the seaweed in the growth substrate) would reduce the cost further [79]. Bak et al. [76] reported a 75 % cost reduction on Saccharina latissima cultivation trials in the Faroe islands with six harvests per growth line deployed, compared to one harvest. 2) *Plant material costs:* Plant material refers to culture strings with juvenile sporophytes, forming about 26 % of the initial seaweed production cost. Capital goods and labor costs majorly influence the plant material costs (about 75 %), indicating that increasing production scale and automation would yield economies of scale effects and reduce the labor expenditures [79]. *3) Boat lease, labor, and Other Costs:* Boat lease costs are driven by the daily rates of the boats required and the deployment, monitoring, and harvesting duration. Labor costs are influenced by the hourly wage rate and the number of persons required onshore (for hatchery) and at sea (installation, monitoring, and harvesting). Other Costs comprise transport, licenses, and diving. Transport costs are influenced by the distance from the harbor to the processing site and the quantity to be transported. As noted in Section 2.2, dewatering seaweed to 20–30 % of water content is beneficial as it lowers the energy consumption of transportation, thereby the costs. By increasing the yield, Other Costs saw a reduction to 0.22 €/ kg_{dw} (longline + V-dropper) from 0.42 €/ kg_{dw} (longline); due to economies of scale.

Bioethanol production cost: The CAPEX and OPEX (excl. feedstock) assumptions applied to estimate the bioethanol cost are discussed in Section 3.1.2. No learning on ethanol conversion CAPEX, OPEX, and conversion efficiency has been considered to estimate future bioethanol production costs initially (see Fig. 12). Later, the impact of improvements in the conversion yield was also quantified and discussed, see Fig. 13. Although ethanol fermentation is a well-established technology, it was challenging to consolidate the existing experience of the process to derive cumulative output. As bioethanol production from seaweed matures, learning through scale, experience, and innovations (e.g., feedstock handling, yeast strains) is expected. The bioethanol production cost reduces from 17.1 €/l at 0.1-million-liter cumulative output to 4.5 €/l at 50-million-liter cumulative output, a 73 % reduction in 9 doublings of cumulative output. Van den Wall Bake et al. [80] reported 17–21 % LR for ethanol production (excl. feedstock cost) in Brazil. Applying 19 % LR (average of the range), the bioethanol production cost reduces to 2.7 €/l at a 50-million-liter cumulative output. However, it should be noted that the existing cumulative experience of the fermentation process and improvements in the ethanol conversion yield were not taken into account, which is discussed below.

On average, 55 ± 12 % carbohydrate contents were observed for brown seaweeds [105]. For laminaria digitata, in particular, the total carbohydrate content varies from 17 % in April to 64 % in August (Location: Denmark), composed of polysaccharides such as laminarin, mannitol, cellulose, alignate, and fucoidan [106]. Alvarado-Morales et al. estimated that 75 kg of ethanol per one ton of seaweed (DW), i.e., 1 L of ethanol per 10 kg of seaweed (DW), can be extracted based on carbohydrate content in the seaweed (cellulose and laminarin alone) [107]. Offei et al. [105] conclude that current enzyme preparations were developed for starch-based and lignocellulosic biomass and are unsuitable for seaweeds. The study also said that identifying fermenting organisms capable of converting the heterogenous monomeric sugars in seaweed is a major limiting factor, resulting in variation in bioethanol yields from 0.5 to 5.4 L of ethanol per 10 kg of seaweed (DW). Fig. 13 shows the impact of improved ethanol yield on bioethanol production costs. The starting investment cost of bioethanol production discussed in Section 3.1.2 is used here, i.e., no learning. At 0.2 € €/kg_{dw} seaweed cost and ethanol conversion yield of 5 L per 10 kg of seaweed (DW), the biofuel production cost is about 0.8 €/l. Currently, the lignocellulosic bioethanol cost is between 0.5 and 0.6 €/l [82], and is dependent on the feedstock cost. This assessment shows the opportunity to achieve cost reductions for bioethanol production from seaweed up to 0.8 €/l by developing roughly eight cumulative doublings of seaweed cultivation. However, support requirements will be needed to compensate for the price gap with lignocellulosic bioethanol, which could be justified considering the benefits of seaweed (Table 1).

4.3. Major uncertainties involved in cost estimation and projections

The major uncertainties involved in the long-term cost assessment of three offshore renewable energy technologies stem from two main factors, 1) Potential radical changes in the development pathway, and 2) Cost reduction assumptions, including LRs and technology components' current development status.

Potential radical changes in development pathway: Before deriving cost reduction assumptions, dominant technology design was chosen by analyzing current market deployments and developers' preferences (Section 2.1). The technology components, cost structure, and performance expectations were derived and applied in this study based on this design choice (Section 3). It is to be noted that radical designs and devices will be tested as the technology matures; to improve prospects of further cost reduction, performance increase, and ability to access far offshore sites [108]. Such developments, which are difficult to foresee, are influenced by several factors, including the outlook of technology price and performance, social acceptance, stakeholder interests, and

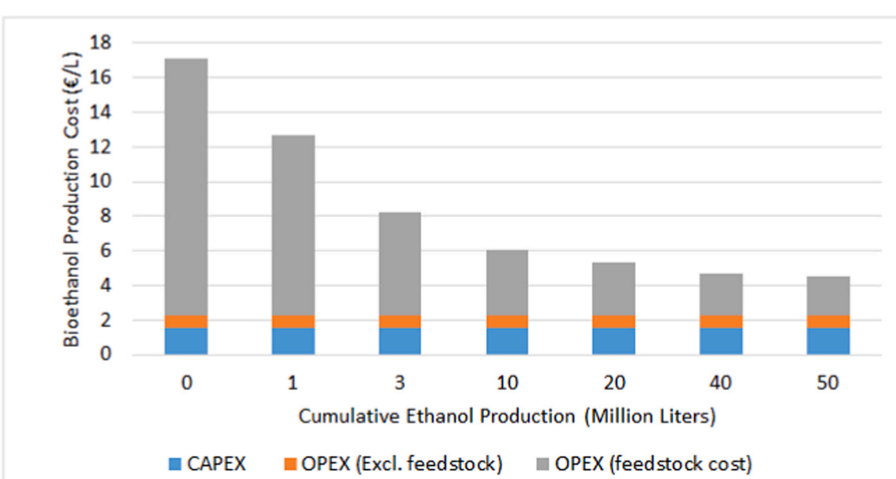

Fig. 12. Long-term prospects for Ethanol production cost with seaweed as a feedstock.

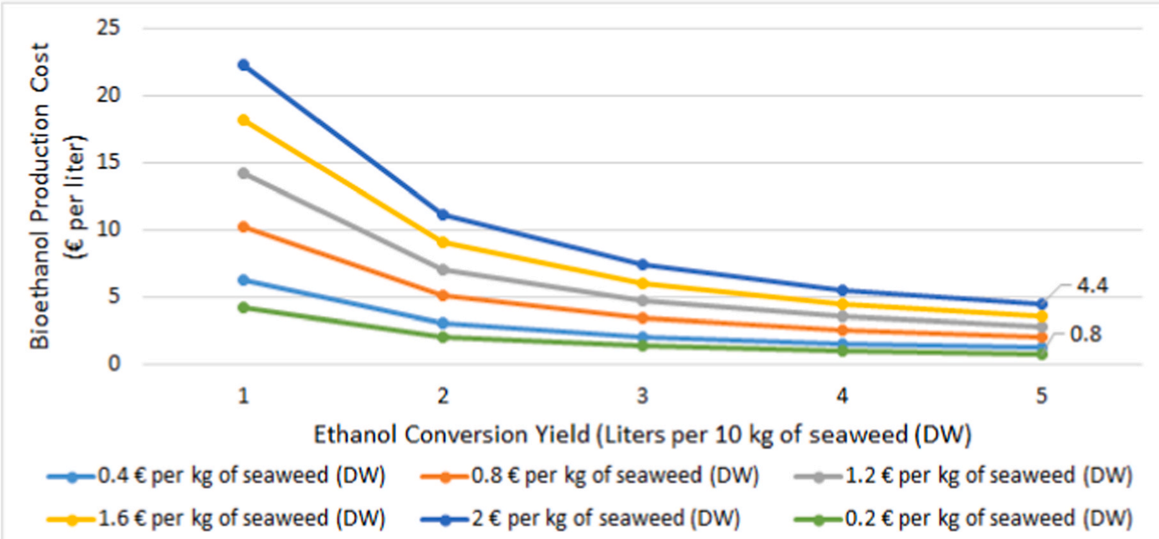

Fig. 13. Influence of seaweed feedstock cost on ethanol production cost.

Table 4
Overview of sources for cost reduction assumptions (Symbols and interpretation: ✓ – Technology Specific Input, X – Assumptions from analogous technology/component, O – Expert opinions/estimates from non-peer reviewed works).

Cost or performance metrics	Tidal stream	Wave	Biofuel production from seaweed
Initial costs for experience curve projections	✓	✓	✓
Starting cumulative installed capacity	✓	✓	✓
LR - DEVEX	O	O	
LR – Turbine/Prime Mover	X	X	
LR – Foundation/Mooring	X	X	
LR – Installation Costs	X	✓	
LR – Electrical Infrastructure	X	X	
LR – Other CAPEX	O	O	
LR – Seaweed Cultivation Cost			X
Initial costs for experience curve projections: OPEX	✓	✓	✓
LR - OPEX	X	X	X
AEP/Annual Yield	✓	✓	✓
Discount rate	X	X	X

policy support [60]. Such developments are uncertain but upon occurrence, these radical improvements would introduce divergence from the discussed cost assessment trend due to potential changes in technology cost structure and contributing drivers.

Two examples are provided to illustrate such possibilities. First, in the tidal stream, floating foundations eliminate most of the high-risk subsea operations and unlock access to far offshore sites. Its installation costs and OPEX are significantly less than fixed devices. However, the cost of floating structure and control strategies necessary will increase to improve stability and maximize AEP [41]. If floating foundations displaces fixed-bottom tidal stream altogether due to their benefits and spillover effects from the emerging floating wind industry, the potential changes in cost structure need to be considered. Second, in tidal stream, there are several other designs in development. A tidal kite is a device tethered to the seabed and carries a turbine below the wing, designed to operate in low-flow tidal streams and ocean currents as low as 1.2 m/s, increasing its deployment potential over a wide range of sites [36,109]. Although the energy conversion principle is similar to HAT design discussed here, tidal kite's operational methods and upscaling potential[9] differ. For example, the resource speed has a cubic relationship to power production. Upscaling the device to higher ratings for low-flow sites will reduce the overall energy yield, as the occurrences of high-speed streams will be insignificant [58]. Hence, the device is expected to be modular, where manufacturing scale economies can be exploited to reduce costs. This distinguished development focus of tidal kites from HAT determines how the cost reduction occurs and what would be underlying drivers.

Cost reduction assumptions: The parameters considered in deriving the long-term cost assessment of the low-TRL offshore energy technologies include initial investment cost breakdown, component level LRs, and starting cumulative installed capacity. Table 4 summarizes the sources considered for the parameters, and it can be seen that only current costs (CAPEX and LCoE) and performance expectations were technology-specific inputs. For extrapolating future costs, analogous technologies and components or non-peer-reviewed literature and expert opinions were considered due to the lack of empirical information specific to technology; resulting from nascent status of technology. Hence, such assumptions' uncertainty needs to be recognized, mainly for LRs, and cumulative installed capacity. The starting cumulative capacity or output assumption, which represents the current development status of the component, also plays a significant role in determining future component costs sensibly. Assuming a lower starting cumulative capacity for a well-established component in the market will generally overestimate the cost reduction as the time or effort for doubling the output is smaller in earlier stages of development. Moreover, the experience of most well-established components like electrical systems and manufacturing processes are dispersed across diverse sectors and geographies, making it extremely difficult to consolidate the cumulative experience. Therefore, lower LRs or no-learning are assumed for such components in experience curve analysis, with starting cumulative capacity of the component being the cumulative output of the technology under study [110]. Understanding the implications of such assumptions are critical in assessing long-term technology cost projections.

In summary, following a disaggregated approach as applied in this study provides a detailed cost outlook and information on cost reduction factors. However, such an approach also introduces more design factors in the assessment, for which empirical information is limited, and their uncertainties are significant. Hence, it is recommended not to interpret the results in a deterministic manner but to gain a detailed account of

[9] Minesto, a leading developer of tidal kite design, distinguishes it product range based on wing span (4m–12m), with rated power ranging from 50 kW to 1.2 MW.

cost reduction factors and acknowledge that there will be variations in quantified results when the assumptions change, due to radical developments or market factors.

5. Conclusion

This study quantifies the long-term cost development of three key emerging offshore renewable energy technologies: tidal stream, wave energy, and bioethanol production from seaweed. Here, a disaggregated approach, combining a component-based experience curve approach and bottom-up cost estimations, was used to overcome the shortcomings present in the existing technology cost assessment and address the research gap in the scientific literature. Based on this assessment and quantified results, three conclusions were made.

First, the assessment shows that the tidal stream LCoE reduces from 260 €/MWh at 0.1 GW to 61 €/MWh at 50 GW. Wave technology LCoE reduces from 365 €/MWh at 0.1 GW to 54 €/MWh at 50 GW. These estimates exclude grid connection costs. In both technologies, CAPEX and AEP were significant cost drivers for LCoE reduction. The inherent design characteristic between the tidal stream (HAT) and wave (PA) energy influences the drivers behind CAPEX reduction and energy capture. The unit-scale economies effect mainly drives the CAPEX reduction in the tidal stream. The AEP of the tidal stream can also be improved by adapting technology design to the resource available, e.g., larger-diameter rotors, placing the rotor at a higher hub height. For wave energy, CAPEX reduction mainly arises through manufacturing scale economies. Due to its modular nature, the AEP improvements can be achieved by accessing higher resource sites and implementing better control strategies; see Section 4.1. A thorough understanding of these differences between the technologies is crucial to implementing targeted policy actions, e.g., R&D investments and site planning. The grid connection cost is another crucial factor for both tidal stream and wave technology, influenced by the distance to shore and technology choices. The grid connection costs increase steeply with the distance to shore for direct AC connections, i.e., without a substation; see Fig. 10. Our assessment shows that sharing grid infrastructure among multiple deployments can lower the net social cost than individual direct connections. Especially in earlier development stages, this Hub-type setup will serve as enabling infrastructure for ocean energy developers and stimulate deployments.

Second, for bioethanol production from seaweed, the production cost reduces from 17.1 €/l to 0.8 €/l by roughly achieving eight doublings of cumulative seaweed production and improving the ethanol yield in the fermentation process (Section 4.2). Like lignocellulosic bioethanol, the seaweed cultivation cost plays a significant role in ethanol production cost. Our assessment shows that the current cultivation cost at a commercial scale is about 1.48 €/kg_{dw} and has the potential to reduce up to 0.2 €/kg_{dw} by achieving eight doublings of cumulative output. The improvement expected in cultivation technology and harvesting will be a significant driver for cost reduction, including introducing 2-D substrate for cultivation, multiple harvests and selective breeding to optimize yield. In the bioethanol conversion process, the major driver is expected to be in identifying fermenting organisms capable of converting the heterogenous monomeric sugars in seaweed, as current products were developed for start-based lignocellulosic biomass. Due to its water content (80–90 %), an energy-intensive process like drying is not recommended. However, dewatering seaweed to 20–30 % water content will reduce the energy consumption in transportation and simplify storage requirements.

Compared with market-competitive benchmarks, like wholesale electricity price for tidal stream and wave, and lignocellulosic ethanol price for seaweed, all three technologies did not break even in our assessment. However, it should be noted that these technologies may provide advantages that are not included in the LCoE assessment. For example, the tidal stream is predictable, and the wave energy generation pattern complements the wind energy generation profile. These advantages benefit the energy systems in balancing and lower energy storage requirements, which are not valued in the LCoE metric. Similarly, seaweed does not compete with land and freshwater resources and does not require fertilizer to grow like 1-G and 2-G biomass. Hence, it is essential to further the research to internalize the benefits of emerging offshore technologies and quantify their system-level benefits.

Third, this study has provided a long-term cost assessment for three emerging offshore renewables with a detailed account of cost reduction factors. Such a thorough technology assessment is expected to improve long-term decision-making and reduce the risks of public and private investment actions. However, the uncertainties involved in the assessment should not be ignored. As these technologies are at a nascent development status, empirical information about their costs and performance is limited. Therefore, it is recommended not to interpret the results in a deterministic manner but to understand the development pathway of these technologies and gain a detailed account of cost reduction factors. Moreover, acknowledging that there will be variations in quantified results when the assumptions change, i.e., uncertainty range.

CRediT authorship contribution statement

Srinivasan Santhakumar: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Hans Meerman:** Conceptualization, Writing – review & editing, Supervision. **André Faaij:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119875.

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