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Feasibility of investment in Blue Growth multiple-use of space and multi-use platform projects; results of a novel assessment approach and case studies

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ABSTRACT

Blue Growth is the creation of economic activity and jobs at sea, while multiple use of space makes efficient use of the available sea area by combining industries. Clearly there are many combinations and many value propositions. However, most technologies to date are considered blue sky concepts, with little robust techno-economic analysis demonstrating profitability.

The paper begins by providing a comprehensive review of Blue Growth and multi-use in Blue Growth; both in policy as well as the wide range of current technologies, including ocean energy, offshore wind energy, offshore aquaculture and desalination.

The Maribe H2020 project provides the vehicle for the research element of the paper. The major contribution is a new methodology for selecting, filtering, developing and ranking business propositions for multiple-use of space (MUS) and multi-use platforms (MUP). Application of the method for the first time identified three case studies where Blue Growth combination projects can be economically viable, with attractive internal rate of return (IRRs). Results presented for the case studies report standard investment metrics and show the relative contribution of each product (energy, food, water) to the system profitability, as well as socio-economic impact. Existing companies were fully engaged in the process. Co-creation between sector experts and industry led to both improved business value propositions and robust assessment of investment readiness. In contrast to the presumption that large scale platforms are commercially attractive, the highest ranking case study companies required smaller capital expenditure (CAPEX) and operated in niche subsectors.

In conclusion, the positive economic performance of the case studies should provide confidence for the EC as well as investors that MUS and MUP have viable economic futures leading towards commercialisation. The

Abbreviations: Maribe, Marine Investment in the Blue Economy; CAPEX, Capital expenditure prior to first operation; DECEX, Decommissioning expenditure; FID, Final investment decision; IRR, Internal rate of return; LCOO, Levelised cost of output; LCOE, Levelised cost of energy; MUP, Multi-use platforms; MUS, Multiple-use of space; NPV, Net present value; OPEX, Operational expenditure after first operation (includes CAPEX items); NPV/CAPEX, Profitability index; WACC, Weighted average cost of capital or discount rate; CS, Case Study

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macro and micro assessment methods will be particularly useful in other Blue Economy contexts and in other multiple product contexts.

1. Introduction

Over 70% of the world's surface is the ocean, with more than 40% of the global population inhabiting the coastal areas [1]. With an ever-growing population and uses of land areas reaching their limit, it is timely to focus on the ocean to solve some of the world's major issues such as security of food, water supply and energy. Significant areas of the ocean remain unused and can potentially provide opportunity for economic growth and resource use.

The demand for ocean resources is an important driver of economic growth. It provides natural resources, access to trade, and opportunities for leisure activities [2]. The ocean has the potential to become an important source of clean energy and marine products. Blue Growth sectors (ocean energy, aquaculture, biotechnology, deep-sea mining and coastal tourism) present an opportunity to generate economic growth and jobs, enhance the security of energy supply and support local produce whilst boosting competitiveness through technological innovation. The European Commission estimates that there will be approximately 5.4 million jobs and almost €500 billion of Gross Value Added (GVA) from Blue Growth in the medium term [3].

As maritime activity increases, however, so does the competition for space as coastal areas become overcrowded. In anticipation, the EU has driven an agenda to realise Blue Growth more efficiently through Multi-Use of Space (MUS) and Multi-Use Platforms (MUP). However, there has been a lack of robust techno-economic analysis examining the economic viability of MUS/MUP combinations of Blue Growth [4–7]. This had led to a lack of confidence from investors in both the technical and the economic viability of sharing marine space, and sharing platform services [8]. A particular issue is that the additional complexity adds to the (perceived) risk of the project. Consequently, the EC awarded the Maribe H2020 project (https://maribe.eu) under the BG5[1] call for projects. The scope of the call was to determine if there is a future for investment in the combining Blue Growth sectors together in MUS and MUP. Key findings from the project are presented here.

The aim of this paper is three-fold: first to present the background context of Blue growth and MUS/MUP (policy and business cases). Secondly to introduce the Maribe H2020 project, objectives and methods. Finally, the paper presents the techno-economic modelling and results of the three most interesting case studies. The further key findings of Maribe are reported in recently published book: Building Industries at Sea: 'Blue Growth' and the New Maritime Economy [9].

Part 2 of the paper presents a review of Blue Growth policy, then the state of the art of the most successful companies and enterprises in the Blue Growth sector, as well as combinations of Blue Growth, under the various sectors of ocean energy, offshore wind energy and offshore aquaculture.

Part 3 presents the structure of the Maribe project, and a description of the novel methodology for selecting and ranking the most viable combinations of Blue Growth sectors, in a staged approach. Existing companies and sector experts engaged with the Maribe team in co-creation, developing business plans and financial models which led to both improved business value propositions and robust assessment of investment readiness for Blue Growth and MUP concepts. The approach identified technical and non-technical barriers to the business and calculated economic performance, using a suite of techno-economic indicators that enabled the balanced comparison of economic performance across vastly differing technical combination projects. The indicators included: levelised cost of energy (LCOE), net present value (NPV) and internal rate of return (IRR). This enabled comparative analysis with other energy sources, gross benefits and efficiencies.

Finally, Part 4 of the paper presents the techno-economic modelling results of three case studies examining the feasibility of the Blue Growth sectors in MUS/MUP projects[2]:

- Albatern and Aquabiotech: Wave Energy combined with finfish aquaculture in the Mediterranean (MUS)
- Wave Dragon and Seaweed Energy Solutions: wave energy combined with seaweed farm in Welsh waters (MUS)
- Ecowindwater: Floating wind energy and desalination in Greek waters (MUP)

Discussion and conclusions draw these findings together with socio-economic factors and put them into a wider context.

1.1. Definitions

To understand the range of options for MUS/MUP the following definitions are proposed (see also video discussion[3])

1.1.1. MUS: Multiple use of space

Any combination of Blue Growth sectors, or Blue Growth and Blue Economy sectors that share the same location but that have no common platform. MUS can share the same infrastructure such as cabling and substations.

1.1.2. MUP: Multi-use platform

Any two Blue Growth sectors, or any Blue Growth + Blue Economy sector that share the same location but also share the same platform facility. Mutual benefits (technical or economic) to both entities enable the production and export of at least 2 products.

Further to this, Maribe split the MUP into 3 different types:

Type 1 MUP service platform (auxiliary): providing services to the combined Blue Growth and Blue Growth and Blue Economy entities surrounding it (e.g. processing, storage, energy, water & habitation) to enable their operations.

Type 2 MUP multiple production platform: hosting technologies of two or more combined Blue Growth & Blue Growth + Blue Economy entities yielding at least two products for export (e.g. desalinated water + electricity both exported; exported electricity produced from wave and wind)

Type 3 MUP combining a service platform with a multiple production platform: yielding at least two products for export (e.g. mixing a floating storage facility with an on-board fixed wind turbine + desalination).

2. Blue Growth context and state of the art

2.1. Blue Growth policy background

In 2007, The European Commission published the Integrated Maritime Policy for the European Union [10] which reinforced the view

[1] https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/bg-05-2014.html.

[2] The paper presents the 'commercial business case' results only for each study. Maribe also conducted 'pilot stage' techno-economic studies which for each case study; these are not presented in this paper, but are available in the Maribe full reports for each case study.

[3] http://maribe.eu/category/cordinator-interviews/.

Table 1
The seven European basins, listing existing cross border MSP policies and basin Action Plans.

Basin Strategy Plans	Ref	Cross Border MSP	Ref	Action Plan	Ref
Atlantic Ocean	[18]	SIMCELT, TPEA & SIMNORAT	[19–21]	Atlantic Action Plan	[17]
Baltic Sea	[22]	Plan Bothnia & BaltSeaPlan	[23,24]	HELCOM	[25]
Black Sea	[26]	MARSPLAN	[27,28]	Black Sea Action Plan	[29]
Mediterranean Sea 1	[26]	BlueMed	[30]	UNEPMAP	[31]
2		SUPREME – east Med	[32]	*	
3		SIMWESTMED - west Med	[33]	*	
Adriatic and Ionian Seas	[34]	ADRIPLAN	[35]	*	
North Sea	[36]	MASPNOSE	[37]	*	
Arctic Ocean	[38]	*		*	

* under development.

that growth and development of EU level maritime industries would benefit from coordinated and streamlined sea basin level initiatives. In 2008, the European Commission (EC) stated that “Harnessing the economic potential of our seas and oceans in a sustainable manner is a key element in the EU's maritime policy” [11]. The EC Blue Growth Strategy [12] in 2012 considered the potential of Blue Growth to contribute to the objectives of the Europe 2020 Strategy [13] as well as greenhouse gas emission reduction goals. The strategy conformed to wider regulative elements applicable for all maritime regions, thus providing a strategic framework for development. These include the Marine Strategy Framework Directive (MSFD) adopted in 2008 [14] and the Maritime Spatial Planning (MSP) Strategy [15]. MSP will be particularly important to establish synergies with existing maritime activities (e.g. shipping, fishing) while MSFD is essential for maintaining good environmental standards including biodiversity, which can impact industries such as aquaculture or tourism. The potential of offshore wind received particular attention, with a dedicated Communication on offshore wind energy [16]. The strategy includes five developing areas in the ‘Blue Economy’ that could create jobs in coastal areas:

1. Aquaculture
2. Coastal tourism
3. Marine biotechnology
4. Ocean energy
5. Seabed mining

Blue growth in Europe is divided into Seven European Sea basins, to encourage tailor-made measures and to foster cooperation between countries. For most of the 7 basins, there is an individual MSP as well as an Action plan, and these are listed with references in Table 1. For example, in 2013, the Maritime Affairs published recommendations for the sea basins: “Blue Growth, opportunities for marine and maritime sustainable growth” [17].

One of the most developed Action Plans is the Atlantic Action Plan [39–41]. The Atlantic Action Plan embraces Blue Growth in its strategy and recognises the importance of collaborative research and development and cross-border cooperation to boost its development. The underlying objective is to identify investment and research priorities in the Atlantic sea-basin that could be considered for EU financial support in the programming period of 2014–2020. Based on the above, the four priorities of the Atlantic Action Plan are:

1. Promote entrepreneurship and innovation;
2. Protect, secure and enhance the marine and coastal environment;
3. Improve accessibility and connectivity; and
4. Create a socially inclusive and sustainable model of regional development;

Ecorys [42] studied Atlantic Arc Blue Growth, and described the maritime economy in terms of 11 economic activities, assessed from a qualitative and quantitative perspective. The methodology and approach was aligned with similar studies for other sea basins.

The European Commission, through its Seventh Framework Programme for Research and Technological Development (FP7) funded the SEAS-ERA (2010–2014) [43] project which aimed to improve coordination, promote harmonisation between national and regional research programmes and at the same time foster synergies at regional and Pan-European level. The project brought together 21 partners from 18 countries with the intention of strengthening maritime research across the European Union. The project also contributed to the Atlantic Research Plan, publishing its own report for the Atlantic [44]. Among the main findings were the needs for increased ocean observation infrastructure (e.g. vessels, observatory) and monitoring (including seabed mapping) to gather relevant data. Such a data set provides baseline data to establish “Good Environmental Status” under the MSFD, a first step towards licencing of new Blue Economy projects.

The challenge for Europe is to develop a positive vision for the future and manage this process to achieve this in a sustainable manner while maximising benefits for maritime stakeholders and the EU economy as a whole. Five key challenges that lie ahead for Blue Growth in Europe are:

1) Building on the existing experience & **position EU as a maritime industries world leader,** and technology exporter.
2) Making **best use of EU sea space** and infrastructure
3) Maintain and enhance the “***good environmental status***[4]” of European Seas under MSFD [45].
4) Achieving **additionality** by accelerating both the pace and scale of investment and job creation beyond that which is possible for individual EU member states.
5) Responding to **regional distinctiveness** within EU seas by recognising regional differences in resource distribution environmental sensitivities, patterns of resource use and socio-cultural and economic priorities.

The EU 2017 report “Report on the Blue Growth Strategy: Towards more sustainable growth and jobs in the blue economy” [46] praised the progress that Blue growth had made in 5 years, and was optimistic on the potential of Blue Growth to add to EU wellbeing and sustainability. The latest initiative by the EC in 2018 is the Blue Invest[5] platform throughout Europe. The program promotes a series of matchmaking events for blue economy entrepreneurs, innovators and investors.

2.2. Review of EU funded FP7 “Ocean of Tomorrow”

Based on the sustainable Blue Growth policy described in Section

[4] http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm.
[5] https://ec.europa.eu/fisheries/blueinvest-2018-ocean-opportunity-right-backing_en.

2.1, the EC designated €12M of FP7 funding to *Oceans of Tomorrow*[7] (OoT) projects in 2011 [47]. MUS/MUPs were considered at a 'blue sky' level of thinking and multiple possibilities were explored up to a Technology Readiness Level (TRL) of 4. Díaz-Simal [48] reviewed the projects and can be summarised as follows:

1. **Tropos**[6]: (completed 2014) There were 4 technology projects explored under Tropos.

1. Floating Hotel
2. Taiwan shipping terminal
3. Offshore wind service hub
4. Aquaculture and renewable energy.

All projects were at TRL 3/4. The capital expenditure for all projects was high, and the financial analysis resulted in negative Net Present Value (NPV). The review highlighted that there were uncertainties in the CAPEX estimates.

2. **Mermaid**[8]: (completed 2014) There were 4 technology projects explored under Mermaid.

1. Wind/wave platform in Spain
2. Aquaculture and renewables in Adriatic
3. Fixed wind and aquaculture in Baltic
4. Fixed wind and mussels in Netherlands.

The review identified one promising project: floating wind/wave device in Spain, conditional on a sufficiently high feed-in tariff.

3. **H2Ocean**[9]: (completed 2012) H2OCEAN was a project aimed at developing economically and environmentally sustainable very large multi-use open-sea platform. Renewable energy included wind and wave power. The MUP would convert some of the energy into hydrogen that can be stored and shipped to shore as green energy carrier as well as supply a multi-trophic aquaculture farm. CAPEX in €Billions, results had very large negative NPV. Independently, Maribe also considered large MUP and undertook two case study developments for proposed projects:

1. Grand Port Maritime Guyana[10] TRL3 Floating shipping terminal, aquaculture and Oil and Gas. Case study in Maribe.
2. Float Inc USA TRL 4: Very large-scale shipping terminal with wave energy power integrated in MUP structure. Case study[11] in Maribe.

In summary, the common theme of these Ocean of Tomorrow projects is aligned to the policy driven, "top down" nature of the funding. Many of the projects considered large scale complex MUP solutions which can only be funded with significant subsidy. The high CAPEX and additional costs associated with operation offshore makes many of these systems non-competitive with land based competitors.

The Oceans of Tomorrow projects were followed up in the H2020 (FP8) programme and by two projects in particular - Maribe (Marine Investment in the Blue Economy www.maribe.eu) completed in 2016 and MUSES (Multi-Use in European Seas https://muses-project.eu/) completed in 2018. Maribe is described in Part 3.1 of this paper. MUSES builds on previous projects and existing knowledge to respond positively to the challenges of regulation and the preservation of ecosystem services. It seeks to mitigate the risks of multi-use developments.

In 2018, two new EU project in Blue growth have been awarded and started:

1. Space@Sea[12]: to provide a workspace at sea by developing a standardised and cost efficient modular island.
2. Blue Growth Farm[13]: design multipurpose offshore floating platform, hosting aquaculture, energy harvesting and test in NEOL tank at TRL5.

2.3. Review of existing Blue Growth MUS and MUP: existing companies and techno-economic studies

2.3.1. Offshore wind (floating or fixed) sharing with aquaculture and shellfish farms

There are few examples for this type of MUS sharing and almost all examples are shellfish rather than cage aquaculture. One example is a study carried out for the Shellfish Association of Great Britain (SAGB) by a Project Team led by Aquafish Solutions Ltd[14] who assessed co-location with offshore wind. To date, offshore wind farms have been extremely reluctant to share space, both due to perceived added unnecessary risk as well as the disproportional scale of investment with aquaculture being very small compared to that of offshore wind. However, recent MSP and national legislation pressure is now encouraging offshore wind farm developers to consider other Blue Growth in their business models. For example, a Belgian consortium,"Noordzee Aquacultuur",[15] of research institutions and companies has started a project to investigate if mussels could be grown on offshore wind farms.

Wageninen University have explored the viability of aquaculture mussels with fixed offshore wind, based on outputs of the Maribe project.[16] Van den Burg et al. [49] assessed the techno-economic viability of co-locating a mussel farm (producing both mussel seed and consumption-sized mussels with semi-submerged longlines) amongst the yet to be deployed Borssele fixed offshore wind farm in the Netherlands. The economic results for the combination showed positive IRR results. Jansen et al. [50], showed a positive economic outlook for mussels with offshore wind in the North Sea. Finally, Bas et al. [51] considered the more general socio-economic benefits of co-locating aquaculture with offshore fixed wind. A lack of information to undertake a thorough social cost benefit analysis made definite conclusions difficult but the multi-use scenario is expected to be sustainable considering current policy and institutional frameworks, as well as the environmental and socio-economic effects.

Bartelings et al. [52] in the Netherlands conducted an economic study of combining Mussels and seaweed in the area of a fixed wind farm. Their study concluded that mussel production was highly profitable, bringing an additional profit of ca. €38 million. Seaweed cultivation was not profitable at the current price for seaweed. Another study by Buck et al. [53] in German waters states that production of consumer mussels with longline technology is sufficiently profitable even under the assumption of substantial cost increases. If existing vessels and equipment can be used this further reduces risk and increases profits. An alternative market for the cultivation of seed mussels depends on using existing equipment to be profitable at typical seed mussel prices.

Finally, two papers explored the socio-economic implications of

[7] http://www.gppq.fct.pt/h2020/_docs/brochuras/bioeco/ocean-of-tomorrow-2014_en.pdf.
[6] http://www.troposplatform.eu/.
[8] http://cordis.europa.eu/result/rcn/183781_en.html.
[9] http://www.h2ocean-project.eu/.
[10] www.portdeguyane.fr/.
[11] http://maribe.eu/download/2505/.
[12] https://spaceatsea-project.eu/.
[13] http://www.thebluegrowthfarm.eu/.
[14] http://www.offshorewind.biz/2013/08/05/shellfish-aquaculture-offshore-wind-farm-study-completed-for-sagb-uk/.
[15] https://www.offshorewind.biz/2017/06/02/belgians-start-growing-mussels-on-offshore-wind-farms/.
[16] http://maribe.eu/download/2511/.

combining aquaculture with fixed wind. Griffin et al. [54] also shows that cooperation between aquaculture farms and fixed offshore wind farms are a positive viability based on potential cost sharing whilst also demonstrating social benefits. Krausse and Mikkelsen [55] state that the main barriers to overcome are unresolved issues of ownership of the process, i.e. which stakeholders are involved in the consent procedure and their relative influence. Furthermore, socio-economic dimensions in aquaculture operation, e.g. emotional ownership of the sea/coastal area by the local residents/stakeholders and the social values that drive this ownership are difficult to capture in such remote offshore settings.

2.3.2. Offshore wind sharing with wave energy

The Netherlands government has mandated that marine space for offshore wind must also be shared with other forms of renewable energy [56]. This policy particularly favours wave energy and consequently the WaveStar UPWAVE[17] project, won a H2020 project in MUS,[18] where it received planning permission to deploy within a cooperative offshore wind farm, ParkWind. Unfortunately, private funding and licencing problems prevented the project proceeding, despite EC funding.

Chozas et al. [57] compared the electricity network balancing costs of a range of diversified wind/ wave power plants compared with a system based only on wind power (Pelamis, Wave Dragon, WaveStar and a fixed wind turbine). Results showed balancing costs of wave converters are 35–47% smaller than those solely based on wind turbines. When wave converters are combined with wind, balancing costs keep low, 45% lower than for wind turbines alone. Perez Collazo et al. [58] conducted a technical review of combining wave energy with offshore wind, the scope was to consider substructures, wave energy conversion systems and performance. The review focused on fixed wind technologies rather than floating. Operations and maintenance was included in the review; however, economics of the combinations was not carried out. Astariz et al. [59,60] examined the potential cost reductions in co-located offshore fixed wind and wave farms and concluded that energy cost is reduced by more than 50% relative to stand-alone wave farms.

The following reviews explore MUP of wind and wave together in a single platform:

Floating Power Plant P80[19]: (Denmark, TRL 6), ½-scale prototype trialled for 1.5 years up till 2015. The full scale P80 will be a single wind turbine ranging from 5 MW to 8 MW, plus 2–3.6 MW wave power

W2Power[20]: (Norway, TRL2, 10 MW) two corners of the triangle support one wind turbine each and the third corner houses the power take-off for the wave energy conversion system.

O'Sullivan [61] examined a singular wind-wave energy platform hybrid system, which included sharing space, transmission infrastructure, O&M activities and a platform/foundation. An economic analysis of the system was undertaken, considering a 210 MW hybrid farm and it was found that the hybrid produced energy at a cost of €0.22–0.31/kWh depending on the source of funding for the project. This device and Floating Power Plant were two of the nine projects subject to micro assessment by Maribe.

Castro-Santos [62] examined two specific hybrid systems: the W2Power and the Poseidon. Results for two locations in Portugal (São Pedro de Moel and Aguçadoura) indicate that the exploitation, manufacturing and the installation costs are the most important ones, with the exploitation cost being the most important for the W2Power and the manufacturing cost being the most important for the Poseidon. The Levelised Cost Of Energy (LCOE) for both devices in both locations ranged from €400–600/MWh, which is high compared to fixed wind. Castro-Santos et al. [63] reviewed the economic viability of floating wind versus wave energy and their combinations. Santos concluded that Floating offshore wind co-located with wave systems are not as economically viable as floating wind systems by themselves.

2.3.3. Wave energy sharing with aquaculture

Finnish wave developer Wello[21] has a diversified business model by marketing next generation technologies to onsite generators. The company will adopt its PowerModule power take-off unit for systems to be installed at fish farms and other remote installations[22].

A group of Chilean companies are analyzing the wave energy potential in the Valparaiso Region, Chile. According to Revista Electricidad,[23] a group of local and foreign companies are working together with the Valparaiso Region's government to evaluate the potential of wave energy of the region, with the specific interest in Robinson Crusoe Island. The collaboration aims to install a wave energy device capable of producing both electricity and desalinated water to aid the aquaculture sector of the region. Zanuttigh et al. [7] explored the technical deployment of Wave Dragon and aquaculture farm off Sardinia Island, Italy, using 8 MUP schemes combining in different ways a fish farm, a wind and a wave energy installation and either a stand-alone or a connected-to-grid solution. They concluded that the combination was technically feasible, with reasonable costs. However, a full techno-economic evaluation was not performed. Wave Dragon are included in one of the case studies in Part 4 below.

Zanuttigh et al. [64] also conducted a study for combined use in the Adriatic. The project examined 12 MUP schemes combining in different ways a fish farm, varying sizes of wind, (floating or fixed), wave energy installation and either a stand-alone or a connected-to-grid solution. The MUP concepts have been ranked accounting for the expected benefits related to production and technological innovation, the impacts on local and costal environment, the installation and maintenance costs, and the risks due to structural, geotechnical, electrical failures, and pollution. The project concluded that the best combination was the stand-alone MUP integrating the fixed wave energy devices, the mini-wind and the fish farm. The preference for the stand-alone solution is mainly given by the large distance of the MUP from the shore, which increases the costs significantly, and by the strong impact that power cables would have on the soft bottom assemblages in this area.

Foteinis et al. [65] conducted a review of mixing wave energy with 6 combinations of Blue Growth, including tourism, and desalination. Foteinis states that “combined offshore aquaculture facilities with WECs would benefit for reduced installation, operation, and maintenance costs, as well as addressing fossil fuel dependence in aquaculture”.

2.3.4. Fixed and floating wind sharing with oil/gas

The ongoing recovery of offshore oil and gas was explored in the Maribe C4 reports,[24] where renewable energy (6 MW turbines) is used to sustainably extract oil using pressured air/water injection. Renewable power is not yet widely used on offshore rigs in this process or for everyday oil recovery operations. However, the technologies behind this process are operating and the use of renewable energy with oil rigs to reduce emissions from gas or diesel fired generation is under active consideration. An early example was the Beatrice platform in the Moray Firth in Scotland where two fixed wind turbines complement the work of the rig. These are operating at the accepted maximum depth limit for fixed turbines of 50 m. Most North Sea rigs lie in far deeper waters. The advent of floating wind turbines opens up new possibilities for oil/wind

[17] https://upwavedoteu.wordpress.com/.
[18] http://cordis.europa.eu/project/rcn/200258_en.html.
[19] www.floatingpowerplant.com/company/.
[20] http://www.pelagicpower.no/today.html.
[21] https://wello.eu/.
[22] ReNews 365, p14.
[23] http://tidalenergytoday.com/2015/10/19/chilean-wave-energy-potential-under-assessment.
[24] http://maribe.eu/download/2487/.

Table 2
Cost of production of desalinated water ($/$m^3$) using a variety of energy sources. *Costs converted from € to $ at €0.8 = $1.

Energy Source	Reference	Cost estimate
Fossil	[70]	0.16*
Fossil	[71]	0.30–1.18
Autonomous production (newer and larger plants)	[72]	0.4–2.8* < 0.96
Off-grid connected RO-PV	[73]	0.183
Electricity and Diesel	[73]	0.166–0.346
Wind	[74]	3.9–6.5 BW 6.5–9.1 SW 5.2–7.8 MVC
Wave energy (WavePiston)	[75]	1.30
Wave energy (Resolute marine)		1.83
SunPower's PV		0.78
Cost of transport of fresh water from land to Greek islands by boat		8.32*

MUPs which are explored by Legorburu et al. [66]. The Norwegian state owned oil company, Equinor (Statoil), is leading this development as a matter of Norwegian government policy. Some Norwegian rigs in deep water, but reasonably close to shore, have already adopted terrestrial renewable sources of power. Floating offshore wind farms moored in the vicinity of oil rigs can supply power both to the rig and for export in large quantities to land, while sharing the costs of infrastructure and operation. Legorburu et al. describe a methodology for identifying the most suitable sites in the North Sea for such a combination.

2.3.5. Desalination combined with other Blue Growth sectors

To date, there have not been many research publications exploring desalination in multiple use scenarios. Desalination needs an accompanying energy source and is energy hungry. Conventional desalination is normally produced by fossil fuels either directly or indirectly, making the process not environmentally friendly. Desalination can be produced using renewables, thus becoming more sustainable. Moreover, renewable powered desalination will benefit from increased social acceptance. However, Ecowindwater[25] installed a (TRL5) 20 m x 20 m platform in Greece from 2012 to 2014 comprising a 35 kW wind turbine with a 10 kW reverse osmosis desalination unit to produce 70 m^3 per day. Further development of this business model is given in part 4 below.

Katsaprakakis [67] examined an offshore wind 'Pumped Storage System'. In times of excess electricity, and where the storage capacity is exceeded, the study modelled the production of desalinated water. The results concluded that the process exhibited attractive financial performance without needing any subsidies". Foteinis et al. [65] conducted a review of mixing wave energy with desalination. Foteinis concluded that "wave energy can directly provide pressurized seawater for reverse osmosis desalination plants, thus achieving significant energy, and reduction of cost and environmental footprint".

He et al. [68], explored the use of "100% off-shore wind power, adopting variable condition optimal control to maintain energy consumption per unit due to wind power fluctuation". A large offshore desalination plant powered by offshore wind increases return on investment of offshore wind farms and increases utilization. Offshore location solves the point source pollution problems caused by on-shore seawater desalination. Tsai [69], also explored large scale desalination powered by offshore wind, gas-turbine and hydroelectric power plants; desalination plants and water-storage tanks and reservoirs are included within the water- supply system. Existing hydroelectric power units were used in combination with offshore wind to assist with peak load. The results showed that the proposed model can fulfil the water requirement of a city the size of Taichung by 2030 at a reduced carbon footprint. The greater expense from desalination could be compensated by the savings accrued from the power sector.

The following Table 2 is a review summary of the cost of production of desalinated water (sometimes referred to as Levelised Cost of Water (LCOW)) from various energy sources. The cost of production is not the same as cost of sale. The cost of sale includes transport costs and other energy related costs, as well as a profit margin. Therefore, cost of production costs are consequently relatively low, and can be misrepresentative of real costs. Furthermore, in small islands, in particularly Greece, the fossil fuel energy used to produce desalinated water is heavily subsidised, thus further distorting quoted production costs of desalinated water. It can be observed from Table 2, that there is a large variation of production costs of desalinated water.

3. Analysis of the Blue Growth business sector and proposed assessment methodology

3.1. Maribe project: introduction and methodology

3.1.1. Maribe project introduction

As part of the Blue Growth initiative of the EC, funding call BG-05–2014 was awarded to Maribe (https://maribe.eu) as a Coordination and Support Action (CSA) project to investigate the economic business case of Blue Growth and MUS and MUP. The primary objective of Maribe was to promote smarter and more sustainable use of the sea through more efficient use of space and resources. It investigated the potential of combining maritime sectors in the same location or on a specifically built platform and paid particular attention to emerging industries that could benefit greatly from the synergies created, increasing their chances of survival and future growth [76]. The Maribe project covered the five 'Blue Growth (BG)' sectors; aquaculture, energy (wave and tide), energy (offshore wind), biotechnology and seabed mining. Maribe also included the four 'Blue economy' (BE) sectors; fisheries, offshore hydrocarbons, shipping and tourism.

3.1.2. Macro assessment methodology

The first four Maribe work packages consolidated understanding of the Blue Growth sector and formed a macro assessment of the business potential. The following is quoted from the Maribe website:

1) WP4[26]: A study on "*Socio-economic trends and EU policy in the offshore economy*", reviewed each sector from a business lifecycle and socio-economic perspective. Policy and planning frameworks were reviewed for each of the sea basins: Baltic basin, Atlantic basin, Mediterranean and Black Sea basin, and the Caribbean Basin.
2) WP5[27]: A study on "*Technical and non-technical barriers facing Blue Growth sectors*", looked at barriers by sector and also by combination and to identify the barriers that exist when two sectors shared marine space or multi-use platforms. Maribe also conducted risk assessment and mitigation assessment for MUP [77].
3) WP6[28]: An "*Investment community consultation*" assesses the current investment environment, as well as best practices and key barriers for investment;
4) WP7[29]: A "*Business model mapping and assessment*" analysed and mapped the business models that lie behind Blue Growth/Economy industries. Fig. 1 presents the 5 BG and 4 BE sectors, and presents examples of companies operating in the sectors. The image visualises how the companies and their related supply chains can have shared and interconnected business models. Fig. 2 presents an example of a generic model for an Ocean energy company using the

[25] www.ecowindwater.gr/ViewShopStaticPage.aspx?ValueId=1995.

[26] http://maribe.eu/blue-growth-deliverables/blue-growth-work-packages/.
[27] http://maribe.eu/download/2581/.
[28] http://maribe.eu/download/2575/.
[29] http://maribe.eu/download/2569/.

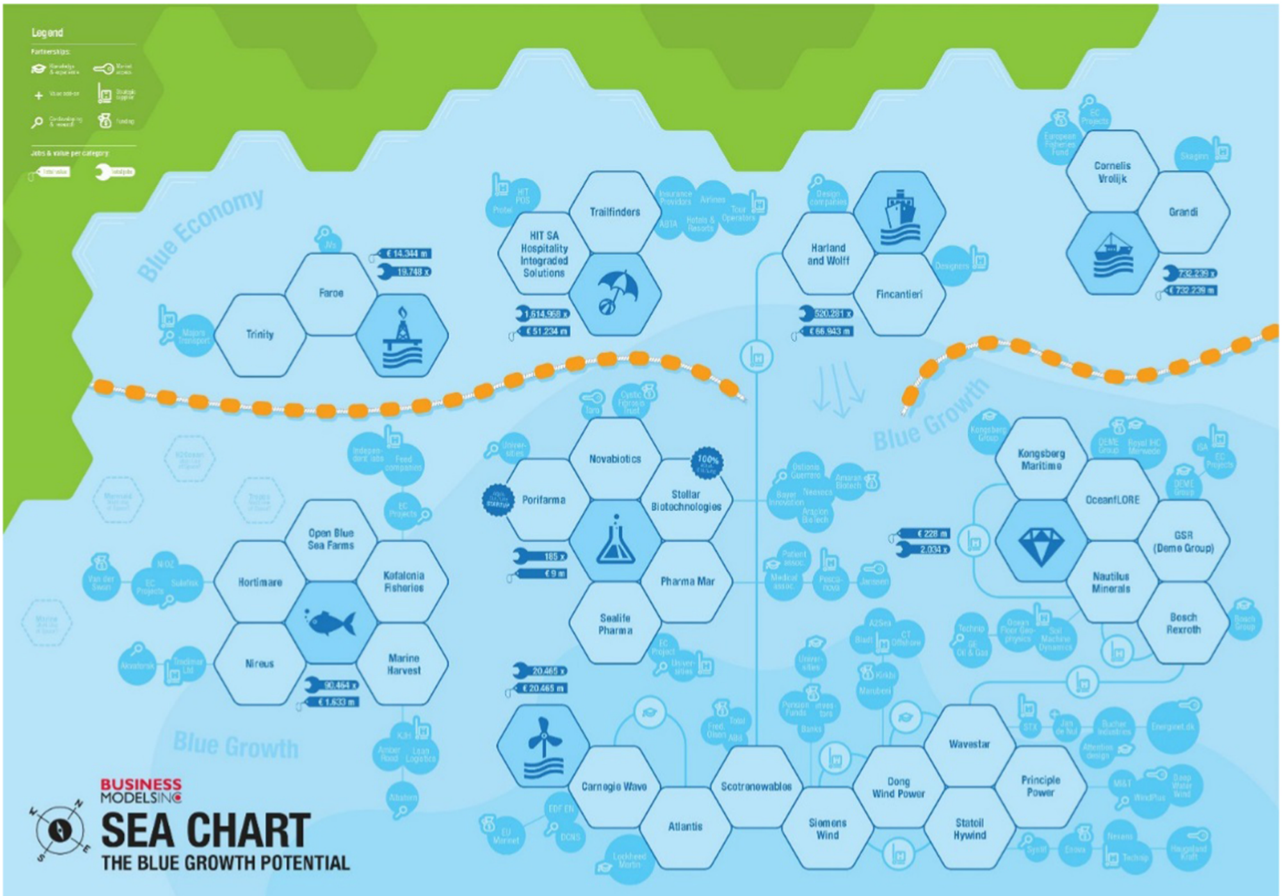

Fig. 1. Five Blue Growth and four Blue Economy sectors presented in an interlinked Business model map: Companies from each sector are presented, and interlinks between the sectors and companies are detailed (image created by BMI Netherland (http://www.businessmodelsinc.com/) for Maribe project, for use in dissemination).

Business Model Canvas.[30] Adoption by BG companies of business model methods at an early stage in development will ensure that their project will develop more successfully to commercial stages.

3.1.3. *Assessment methodology*

Building on the above four workpackage deliverables, the Maribe consortium conducted 4 stages of review and rating exercises to derive a final list of potentially viable BG companies and projects. Therefore, presented here is a novel multidisciplinary methodology for selecting, filtering and ranking business propositions as outlined in Fig. 3.

3.1.3.1. Step 1. Each of the 11 sectors (5 Blue growth + 4 Blue economy) were combined in pairs to form MUS and/or MUP, resulting in a total 69 combinations pairs examined. The 69 combinations were then also reviewed relative to the 4 Maribe basins: Atlantic, North Sea/Baltic, Mediterranean/ Black Sea, and the Caribbean. The potential for each combination pair was rated from a technical, environmental, socio-economic, financial and commercial perspective (the evaluation template[31] rated 1–5 for each criteria, 5 being the highest).

3.1.3.2. Step 2. In preparation for the rating exercise, Blue Growth combinations reports were written covering a wide range of sectors, and possible combinations. Each report contained a justification why there was potential for that combination based on evidence of existing companies in the sector, or the potential based on the expertise of the authors of the reports. Out of the 69 combinations, the 24 highest rated potential Blue growth combinations were selected and published.[32] The Maribe website presents 11 of these promising combinations,[33] which did not make it to the case study stage, either due to lack of companies to match the combination, or the rating wasn't sufficiently high enough.

3.1.3.3. Step 3. The next task was match real Blue Growth company examples with each of the shortlisted 24 Blue Growth combinations. Businesses were contacted to establish their willingness to participate in Maribe as a case study in developing their business models. The most important criteria for acceptance as a case study was that the company (or combinations of companies) would be willing to divulge economic information on the company performance, and future estimated commercialisation costs to the Maribe consortium (under NDA). The requirement to share sensitive information was challenging to many companies and restricted them from participating in the case studies. Eventually, 9 companies were sourced to provide 9 case studies combination concepts.[34] Each of the 9 case studies had a business case report completed for them involving co-creation of the case study including business plan, risk assessment and financial evaluation,

[30] https://strategyzer.com/canvas/business-model-canvas.
[31] https://www.dropbox.com/s/a5paebsom75tzmn/Atlantic%2069%20combinations%20rating.xlsx?dl=0.
[32] https://www.dropbox.com/s/qa61mqw8aqz9hrf/Final%20Combination%20Selection.xlsx?dl=0.
[33] https://maribe.eu/blue-growth-deliverables/case-studies-with-no-company/.
[34] http://maribe.eu/blue-growth-reports/case-studies-with-companies.

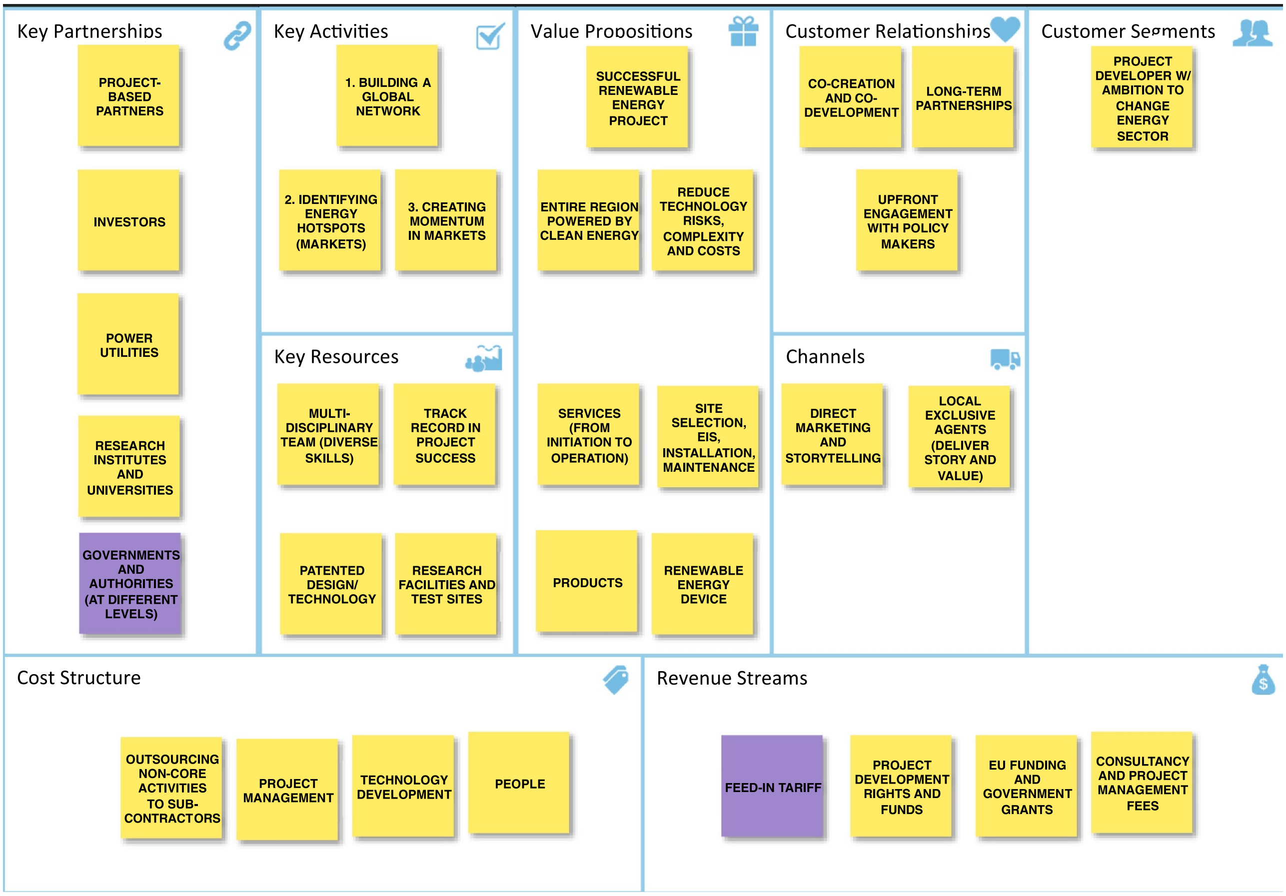

Fig. 2. Generic business model for ocean renewable energy technology developer [78] (image created by BMI Netherland (http://www.businessmodelsinc.com/ for Maribe project for use in dissemination).

followed by expert panel review and ranking.

3.1.3.4. Step 4. The 9 case studies were ranked on performance by indicators. Section 4.1 of the paper describes the filtering process, and then presents the final three case studies selected for discussion here.

3.2. Maribe assessment parameters and indicators

To model the economic performance of the combinations under as consistent conditions as possible, standard economic metrics were used in the techno-economic modelling (Table 3) and Table 4 presents the tariff input rates and other revenue sources used. In addition, the following assumptions were adopted:

- **Comparable point of the product life cycle**
  The project cost model was assumed to occur after the second commercial scale project has been delivered. This is the point in the project lifecycle where costs will have stabilised somewhat, so it can be meaningfully compared with existing commercial marine projects such as offshore wind. On the other hand, this point is not too far in the future so that its cost can be meaningfully extrapolated from the companies' current knowledge.
- **Similar time of build**
  The work completion date was assumed to be 2020, with final investment decision (FID) in 2016. In reality, different combinations will have different timescales but this avoids the uncertainty in predicting changes to underlying costs such as the price of steel and inflation over time.
- **Using consistent weighted average cost of capital (WACC)**

The default WACC value was assumed to be 8.9%, in line with that used by the UK Government Department of Energy and Climate Change in 2016 when assessing energy technologies (Table 3). As an exception, the Greek project used a WACC of 7.9%, due to perceived lower risk due to higher government participation in funding the project resulting in a lower cost of capital. Some commercial offshore wind projects are known to have achieved a lower cost of capital, but it is unlikely that early commercial projects will secure low loan interest rates.

Maribe used 8 model parameters/ indicators to assist in the complex assessment of multiple Blue Growth sector combinations, and their performance relative to each other. Some of these such as LCOO and Cost Comparator are modified indicators, and therefore could be considered novel. These indicators are described in the next sections.

3.2.1. Levelised cost of output (LCOO) for mixed Blue Growth combinations

To enable comparisons that include combinations of one Blue Growth sector with another Blue Growth Sector that have differing products (e.g. wind generated electricity in €/MWh and aquaculture in €/kg), an alternative levelised cost of output (LCOO) was devised by the Maribe project. LCOO is the annualised cost divided by annual revenue and is used instead of levelised cost of energy (LCOE) where annualised cost is divided by annual energy yield. LCOO is expressed as a percentage. As with LCOE, the lower its value, the better its financial performance. Where it is greater than 100%, then the costs are more than the revenue. Its value depends on the sell price of the product, which is different to LCOE where value is dependent only on the cost of product. LCOO is a measure of profit and it is relatively simple to show that (1-LCOO) is mathematically equivalent to net margin. The Maribe project steering committee decided not to use 'industry-standard comparator' for each of the technologies in the combination (e.g. LCOE for

Paper section	Description of method and subtasks of the Maribe Project	
Step 1 Section 3.1.2	Blue Growth Sector review and knowledge consolidation	Macro assessment
	Socio-economic trends and policy; Technical and non-technical barriers; Investment community consultation; Business model mapping and assessment	
	Identification of potential MUS/MPP projects. **69** possible combinations, rated under 5 criteria	
	Socio-economic; Environmental; Technical; Financial; Commercial	
Step 2 Part 3.1.3	**24** highest rated selected.	Micro assessment
	Taken forward to Micro Assessment if match found with existing MUS/MPP companies. Agreement to engage achieved with 9 combinations, many involving more than one company.	
Step 3 Section 3.2	**9** case studies where a business case was developed	
	Business plan development, co-creation with experts and company; Risk Assessment, co-creation with independent review; Financial evaluation, using novel indicators and expert cost evaluators	
	Expert panel review to recommend most promising combinations	
Step 4 Section 4.1	**3** case studies selected for paper	

Fig. 3. Maribe Flowchart describing methodology for selection of most favourable Blue Growth sectors, leading to selection of final 3 case studies for the paper.

Table 3
Standard financial metrics definitions (Dalton et al. [81]).

Metric	Definition
Cost of finance	The amount of money needed to provide the return to debt and equity investors. Calculated using WACC.
WACC	'Weighted average cost of capital' resulting from all sources of investment and ownership.
Simple payback	The time it takes for the project CAPEX and OPEX spend to be recovered from the revenue, ignoring the cost of finance.
Payback	The time it takes for the discounted project CAPEX and OPEX to be recovered from the discounted revenue.
Net present value (NPV)	The difference between the present values of all the cash inflows and outflows. The NPV varies according to the year that is assumed to be 'present'.
NPV (yr −4)	NPV at a point 5 years before the start of operation, where CAPEX spending has commenced without revenue generation
NPV (yr 0)	NPV at the point the project finishes construction work (end of year 0), just before the start of operation (beginning of year 1).
IRR	'Internal rate of return' is the return generated on the CAPEX invested (including costs of capital during construction) by the undiscounted cash flows during project operation. It is also the discount rate at which NPV(yr 0) equals €0.00. hence it provides the maximum financial cost affordable by the project without entering into losses, IRR is recommended to be above 10% to be attractive to bank finance.
Levelised cost of electricity (LCOE)	In some of the Maribe case studies where combination of sectors are energy only (wave + floating offshore wind), LCOE will be used, which is derived independently of any price or tariff[a]. A central scenario for LCOE for fixed foundation offshore wind with FID in 2016 is $€_{2016}$ 131/MWh [79]. This corresponds with the baseline LCOEs in DECC Simple Levelised Cost of Energy Model [80].[b] Levelised Cost of Energy (LCOE) is calculated as "average annual spend"/"average annual energy". Annual spend is the average repayments for CAPEX and any annual costs. LCOE represents the charge to be levied on each Kwh produce in order to recover the total costs involved.

[a] Using LCOE as a comparison indicator should be conducted with care, as explained by Dalton et al. [81], due to the many varying factors inherent in the indicator calculation.

[b] DECC Simple Levelised Cost of Energy Model is designed to show the impact of innovation so its baseline LCOEs are those for FID 2020 if no innovation occurred. They are effectively those for FID 2016.

the energy conversion devices), with the shared costs of the platform or marine space divided between the technologies for the numerator of each, as this approach is only feasible for MUS combinations. One of the paper's cases studies is a MUP, and dividing costs like 'allocating overhead costs in a business' is not so simple. An investor is faced with investing in one project and LCOO as a way of measuring the whole project and not based on an arbitrary spilt. It may well be that one of the combinations is poorer than typical of its sector but by combining with another sector the overall combination is a better investment.

3.2.2. Cost comparator

The 'Cost Comparator'[35] method has been modified by Maribe modellers for the purpose of this project. It compares the project LCOO against that of the project's closest competitor at Commercial phase. The Cost Comparator logic is based on the premise that it *is likely that the investors will not invest if the LCOO is not "At Least as competitive as its*

[35] http://onlinelibrary.wiley.com/doi/10.1002/gas.21809/full.

Table 4
Economic tariff input rates and other revenue sources.

Item	Reference	Values used in case study modelling
Electricity price sold (wind energy) (€/MWh)[a]	[82]	140.0
Electricity price sold (wave energy) (€/MWh)[b]	[83]	312.7
Aquaculture finfish (€/ton)	Price provided by Aquabiotech[c]	5000
Aquaculture seaweed (€/ton)	[d]	1000
Desalinated water (€/m^3)	[e]	2.5

[a] The base FiT for offshore wind is €108.30/MWh in Greece in 2012. A 30% increase is possible on a per project basis (hence FiT = €140/MWh).
[b] UK Renewables Obligation bands list wave below a 30 MW cap as support of 5 ROCs/MWh in 2016/17. A ROC is worth about £ 43/MWh and electricity about £ 50/MWh. Assuming that the generator is a licensed electricity supplier, 1 MWh of wave generated electricity is worth 5 * 43 + 50 = 265.0 £ /MWh (€312.7/MWh). Assume exchange rate is £ 1 = €1.18.
[c] **Aquabiotech** https://www.aquabt.com/.
[d] Price provided by Seaweed energy solutions (SES www.seaweedenergysolutions.com/en). Conservative, due to modelling future commercial project. Price contains several demand uncertainties. Current prices would be rather close to 2000 EUR/ton.
[e] EcoWindWater proposes to set a sale price of 2.5 EUR/m3 to sell the desalinated water. Price covers CAPEX and profit required.

competitor". For example, a project with a specific type of wave device may have an economic performance that looks good against projects with other wave devices but it needs to perform well against the market leading projects producing renewable generated electricity such as offshore wind to actually warrant investment. The Cost Comparator is in %, and values below 100% are positive for the combination showing it to be better performing than its comparator, while those above 100% show it to be worse.

3.2.3. Jobs/km^2

This metric provides a purely socio economic metric, and measures the spatial density of jobs arising from marine space. The space itself is becoming increasingly precious and public funding and investment ever more competitive. Jobs/km^2 (jobs per square km) features infrequently in the literature and data are presented in Table 5. These are job densities for cities. No references could be found for job densities for projects.

3.2.4. Jobs/CAPEX

A search by the authors did not reveal any reference where Jobs/CAPEX metric was used, or statistic results were available.

3.2.5. Profitability Index (NPV/CAPEX)

NPV/CAPEX is another metric not often used in the literature, sometimes referred to as Profitability Index (PI) or Investment Efficiency (IE). In the Maribe project, NPV is normalised against CAPEX, thus allowing comparison of NPV profit returns across a range projects. It is expected that large CAPEX expenditure projects will expect large NPV returns, while smaller CAPEX projects will naturally derive smaller NPV results. Therefore, using NPV solely as a comparison metric between projects of varying size, is disadvantageous to smaller projects. The metric is described amongst a list of other metrics in the following references [87–95]. Unfortunately, accessing the hard data in the papers was difficult, and NPV/capex results could not be sourced for this review. The deep sea and oil industry seem to use the metric more frequently that other sectors. Dalton et al. [96] used a related metric: NPV/MW.

3.2.6. Business plan score

Business plans were rated out of 5: 5 = best, 0 = not good. The ratings were based on assessments made of the submitted plans, rated by Maribe Business plan team in MaREI. The Business plans were based on the Business Model canvas method (https://strategyzer.com/canvas). The canvas consists of 9 blocks, with 2 extra sections added by Maribe. These were: Value proposition, Customers, Channels, Relations, Revenue, Resources, Activities, Partners, Management, Competition, Markets. All three of the paper case studies started the business plan preparation from scratch.

Table 5
Jobs/km^2 from referenced sources.

Reference	Location and details	Jobs/km^2
[84]	Employment Centres and the Journey to Work in Sydney: 1981–2001	2470
[85]	"Tokyo has one of the largest Central Business District (CBD) of the world with 3 million jobs,	58,600
[86–88]	Spain (average jobs/km^2)	293.7
	Barcelona	7828

3.2.7. Risk score

A risk matrix was used based on the likelihood and impact (Fig. 4). The 6 risk categories considered were (quoted by Maribe report):

1. "Operation -all stages"
2. "Economic & Political"
3. "Financial"
4. "Environment"
5. "Socio-Economic"
6. "Health & Safety"

The risk % was calculated as an average of the % of red critical risks to the overall spread of risks of the 6 risk categories.

Each risk was assessed pre-mitigation, and then post-mitigation mitigation. Limitations on risk assessment included risk appetite and/or understanding and/or experience of risk assessment in the offshore by individual companies involved in the Maribe risk identification and risk response strategy (published in Williams et al. [77]).

3.2.8. Advisory Panel score and Consortium Partner score

The Maribe project held one project consultation session in Brussels (called the Advisory Session). Maribe invited 14 advisors to review pitches made by the companies involved in each combination, based on their business plans. The Advisory Panel rated each project pitch based on Business Plan content and delivery of the pitch. The Advisory Panel scores were scored out of 10: lowest 1; highest 10. Details of the panel are available.[36] At the end of the Maribe project, the Maribe consortium partners assigned a review score to each of the case study projects. The scores submitted by the Maribe consortium partners were based on the overall rating of the full Business Case report for each project combination, consisting of the 5 sections of their reports: technical, financial, business, and risk sections. Similar to the rating score method of the Advisory Panel, as above.

[36] http://maribe.eu/2016/05/24/maribe-advisory-sessions-15-16-june-2016-brussels-belgium/.

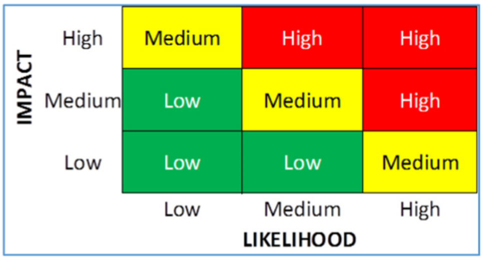

Fig. 4. Risk matrix- Likelihood and Impact.

4. Three case studies: company description, data inputs and case study results

4.1. Results of filtering process

Following macro assessment, nine companies agreed to take part in micro assessment and to provide nine case study combination concepts[43]. For the purposes of this paper, the three most commercially advanced projects were selected to be presented in the paper,[37] (CS 1, 2, 3) as outlined in Table 6. Only the commercial business cases are presented in this paper.[38]

4.2. Case study 1 (CS1): Wave Dragon and SES

4.2.1. Company descriptions

The project is composed of two companies, Wave Dragon and Seaweed Energy Solutions (SES), and the independent organisation Bellona Foundation. Wave Dragon[39] is a private Danish/UK based company working towards the commercialisation of wave energy converter (WEC) technology to extract electricity directly from ocean waves. Seaweed Energy Solutions (SES)[40] is a Norway-based seaweed innovation and business development company. Bellona Foundation is an independent environmental NGO that aims to mitigate challenges of climate change through identifying and implementing sustainable environmental solutions".

Wave Dragon has deployed a grid connected 1:4 scale pilot 237 t wave energy converter (WEC) plant in Nissum Bredning,[41] Denmark. The technology is a floating, slack-moored energy converter of the overtopping type. The current status of the technology is at TRL 6. Wave Dragon features regularly in research literature, with many of the paper topics exploring multiple use [97–105]. The costs and LCOE for these MUP concepts are given in Table 7.

SES features in the following research publications [106–108]. SES has proven capacity to cultivate brown seaweed (*Saccharina latissima* and other kelp genus) on a large scale (long-lines). It provides a platform for the further development of cultivation technology. An industrial scale hatchery was built, and it successfully supplied seeds for 100–150 t wet weight biomass. A pilot farm in Frøya[42] is one of the largest seaweed cultivation farms to date in Europe. Current products are distributed to a niche food industry market. The technology current status is TRL 9 for seaweed cultivation in SES.

[37] Another equally important factor contributing to the selection of the 3 case studies was the fact that all 5 companies were agreeable to have their financial as well as their case study results published.

[38] The pilot business cases were also produced by the Maribe project for each combination, but for sake of length are not discussed in this paper.

[39] http://www.wavedragon.net/ and http://www.wavedragon.co.uk.

[40] www.seaweedenergysolutions.com/en.

[41] http://www.wavedragon.net/index.php?option=com_content&task=view&id=12&Itemid=14.

[42] http://www.seaweedenergysolutions.com/en/commercial-projects/pilot-farm-norway.

Table 6
Details of the three Maribe case studies of Blue Growth combinations presented in the paper and links.

Case Study	Company 1	Technology 1	Company 2	Technology 2
CS1	WaveDragon Denmark	Wave Energy	Seaweed Energy Solutions	Seaweed macro Algae
CS2	Albatern Scotland	Wave Energy	Aquabiotech	Aquaculture Finfish
CS3	EcoWindWater Greece	Desalination	Same as Company 1	Floating wind

4.2.2. Strategic roadmap to commercialisation for Case study 1 combination

The combination is planned to be in Welsh offshore waters (Fig. 5). Wave Dragon will provide calmer waters in its lee for the seaweed farm as well as provide power for a storm submergence system, which will increase the operational days and thus make kelp production feasible in exposed waters (Fig. 6). Wave Dragon has plans for further technology development at commercial farm scale. SES is looking to improve further its harvesting technologies, including mechanisation, and to help increase harvest volumes. The processed seaweed can be sold as a high value material for food and health products (nutraceuticals), cosmetics, animal feed markets, among others.

The commercial development and growth plan for the MUS combination is summarised in Table 8. The pre-commercial *pilot* project at TRL7 will be a single WEC overtopping platform incorporating 16 turbines (4 MW) deployed in front of a small 4-hectares seaweed farm (approx. 80 t/y). The 1st commercial farm at TRL9 will see the project expanding to 9 WECs with seaweed capacity increased 50-fold. A 2nd commercial farm will likewise include 9 WECs with a 4000 t/y seaweed capacity farm at a new site. The business case described here is for the 3rd commercial project at the same site which will see subsequent expansion into 5 farms of 9 WECs (180 MW) and 20,000 t/y of seaweed at total investment of €661 M (Fig. 6). The project will be located: 13 km from shore of Pembrokeshire coast in a water depth of 40–60 m and covering a combined footprint of approx. 3200 × 1700 m. The project will be cable connected to shore by 33 kV cable with inter array connection of 10–33 kV. The moorings for Wave Dragon will be catenary chains/ropes; seaweed string will use chains + ropes. The project technologies will be fabricated at the nearby Port of Milford Haven.

4.2.3. Company perceptions of the advantages of combination

The combination will benefit from an easier licensing process due to the multiple use of space and will also benefit from positive public perception due to the combination of two environmentally friendly products. The seaweed part of the project gains the most from the partnership due to calmer water provided by wave devices as well as ready access to power for storm submergence. Expected cost reductions for either technologies due to synergies in installation, inspection and maintenance operations will be minimal.

Advantages to Wave Dragon

- "Sale of electricity power to seaweed farm"
- "Reduction in operational cost by using the same vessel for both activities".
- "More frequent activities on site: better detection of potential anomalies".

Advantages to Seaweed Energy Solutions

The WEC farm allows more days of operation for the aquaculture venture due to:

- "WEC farm will provide calmer waters by nature of the dampening effect of the devices, which extract energy from the ocean".

Table 7
LCOE for Wave Dragon case studies.

Source	Ref	LCOE	
Performance and economic feasibility analysis of 5 wave energy devices off the west coast of Ireland.	[96]	1–5 MW	€0.30/kWh
		100 MW	€0.15/kWh
Feasibility and LCA for a Wave Dragon platform with wind turbines (at location of 36 kW/m)	[104]	7 MW	1 device €0.083/kWh
		700 MW 100 devices	€0.04/kWh
7 MW Wave Dragon + 2 × 2.3 MW of Wind	[104]		€0.05/kWh

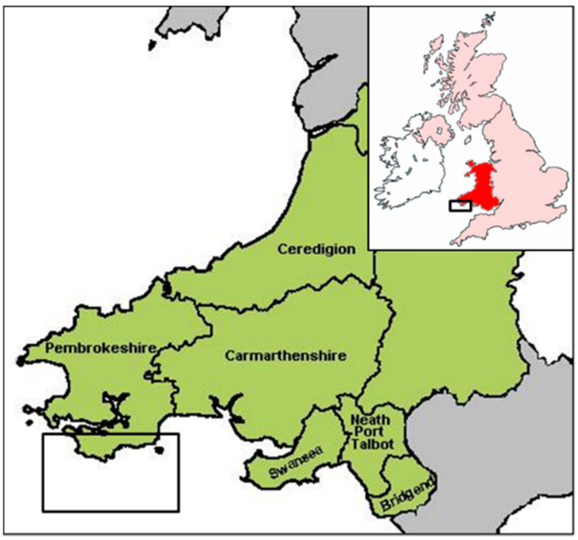

Fig. 5. Location of the combination of Wave Dragon with SES in South Wales, UK.

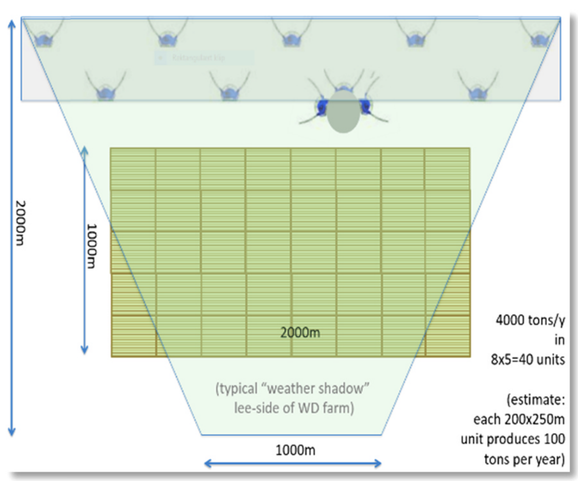

Fig. 6. 2nd commercial farm layout: Wave Dragons at the top and seaweed farm in lee of Wave Dragons.

- "Electricity from the WECs can be used to winch the seaweed farms lower into the water, protecting them from any ill-effects. This will enable them to be located in areas further offshore which would not normally be viable. - larger areas, with deeper and cleaner waters, fewer environmental issues and less conflict of space".

4.3. Case study 2 (CS2): Albatern and Aquabiotech

4.3.1. Company description

"AquaBioTech Group[43] is an international aquaculture consulting and technology supply company located on the island of Malta, operating with clients and projects in over fifty-five countries [109–111]. AquaBioTech uses the Subflex[44] submersible cages technology, as it considers it as well suited to the offshore application in the Mediterranean due to their use of a single mooring point supporting a series of linked cages, resulting in minimised space use and environmental impact, as well as the ability to be submerged below the destructive energy zone of the waves during a storm".

"Albatern[45] is a Scottish based company. Albatern's wave energy device is called the WaveNET[46] (Fig. 7) [112,113]. The energy produced by the WaveNet is relatively small, but is ideal to service small energy project requirements, as well as projects that require autonomous energy supply. Aquaculture farms are an example of an ideal customer."

The current status of both technologies is considered to be at TRL 7. It is based on:

- the proven ability of the SubflexTM cage farming technology used by Aquabiotech and
- the level of testing of the Albatern wave energy devices in Scotland

"Albatern is already testing its device in combination with an aquaculture company Marine Harvest in Isle of Muck, Scotland, at pre-pilot scale (called the Pathfinder project[47]). WaveNET device is positioned slightly away from the cages but in a protected environment. The aim of this installation is to prove the functionality of the system and give a level of confidence that the WaveNET is a secure system and there is minimal risk to the cages, as well as to identify any unforeseen problems that need to be resolved. The technology is yet to be verified in the less energetic Mediterranean where performance is expected to be reduced. A "Hybrid" storage system that will convert and store the wave energy offshore and provide the necessary power on demand is currently also being developed".

4.3.2. Strategic roadmap to commercialisation for case study 2

"The two companies have come together to form a Special Purpose Vehicle (SPV) to provide a one-stop-shop for wave energy enabled aquaculture solutions to provide electricity for energy intensive aquaculture installations", facilitating commercial cage farming further offshore. The SPV's value proposition will be to provide autonomous wave energy power to both existing and new cage farming operations. "Fish can be produced with a vastly reduced environmental impact by utilising the renewable electricity provided by the WaveNET devices. It is envisaged that the WaveNET will also be utilised on more large scale projects, providing power (and potentially potable water) to shore based marine aquaculture facilities in areas where wave energy is suitably abundant and supply of grid-based electricity is expensive or unavailable".

The targeted market stretches across the globe with the SPV initially

[43] www.aquabt.com/.
[44] https://www.subflex.org/.
[45] http://albatern.co.uk/.
[46] www.waveenergyscotland.co.uk/news-events/wave-energy-first-for-scottish-aquaculture/.
[47] https://marineenergy.biz/2016/10/21/scottish-waves-to-power-a-working-fish-farm/.

Table 8
Wave Dragon/SES project roadmap of deployments to full commercialisation.

Company	TRL 8 pre-commercial farm (Pilot)	TRL 9 1st commercial farm	TRL 9 2nd commercial farm	TRL9 3rd commercial farm (Case Study)
Wave Dragon SES	1 WD @ 4 MW = 4 MW 80 t seaweed/y	9 WD; 30 MW 4000 t/y	9 WD; 30 MW 4000 t/y	45WD@ 4 MW = 180 MW 20,000 t/y

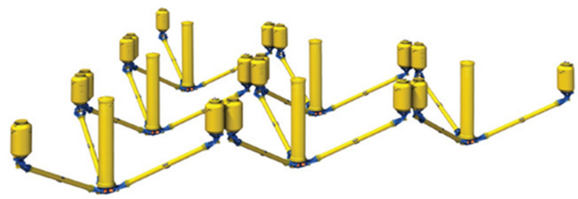

Fig. 7. Concept Drawing of WaveNET Array Configuration (image permission from Albatern).

focussing on the Mediterranean and broader European sea basins where space for inshore aquaculture farming is fully utilised and now requires movement offshore. Fig. 8 presents the possible locations for deployment at various stages of commercial offshore aquaculture development in Malta. "The SPV's intention is to initially deploy a pilot combination of one full Subflex cage system able to produce 1000 t of fish serviced by a WaveNET system and associated Hybrid plant housed in the farm service vessel. Once proven to be successful, a full commercial scale of 6000 t will be deployed and serviced by a much larger WaveNET grid and associated Hybrid plant service vessel, which will then be the commercial demonstrator utilised for the approach to the market".

The Technical Specs of 3rd commercial scale farm for case study 2 comprises of 96 x Series 6 Wavenet Albatern: (7.5 kW) plus Hybrid Plant (total 720 kW rated capacity). The WaveNETs will service 48 Subflex cages (each of 7240 m^3) with target output of 6,000MT per annum – 500 MT/Month. The total footprint of the cages will be 34,560 m^2, and the WaveNET of 48,000 m^2. The project would be located 5–8 km South-East of Malta Mainland in a water depth of 50–70 m. Power from the WaveNETs will be connected to Service Vessel by a cable, with Diesel Back-Up. The WavenNETs and the Subflex cages will have separate moorings: Albatern devices and moorings will be fabricated by made by Albatern. The Subflex Cages and respective moorings will be made by Aquabt/Gili Ocean Tech. Ltd./Marine Contractor.

4.3.3. Company perceptions of advantage of combination

Cost savings are expected to be the big advantage and incentive for both sectors, technologies and companies. These will come primarily in "Installation and Commissioning and O/M due to shared vessels", as well as "Cost savings on Technical Support Team and Overhead (Skippers, engineers, workshop, maintenance, Support/Operational base facilities, Moorings, Key Executives (CEO, MD admin staff)".

The benefits for Aquaculture company are

- "Cost savings on energy due to energy supplied by sustainable power from on site wave resource".
- "Reduced handling diesel fuel in rougher waters offshore",
- "Wave farm to provide protected calmer water for aquaculture cages from rough seas, enabling the aquaculture farm to be further offshore where clean nutrient rich water exists, higher stocking densities due to the depth and limited environmental impact. It is expected that the offshore location will vastly increases aquaculture production capacity and enables the propagation of a wider range of species farmed in the Mediterranean".
- "Farm serviced by wave-energy has marketing edge of renewably powered farm produce with sustainable margin at least in the medium term".

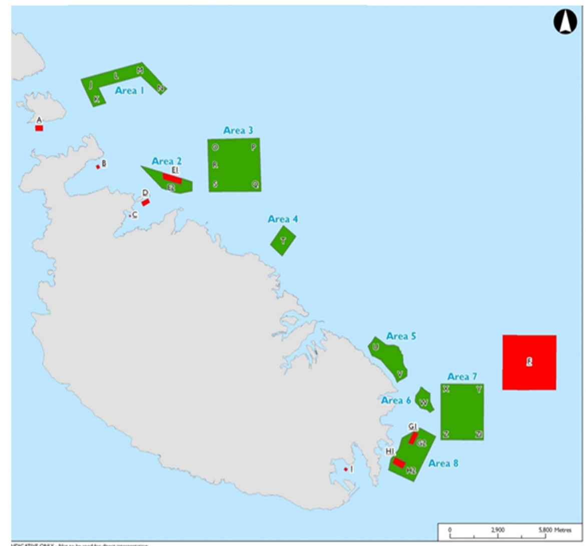

Fig. 8. Planned and existing aquaculture zones of Malta: "Green zone Area 8 is designated for the transfer cages plan, Red zone area F designated as a future aquaculture zone for the offshore cages" [114].

The benefits for Wave energy company are

- "Guaranteed sale of electricity to aquaculture customer".
- "Low electrical losses and cabling costs due to proximity of customer".
- "At full commercial scale, the wave energy farm could provide electricity provision for onshore enterprises and national grids, which are in constrained grid environment with high power costs enabling earlier parity achievement"

4.4. Case study 3 (CS3): EcoWindWater

4.4.1. Company description

EcoWindWater[48] (EWW) is a Greek clean-tech company. EWW value proposition is in addressing the scarcity of freshwater and energy commodities in identified domestic and global markets by delivering both fresh water and electricity in a dynamic configuration meeting customer needs including catering for seasonal fluctuations. EWW's domestic market focuses around several Greek islands especially in the Cyclades complex that experience water stress during the high tourism season and having to import fresh water to meet their needs. The global market stretches to other island locations in the Caribbean and Canaries but also to countries of the Middle East that face extremely high levels of water stress as underground aquifers are depleted and where water management is becoming increasingly costly.

EWW has trialled the Ydriada MUP platform since 2010 at 1:2 scale located offshore environment of Heraclea (Fig. 9) [115–121] and delivered desalinated water to the grid via a pipe at 70 m^3/day maximum capacity. The technology current status is at TRL 6. The corresponding

[48] www.ecowindwater.gr/ViewShopStaticPage.aspx?ValueId=1995.

Fig. 9. Ydriada platform with 35 kW wind turbine in Heraclea *(image permission from Ecowindwater)*.

Technology Performance Level (TPL) is considered to be at TPL7+ and the Investment Readiness Level (IRL) positioning is at IRL 4+.

4.4.2. Strategic roadmap to commercialisation for case study 3

The commercial development plan for the technology has three key stages, currently planned off the coast of Chios Island (Fig. 10):

(I) The first stage is a 800 kW demonstration MUP platform.
(II) The next stage will see the construction of a 2 MW Pilot MUP (2nd generation MUP).
(III) At commercial level, the 2 MW MUP will be optimised with a maximum output of 3360 m^3 per day.

Chios Island offers a few ideal sites with water depths of between 50 and 100 m within few kilometres of shore, which allows extra flexibility to avoid conflicts with other active sectors such as tourism. The Technical Specs of 3rd commercial scale farm for case study 3 comprises of 1 MUP, 250 m × 250 m, consisting of one 2 MW wind turbine and one desalination unit with 3360 m^3/d potable water capacity. The project will be located 2 km off the coast of Chios, Greece in a water depth of 60–100 m. The electricity will be exported to grid via 33 kV/2 MW cable (capacity can increase for multiple MUPs). The moorings for the MUP will be a standard anchor and chain mooring system (e.g. Stevshark Mk5). The MUP and all assembly will be fabricated and installed at Eleusis Port, Athens.

4.4.3. Company perceptions of advantage of combination

Cost reduction are the major tangible benefit, saving space costs, maintenance and power costs. Construction costs savings arise from fabrication and assembly in its upright position at shipyard and towed to offshore location. Its major value proposition offer is that the MUP technology is not geographically/morphologically site-specific, it is mobile and can be moored at various locations avoiding conflicts with other sectors (such as fishing, aquaculture, tourism, leisure (marinas) and port/shipping). The dynamic configurations of the MUP is also totally flexible maximising either water and/or electricity production depending on seasonal needs. Finally, the MUP offers 100% renewable power source with low carbon footprint.

The benefits for Desalination company are (quoted by Maribe report**)**

- "Lower costs than land-based conventional desalination, due to cheaper wind power than diesel".
- "Environmentally friendly chemical-free renewable powered desalination system compliant with EU directives"
- "Mobile site selection process on case-by-case basis working closely with local stakeholders".

The benefits for Wind company are (quoted by Maribe report**)**

- "Energy used at source, therefore low losses".
- "Guaranteed customer for electricity purchase"

4.5. Results

Table 9 presents the essential case study financial inputs. A summary of all the results is presented in Table 14. The following sections give the results for each of the metrics described in Section 3, for each of the 3 case studies, and compares the results to the literature presented in Section 3, if the figures are available.

4.5.1. Levelised Cost of Output

The summary of the Levelised Cost of Output of the combination for each case study is presented in Table 10. CS1 combination with Wave Dragon and SES has the lowest LCOO, 40.2% so, well under the 100% threshold for an attractive project. The results were driven by the two positive factors in the calculation: The Capex cost per MW of the Wave Dragon is comparatively low, benefiting from economy of scale in the large 4 MW unit construction costs, and learning gained in reaching commercial level. The revenue earned over the 25 years of the project was also high, for two reasons:

- The commercial farm contained 45*4 MW Wave Dragon, totalling 180 MW. This is a relatively large amount of electricity in MW for export.
- The use of the highly favourable old UK wave ROC equivalent of €312.7 MWh (see Table 5).

CS2 had a LCOO result of 75%, comfortably below the 100% threshold. The project size is generally smaller in scale, and with all smaller scale projects, CAPEX costs are relatively higher (not benefiting from economies of scale, as in CS1), while revenue is relatively lower, resulting in a less favourable LCOO than CS1. The major player in the combination is aquaculture, contributing to the majority of the capital expenditure costs and the revenue earned. The results indicate that revenue derived from Aquaculture are substantial and are sufficient to cover expenditure and still make a return.

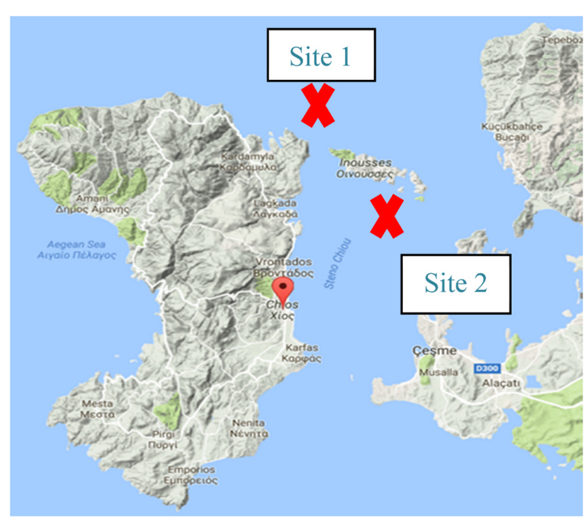

Fig. 10. Chios Island: two possible sites for TRL7 and TRL8 deployments.

Table 9
Summary of the Maribe case study inputs and indicator results for LCOE and LCOO.

Item	CS1 Value	CS2 Value	Unit	Item	CS3 Value	Unit
Project rating, WAV	180	0.72	MW	Project rating, FLW_DES	2	MW
Project rating, AQ	20,000	6000	tonnes / year			
CAPEX	661	26.3	€million	CAPEX	12.9	€million
OPEX	289	287	€million	OPEX	17.2	€million
DECEX	3	0.9	€million	DECEX (net of scrap value)	0	€million
Cost of finance	832	24.4	€million	Cost of finance	15.4	€million
Energy generated	10,800	31.4	GWh	Fraction of water intentionally exported	100%	–
Product produced	400,000	90,000	tonnes	Energy intentionally not exported (wind)	130	GWh
				Water exported	23,179,044	m^3
Electricity price sold	312.7		€/MWh	Electricity price sold (wind)	140	€/MWh
Fish or Seaweed price sold	1000	5000	€/tonne	Water price sold	2.5	€/m^3
				Energy exported (wind)	10	GWh
Simple payback	3.5	2.5	years	Simple payback	6.1	years
Discount rate or WACC	8.9%	8.9%		Discount rate or WACC	7.9%	
Operating for	20	15	years	Operating for	20	years
Payback	5	3	years	Payback	10	years

(WAV = Wave Energy, AQ = Aquaculture, FLW_DES = Floating Wind Desalination).

Table 10
Levelised Cost of Output calculation of the 3 combinations (M = Millions).

	CS1	CS2	CS3
Annual Cost €/yr	€76 M	€22.5 M	€1.13 M
Annual revenue €/yr	€189 M	€30 M	€1.485 M
LCOO	40.2%	75%	76%

CS3 also had a similar LCOO result to CS2 of 76%, an attractive result, again comfortably below the 100% threshold. The majority of the revenue is derived from the sale of desalinated water (only a small amount of electricity is exported), sufficiently profitable to support the annual costs.

4.5.2. Comparator

1) CS1: Wave and Seaweed

CS1 project's revenue was mostly from the wave energy export, and was thus the basis of the comparator. The wave energy LCOE was compared to its rival fixed wind. The LCOE for the Wave Dragon was an attractive €139/MWh (Table 11), The extremely positive CS1 LCOE result was due to:

- 3rd Commercial scale project, a future predicted scenario
- large economy of scales,
- large MWh produced and
- economical CAPEX/MW.

2) CS2 project Wave and Aquaculture finfish
Similar to the method used in CS1, the wave energy production and resultant LCOE were used in the Comparator determination for CS2. The case study is modelling an autonomous project, non-grid connected, therefore alternative power supply would be via diesel. LCOE figures were readily available for wave and its competitor diesel. The comparison of Aquaculture with comparator would be much more difficult, thus the choice of using energy LCOE as comparator for CS2. The LCOE for Albatern wave energy device modelled in the Malta location was very high at €542/MWh (especially compared to CS1 LCOE), due to high installation cost, and low wave energy resource (same FIT was used as in CS1 case). The Albatern LCOE was of similar range to the other published papers of their results. However, in favour for the Albatern device and MUS combination, Malta is an island, and currently has very high costs and LCOE for imported diesel (€ 530/MWh). Thus the result comparator was quite favourable at 102%.
3) CS3 project floating wind and desalination

EWW techno-economic modelling used a sale cost price for 3rd commercial scale production of desalinated water at €2.5/m^3, which is half of the cost of imported water used as a reference. This results in the best comparator of the 3 projects (and of the entire Maribe case studies), at 55%.

4.5.3. Jobs/km²

The jobs statistics used in the 3 case studies are presented in Table 12

The 3 case studies varied immensely in their results for jobs/km², reflecting the diversity of value proposition they offer.

CS1 had the lowest result, at 3.6 jobs/km². The project combines an energy farm and seaweed. Regarding energy farms, besides their initial construction (offsite), they have low maintenance onsite. Wave Dragon in particular forecast high device reliability, due to basic design. Wave Dragon is also an extremely large device, the farm size is large with 45 devices each spaced apart at least 0.5 km distance between devices. Seaweed farms are similar, in requiring very low maintenance: besides initial seeding, only once a month inspections and harvest after 1 year. The combination therefore has the lowest result.

CS2 had a medium result of 205 jobs/km². The aquaculture finfish has much different job intensities than seaweed production. Finfish require daily feeding, and monthly sea lice conditioning. Nets are also

Table 11
Comparator calculation for three case studies.

	Maribe	Competition	Comparator %
CS1	Wave energy LCOE €139/MWh	Fixed wind LCOE €126/MWh[a]	108%
CS2	100% wave energy LCOE € 542/MWh	100% diesel energy LCOE € 530/MWh[a]	102%
CS3	Price of desalinated water provided by MUP 100% wind €2.5 /m^3[b]	Cost of imported water discounted 50% €5.1 /m^3[c]	55%

[a] Modelled by Maribe.
[b] Sale price €/m price determined during Maribe project interview process with EWW to make a profitable case.
[c] Water transportation price for 2017 is €**10.3** + (VAT 24%) for transportation of 320.000 m^3 to anhydrous islands [122]. Maribe decided to halve the value in order to produce a competitive rival cost.

Table 12
Jobs inputs and Jobs/km^2 results for 3 cases studies.

	CS1		CS2		CS3	
	Jobs	**Years**	**Jobs**	**Years**	**Jobs**	**Years**
	Construction		Construction		Construction	
	2240	5	30	3	53	5
	OPEX		OPEX		OPEX	
	801	20	9	15	64	20
	DECEX		DECEX		DECEX	
	0	0	0	1	0	1
	Total	**Total**	**Total**	**Total**	**Total**	**Total**
	3041	25	39	19	117	26
Annual Jobs	3041/25 = 122		39/19 = 2.05		117/26 = 4.5	
km^2	36		0.01		0.008	
Jobs/km^2	3.4		205		562	

high maintenance. Fish are transferred from hatchery to various pond sizes as they mature. Despite finfish farms being spread over a large area, their job intensity remains high. The combination of finfish and wave therefore has a medium job intensity.

CS3 has the highest result of 562 jobs/km^2. The Ecowindwater is a floating platform, 20 m × 20 m, however a single unit will still require 1/2 km space surrounding it; in comparison to the other two case studies it is relatively small in total area. The technologies on board do not require a large job intensity in operations and maintenance. Desalination process is mostly automated; water created and pumped to shore. Floating wind power generation only requires monthly maintenance. Despite the low operations required, the small square km value used in the modelling resulted in the combination of floating desalination powered by wind as a very high job intensity (Table 13).

4.5.4. Jobs/CAPEX

- For CS1, the high jobs created in the large commercial project was offset by the large CAPEX expenditure, producing a medium jobs/ CAPEX result.
- For CS2, the project fared the worst; the relatively low annual jobs created and relatively high CAPEX expenditure created low Jobs/ CAPEX result.
- For CS3 faired the best of the 3 projects; the higher jobs required that aquaculture, with the lower CAPEX cost resulted in the most favourable result of the three.

The jobs/CAPEX has a less extreme variation than Jobs/ Km sq, and thus perhaps a more robust metric. Unfortunately, there are no literature review figures to compare results.

4.5.5. Profitability Index (NPV/CAPEX)

When considering the normal indicators of NPV and IRR, all three projects had a positive NPV and over 10% IRR. However as explained in Section 3.2.5, these results do not easily show which of the projects would be most profitable and so the profitability index allows the case studies to be compared more equally. Results are presented in Table 14.

- CS1 gave rise to a medium result for NPV/CAPEX. Although the NPV was high and recorded a favourable IRR of 22.4%, the very high CAPEX of almost €0.5B, reduced the overall profitability index compared to the other two projects.
- CS2 had the best NPV/CAPEX. Moderate NPV returns, together with moderate CAPEX, resulted in 2.3 times return.
- CS3 returned a low result for the NPV/CAPEX indicator. The project did not return a high NPV, as revenue for the water sale was modest. The CAPEX was relatively high, together with the relatively low NPV returns resulted in the lowest NPV/CAPEX of the 3 projects.

Unfortunately, as no raw data result figures were available for the literature of NPV/CAPEX as explained in Section 3.2.5, it is not possible in this paper to compare the Maribe results and discuss whether favourable or not against other projects.

4.5.6. Business Plan score

The 3 cases studies had similar medium ratings, ranging from 3.25 to 3.82. CS3 Ecowindwater had the highest rating, in part due to close connection and networking with the Business model team, where extensive time was committed by the company in preparing the plan.

4.5.7. Risk score

All three projects received a medium-low Risk score of between 19% and 22% (Fig. 11). Common to all three was the high risk of funding and economic viability. Also common to all was the health and safety issues. CS1 was rated harshest on its operations risk, due to the size of the device and weather windows concerns.

4.6. Summary of results

All three of the case studies have favourable economic potential when examining the conventional indicator results of LCOE, NPV and IRR. However, the vastly divergent technologies involved in the three combinations make comparison of the economic performance difficult. Consequently, one novel economic indicator and four other rarely used indicators were applied to each case study, to enable a more balance comparison of the projects performance, these are summarised in Table 14 (four other minor indicators were presented in the results section, but will not be discussed in the Discussion section: Business Plan score, Risk, Consortium and panel score).

The first and novel indicator was LCOO, with parallels with LCOE for electricity commonly used for comparing energy projects. All of the three projects fared well in this indicator. The second interesting indicator was the 'Comparator', which determined how the combination fared economically compared to its nearest competitor or rival technology. The CS3 desalination project fared best here, due to the competitive cost of desalinated water via renewable energy in comparison to the existing very expensive costs of importing fresh water via boat to remote islands in Greece.

The third interesting indicator was Jobs/km^2. This indicator will perhaps be most important in the future, as marine space becomes more restrictive and public funding more competitive. CS3 fared best in this indicator, as it was the most economical in space, whilst still providing relatively good employment. Results compared favourably with European city averages. The fourth indicator was Jobs/CAPEX. Creating jobs is an imperative in Europe, but the expense to society must be critically assessed. Unfortunately, this indicator is rarely used, so comparison to other projects was not possible in this paper. Of the 3 cases studies, CS3 again fared the best with low CAPEX costs producing the most favourable result.

The fifth and final indicator is NPV/CAPEX expenditure. This indicator made it possible to compare vastly different scales in project size, without the distortion of the capital sums invested. CS2 fared best under this indicator. The relatively high CAPEX costs for the CS1 project penalised the CS1 project. It was the only metric where CS3 fared badly.

Table 13
Jobs/Capex inputs and results for 3 case studies.

	CS1	CS2	CS3
Annual Jobs	122	2.05	4.5
CAPEX €m	661	26	13
Jobs/CAPEX	**0.18**	**0.07**	**0.346**

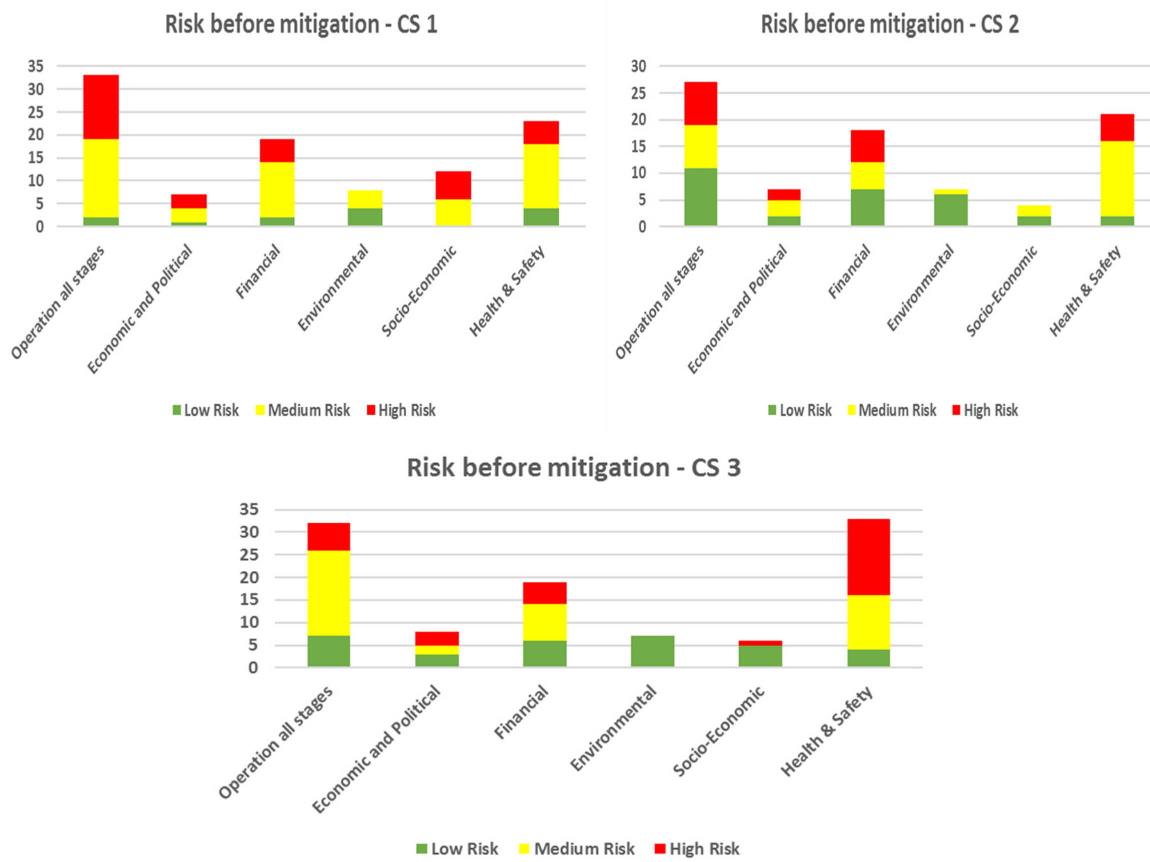

Fig. 11. Risks before mitigation for 3 case studies: CS 1,2,3.

Table 14
Summary table of results for 3 cases study.

Indicator Metric	WD + SES Maribe CS1	Albatern + ABT Maribe CS2	Ydriada + EWW Maribe CS3
CAPEX (€M)	661	26	13
NPV (€M)	916	59	7
IRR (%)	22.4	34.5	13
Jobs	122	2.05	4.5
Occupied area (km^2)	36	0.01	0.008
LCOO ((€/€)%)	41	76	78
Cost Comparator (%)	108	102	60
Jobs/km^2	3.4	205	562
Jobs/CAPEX	0.18	0.07	0.34
NPV/CAPEX (€)	1.4	2.3	0.5
Business plan score (1–5)	3.25	3.79	3.83
Risk score (%)	22	19	22
Panel score	5.81	7.6	7.3
Consortium score	6.3	6.6	7.2

5. Discussion

5.1. Discussion of the review section

The economy of the sea can be divided in two: the mature Blue Economy industry sectors and the emerging innovation of the Blue Growth sectors. The global value of the established Blue Economy is enormous; the OECD [129] estimates that the global gross value added (GVA) of the whole Blue economy is estimated by to grow to more than US$3 trillion (at 2010 prices) by 2030, about 2.5% of total global GVA. In 2010 it was recorded at about US$1.5 trillion when it was dominated by the established industries of offshore oil and gas (34%) and maritime tourism (26%). Ship transport and shipbuilding accounted for 9% with a further 13% attributed to port activities and 11% for marine equipment. Catch fisheries featured at only a 1% share of the ocean economy with a further 5% in fish processing.

It is recognised that two of the four traditional mature Blue Economy sectors (Catch Fisheries and offshore Oil and Gas) have reached peak capacity and are in decline. Shipping continues to grow along with growth in global trade and tourism continues to expand along with disposable income in emerging economies. However, the Blue Growth innovation sectors are targeted in policy to be the main drivers of the new maritime economy. However, in the OECD report [129], the new Blue Growth industries are currently minimal, with only aquaculture and offshore wind showing at less than 1% each. Offshore wind shows the most energetic growth to 2030, rising to 8% of the whole. There has been a concerted drive in public policy to stimulate the potential for Blue Growth. Section 2.1 described 20 years of Global and EC policy and regulation mechanisms with both push and pull policy drivers. In a European context this is based around MSFD and MSP strategies being implemented nationally, regionally and by each sea basin.

Simultaneous to regulation policies, there have been a raft of public funding schemes (both EU and national) to drive Blue Growth. The success of these schemes for Blue Growth is as yet not proven, except in the offshore wind sector where a number of factors have catapulted it to success. A recent initiative of the EC, the Blue Invest platform, is perhaps signalling the sector to be innovative in the sourcing of its future funding. Blue Invest has accumulated an impressive list of investors, and the platform is experimenting in the latest techniques of matchmaking and project promotion – similar to a Dragons Den style format. The multi-use concept is designed both to be a catalyst for marine industries and a way to make efficient use of space and facilities with reduced environmental harm. Section 2.3 presented a state for the art review of the various combinations of Blue growth technologies and their degrees of success.

Aquaculture is a rapidly expanding sector responding to the expanding global demand for protein and food fish. Currently it mainly refers to nearshore aquaculture, which is well established and mature, and in some cases in decline. Aquaculture in Blue Growth is defined as offshore aquaculture which holds large promise, with removal of space constraints, cleaner seas, and much reduced environmental impact. It is an emerging sector facing many barriers, both technological and cost related. It also faces competition from other sources of food protein in the form of wild fish, meat and vegetables. There is also controversy with regards to environmental concerns, and pressure to produce stock both organically as well as sustainably - such as with renewable power. Offshore aquaculture will benefit tremendously by combining technically as well as commercially with other Blue Growth sectors: sharing of the space will provide much needed protection from extreme resource, as well as shared facilities and operating costs.

Offshore Wind Energy is the most rapidly expanding sector in the ocean economy. The technology has advanced rapidly over ten years, increasing output of individual turbines from 3 MW capacity to 10 MW capacity or more combined with increased efficiencies of generating electricity direct to grid. This technology development and economies of scale has meant that the levelised cost of electricity (LCOE) from offshore wind has tumbled from over €300 per MWh to some recent (2017) strike prices below €75 per MWh. In July 2016 ∅rsted Energy (formerly DONG) won the Netherlands auction for an offshore wind farm at Borssele I & II at a price of € 72.7 /MWh (LCOE about €68/MWh) [126]. This excludes transmission costs and development costs were paid by the government. Adding the transmission connection at a (fairly modest) €14/MWh to the costs, giving a total project LCOE of about €82/MWh. In December 2016 Shell and partners won the latest Netherlands auction for an offshore wind farm at Borssele III & IV at a price of €54.5/MWh (25% lower than that achieved by ∅rsted in July 2016 for Borssele I & II). Adding the transmission connection brings project LCOE close to the price of electricity [127,128]. Clearly, offshore wind is approaching a fully competitive level with other forms of electricity generation including fossil and nuclear. Constraints on expansion of the industry are suitable sites for fixed turbine towers and the large areas of marine space needed in possible conflict with other activities. Visual intrusion on seascapes has also been a significant factor in objections to some proposals. The innovation of floating turbines is progressing which, if successful and commercial, will release the industry from many of the site constraints. Floating wind has overcome some crucial technology problems, as well as the very large reduction in development costs for prototypes. Floating wind has now moved past the 'valley of death', and into TRL8 prototype array deployments. The need for offshore wind to share space or combine on platforms is minimal. Yet the benefit it would contribute to other Blue Growth sectors will be significant.

Wave and Tidal Technologies (covered by the term ocean energy) are still at an early stage TRL despite 40 years of development. Examples of fully commercial enterprises are some years away. Tidal stream devices are more advanced with the first arrays installed but their ultimate capacity is relatively small compared to wind and wave with the majority of potential concentrated into a few suitable locations. Tidal barrage systems have been operating for decades (e.g. the La Rance barrage) and are cheap in the long term, but the high CAPEX and extensive civil engineering works are a barrier to investment. Research is still ongoing in this area [130]. The size and apparently ubiquitous nature of wave resource has to date been a key driver in research. Wave energy has failed so far to achieve a potentially commercial power take off (PTO) technology (except for Wave Dragon, which utilizes standard type hydro turbines), and drivers to develop the technology are diminishing, partly because the market for significant renewable energy to the grid is being met by offshore wind. The 2016 JRC Oceans report [124] states that current LCOE of wave energy ranges between €600/MWh and €1100/MWh, with a reference value of about €850/MWh. At the extreme, values can reach up to €1390/MWh in case of a poor resource and can go down to about €440/MWh in case of a good resource. Whilst wave and tidal held equal promise to offshore wind energy 15 years ago, this is not now the case. Confidence in floating wind to fill the remaining gap of remote high energy in deep waters is high, where wave is still yet to succeed in a successful TRL 6 prototype deployment. Thus, the 'valley of death' scenario is increasing becoming a large barrier for the sector, where financial investors either will not fund or withdraw funds when ocean technologies reach this stage. In the light of these difficulties for the sector, ocean energy is diversifying and seeking other partners in Blue Growth to add to its value proposition and help reduce costs and risk. Thus wave energy is combining with aquaculture and even with its rival floating wind, to explore multi-use, with aims to reduce its costs, as well as learn from these more mature sectors. EC funding is particularly favouring this initiative with a number of funding schemes.

The search for synergies between different Blue Growth sectors is hoped to enhance the economic performance of these struggling Blue Growth activities, promoting at the same time a more efficient use of infrastructure and logistical resources. Furthermore, the grouping and combination of activities enables marine spatial planning to facilitate an efficient and environmentally sustainable management of maritime industries, reducing conflicts over the use of marine space and the associated environmental harm. In most cases of multi-use, it is offshore wind which is providing the practical lead in the concept. Active research and trials are underway to combine wind farm areas with catch fisheries and aquaculture. This is largely in response to the need to offset opposition created by displacing established fisheries from such large areas of sea. Offshore wind is setting the standard in community benefit payments to the coastal communities affected by their operations. Unfortunately, many types of multi-use combinations may simply add complexity and hence reduce profitability.

5.2. Discussion of Maribe case study results

Section 3 of this paper presented the results for three of the nine Maribe case studies exploring the viability of multi-use of space and multi-purpose platforms. Each case study presented a combination of two or more Blue Growth sectors. The Maribe project succeeded in securing the cooperation of companies active in the field to provide real data for each of the case studies. The results section of the paper presented the financial data and results using the Maribe metrics. This discussion section compares the results to other research conducted in the field, already described in the Literature review section.

5.2.1. Comparison to Oceans of Tomorrow (OoT)

The Oceans of Tomorrow (OoT) projects were reviewed by Díaz-Simal [48] on behalf of Maribe. It will first be noted that none of the technologies or companies from any of the OoT projects were part of the Maribe studies, as already explained, due to a lack of advancement in the concepts.[49] All the OoT projects conducted their own techno-economic assessment of the concepts, each one concluding that the costs of operations were not viable in the current form. This contrasts to the positive commercial case for the three Maribe case studies presented in this paper, as well as the remaining six in Maribe. The proof of viability is largely due to the economic and commercial expertise contained in the Maribe consortium. The advice from industry resulted in improvements to feasibility by identifying more accurate estimations of CAPEX and OPEX and in refining the project structures.

[49] Only one of the OoT concepts was explored by Maribe, fixed wind sharing with aquaculture, on the basis that a general business case assessment would be performed without the contribution of data by companies. It is worth noting that this case study received one of the higher Maribe ratings, and has been presented in van der Burg [76].

5.2.2. Comparison to other literature case studies

This section will compare the three Maribe case study results with similar case studies found in the literature as presented in Section 2.3. Comparison is only possible for some of the metrics as many used in this paper are infrequently used in academic publications, but they are well established.

- Levelised Cost of Output cannot be compared to other studies as the metric is unique to the Maribe study.
- When the results for jobs/km^2 are compared to the literature review results in Table 5, CS2 and CS3 are similar to the average for jobs/km^2 for Spain. They do not compare to the job density of cities. There are no statistics available to compare to the intensity of other projects. The use of jobs/km^2 metric has to be carefully used, as the area involved can vary immensely and distort results. The CS3 single unit deployment demonstrates how easily the figure can be skewed.
- The comparator metric was the main metric which enabled comparison to other literature sources as it used euro costs per unit quantity; either Euro per kWh for energy, or Euro per m^3 for water. These two metrics are commonly used.

1) CS1: Wave and Seaweed: The Maribe case study LCOE for Wave Dragon is similar to Dalton's [96] LCOE results for 100 MW of Wave Dragon resulting in €150/MWh (Table 7) but higher than Sorenson et al. [123] who quoted a very low LCOE for commercial stage Wave Dragon (as low as €30/MWh). Sorenson et al. also model a 7 MW wave Dragon with two 2.3 MW wind turbines in MUS (LCOE €51/MWh). On the other hand, this is far more positive than that predicted by JRC Oceans report [124] as discussed above. The attractive LCOE for CS1 is in-line with BVGA predictions for 2030, whereby, assuming a LCOE at 2016 of £ 200/MWh, using a LCOE learning rate of 12%, and market growing from 10 MW in 2016–2000 MW in 2030, LCOE could reduce to £ 75/MWH by 2030 [125]. For the fixed wind LCOE, Maribe used the 2016 LCOE of €126.[50] This comparator LCOE resulted in a comparator result with wave energy of 108%. However, the offshore wind LCOE used in the Maribe study is rapidly superseded in a downward spiral as offshore wind costs continue to fall. Despite wave energy resulting in a very attractive LCOE of €139/MWh, it suffers in comparison to its rival offshore wind, which is likely to be as low as €50/MWh. Using these low LCOE, the comparator could increase drastically up to 200% or more.
2) CS2: Wave and Aquaculture Finfish: The LCOE for Albatern wave energy device modelled in the Malta location was €542/MWh (especially compared to CS1 LCOE), due to the proportionally larger cost of installing a small array of devices, and low wave energy resource (same FIT was used as in CS1 case). The Albatern LCOE was of similar range to the other published papers of their results. However, in favour for the Albatern device and MUS combination, Malta is an island, and currently has very high costs and LCOE for imported diesel (€ 530/MWh). The LCOE of €542/MWh compares in magnitude to other very early TRL ocean energy technologies, or technologies with very high initial Capex costs. In a paper by O'Connor et al. [131], the Wavestar and Pelamis had similar LCOE for low wave energy locations of Denmark and Greece (€450/MWh). However, the differences between the two value propositions could not be greater: Wavestar was a 2 MW device, and had a strategy of driving to reliability first, incurring huge Capex costs, and dealing with cost reduction later. Thus, Wavestar prototype had very large LCOE of similar magnitude to Albatern. As stated in the review section, a TRL7 deployment in multiuse of space with fixed wind did not proceed, due to a withdrawal of private funding and licencing problems. EC funding was in place. The failure to progress in this case is a key negative result for the multi-use sector - either the technology is wrong or the market drivers are not strong enough. Albatern, are at the opposite end of the power spectrum providing only 7 kW of generating capacity. Although their LCOE is large, the non-grid connected aquaculture market it caters for can afford it. The diesel alternative costs are the same. Therefore, the comparator result CS2 was quite favourable at 102%.
3) CS3: Floating Wind and Desalination: Statistics for costs for conventionally produced desalinated water are readily available and make comparison to renewable powered desalination viable. Imported water via boat is currently very expensive for non-grid connected Greek islands, at €10.3/m^3. Maribe used half this price as the comparator €5.1/ m^3. EWW techno-economic modelling used a sale cost price for third party commercial scale production of desalinated water at €2.5/m^3, which is half of the cost of imported water used as a reference. Table 2 list costs of production costs of producing desalinated water. The production costs quoted ranging from €0.3–3.3/m^3 are similar to the sale price quoted for EWW of €2.5/ m^3. These costs of production do not include transport costs, other energy costs, or a profit margin. Therefore, the expected sale costs for the water produced should be necessarily higher than the range from €0.3–3.3/m^3. consequently, the comparator figure result of 55% could be considered a worst case result for Ecowindwater and this is an attractive business proposition.

6. Conclusions

This paper has reviewed the policy interventions and supported projects to promote Blue Growth projects and multiple use of space and multi-purpose platforms. The paper demonstrated that there has been a consistent push from the EU to drive the agenda of Blue Growth, and the development of MUS and MUP. At a first glance the idea behind MUS/MUPs is rather simple: two (or more) maritime industries sharing the same space and/or infrastructure. MUSs and MUPs are novel concepts, and as such their development will require either the creation of new business models or the participation and investment from both public and private agents. In order to optimise these investments and make MUS/MUPs commercially viable, a good knowledge of the maritime industries involved becomes crucial. The knowledge of their operational methods, strengths, weaknesses and potential for growth is not only useful for management planning, but also it opens the door for the consolidation of emerging maritime sectors. However, no commercial projects have yet emerged. The common barrier faced by the projects in the review section was that the large scale complex MUP solutions proposed can only be funded with significant subsidy. The high CAPEX and additional costs associated with operation offshore makes many of these systems non-competitive with land based competitors. Furthermore, lack of access to hard data and estimated financial performance creates uncertainty in determining the best value propositions. Moreover, data and results are often presented using economic indicators that make comparison difficult.

Therefore, this paper proposes a novel methodology to filter the many competing concept ideas of Blue Growth, MUS and MUP down to a handful of viable concepts that have made significant efforts to create a robust business case.

The paper then presented the results of three of the case studies conducted by the Maribe H2020 project, which successfully accessed hard financial data, with permission to publish results, and presented the results using a suite of normalised indicators, facilitating the projects comparison. The three cases presented concentrated on the Blue Growth sectors of wave energy, offshore wind energy, aquaculture and desalination. It is interesting to observe that all of the case study business propositions are relatively small niche market propositions. The results indicate that financial support for MUP and marine renewable technologies should prioritise small market technology cases,

[50] https://cleantechnica.com/2016/11/01/offshore-wind-costs-22–126mwh-bnef/.

initially, with the future ambitions of achieving economies of scale and cost reduction in the same way as offshore wind over the last 20 years. Alternatively, policy and investment should support “bottom up” market driven approaches.

Maribe succeeded in economically assessing and comparing divergent Blue Growth combinations by using a suite of economic indicators (metrics) especially suited to comparison of non-related technologies. All three case study projects had economic merits and excelled under different indicators. Based on all the positives and negatives, CS3 project had the most promising results, as reflected in Table 14 where CS3 had the greatest number of highest scoring indicators. The consortium and panellists also rated CS3 as the most promising. The paper concludes that a carefully structured Blue Growth multi-use business can create a profitable operation and provide the jobs and value that Blue Growth aims to provide.

The methodology presented is robust and can be applied in other contexts where private and public organisations wish to invest in companies via grants or venture investments. It is hoped that this paper has demonstrated the scientific benefit of using these metrics, in particular from the perspective of allowing comparison. The macro and micro assessment methods will be particularly useful in other Blue Economy contexts and in other multiple product contexts.

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Data access

Summary data is included in the paper, detailed data is the property of the respective companies and cannot be shared due to contractual restrictions.

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