

Unlocking the potential of macroalgae for a thriving European blue bioeconomy

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Socio-economic impacts of upscaling European macroalgal cultivation and biotransformation

SEAMARK DELIVERABLE 8.4

Sjókovin



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SEAMARK DELIVERABLE 8.4: SOCIO-ECONOMIC IMPACTS OF UPSCALING EUROPEAN MACROALGAL CULTIVATION AND BIOTRANSFORMATION

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Abstract

The overall objective of the SeaMark project is to demonstrate how to scale up innovative seaweed cultivation and processing into price competitive product applications, making the entire supply chain attractive for commercial investments. To reach this objective, it is essential to create innovations across the supply chain and to understand where there is the most potential for improvement to reach economic profitability. This deliverable is the fourth report from the work package (WP) titled 'Conduct Techno-Economic and Socio-Economic Assessments' and presents an assessment of the socio-economic impacts of upscaling seaweed cultivation and biotransformation. The report will analyse the socio-economic impacts, such as on revenue, gross value added (GVA) and employment, of upscaling and biotransformation scenarios and consider the impact on ecosystem services.

Building on SeaMark production processes, this assessment is based on the operations of cultivation companies and estimates the impacts depending on the various biotransformation or processing scenarios. The data used for the assessment is from the previous value chain and techno-economic assessments conducted in the project with supplementary expert interviews where data and information were not available.

The analysis presented in this document is based on two main production setups: a current, labour-intensive model that reflects today's typical practices, and an optimised, capital-intensive model that incorporates cost-saving innovations. The latter is considered necessary for economic viability at scale, given the high labour costs in Europe. These scenarios are assessed at both a regional scale – representing 50,000 tonnes of wet weight seaweed, which is suitable for supporting one large or two mid-sized biorefineries – and a European scale, estimated at 5 million tonnes, which has been selected to represent the sector's full cultivation potential in EU waters.

In the assessment, a combination of two processing pathways is examined: bulk processing, which involves low-cost methods such as fermentation or ensilage, and high-value extraction, which produces more refined products like fucoidan and alginate. For the purposes of this study, it is assumed that half of the seaweed is processed in bulk and the other half through high-value extraction.

In terms of revenue and value added, the regional production scenario is projected to generate approximately €36 million in revenue, with about €17 million contributing to GVA. At the European fully upscaled level, the revenue is estimated at €3.6 billion, and the corresponding GVA at €1.7 billion. These figures are calculated based on cost structures and a standard 15% profit margin,

without relying on speculative market prices. For comparison, the European aquaculture industry generated approximately €4.8 billion in production value in 2023.

Under the regional scale scenario, the effect on employment is estimated to be approximately 106 full-time equivalent (FTE) jobs. Around two-thirds of these jobs are in the cultivation stage, and the remaining third in processing. Within cultivation, employment is relatively evenly distributed across farming, management, hatchery, and harvesting. At the large European scale, the industry could generate around 10,550 FTE jobs.

The study highlights an important trade-off between cost efficiency and socio-economic benefit. While optimised capital-intensive setups significantly reduce production costs – by up to 74% – they also lead to a steep reduction in employment, especially in the total cost of salaries, which may decline by as much as 89%. Conversely, while high-value extraction processing increases both costs and complexity, it also substantially boosts employment and GVA – creating three times as many jobs as bulk processing. However, the analysis assumes that large-scale seaweed cultivation will only be economically feasible under the optimised cost structure, meaning the labour-intensive setup is not viable in the long term and at full scale.

Building on the quantification of ecosystem services conducted in the project, the implications for regulating ecosystem services is also considered. There were some limitations to this ecosystem quantification, and further research is needed to confirm the results. However, using the results from the assessment, we estimated at a regional scale (50,000 tonnes), seaweed cultivation could remove 60–126 tonnes of nitrogen and 5–40 tonnes of phosphorus, helping to combat eutrophication and sequester 2,250–4,950 tonnes of carbon (in CO₂ equivalents). At a European scale (5 million tonnes), it could remove up to 12,600 tonnes of nitrogen, 4,005 tonnes of phosphorus, and sequester 495,000 tonnes of carbon dioxide (CO₂ equivalents) – corresponding to the emissions of 46,000 average Europeans. An upscaled seaweed industry could therefore play a significant role in supporting key European Union policy goals related to climate mitigation and marine environmental protection. However, these regulating ecosystem services must not be considered in isolation. Seaweed potential to reduce climate (Van Den Burg et al., 2023) and environmental impacts by substituting or contributing to lower-impact products should not be overlooked.

Overall, the findings suggest that the European seaweed sector holds significant potential for value and job creation, with a potential of the sector to generate meaningful employment in remote and coastal regions, creating opportunities across a range of skill levels and potentially supporting gender inclusion in aquaculture. This socio-economic assessment can provide an idea on how various development paths of the European seaweed industry can affect socio-economic benefits and ecosystem services in rural coastal communities in Europe.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalents
FTE	Full-time equivalent
GVA	Gross value added
kg	Kilograms
N	Nitrogen
P	Phosphorus
WP	Work package
ww	Wet weight

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1. INTRODUCTION

The overall objective of the SeaMark project is to demonstrate how to scale up innovative seaweed cultivation and processing into price competitive product applications making the entire supply chain attractive for commercial investments. To reach this objective, it is essential to create innovations across the supply chain, and to understand where there is most potential for improvement to reach economic profitability. This deliverable is the fourth report from the work package (WP) titled 'Conduct Techno-Economic and Socio-Economic Assessments' and presents a socio-economic assessment of the impacts of upscaling seaweed cultivation and biotransformation.

The report analyses the socio-economic impacts, such as revenue, gross value added (GVA) and employment, of various upscaling and biotransformation scenarios, and assesses their impact on ecosystem services. The assessment is based on the operations of cultivation companies. The data used for the assessment is from the previous value chain and techno-economic assessments conducted in the project. Supplementary expert interviews were also conducted, where data and information were not available from previous assessments. This assessment can provide an idea on how various development paths of the European seaweed industry can affect socio-economic benefits and ecosystem services in rural coastal communities in Europe. As such, the results of this report provide input into the strategic development plan for the scale-up of the European seaweed industry.

The target audience of this report is the research community, the seaweed industry and policy makers in Europe. The report is organised as follows: The first section considers the potential for upscaling seaweed cultivation and biotransformation, followed by an outline of the methods applied in analysis. The next section presents the socio-economic assessment and the implications of the upscaling scenarios for ecosystem services in Europe. The final part brings together the analysis with discussion and concluding remarks.

1.1 Current state and the need for upscaling

According to the FAO (2024), the global algae production was 37.8 million tonnes, of which almost all was seaweed. Approximately 98% of the production originates in Asian countries (World Bank 2023). Globally, about 97 % of the seaweed production is from aquaculture, whilst 3 % is from wild harvest. In Europe, however, the picture is reversed, where the vast majority is from wild harvest, whilst the production from aquaculture is negligible (less than 1000 tonnes a year) (World Bank 2023). This illustrates that seaweed cultivation in Europe is in its infancy, with very limited production.

Previous assessments (D8.2, 2023; D8.3, 2024) delivered by the SeaMark project have emphasised the critical need to scale up

cultivation to achieve economic viability (See also D8.5, 2024; D8.6, 2024). However, there are still several barriers which impede the growth and hamper the economic feasibility of the sector, including challenges related to licensing, food safety standards, breeding and technologies.

Despite the challenges facing the sector, the European market for algae-based products is projected to grow significantly, with some estimates suggesting production could reach 8 million tonnes by 2030 (European Commission, 2022). Driven by the green transition, seaweed is increasingly seen as a sustainable alternative in sectors such as food and nutrition, cosmetics, pharmaceuticals, biostimulants and animal feed, and biomaterials (e.g., packaging and textiles). Rising consumer awareness of climate change, interest in plant-based diets, and corporate sustainability commitments are among the main reasons for the increasing demand for seaweed-based products. The European Union also sees seaweed farming as a key pillar of its blue bioeconomy strategy. Strategic EU policies, including the Strategic Guidelines for Aquaculture 2021–2030 (European Commission, 2021), the Food from the Oceans report (European Commission, 2017), the European Green Deal, and the Farm to Fork strategy, have all emphasized the role of seaweed in advancing climate neutrality, food security, and sustainable resource use.

The European Commission has also highlighted seaweed's role in restoring marine habitats and reducing land-use pressures. The communication on a Strong and Sustainable EU Algae Sector (European Commission, 2022) further underscores seaweed's potential to transform environmental challenges into economic opportunities. The strategy recognizes the growing interest from entrepreneurs, research, and innovation as a momentum to harness Europe's seaweed potential in the coming decade and concludes that "Europe in a very good position to harness its algae potential over the next decade" (European Commission, 2022).

There is significant potential for upscaling seaweed cultivation in Europe, both in terms of spatial availability and market demand. While some EU marine regions - such as the Mediterranean and Black Sea - are not well-suited for seaweed farming due to limited nutrients, a significant share of European waters remains viable for development. According to Macias et al., (2025), an estimated 1.5 million km² of water is potentially suitable for intermediate species and over 1 million km² for cold-water species. Macias et al., (2025) estimate that when using a precautionary upscaling scenario, as proposed by van Oort et al (2023), utilizing just 1% of a suitable area could allow a production of 5 million tonnes of seaweed per year in European waters. This is a considerable increase compared to the current EU production of 0.3 million tonnes per year and could substantially contribute toward meeting the projected demand of 8 million tonnes per year 2030 (European Commission, 2022). Beyond cultivation, seaweed also holds strong potential for biotransformation into high-value

products such as food, animal feed, bioplastics, biofuels, and pharmaceuticals. And as the industry is still in its early stages, there is great potential for innovation in cultivation technologies, site selection strategies, and circular bioeconomy integration, making this an interesting area for investment and policy support.

Although cultivated macroalgae can improve marine environmental quality by assimilating nutrients and potentially mitigating eutrophication (Kotta et al., 2022), the ecological impacts of large-scale nutrient assimilation would have to be carefully considered. Large scale and intensive cultivation could potentially disrupt nutrient ratios, phytoplankton dynamics, and food webs (Bach et al., 2021; Sheppard et al., 2023). Therefore, robust environmental impact assessments are crucial to ensure the sustainable development of the sector to avoid undesirable ecological impacts.

2. METHODS

Socio-economic assessment is a systematic evaluation of social and economic impacts of a given activity, policy, or industry on communities, stakeholders, and broader society. In the case of the developing seaweed industry, it can serve as a tool to identify the benefits and trade-offs associated with its development. Through socio-economic analysis, it is possible to assess the potential for job creation, income generation and regional development. Moreover, such analyses support evidence-based decision-making (Rodrigues & Rituerto, 2022) by highlighting how different value chains and market pathways may influence local economies. As such, understanding the socio-economic dimensions of the sector can help ensure that industry growth aligns with sustainable development goals (Alleway et al., 2019; FAO, 2021).

The basis for the calculations of the socio-economic effects has been the characterisation of production process (D8.1, 2022), value-chain analysis (D8.2, 2023) and techno-economic assessment (D8.3, 2024) performed in the SeaMark project. The purpose of this assessment is to evaluate the impact of an upscaled seaweed cultivation and biotransformation in socio-economic terms by estimating the effect on revenue, GVA and job creation. To support this, biotransformation and cost structure scenarios have been defined as to serve as the foundation for the socioeconomic assessment. one at regional scale and one at the European scale. These will be described below.

2.1 Current and optimised cost structure

Socio-economic impacts are highly dependent on the production setup of a given sector: a labour-intensive setup typically results in high job creation, whereas a capital-intensive setup leads to significantly lower levels of job creation. The current production set-up in the seaweed industry is quite labour-intensive. However, there is a broad recognition in the industry that high European labour costs necessitate a shift towards a more capital-intensive production setup to reduce labour costs. This shift in production setup has

been a major focus area in the SeaMark project, with a key objective of the value-chain and techno-economic analyses being to explore avenues for reducing costs, thus creating a more optimised and sustainable cost structure. The assumptions behind the improvements are made in collaboration with relevant industry partners and literature. To illustrate the above, two scenarios have been selected to calculate the socio-economic effects of the seaweed cultivation and processing setup:

1. **Current labour-intensive cost structure** (data mainly sourced from the value-chain analysis).
2. **Optimised capital-intensive cost structure** (data mainly derived from the techno-economic analysis, assuming full implementation of cost-reducing measures).

Where data gaps exist—particularly for scaled-up, high-value processing—supplemental estimates have been made in collaboration with industry partners in the SeaMark project.

2.2 Biotransformation scenarios

The socio-economic effects also heavily depend on the level of seaweed processing. High-value processing normally implies a higher job creation and higher GVA.

SeaMark develops 12 products from cultivated seaweed biomass. The SeaMark flagship products are fibre, pig feed supplement and green alginates (See Figure 1). The production processes of these products have been described in D8.1.

To illustrate the different outcomes of processing, two distinct processing scenarios are compared:

1. **Bulk processing**, which is low level processing like fermentation or ensilage. An example could be the product used in the flagship product of the pig feed supplement (P5).
2. **High-value extraction**, which refers to processing the biomass into refined products like alginate, fucoidan or beta-glucan, as in the SeaMark products of P1, P2 and P7. Since these processes are relatively similar in terms of production steps, labour requirements and costs, the calculations have been conducted with average costs for the productions.

2.3 Upscaling scenarios

Lastly, the assessment will be conducted in two production scales. The first scale is to estimate the socio-economic effects of a regional upscaling, while the latter scale is for a full European wide upscaling:

1. **50,000 tonnes** wet weight (ww) seaweed, which is the value we have selected to represent a regional level upscaling. This is also considered a good resource base for an adequate size biorefinery.
2. **5 million tonnes** wet weight seaweed, which is an estimate of the full potential for seaweed cultivation in EU waters as explained above (Macias et al., 2025).

2.4 Assumptions about the profit ratio

In both the current and optimised cost structures, profitability is a key challenge. In the current production setup, costs are often too high to generate profits, leaving zero or negative profits. In contrast, an upscaled production with an optimised setup would make the industry profitable but would push down the sales prices, and thereby, revenue and profits.

To account for profit dynamics and supply effects on the market, the profits are calculated as a markup profit of 15%. This approach takes into consideration the expected market adjustment: as the industry is scaling up, the sales prices will continue to fall, leaving a normal profit ratio. While this method ensures a realistic projection of the upscaled optimised scenario, it inaccurately assumes a positive profit in the current production setup, which clearly is not the case. This has no impact on the calculations of job creation, but it means that the revenue and GVA is likely overestimated in the 'current' scenario.

2.5 The scope of the assessment

The scope of this socio-economic assessment covers all the steps in the cultivation process as well as the processing of the seaweed. It is important to note that the assessment ends at the ab-works stage, which means that it does not include subsequent stages, like marketing, sales or distribution. Most of the products in this analysis are intermediary products that will be used as raw materials in other value chains. Examples include fermented seaweed, alginate and fucoidan, which are usually not final consumer products.

2.6 Consequences of the upscaling assumptions

In this section we will discuss the consequences for the socio-economic impacts.

2.6.1 Scaling Seaweed Cultivation: The Trade-off Between Cost Efficiency and Socio-Economic Outcomes

As outlined in the methods section, the socio-economic effects of an upscaled seaweed sector are highly dependent on the production setup, where labour-intensive and capital-intensive setups may generate comparable revenues and GVAs, while their job creation may differ substantially. To analyse these effects, this assessment evaluates two scenarios. The 'current' scenario is based on the existing production setup for cultivating seaweed and the 'optimised' scenario, taken from

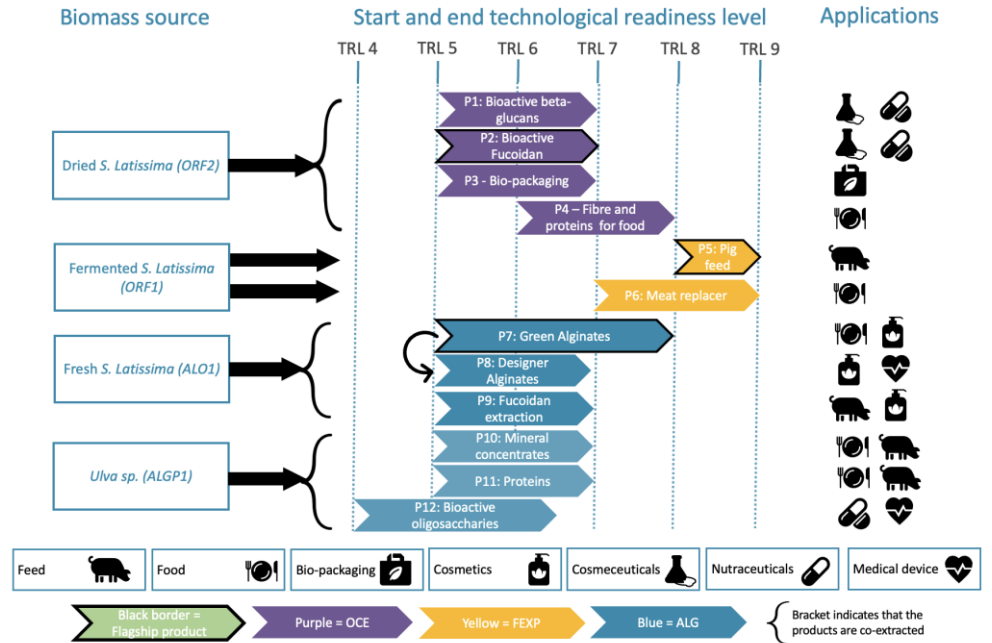


Figure 1: An overview of the SeaMark products, illustrating their relationships, biomass source, start and end technology readiness level (TRLs), and applications. SeaMark Flagship products have a black border. The brackets indicate that the products are co-extracted in a biorefinery process. Purple products are produced by Oceanium (OCE), yellow by Fermentation Experts (FEXP) and Blue by Algaia (ALG). (Note: A medical device is any article that is used to diagnose, prevent, mitigate, treat., or cure disease or other conditions, e.g. dressings for wounds) (Source: adapted from SeaMark D8.1)

the techno-economic analysis, assumes full implementation of cost-reducing measures, e.g. related to seeding, harvesting and processing technologies. Figure 2 compares the cost structure of the current and optimised scenarios for seaweed cultivation within the SeaMark project. The left side shows the current costs, while the right side depicts the optimised cost structure after the cost-reducing initiatives have been implemented.

As illustrated in the figure, the cost reduction from optimising the cultivation process is estimated to be around 70%, a significant and necessary reduction. These changes in the cost structure can be seen in the various production stages, for example, the figure shows a significant drop in the harvesting costs. Similarly, within the categories, the cost of salaries declines relatively more than other expenses.

These changes in the cost structure have many implications on the value chain and on the socio-economic outcomes. Notably, the cost reduction makes not only the seaweed cultivation profitable but also lowers the cost of the processing of the industry's most important raw material - seaweed - hence making that part of the industry more profitable. However, it also reduces the overall job creation, due to the shift from labour to capital. Finally, assuming a fixed production level, it reduces both the revenue and the GVA of the sector. This trade-off between efficiency gains and socio-economic benefits represents a key challenge for the upscaling of the

industry. While essential for competitiveness, the transition to capital-intensive production fundamentally alters the sector's economic profile and employment potential.

The same trade-off can be seen in the processing part of the value chain, looking at two different biotransformation scenarios: bulk processing and high-value extraction. Figure 3 compares cost structures of current and optimised scenarios in the context of bulk processing the seaweed. The left side shows the current costs, while the right side depicts the optimised cost structure after the cost-reducing initiatives have been implemented.

As above, the projected cost reduction is around 74 percent, while total salaries are reduced around 80 percent in the optimised cost structure. In comparison, Figure 4 compares the change in the current and optimised cost structure for high-value extraction. Here, the overall cost reduction is calculated to be similar to bulk processing, around 74 percent, but the reduction in costs of salaries is even steeper, around 89 percent.

This highlights the transformative cost reductions required to make the industry profitable, but at the same time, this underscores the reduction in job creation that accompanies these efficiency gains.

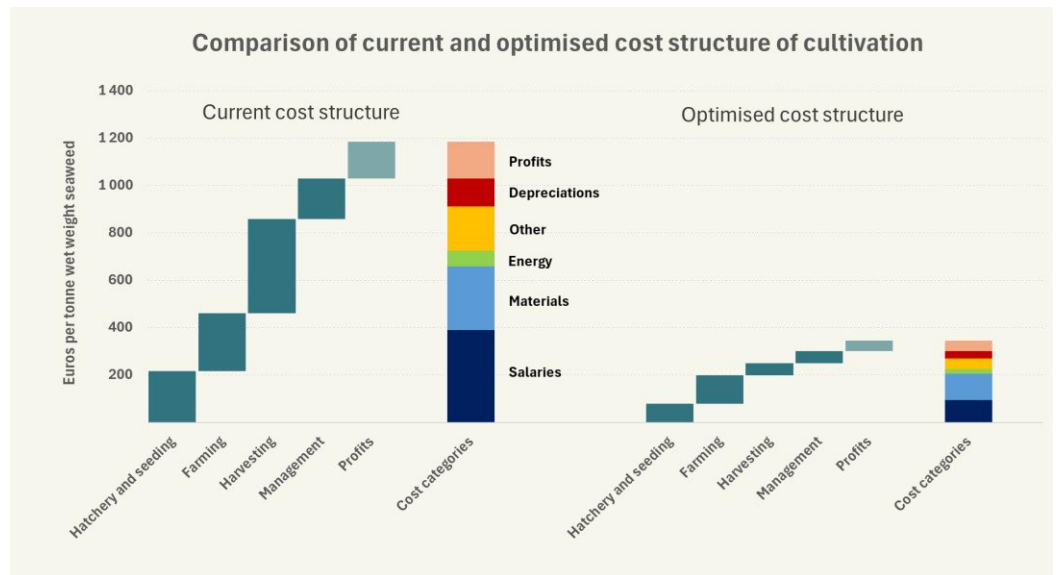


Figure 2: Distributed cost structure along the current and optimised cultivation steps

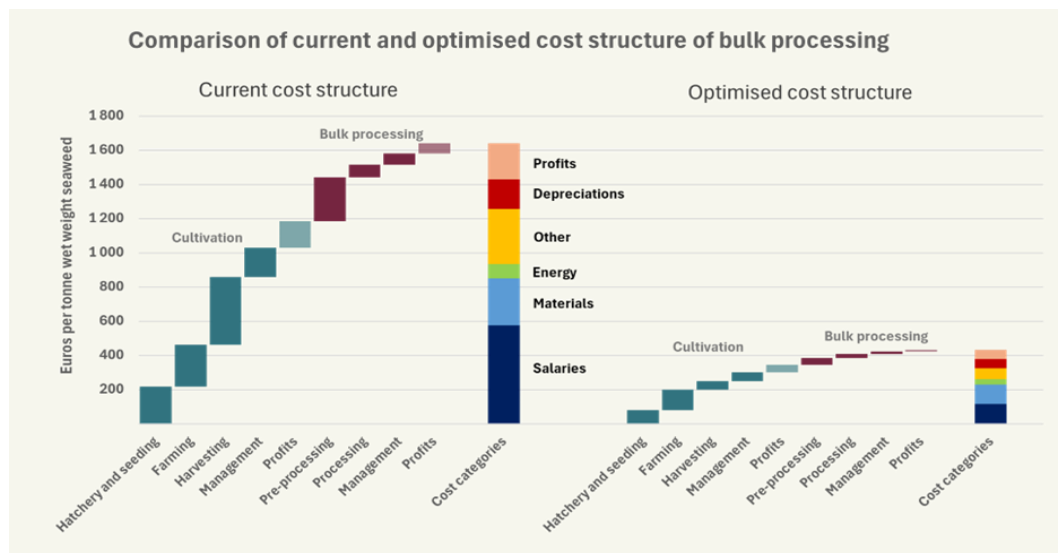


Figure 3: Distributed cost structure along the current and optimised bulk processing steps

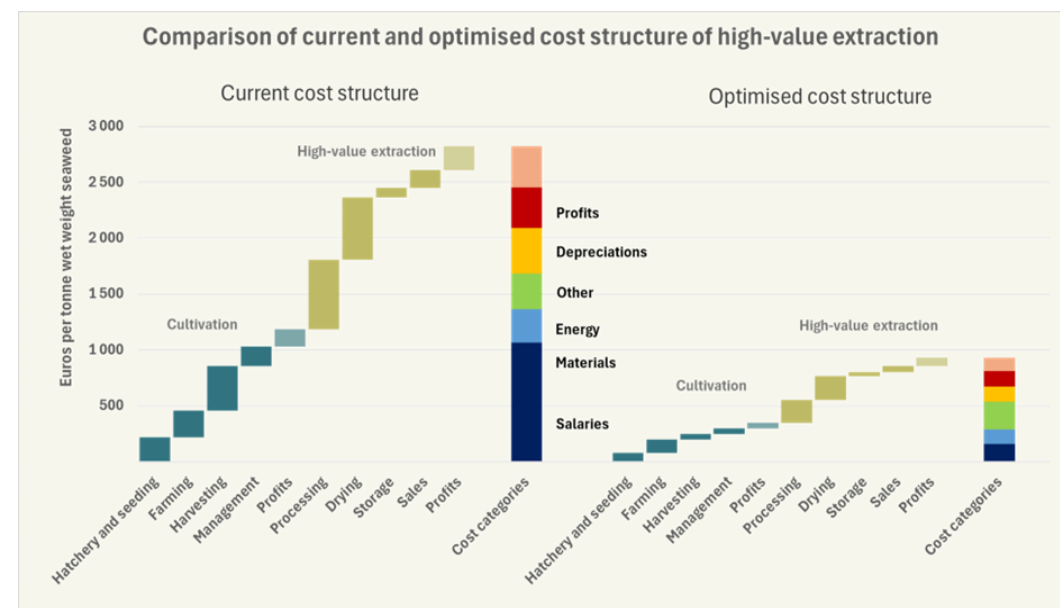


Figure 4: Distributed cost structure along the current and optimised high-value extraction steps

2.6.2 High-Value vs. Bulk Processing: How Processing Level Shapes Socio-Economic Outcomes

In this section, the following calculations of the socio-economic outcomes assume that there will be no large-scale seaweed cultivation based on the current production setup, as this is not economically feasible. Accordingly, processing scenarios are only analysed against the optimised cost structure, where all the cost-reducing measures have been implemented.

Figure 5 contrasts the socio-economic outcomes of low-level (bulk) and high-level (high value) seaweed processing under the optimised scenario. On the left side is the bulk processing, and on the right side is the high-value extraction. The value added to the final product is far higher for the high-value extraction compared to the bulk processing. In addition, the salaries and thus job creation is three times higher in the high-value extraction compared to the bulk processing.

This illustrates the importance of the assumptions behind the socio-economic calculations, that if the seaweed is bulk processed, the impact on GVA and job creation is far lower than in a high-value extraction scenario.

In the following calculations of the socio-economic outcomes, the assumption is that there will be a mix of processing levels, where half of the seaweed will be bulk processed while the other half will go into high-value extraction.

3. SOCIO-ECONOMIC IMPACT ASSESSMENT

The following sections discuss the results from the socio-economic assessment and compare it with a similar assessment from *Seaweed from Europe* (Vincent et al., 2020). The last section discusses the ecosystem services provided by a full-scale seaweed industry in Europe.

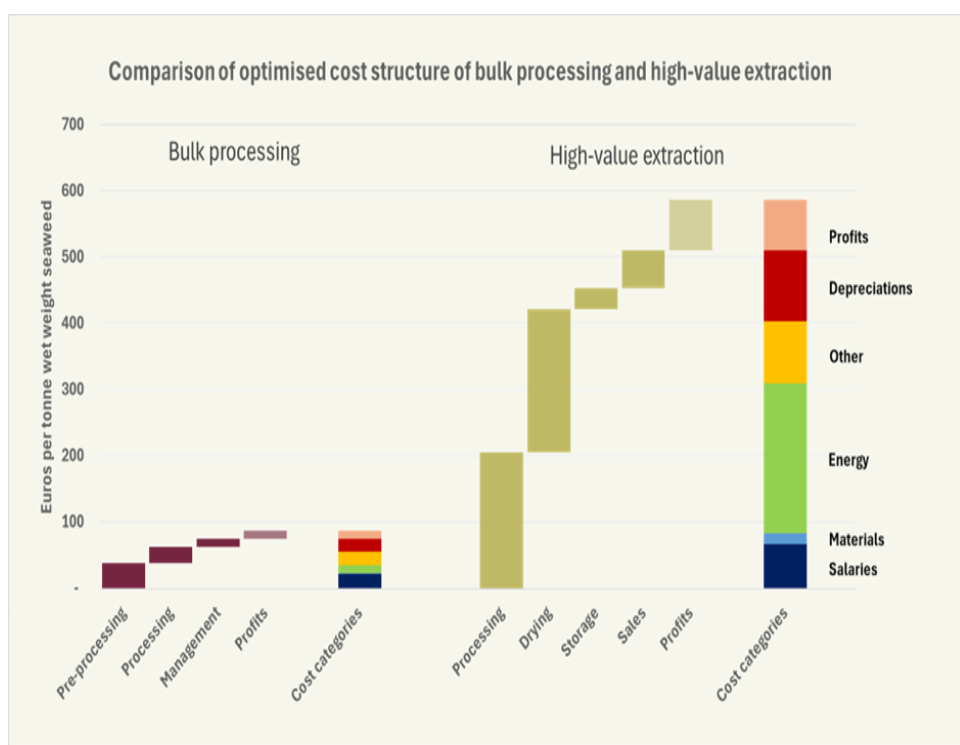


Figure 5: Distributed cost structure along the current and optimised high-value extraction steps

Employment Impacts at Regional and European Scales

Table 1 presents the key findings from the socio-economic assessment, focusing on the direct employment in the seaweed sector across the production steps for the regional level as well as European scale.

In an optimised seaweed industry, a region with a production of 50,000 tonnes of wet weight seaweed would require around 106 full-time equivalent (FTE) jobs, where two thirds of the jobs would be in cultivation and one third in processing. The ratio between cultivation and processing is based on the assumption that half of the seaweed is bulk processed and the other half goes through high-value extraction. If all the seaweed went into a high-value extraction, total employment in processing would nearly double. High-value processing employs significantly more workers than bulk processing, emphasising its social importance.

Table 1: Estimated direct employment in the seaweed sector across production steps for regional and European scale.

Direct employment	Hatchery	Farming	Harvesting	Management	Bulk processing	High value processing	Total
REGIONAL SCALE							
50,000 tonnes	15	22	15	19	8	27	106
Optimised practice							
EUROPEAN SCALE							
5,000,000 tonnes	1,530	2,150	1,470	1,870	810	2,720	10,550
Optimised practice							

Within the cultivation segment, the job creation is fairly evenly distributed across activities, with 22 in farming, 19 in management, 15 in hatchery and 15 in harvesting.

Scaling up to a full European production capacity of 5,000,000 tonnes wet weight seaweed – 100 times the regional level – gives us an impression of the full impact of a mature European seaweed industry. At this scale, the industry would employ around 10,500 people, around 66 percent in the cultivation part and the remaining in processing.

In comparison, in 2023 the aquaculture industry in the EU employed approximately 52,000 people (Eurostat, 2024).

A comparable socio-economic assessment was conducted by Seaweed for Europe in 2020 under the title "*Hidden Champion of the Ocean: Seaweed as a Growth Engine for a Sustainable European Future.*" Comparing the two assessments offers useful insights into both their similarities and differences.

Figure 6 presents a side-by-side comparison, with the SeaMark assessment on the left and the Seaweed for Europe (Vincent et al., 2020) assessment on the right. While the value chain steps are structured somewhat differently, they largely cover the same components of the seaweed production process.

Both assessments estimate that the cultivation stages generate approximately 14 full-time equivalent jobs per 10,000 tonnes of seaweed – a notably consistent finding. The major

difference is in the processing segment, where the SeaMark assessment has a significantly lower estimate compared to the *Hidden Champion* estimate. Here, it should be noted that if the SeaMark estimate was based solely on a high-value extraction scenario, the assessments would be more similar.

The *Hidden Champion* assessment also includes additional value chain steps such as *Marketing & Sales*, which are not explicitly included in the SeaMark assessment, although *Management* is included in the SeaMark assessment. Furthermore, *Hidden Champion* includes *Distribution*, which is not included in the SeaMark scope, since the assessment ends at the factory gate stage.

While the total number of jobs is of considerable interest, the upscaling of seaweed cultivation could generate employment in coastal regions where opportunities are otherwise scarce. Beyond the total number of jobs, the sector will need to fill a wide range of roles across the value chain – from cultivation and harvesting to processing, logistics, research, and product development – resulting in job creation for both skilled and unskilled labour. Importantly, several stages of production demand a more educated workforce, which not only fosters local capacity building but also creates opportunities for greater gender inclusion, particularly for women in the aquaculture sector.

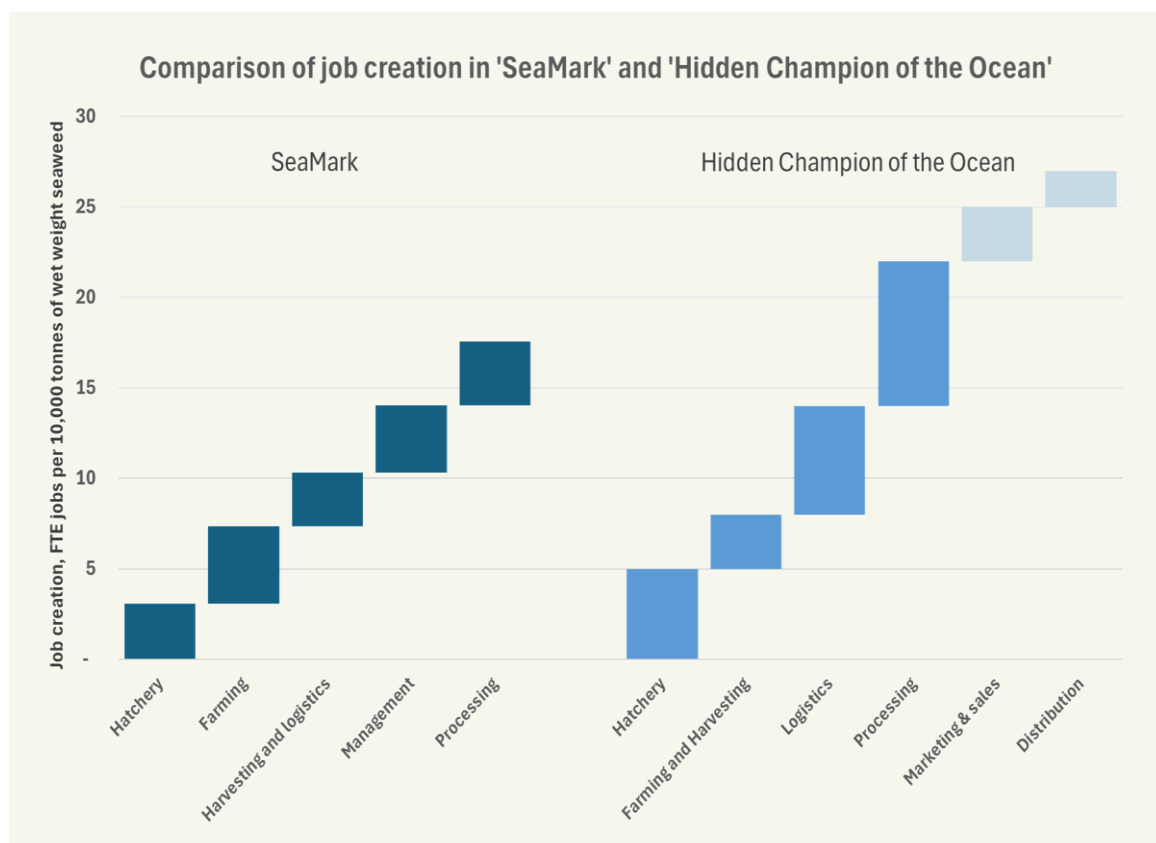


Figure 6: Comparison of estimated job creation across the value chain in this assessment and hidden champion

Table 2: Estimated revenue and GVA in the seaweed sector at regional and European scale.

	Revenue (million €)			Gross value added (million €)		
	Cultivation	Processing	Total	Cultivation	Processing	Total
REGIONAL SCALE						
50,000 tonnes	17	19	36	9	8	17
Optimised practice						
EUROPEAN SCALE						
5,000,000 tonnes	1,730	1,890	3,620	850	820	1,670
Optimised practice						

3.2 Impacts on Revenue and GVA at Regional and European Scales

Table 2 presents the estimated revenue and GVA for the seaweed sector at both regional and European levels.

At the regional level, the total revenue from producing 50,000 tonnes of wet weight seaweed is estimated at approximately €36 million. This revenue is relatively evenly split between cultivation (€17 million) and processing (€19 million). The figures are calculated based on the total cost of cultivating and processing, with a 15% profit margin added. Importantly, this approach does not rely on assumptions about future market prices for seaweed but is instead grounded in cost estimates and a standard profit rate.

Based on the cost structure, it is calculated that around half of the revenue contributes to GVA, meaning that roughly €17 million of the €36 million ends up as GVA.

Extrapolating to the European level, based on a production of 5 million tonnes of seaweed, the sector is projected to generate approximately €3,6 billion in revenue, with around €1,7 billion in GVA.

In comparison, the aquaculture industry in Europe had a production value of around €4,8 billion in 2023 (Eurostat, 2025a).

3.3 Environmental Benefits and Ecosystem Services of Seaweed Cultivation

Seaweed has been termed a “climate champion” by the United Nations Global Compact and is being studied as a key to restoring our oceans thanks to its ecosystem services

(Duarte et al., 2020; Vincent et al., 2020).

Ecosystem services are the benefits humans gain from the ecosystems.

These are often grouped into:

1. Provisioning services i.e. cultivating food and feed
2. Regulating services i.e. carbon sequestration and nutrient mitigation
3. Supportive services i.e. Habitat creation
4. Cultural services i.e. Recreational purposes such as tourism

WP9 in the SeaMark project is dedicated to investigating further the interaction between seaweed cultivation and the environment. In D9.3 (2024), SeaMark assessed the ecosystem services provided by seaweed cultivation in three cultivation sites in Norway, Faroe Islands and France. For all three sites, the assessed nutrient bio-extraction and carbon sequestration.

This assessment had several limitations, as it did not account for emissions from deployment, harvesting, and air-sea exchange, and other remaining unknowns regarding carbon sequestration which are crucial for assessing net carbon balance in seaweed aquaculture (see more details in D9.3). However, using the results from the assessment as a foundation, we can estimate the impact of the upscaling scenarios.

The results from the assessment in the different sites are presented in Table 3. Here we see that the variation in uptake reflects local environmental conditions, with seaweed grown in the Faroe Islands demonstrating the highest uptake rates when it comes to nitrogen (2.52 kg/tonne ww) and the amount of potential carbon sequestered through rip off (99 kg in CO₂ equivalents/tonne ww). In terms of phosphorus, the seaweed

Table 3: Ecosystem services of cultivation of *Saccharina latissima* (kilograms per tonne wet weight) in different locations. Source: Koch et al (2025).

Location	Nitrogen harvested	Phosphorus harvested	Carbon harvested	Carbon rip off
Faroe Islands	2.52	0.49		99
Norway	1.2	0.101		45
France	1.91	0.801		68

Table 4: Estimate of implications for uptake of N, P, and CO₂ for the two upscaling scenarios.

Implications for ecosystem services	Regional scale (50,000 tonnes)	European Scale (5 million scale)	Unit
Nitrogen (N) uptake	60 – 126	6,000 – 12,600	Tonnes
Phosphorus (P) uptake	5 – 40	505 – 4,005	Tonnes
CO₂ rip off (kg CO₂e)	2,250 – 4,950	225,000 – 495,000	Tonnes CO ₂ equivalent

cultivated in France removes the highest amounts (0.801 kg/tonne ww).

Since such values reflect local environmental conditions, and therefore are very site specific, it is still possible to get a rough estimate of how regulating services would be affected by an upscale. Since we have not determined the geographical locations of the upscaled seaweed cultivation, we choose to use the variation in ranges to make an estimate. Table 4 presents the environmental implications at both regional and European scales based on the two upscaling scenarios used in this report.

For the regional upscale scenario (50,000 tonnes of wet weight seaweed), cultivation would remove between 60 and 126 tonnes of nitrogen (N) and between 5 and 40 tonnes of phosphorus (P) from the marine environment. These nutrients are among the primary contributors to eutrophication, a process that can lead to harmful algal blooms and dead zones in coastal waters. An upscaled seaweed cultivation could therefore play a valuable role in improving water quality and restoring ecological balance in nutrient-stressed marine areas. However, it is important to note that this ecosystem service is only valuable in cases where there is a nutrient overload. In European waters, by far the most problematic areas are the Baltic, where 99% of assessed areas suffer from eutrophication, followed by the Black Sea, where the corresponding figure is 53% (European Environment Agency, 2019). The coastal areas in the Northeast Atlantic suffer to a much more limited degree from eutrophication, where 7 % of assessed areas are eutrophic. However, great care must also be taken in expanding in a nutrient-limited area, to avoid depletion and competition with phytoplankton (Aldridge et al., 2021; Koch et al., 2024).

When considering the carbon sequestration for the regional upscale scenario, an estimate of between 2,250 and 4,950 tonnes of carbon (CO₂ equivalent) would be sequestered. To place this in perspective, the Faroe Islands, with its 54,000 inhabitants, emit approximately 1 million tonnes of carbon (CO₂ equivalents) per year (Environment Agency). To provide some context, If these 50,000 tonnes were cultivated in the Faroes, they would reduce the Faroe Islands CO₂ emissions by half a percent.

When we consider the European upscaling scenario of 5 million tonnes, the estimates suggest a potential uptake of 6,000 to 12,600 tonnes of nitrogen, 505 to 4,005 tonnes of phosphorus,

and the sequestration of 225,000 to 495,000 tonnes of CO₂ equivalent. The uptake would support key nutrient mitigation targets, such as those in the water Framework Directive and the Marine Strategy Framework Directive. To place this figure into some context, the total removal of phosphorous in the large upscale corresponds to between 2-15% phosphorus input in the Baltic Sea (HELCOM, 2020). Placing the carbon sequestration into perspective, the removal of 495,000 tonnes carbon dioxide (in CO₂ equivalents) corresponds to the carbon footprint of about 46,000 European citizens (Eurostat, 2025b). The value of the uptake of nutrients and carbon sequestration will be further explored in two upcoming deliverables of the SeaMark project, where in D9.4, a valuation of ecosystem services will be conducted, and in D9.5, where potential pathways for payment for ecosystem services will be explored. Overall, these results indicate that a mature European seaweed industry could thereby deliver environmental benefits alongside economic development and could help address key ecological challenges relating to climate change and marine pollution. However, it is important not to consider bioremediation and carbon sequestration in isolation, but also consider the provisioning services provided by the seaweed cultivation. For example, upscaling cultivation could supply raw material for food and feed, typically with a lower negative environmental impact than the products they might replace. In upcoming work within SeaMark, the project will conduct life-cycle assessments for the SeaMark products, and this will provide further insight into the potential of seaweed-based products to reduce environmental impacts by replacing other products with higher negative environmental impacts. These results will be presented in the forthcoming deliverable 9.7.

4. DISCUSSION AND CONCLUDING REMARKS

The socio-economic assessment of a scaled-up European seaweed industry reveals a large potential for regional development and economic diversification. The analysis presented here estimates that a fully upscaled seaweed industry has the capacity to create over 10,000 direct jobs and

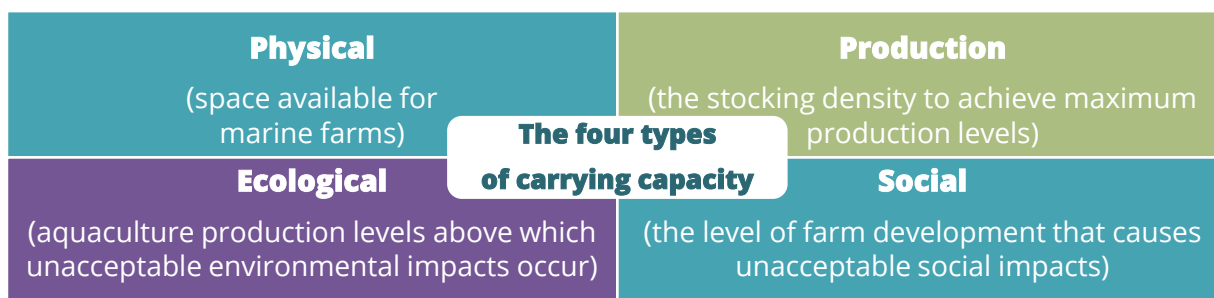


Figure 7: The four types of carrying capacity.

generate approximately €3.6 billion in revenue at full scale. An upscaled seaweed industry would thereby become a vital component of Europe's blue economy. At a smaller regional level, producing 50,000 tonnes of seaweed annually, the sector is estimated to support over 100 full-time jobs. Another aspect worth emphasising here is that beyond sheer employment figures, the seaweed industry would create diversified job opportunities. Many stages of the value chain require skilled labour, supporting local capacity building and fostering gender inclusion, especially in roles related to research, product development, and management. These findings showcase the potential role of seaweed cultivation in revitalising coastal and rural economies, offering sustainable livelihoods where employment opportunities may otherwise be scarce.

In addition to its economic potential, upscaled seaweed cultivation offers environmental benefits, particularly in nutrient-stressed regions. At the European scale, cultivation could remove up to 12,600 tonnes of nitrogen and 4,005 tonnes of phosphorus annually - supporting goals under the Water Framework Directive and Marine Strategy Framework Directive. Carbon sequestration potential is estimated at between 225,000 and 495,000 tonnes of carbon (CO₂ equivalent), the higher level corresponding to the annual emissions of around 46,000 European citizens. Seaweed could also contribute to climate mitigation by replacing higher-impact raw materials in food and feed, further amplifying its role in meeting EU climate targets (Van den Burg et al., 2023). Future SeaMark deliverables will explore the valuation and payment schemes for these ecosystem services, as well as the climate impact of seaweed-based products.

However, here we have only presented the assessment of a potential upscaling. Despite the opportunities, the seaweed sector still faces significant barriers to growth that need to be overcome. The European Commission has identified five main limitations to the expansion of seaweed aquaculture, including high production costs; low scale production; fragmented governance framework; limited knowledge of the risk and environmental impacts of algae cultivation; and limited knowledge of the market and consumers (European Commission, 2022). In addition, a study examining the EU Algae Initiative of the European Commission identified further barriers- including limited market demand and consumer awareness, high concentrations of iodine and heavy metals, and discrepancies between the species in highest demand and the species produced in greatest volume (Kuech et al., 2023).

Other studies have also identified social conflicts and post-harvesting challenges in logistics with 'social capital' as bottlenecks in the seaweed sector (Cerca et al., 2023) as well as barriers within regulations (Lähteenmäki-Uutela et al., 2021).

Overcoming these constraints will be essential for ensuring sustainable development of the sector, and this must be done within the carrying capacity of social-ecological systems to avoid negative and potentially irreversible impacts. Sustainable development requires consideration of carrying capacity. This concept allows a holistic consideration incorporating four main 'types' of carrying capacity: physical, ecological, production, and social limits (Inglis et al., 2000; McKindsey et al., 2006). The aim of the concept is to assess the limits of acceptable change, beyond which further growth has negative and potentially irreversible impacts (McKindsey 2013) (See Figure 7).

While there is no doubt that seaweed cultivation has the potential to improve marine environmental quality (Kotta et al., 2022), large-scale operations must be carefully managed to avoid ecological disruption, such as shifts in nutrient balances, phytoplankton dynamics, or local food webs. As discussions proceed on the upscaling of the seaweed industry, the concept of carrying capacity is an important tool for aquaculture management (Koch et al., 2024).

One important trade-off highlighted in this assessment lies between economic efficiency and employment creation. To remain competitive in a high-cost labour environment, the seaweed industry will need to transition from labour-intensive to capital-intensive models. While this may reduce overall job creation, it is necessary for achieving commercial viability. The level of processing applied to the biomass also influences socio-economic outcomes. High-value extraction processes – such as those producing alginate, fucoidan, or beta-glucan – can yield higher economic returns and employment opportunities than bulk methods like fermentation or ensilage. This assessment has assumed a mixed processing scenario, with half of the biomass processed at each level, but strategic investments in high-value applications could substantially enhance both employment and value-added potential.

To realise the full benefits of a mature seaweed industry, targeted public investment and policy support will be essential. Additionally, mechanisms to monetise and compensate

ecosystem services – such as nutrient removal and carbon sequestration – should be developed and integrated into blue economy strategies. With the right combination of innovation, planning, and policy support, the seaweed industry has the potential to become a model for inclusive, sustainable blue growth in Europe. It offers a unique opportunity to align economic, environmental, and social goals, fostering resilient coastal communities while addressing urgent challenges related to climate change, marine pollution, and resource sustainability.

5. DATASET

For this deliverable, data have been added to a dataset, which is confidential. The description of this dataset can be found in the Data Management Plan of SeaMark openly available to Zenodo: <https://doi.org/10.5281/zenodo.7261409>. The dataset in itself will not be publicly available as it contains information that is commercially sensitive for the companies.

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