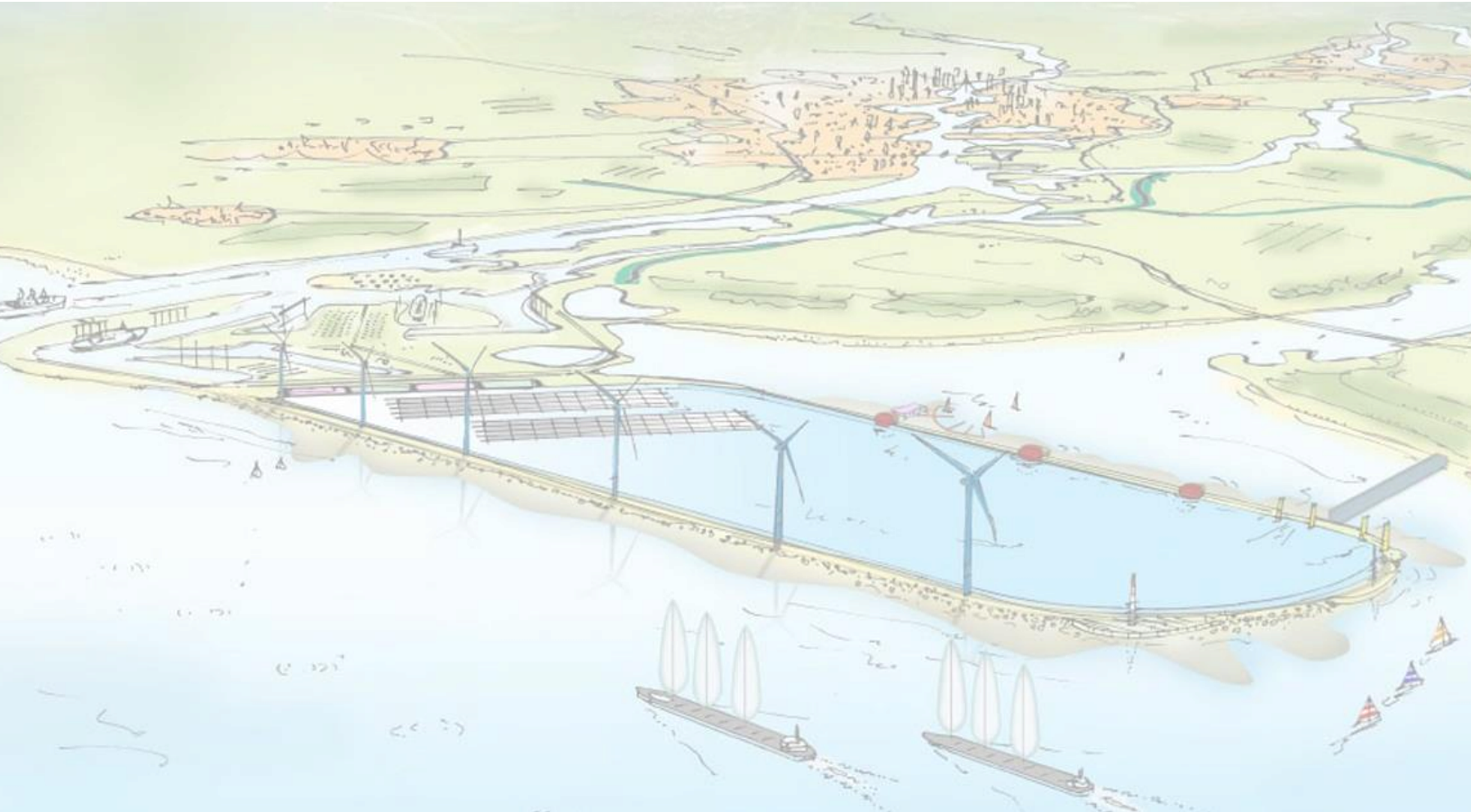


Evaluating Different Aquatic CO₂ Mitigation Pathways with the Energy Storage Lake of Delta21



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Summary

Delta21 is a multi-functional flood mitigation project that aims to (1) lower flood risk, (2) increase biodiversity in the Haringvliet and (3) produce clean energy. Flood protection is at the core of the Delta21 project. During storm surges and high discharge events, excess river water can be discharged through the Energy Storage Lake (ESL) which reduces inland flood risk and the need for higher dikes. With this scenario being infrequent (~once every 10 years), the ESL is generally used for clean energy production. At night during off-peak hours, surplus energy is used to partly pump the lake empty, creating a gradient between the lake and the sea. When energy demands are high, water is released back into the lake, passing through generators to produce energy.

With its multifunctional philosophy, the sustainable vision of Delta21, and considering the relatively large area of the ESL, the project managers came to the idea to additionally mitigate carbon within the ESL to make a small contribution to the climate problem. Therefore, previous ACT groups have already investigated the possibilities of cultivation of aquacultural practices. For this study however, questions regarding the specific uptake and viability of those aquacultural practices were to be answered. This led to the following research question: To what degree could CO₂ mitigation take place within the ESL? To answer the research question, the following sub questions were explored: (a) How can aquaculture be utilized for *passive*¹ mitigation of carbon dioxide in the atmosphere? (b) In what way can *active* CO₂ absorption be implemented in the ESL? (c) How can produced byproducts reduce (non-) local environmental impacts? (d) What is the mitigation potential of each mitigation pathway in the ESL? (e) Which pathway is the most viable to mitigate carbon emissions?

The conditions in the ESL provide opportunities that can be exploited by seaweed and mussel aquafarming, with seaweeds having a greater yield per hectare than terrestrial crops. Sugar kelp and Sea Lettuce were selected as the two seaweed species. These two species are native, already cultivated in a few seaweed farms in the North Sea, and grow in different seasons, therefore maximizing overall yield. Sugar Kelp is grown in the winter months, whilst Sea Lettuce favors Dutch summers. Blue mussels were selected as another aquaculture practice that could play a role in carbon sequestration.

Enhancing the sequestration by pumping CO₂ into the ESL could potentially enhance the uptake and is what we refer to as *active* carbon mitigation. Pumping CO₂ into the ESL is technically feasible, although the biggest concern with this is doing so without causing any detriment towards the surrounding ecosystem. Carbon is not the limiting factor in the ESL and as such, pumping it in would result in acidification.

A life cycle analysis (LCA) of different pathways was conducted to determine the mitigation potential of each pathway. The pathways are based on research into the uses for both mussels and seaweed. The pathways this report investigated as potential mitigation pathways are I. CO₂ addition for enhanced productivity (from industries), II. Mussel cultivation for food production (raw at packaging), III. Seaweed for fish feed production (protein rich fish feed ingredient), IV. Seaweed for fertilizer production (fertilizer supplement), V. Seaweed for biogas production (energy generation), VI. Seaweed for fodder production (maize substitute). Pathway (II) & (VI), were found to be the most promising pathways in terms of mitigating carbon.

Furthermore, a Multi-Criteria Analysis (MCA) compared the pathways alongside further criteria: synergies and trade-offs with other techniques, side effects specific to the concerning activity, feasibility, and cost. Based on these criteria it was concluded that pathway VI. Seaweed for fodder production, and III. Seaweed for fish feed production, seem most promising for carbon mitigation within the ESL.

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1. Introduction

The Dutch have long been highly innovative with respect to reducing the consequences of flooding (Neuvel et al. 2009); however, with climate change even more innovation will be needed to maximize safety/minimize risk (Botzen & Den Bergh, 2009). Climate change will cause a rise in the sea level and affect the hydrological cycle, which will lead to risks such as more frequent and more extreme flooding events and as a result the Maeslantkering, which can only be used a limited number of times, will need to be used more frequently (Jiménez Cisneros et al., 2014). This combination of events creates problems inland where a prolonged closure leads to the obstruction of the river, increasing the risk of flooding inland. These storm surges generally coincide with high discharge events making the probability of flooding significantly greater. Furthermore, the Netherlands must be aware of the relatively small space available to them. This is where the Delta21 project comes in, a multifunctional flood mitigation project that aims to ensure lower flood risk, increase biodiversity in the Haringvliet, and produce clean energy.

Flood protection is at the core of the Delta21 project. During storm surges and high discharge events, water can enter the ESL and be released out into the sea, reducing flood risk, and removing the necessity of building additional dikes. With this scenario being infrequent, the ESL is generally used for clean energy production. At night during off-peak hours, surplus energy is used to partly pump the lake empty, creating a gradient between the lake and the sea. When energy demands are high, water is released back into the lake, passing through generators to produce energy. With this system being already multifunctional, the Delta21 project aims for more. Considering the relatively large area of the ESL, the project managers came to the idea to additionally mitigate carbon with aquaculture to make a small contribution to the excess of CO₂ in the atmosphere and the Dutch climate plans (Ministry of Economic and Climate Policy, 2019). Aquaculture is one of the most rapidly expanding food sectors on the planet, and bearing that seaweed production has increased with an 8% growth per year the idea was to additionally cultivate aquatic organisms in the ESL (FAO 2011). However, to what degree CO₂ mitigation through aquaculture could take place within the ESL remained unanswered. Therefore, this project has been looking into the opportunities for mitigation pathways consisting of aquacultural activities in the ESL and to what degree these pathways could mitigate CO₂. This was done by addressing the following research question and sub-questions:

To what degree could CO₂ mitigation take place within the ESL?

- a. How can aquaculture be utilized as passive mitigation of carbon?
- b. In what way can active CO₂ absorption be implemented in the ELS?
- c. How can produced byproducts (e.g., seaweed) reduce (non-)local environmental impacts?
- d. What is the mitigation potential of each mitigation pathway in the ESL?
- e. Which pathway(s) is/are the most viable to mitigate carbon emissions?

With the mitigation pathways being:

- I. CO₂ addition for enhanced productivity (from industries)
- II. Mussel cultivation for food production (raw at packaging)
- III. Seaweed for fish feed production (protein rich fish feed ingredient)
- IV. Seaweed for fertilizer production (fertilizer supplement)
- V. Seaweed for biogas production (energy generation)
- VI. Seaweed for fodder production (maize substitute)

1.2 Reading Guide

First, we have looked into how aquaculture can be utilized as passive mitigation of carbon. For example, by promoting growth of shellfish, micro and macro-algae. Secondly, we looked at ways to absorb carbon actively by directly adding CO₂ to the ESL (e.g. from Rotterdam Industries). Furthermore, we have analyzed how the concerning aquacultural activities could contribute to reduction of (non-) local environmental impact and how this could (in)directly influence the mitigation potential. When the selected aquacultural activities and mitigation options were determined we analyzed both the emission and mitigation potential by using the Carbon Footprint (CFP) method (i.e. Life Cycle Analysis (LCA) study based on the single impact category climate change). Lastly, we have used all the relevant data to determine the most promising mitigation options for aquacultural activities by conducting a Multi-Criteria Analysis (MCA).

However, this report will start with the conclusion (Section 2) and recommendation (Section 3) and will subsequently follow the structure as mentioned above, answering sub-questions a, b, and c through literature review including a method, results and discussion paragraph (Section 4, 5 & 6). Then, the CFP (Section 7) will be answered with a life cycle inventory (LCI) followed by a life cycle impact assessment (LCIA) and a mitigation potential for each concerning activity. Afterwards, the MCA (Section 8) will connect all other Section and will discuss which activity is most promising for mitigation of carbon within the ESL. Lastly, an overall final discussion which will be followed by an advice on topics for further research. By working on this project for the last 8 weeks the project team has gained a lot of insight on which parts are important and which topics need further research.

1.3 Technical Description of the ESL

The ESL) also called 'Valmeer' is adjacent to Maasvlakte 2, an expansion project of the port of Rotterdam, located to the west of the Maasvlakte (Figure 1). Flood protection is at the core of the Delta21 project. During storm surges and high discharge events (~once every 10 years), water can enter the ESL and be pumped out into the sea. Therefore, the ESL will be equipped with a large pumping station to pump large quantities of excess water into the sea. However, the ESL will also function as a battery with hydropower by pumping seawater into an ESL, therefore creating energy through the storage and release of seawater (Berke & Lavooij, 2017).



Figure 1 Location of the ESL

1.3.1 Physical conditions of the ESL

The ESL is 22.5 meters deep and will have a water height difference of 17.5 meter on average daily (because the water is being pumped for energy production). Approximately a 5 meter deep (vertical) water layer will always remain in the ESL. The total surface of the ESL is 26 km² at its highest point, and at its lowest point 19 km² (Figure 2). Due to the excess energy production during the night, the expectation is that the lowest water level will be in the morning when the lake has been pumped empty (Berke & Lavooij, 2017).

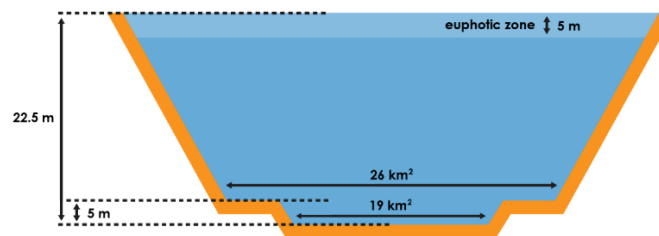


Figure 2 Dimensions of the ESL

The photic zone in the ESL will probably not extent much deeper than -5 meters. However, the depth of the photic zone that is mainly dependent on turbidity, could show small variations due to seasonal changes (ConsultanSEA, 2020).

Additional and more detailed information regarding material characteristics of the ESL, expected time of drought exposure, and chemical conditions of the ESL can be found in Appendix A.

2. Conclusion

To what degree could CO₂ mitigation take place within the ESL?

a. *How can aquaculture be utilized as passive mitigation of carbon?*

The ESL is suitable for the cultivation of (1) seaweed and (2) mussels:

- (1) Consecutive cultivation of Sugar Kelp and Sea Lettuce results in higher biomass-yields than any land-based crop. Per ha seaweed can compensate the carbon footprint of 11 Dutch citizens. In addition, the seaweed has many different uses post harvesting as discussed in section c. A possible problem of seaweed cultivation is the risk of nutrient depletion in and outside the ESL when growth rates are high.
- (2) Mussels are, compared to other sources of animal protein, a sustainable food source for humans. Within the ESL stocking densities should be monitored closely to prevent overgrazing, resulting in the depletion of nutrients in the ESL, potentially interfering with the surrounding ecosystem functioning.

b. *In what way can active CO₂ absorption be implemented in the ESL?*

Technically this is feasible, however carbon is not the limiting factor for plant growth. Enhancing dissolved CO₂ will not be effective and increases the risk of acidification.

c. *How can produced byproducts (e.g., seaweed) reduce (non-)local environmental impacts?*

The impact is entirely dependent on the species and the use. The most direct carbon offsetting would be incorporating the seaweed into fish or fodder feed. Using seaweed in fodder and fish feeds would reduce the dependency of soy; which is prominent in both feeds. Both species can also be incorporated into these two pathways and maximize the benefits of the overall yield from the ESL. These two pathways provide opportunities to substitute highly emitting and unsustainable sources of feed. There are not just singular benefits of each of these pathways, but the benefits are seen throughout including on the animal themselves; benefitting the producers (cost of production), animal (health), environment (less synthetic additives), and in terms of this report the mitigation capacity.

d. *What is the mitigation potential of each mitigation pathway in the ESL?*

Pathway I. CO₂ addition for enhanced productivity (from industries) has a relatively high emission due to the use of steel, rockwool, and diesel that is being used for production and installment of the pipelines. Pathway II. Mussel cultivation for food production (raw at packaging) is relatively CO₂ intensive due to the use of steel machinery. Pathway III. Seaweed for fish feed production (protein rich fish feed ingredient) has a relatively low emission because the process of seaweed cultivation and hydrolysis is not CO₂ intensive. Because this pathway is offsetting import of soy (which is CO₂ intensive) its mitigation potential seems promising. Pathway IV. Seaweed for fertilizer production (fertilizer supplement) has a relatively low mitigation potential because the product has a low concentration of phosphorus. Pathway V. Seaweed for biogas production (energy generation) seems like a promising technique to mitigate carbon but burning biogas will still emit (biogenic) carbon emissions into the atmosphere. Pathway VI. Seaweed for fodder production (maize substitute) has a relatively low emissions since the seaweed cultivation is not energy intensive and the product can almost directly be fed to chickens. Because the seaweed is replacing maize production, which is relatively CO₂ intensive the mitigation potential of this pathway seems most promising. Altogether, it seems like either valorizing the product (of seaweed in this case) or using the raw material directly will be most promising to mitigate carbon emissions. To get an idea of the mitigation potential of a certain pathway within the whole ESL (19 km²) we compared the amount of carbon mitigated by wind turbines. As an example, we used pathway III. Seaweed for fish feed production (protein rich fish feed ingredient). This pathway has an annual mitigation potential of 62235 ton CO₂-eq, which equals a CO₂ displacement of a set of wind turbines with the capacity of 55MW and a carbon price (EU ETS) of approximately 3.23 million euros (Appendix E).

e. *Which pathway is the most viable to mitigate carbon emissions?*

The most effective way to mitigate carbon emissions is to cultivate seaweed and produce fodder (pathway VI), closely followed by the production of fish feed from seaweed (pathway III).

3. Recommendations

Finding 1: Based on a conducted Multi-Criteria Analysis, this report concludes that the pathway seaweed cultivation, that can be used for fodder production is the optimal way to utilize the space of the ESL.

Seaweed can be used for fodder production for cattle, this means that it directly substitutes for maize (Abudabos et al., 2013; Costa et al., 2021), this gives it its high carbon mitigation potential. Additionally, the cultivation of seaweed has positive synergies with other pathways such as mussels. Section 4.2 and section 6 go more in depth about seaweed cultivation and the possible pathways with seaweed. Section 8 goes more in depth about the methodology and results of the MCA.

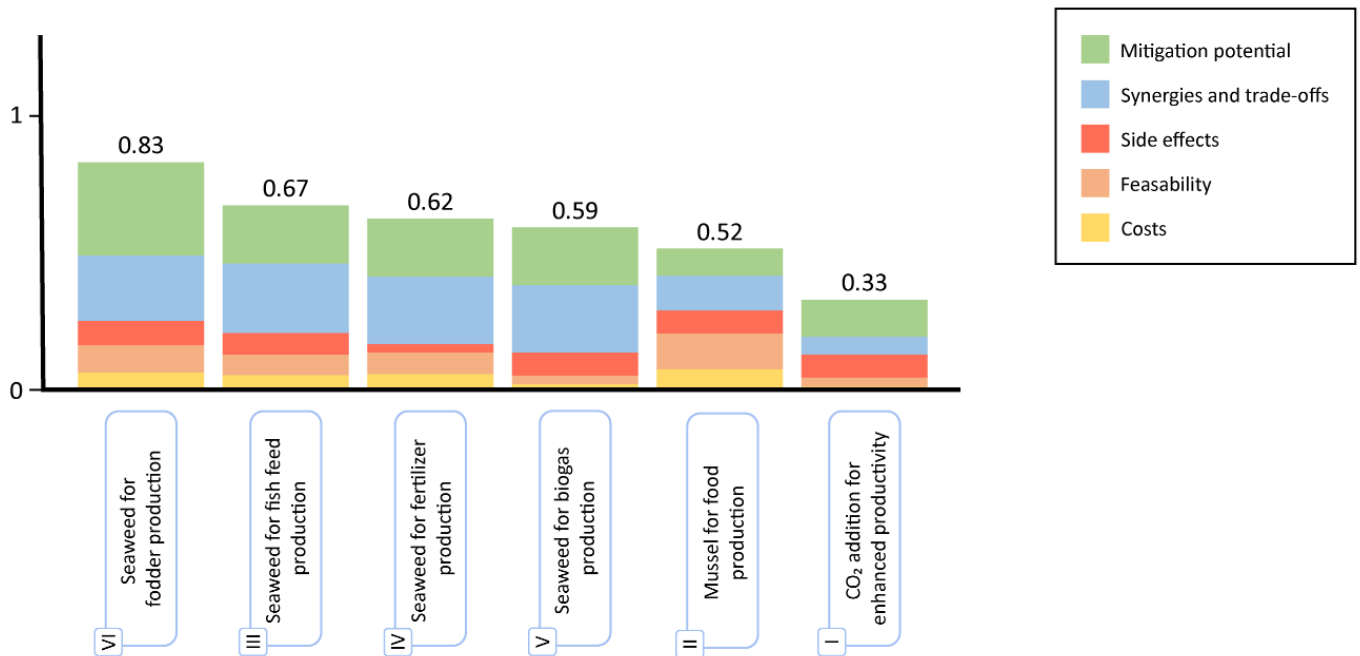


Figure 3 Results of the MCA

Finding 2: Even though mussel production scored significantly lower in the Multi-Criteria-Analysis, this report concludes that it still beneficial to implement it alongside the seaweed cultivation.

The joint cultivation of mussel and seaweed offers benefits for both species (Michler-Cieluch & Kodeih, 2008; Holdt & Edwards, 2014), and since the mussels can be grown on the walls and on the pumps of the ESL they do not compete for space. Meaning that the inclusion of both these species can be an effective way to mitigate even more CO₂ in the ESL. Shellfish cultivation will be explained further in section 4.4.

Finding 3: To ensure that local biodiversity is not disrupted, and the North-sea is not further depleted, this report concludes that further research should be conducted surrounding nutrient depletion and the need for supplementary fertilization.

Due to the ESL being an open system, it is linked to the North-Sea, if aquaculture is implemented in the ESL, the aquaculture could take up nutrients from the North-Sea. This could have negative consequences, since the amount of nutrients in the ESL is already relatively low (T. Murk, personal communication, May 10, 2021). Further research should be conducted whether this is a significant risk and if it is, whether nutrient addition can be done safely. For this, nutrient uptake should first be analyzed through modelling. When applied to the lake, nutrients should be monitored and dosed precisely to ensure minimal differences between the inflowing and outflowing water. This will ensure minimal ecological impacts on the ecosystem within and outside of the ESL. See section 4.3 for additional information.

Finding 4: *Active implementation of CO₂ into the ESL is not advised due to the ESL being an open system and addition of CO₂ could lead to acidification.*

The active addition of CO₂ into the ESL lake could cause serious acidification problems in the North-Sea, due to the ESL being an open system. Furthermore, CO₂ is not a limiting factor for growth in the ESL, thus it is not as beneficial than adding additional nutrients. Section 5 discusses this topic further.

Finding 5: *The most beneficial system would be an integrated multi-trophic system.*

Our findings show that seaweed cultivation is most beneficial in term of carbon uptake and mitigation potential. However, we should be aware that with most monocultures, repetitive cultivation of the same crops increases the risk of diseases. By combining the cultivation of two crops (Sugar Kelp and Sea Lettuce) or mussels, these risks are already reduced and to further reduce the risk, an integrated multi-trophic system could be created. Another benefit of an integrated multi-trophic system is that it also increases the yield due to symbiosis between aquatic organisms.

Finding 6: *The ESL has potential as a playground for aquaculture.*

Building on finding 3, Delta21 could develop a closed system in the vicinity of or within the ESL. The closed system can be seen as playground to test how ocean (precision) farming can be effectively implemented (with monitoring). In this closed system nutrients and CO₂ can be added without risking environmental damage.

4. Passive Adsorptions of CO₂

4.1 Introduction

Promotion of algae growth has been proposed as a suitable carbon sink and is often referred to as Blue Carbon (Arenas & Vas-Pinto, 2014). Not only do algae take-up CO₂ via photosynthesis, but they also do not compete with other forms of land-use as, for example, the case with growing rapeseed for biodiesel. Mussels can also sequester CO₂ in their shells. The uptake of carbon via aquaculture is what we refer to as *passive* uptake of carbon. In this section we will focus on the feasibility, yield and carbon uptake of seaweed (macro-algae) and shellfish (mussels & oysters) within the ESL. We have also looked into the cultivation of microalgae and seagrass, but found these practices to be unfeasible within the ESL, see Appendix B6 & B7.

4.2 Seaweed Cultivation within the ESL

The current market for seaweed is underdeveloped in western countries. In Asia however, seaweed is produced on large scales. This proves that utilizing the ocean for macroalgae-agriculture is very feasible. Aquaculture is already the fastest growing food sector with seaweed demonstrating the fastest growth of 8% per year (Froehlich et al., 2019). It is expected to increase exponentially over the years (blue area in Figure 4). Sadly, predicted demand will not compensate our current emission of CO₂, but it will offset carbon emissions, see Figure 4.

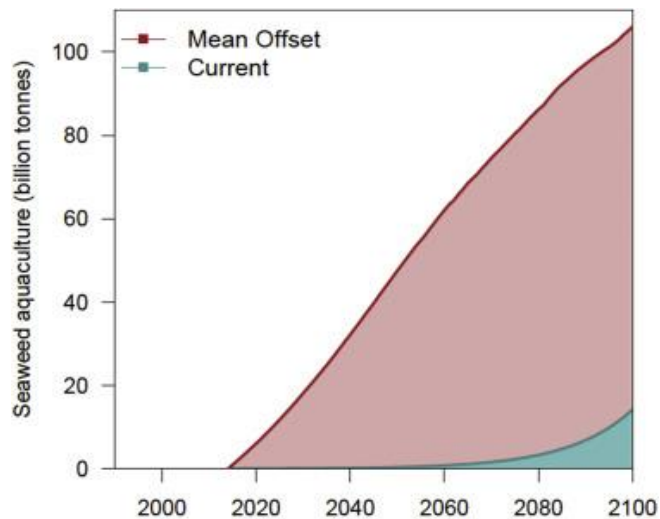


Figure 4: Comparative Trajectory of Seaweed Aquaculture, in ton Seaweed production under current exponential growth trends (aqua) versus the average amount needed (red) to incrementally increase (0.15% CO₂eq sequestration per year) offsetting the agricultural sector (12% of direct global emissions) by 2100, under current global climate policies. Taken from (Froehlich et al., 2019).

Cultivation of seaweed in the open North Sea is currently not feasible from a financial point of view. This is due to the (i) high costs of seeding longlines, (ii) rough conditions at sea and (iii) underdeveloped process technologies (Bikker et al., 2016). However, since the ESL will be close to shore and closed off from the open sea, conditions will be more favorable for seaweed cultivation. In addition, multiple initiatives have been set up aiming to make seaweed cultivation in the North Sea technologically and economically viable (Bikker et al., 2016).

A previous study done by ConsultanSEA (2020) proposed three possible seaweed species that could be cultivated in the ESL. These species are: Sugar Kelp (*Saccharina Latissima*), Sea Lettuce (*Ulva Lactuca*) and Dulse (*Palmaria Palmata*). In addition, Joost Wouters (J. Wouters, The Seaweed Company, personal communication, May 3, 2021) mentioned Oarweed (*Laminaria Digitata*) as a potential sea crop. However, Dulse and Oarweed were found to be unsuitable for cultivation in the ESL (Appendix B3 & B4). Focus will thus be on the most suitable species: Sugar Kelp & Sea Lettuce. How the harvested seaweed can be used instead of or in addition to other products (food, feed and biofuels) will be discussed in Section 6.

4.2.1 Potential Yield from Seaweed

Of the four aforementioned seaweed species, Sugar Kelp and Sea Lettuce have the most potential. Because the growth seasons of these species do not overlap, it is a common idea to grow both species consecutively. Table 1 below shows the estimated yield and quantity removed carbon (C), Nitrogen (N) and Phosphorus (P). The total dry weight (DW) yield then amounts to: ± 27.5 ton/ha, see Table 1. That is far more than any land-based crop (e.g. Maize). Assuming the entire ESL lake (19 km²) would be used for cultivating seaweed, the total yield would amount to 5.7×10^4 ton DW.

To put those numbers into perspective: the average CO₂ emission surplus (import minus export) in the Netherlands is 2.8 tons/capita. The factor to convert C to CO₂ is 3.67, therefore seaweed could potentially take up 30.9 ton CO₂/(ha yr). This means that cultivating 1 ha of seaweed in the ESL would compensate the emission of 11 Dutch citizens. Upscaled for the entire ESL (19 km²) that would amount to 20968 people. NOTE: be aware that the uptake of carbon is either (partly) permanent or temporary depending on the pathway, see Section 7.

Table 1: the estimated yield and removed nutrients of Sugar Kelp and Sea Lettuce, compared to maize.

	Sugar Kelp	Sea Lettuce	Maize
DW Yield (ton/ha)	12.5	15	9
C removed (ton/ha)	3.5	4.9	-
N removed (kg/ha)	193	375	-
P removed (kg/ha)	73	19.5	-

4.3 Discussion on Seaweed Cultivation

4.3.1 Risk of Nutrient Depletion

The North Sea is no longer eutrophicated. On the contrary, there is now the risk of nutrient depletion and aquaculture farmers and nature are starting to compete for nutrients (T. Murk, personal communication, May 10, 2021). Therefore, the removal of nutrients in the ESL might result in a nutrient-shortage outside the ESL. Table 1 gives a rough estimate of the amount of nutrients removed by the seaweed.

Based on the average summer and winter N and P concentration of the seawater, the flux of nutrients in the ESL can be computed. Upscaled to half a year, the flux can be compared to the uptake by each seaweed. In case the whole ESL would be cultivated with seaweed; 0.70% & 1.45% of the N, and 3.14% & 0.85% of the P would be removed by Sugar Kelp and Sea Lettuce respectively, see Appendix B5.

The risk of depleting the area surrounding the ESL of nutrients seems quite small. It must be noted that the above values are based on the average uptake of nutrients by the seaweeds. In reality, the uptake fluctuates depending on the maturity of the plant, see 4.3.2. When Sea Lettuce blooms for example, the risk of depletion increases. Possibly the ESL or surrounding areas will experience nutrient stress. Temporal fertilization or extra nutrient input might in that case be advisable. However, further research must be done to determine if this is the case.

If fertilization is needed it is important that the fertilization rate does not exceed the uptake rate of seaweed. If it does, the excess nutrients will be pumped out of the ESL with the risk of eutrophicating the surrounding

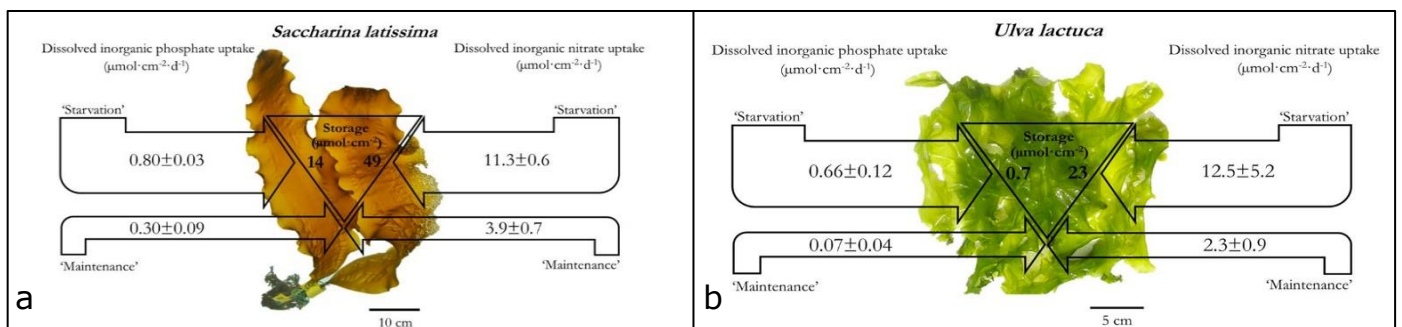


Figure 5 a & b: The uptake rate and internal storage of Sugar Kelp (left) and Sea Lettuce (right). Taken from NIOZ

system. Figure 5 a & b below depicts the uptake rate of P and N of Sugar Kelp and Sea Lettuce depending on the state of the tissue (starvation or maintenance).

More research is required into: (1) the change in uptake with the maturity of the seaweed, see section 4.3.2, (2) the dilution of the fertilizer in the ESL and (3) the increase in yield due to nutrient addition. Reith et al (2006), estimated that the potential macro-algae yield in the North Sea can increase to 50 DW ton/ha when extra nutrients are added directly or by creating an integrated multi-trophic aquaculture system. In the latter, feces of fish or other heterotrophic animals will provide the necessary nutrients.

4.3.2 Stoichiometry

C:N ratio and plant maturity

The % N in plant tissue is largest at the beginning of the growing season. For sugar kelp, the %N decreased from 2.76% to 1.65% of dry weight from January to June (Augyte et al., 2017). The authors argue that the decrease in N% follows the seasonal variation of total dissolved inorganic matter, which steadily decreases from January to late May. When N- becomes limiting in the water column, the kelp uses the N it has stored to build tissue instead. This implies that Sugar Kelp can survive with less N as it matures and as a result the amount of fertilizer needed decreases over time.

Contrary to N, the tissue C-content of Sugar Kelp has shown to either increase or decrease with 5% over time. However, due to the decrease in %N, the C:N ratio in both cases increases (Augyte et al. 2017). Thus, carbon removal by Sugar Kelp is most effective at the end of the growing phase.

C:N:P ratio and nutrient limitation

The C:N and N:P ratios differ strongly over the various field-experiments. Based on the values in Table 1 and the molar mass of C,N & P, the stoichiometry can be computed, see Table 2.

Table 2: The stoichiometry of Sugar Kelp and Sea Lettuce

	Sugar Kelp	Sea Lettuce
<i>N:P</i>	6 : 1	43 : 1
<i>C:N</i>	21 : 1	15 : 1
<i>C:N:P</i>	124 : 6 : 1	650 : 43 : 1

Generally, the nutrient ratio (N:P) has a range of 4:1 to 80:1 with the mean optimal around 30:1 (Froelich et al., 2019). The average C:N:P ratio for seaweed (based on 92 types) is 550:30:1 (Lubsch & Lansbergen, 2020). That is far higher than we computed for Sugar Kelp based on field data. This implies that when Sugar Kelp is cultivated in the North Sea, it is N limited. This means that C is not a limiting factor for the cultivation of Sugar Kelp.

If we apply the N:P ratio of 43:1 found for Sea Lettuce on the nutrient concentrations found in the North Sea, the system shows to be N-limited as well. Therefore, we can conclude that for both Sugar Kelp and Sea Lettuce N is the most common limiting factor. Lubsch and Lansbergen (2020) predict that in future P may become limiting due to increasingly better wastewater treatment and changing agricultural management. Either way, C is not the limiting factor. This conclusion is relevant for the application of the active carbon pathway, see Section 5.

4.3.3 Other Model studies on CO₂ Uptake

A couple of studies have computed the uptake of C or CO₂ using a model or averaged value. Froelich et al (2019), computed a carbon uptake of 3.6-ton C/ha which equals 13.24 ton CO₂. Some studies correct this value for the CO₂ remitted during harvest: ~16%. This brings the estimate down to 11.1 tons/ha (Fry et al., 2012; Pechsiri et al., 2016). Another model study into the feasibility of macroalgae in the North Sea had similar results. Close to Seaport of Rotterdam the carbon uptake was modelled to be between 3.2- and 4.9-ton C/ha (McCulla, 2013). These studies focus on monoculture of one seaweed type. Therefore, our estimates, 3.5-ton C/ha for sugar kelp and 4.9 ton C/ha for Sea Lettuce, fall within an acceptable range.

4.3.4 Storm Events & Diseases

During extreme storms, the ESL will be used for freshwater discharge. As discussed in appendix B1 & B2, the change in salinity will lead to mortality of Sugar Kelp and to a lesser extent of Sea Lettuce. But during less extreme storm events the ESL remains salty. The ESL then has the advantage that the water levels can be lowered to protect the seaweed from harsh winds and high waves. This is something that is impossible at open sea (T. Murk, personal communication, May 10, 2021).

As any form of monoculture, repetitive cultivation of the same crops increases the risk of diseases. By combining the cultivation of two crops (Sugar Kelp and Sea Lettuce) these risks are already reduced (Groenendijk et al., 2016). Further reduction of pathogen-risk would be to create a multi-layer system with mussels or fish (T. Murk, personal communication, May 10, 2021).

4.4 Conclusion on Seaweed Cultivation

Consecutive cultivation of Sugar Kelp and Sea Lettuce has high yields 27.5 tons DW/ha. That is more than any land-based crop. In addition, the rotating crop-system reduces the risk of disease. Per hectare, seaweed can remove 30.9 CO₂/ha/yr. which is enough to compensate the emission of ±11 Dutch citizens.

The structure of the ESL structure can protect the seaweed during storms especially if the water level is lowered. However, during extreme discharge events the discharge of freshwater through the ESL will lead to the deterioration Sea Lettuce and death of Sugar Kelp.

On average the cultivation of seaweed does not increase the risk of nutrient depletion. But, when seaweed is young, there is a surge in nutrient uptake which might cause temporal risk of depletion. Future research has to be done to determine if this occurs and how fertilization can replenish the nutrient pool.

Fertilization can also increase the yield to 50 ton/ha, but creating an integrated-multi trophic system will have the same result. Currently the system is N-limited, but in future P may become limiting. Either way, without addition of N and P, C and thus CO₂ will not be limiting.

4.5 Sequestration Through Shellfish Culture

One of the possible uses of the ESL regarding aquaculture is the culture of shellfish. Previous ACT research has shown that the certain parts of the ESL are suitable for the growth of blue mussels and/or oysters. These filter feeders have the capacity to filter out large amounts of primary producers, which might make shellfish an effective pathway of carbon sequestration while also producing a sustainable, high quality food source for humans. Shellfish use of the carbon ingested for the growth of their carbonate shells, which makes up the largest part of their weight.

As seen in the Table 3 below, over 20% of the total harvested weight of mussels consists of carbon that is integrated in the shell. This form of carbon, the mineral calcium carbonate, is resistant to organic decomposition making it an effective pathway to sequester carbon emissions through (deep) burial in the soil. It was shown that for a ton of mussels harvested 0.22 tons of CO₂ is sequestered while twice as much is sequestered for a ton of oysters harvested (SARF 2012 as cited by Ahmed et al., 2017).

As oysters take two to three years to reach a harvestable size opposed to one for mussels, only mussel cultivation will be elaborated on below. This decision was made because future climate conditions will increase the likelihood of high-discharge events of fresh water into the ESL, resulting in an extinction of the population.

Besides the carbon mussels capture for growth, it has also been shown that the harvest of mussels has a positive effect on the availability of nutrients nitrogen (N) and phosphorus (P) (Table 3), possibly mitigating eutrophic conditions of the sea water. For example, mussels have been used as a way to remove inorganic N from eutrophic fjords in Norway (Haamer, 1996). Mussels also have been reported to be a sink of P in the environment, whereas most sources of animal protein produced cause a large release of P into the environment (Aubin et al., 2018). This release of P is known to cause problematic eutrophic conditions and consequently the occurrence of harmful algal blooms in surface waters. Silicon was shown to be the most limiting nutrient for the growth of diatom algae species and phosphorus for other algae types mainly present in spring (van Bennekom et al., 1975). Thus, decreasing the P load in coastal waters is hypothesized to be able to limit algae growth which could potentially create more favourable clear water conditions for the growth of seaweed in the ESL.

Table 3 Carbon and nutrient uptake through mussel cultivation as reported by Aubin et al., 2018.

Element in shell or flesh	Per ton of harvested mussels
C in shell from ingested C (Brigolin et al. 2009)	198 kg C
C in shell from dissolved C (Chairattana et al. 2012)	18 kg C
N in flesh (Brigolin et al. 2009)	4.17 kg N
P in flesh (Brigolin et al. 2009)	0.38 kg P

Other research however suggests that a fine balance between the stocking density of filter feeders and primary production is essential in a system. In the Oosterschelde for example, it is suggested that the decreasing trend in the primary production was caused by overgrazing by filter feeders above nutrient limitations. This in turn could lead to a lower flesh content, the main quality indicator of farmed mussels (Smaal et al., 2013). Although eutrophication is sometimes still mentioned as a problem in the North Sea, nutrient concentrations have decreased dramatically over the past decades. Currently, phosphorus is often limiting for the production rate that primary producers can reach and problems with eutrophic conditions are no longer occurring (T. Murk, personal communication, May 10, 2021). This leads to the conclusion that the filter feeder population size needs to be precisely calculated and controlled in the ESL if it was to be used to achieve maximum uptake rates for carbon while minimizing nutrient depletion.

One of the potential problems that requires additional research when using shellfish to sequester carbon and other nutrients, or implementing shellfish into the ESL in general, is the excretion of faeces and pseudo faeces. Due to this, increased sedimentation rates have been observed in mussel farms (Hartstein and Stevens, 2005). The exact sedimentation rate would depend on stocking densities and the conditions in the ESL. Depending on the sedimentation rate the need for dredging might occur, which is likely to release a substantial portion of nutrients and carbon emissions back into the water column. This would interfere with the goal of sequestering carbon and nutrients through the farming of shellfish in the ESL making it advised to be investigated in more detail in the future.

The by-product of shellfish farming, the carbonate shells, could in theory be turned back into clean CaCO_3 (calcium carbonate) powder. This CaCO_3 could potentially be brought back into the ESL to increase the supply of calcium into the lake and buffer the potential increase in acidity caused by increasing CO_2 concentrations. Ocean acidification will be discussed in more detail further on in this report. Unfortunately, it has been shown that turning shells back into CaCO_3 is only viable for large production systems and that the economic, technical, and environmental aspects still need to be improved to compete with CaCO_3 produced from other sources (Barros et al., 2009). Others suggest deep burial/landfilling of shells as an effective measure to store carbon on the long term, as the inorganic form of C in the shells is considered to not be degradable (Aubin et al., 2018).

When taking all sources of emission into account, shellfish culture will still have an impact on the environment. This is due to the emissions from harvesting, processing, packaging, and shipping. Innovations are however being made in all these sectors making production more sustainable. Generally spoken, shellfish culture and especially the culture of mussels provides one of the most sustainable sources of animal protein when compared to other matured industries like meat and fish.

5 Active Carbon Absorption Pathway

To reduce the CO_2 in the atmosphere, there have been initiatives to pump and store CO_2 in the deep sea. In case of the ESL, the CO_2 would be either dissolved into the water or taken up by vegetation. Similar to how increased CO_2 in the atmosphere results in carbon fertilization of terrestrial vegetation, pumping CO_2 into the ESL could enhance the growth rates of the aquatic vegetation (Ferreira-Filho, 2005).

5.1 Technical Feasibility & Maturity

Throughout literature and in practice there is little research or implementation of largescale CO₂ pumping to enhance the productivity of aquatic vegetation. However, CO₂ enrichment is a common practice within the aquarium-world where pressurized CO₂ is diffused into aquariums to enhance growth and depth of color. Various studies have also outlined this as a potential for increasing macroalgae productivity when looking into the impact of climate change and the associated increase in CO₂ (Palacios and Zimmerman, 2007; Britton et al., 2019; Cox et al., 2016; Suárez-Álvarez et al., 2012). These scientific studies use processes similar to that of aquariums (although on a larger scale), and in some cases as such with Palacios and Zimmerman (2007), flume gas containing CO₂ and NO_x was directly fed into constructed saltwater ponds from an energy powerplant. These examples indicate the potential for enhancing seaweed growth at a larger scale.

The CO₂ could be sourced from local industry (Rotterdam), but it would be easier, cheaper and more efficient to use the existing OCAP-infrastructure. OCAP supplies CO₂ to over 600 greenhouses in the Netherlands. The CO₂ is captured and transported in the same way conventional carbon capture and storage captures it. CO₂ is captured from hydrogen, biogas and bioethanol plants through amine scrubbing (Boot-Handford et al., 2014), then cooled and pressurized until it becomes a liquid (Gambhir and Tavoni, 2019). The liquified CO₂ can be transported in the same way oil is transported and is taken to horticulturalists via a pipeline. Previously, horticulturalists used to truck in liquid CO₂, but this ended up being costly having to do this at a high frequency. The most efficient, low emission and cost effective is via pipeline. OCAP plans to expand its pipelines bringing more CO₂ that would end up in the atmosphere to more greenhouses (OCAP, 2021).

To calculate the optimal dosing of CO₂, OCAP have developed complex model that accurately determines the optimal dosage for a particular time period: *OCAP Optimal*. The model takes into account various variables including: crop-type and its needs, the data from the climate computer (internal conditions), and the potential added value of additional CO₂. The last variable evaluates the costs of CO₂ addition to the current price of the crop and the effect on yield/value. OCAP optimal, or a similar model could be added to increase the efficiency and avoid damage to the external ecosystem of the ESL.

5.2 Risks of CO₂ Addition

From a technical point of view, pumping CO₂ into the ESL lake is feasible and the potential for increasing carbon storage, offset emissions and increase macroalgae productivity within the ESL is there. However, injecting additional CO₂ directly into the ESL could lead to the acidification of the water (Doney et al., 2009). This will be problematic for the aquaculture in the ESL lake because acidification damages planktonic systems and slows calcification processes, with the latter being especially harmful for the potential mussel population in the ESL as will be discussed in the next paragraphs. (Gazeau et al., 2010; Iglesias-Rodr et al., 2008; Doney et al., 2009). Furthermore, in some cases the additional dissolved carbon dioxide might react with leftover waste from agriculture, this could result in the formation of HNO₃- and H₂SO₄, these chemicals can have negative effects on the environment and local ecosystems (Doney et al., 2009).

CO₂ concentrations in the atmosphere keep increasing due to anthropogenic emissions and the amount of dissolved CO₂ in the oceans increases accordingly, which causes the oceans to acidify. CO₂ concentrations are projected to rise to levels between 540 and 970 ppm while current concentrations are around 420 ppm (May 2021). This acidification interferes with the calcification rate of calcareous marine organisms such as shellfish as well as diatoms, which is a major group of microalgae found in oceans and an important foundation for primary productivity in the system. Calcification rates were found to decrease linearly with an increase in the amount of dissolved CO₂ (pCO₂) in the water (Gazeau et al., 2007).

Scientists have not only reported decreased calcification rates as a negative impact of ocean acidification on the growth of mussels but also numerous other disadvantages. For example, decreased hatching rates and shell growth was found in juvenile blue mussel larvae for conditions that match CO₂ concentrations predicted for the end of the century (Gazeau et al., 2010). Furthermore, a decrease in byssal thread strength has been reported (O'Donnell et al., 2013). This could be problematic for any form of raised mussel culture such as on lines or wooden stakes, as the mussels become less resistant to higher flow velocities of the water or increased wave action. Also, ocean acidification was shown to increase stress in blue mussels, resulting in a decrease in functioning and protection against pathogens in the mussel (Asplund et al., 2014; Bibby et al., 2008)

To conclude, increasing the amount of CO₂ in the ESL on top of the increased atmospheric input will negatively impact the functioning of a possible shellfish population due to increased acidification of the water. The possibility even arises that shellfish and important species of algae are unable to survive within the ESL in

these conditions as the organisms are unable to use the calcification process essential for their development. This would thus make the lake unsuitable for shellfish culture unless the acidification is actively prevented, for example by the addition of basic substances as discussed in 5.3

5.3 Mitigating the Risk of CO₂ Addition

There are multiple options to mitigate the possible acidification of the lake: (1) iron fertilization, (2) addition of limestone, (3) carbon uptake by the aquaculture and/or (4) decarbonation (Cao & Caldeira, 2010; Rau et al., 2007; Harvey et al., 2008; Bonney et al., 2009). Iron fertilization has drawbacks such as eutrophication and disrupting natural ecosystem, which will be especially problematic when the ESL pumps this water into the North Sea (Beusseller et al., 2008). Limestone on the other hand, shows a higher potential with no additional side effects as long as the limestone is pure (Harvey, 2008). But, it will require a working infrastructure to obtain, transport and grind the limestone, which could provide additional costs for the project (Rau et al., 2007).

Lastly, acidification could be mitigated by aquaculture. There are specific species such as the *Zostera Marina* seagrass and *Trichodesmium* cyanobacteria that could prove to be beneficial to reduce the acidity of the ESL (Palacios & Zimmerman, 2007; Fu et al., 2007; Barcelos et al., 2007). Addition of CO₂ (active uptake) could also be combined with cultivation of seaweed (passive uptake). However, carbon is currently not the limiting factor for seaweed growth, see section 4.3.2. Therefore, the addition of extra CO₂ will not act as a fertilizer and increase seaweed yield without additional nutrients, especially N.

Technically, one could still add the same amount of CO₂ as taken up by the seaweed without risking acidification. However, the determination of the correct dose is still challenging due to the many (changing) variables. E.g., the changing water level which influences the mixing and dilution of the added CO₂, or the daily uptake cycle and maturity of the plants. At night for example there is no photosynthesis and there will be no CO₂ taken up.

Lastly a method to keep the acidification risk contained to the ESL, would be to decarbonate the water prior to pumping it back to sea. This is a common practice in treatment of groundwater, which generally groundwater is undersaturated with oxygen and oversaturated with CO₂. To elevate the O₂ and decrease CO₂, the groundwater is mixed with air. This can simply be done by creating a small waterfall or adding air bubbles. If the outlet of the pump is above the seawater level, the created drop might be enough to remove the excess CO₂ and increase the pH.

5.4 Discussion

As discussed previously, adding additional CO₂ to the ESL is technically feasible. The biggest concern however is getting the CO₂ added through a method in which it is dosed so that it is taken up almost immediately by primary producers to prevent acidification of the water. If a method of getting the CO₂ to be taken up effectively cannot be established this would mean that the with CO₂ enriched water will simply flow out the North Sea because of the daily emptying of the ESL (T. Murk, personal communication, May 10, 2021).

To avoid acidification outside the ESL, decarbonation might be a solution, but it raises the question whether the adding CO₂ to ESL to only remove it later, is worth the effort. The ESL is already a highly dynamic system with water being continuously refreshed and aerated. Therefore, the exchange between atmospheric and dissolved CO₂ is optimal and in equilibrium. As long as CO₂ concentration at equilibrium is not limiting, adding CO₂ to the ESL seems impractical. Yet, adding nutrients is also challenging. Precise dosing and rapid uptake are must, especially because the surrounding Natura2000 area may not be influenced by practices in the ESL. The changing water levels, the resulting dilution of added nutrients and scale of the ESL, complicates this further.

From both literature reviews and expert interviews, we conclude that addition of CO₂ to the ESL in combination with the required additional nutrients is challenging. More research and modelling is required as well as detailed risk assessments. At this moment we would advise to increase production rates through other natural interactions within the ecosystem due to the connectivity between the ESL and the Dutch coastal waters.

The idea of using additional CO₂ to increase aquacultural production is however not a concept that would not be effective in any system. Instead of implementing it in a (semi-)open system like the ESL, adding CO₂ to increase aquacultural production has a large potential for closed systems. Having a closed system means that

CO₂ input and output as well as other parameters can be closely monitored and possible effects on the surrounding environment are eliminated.

An interesting form of a closed system is the Recirculatory Aquacultural Systems (RAS). In the RAS, the water is filtered and reused, sometimes with the use of natural filter systems. Often, these systems contain multiple basins in which separate steps in a multitrophic system or food chain are being cultivated while parameters can be closely monitored in every level. One of these systems could for example be growing algae in the first tank, shellfish fed by algae in the second and lobsters fed with the shellfish in the third tank. These kinds of systems are very suitable for CO₂ addition in the first step of the food chain. Making the system closed from contact with the atmosphere and using artificial lighting were suggested to increase the primary productivity even further. With these kinds of systems primary productivity can be increased greatly while the other organisms in the food chain are not affected by changes in acidity and other parameters such as oxygen depletion. Furthermore, nutrient inputs can be closely regulated and the problem of nutrient depletion of the surrounding environment is no longer an issue (Murk, personal communication, May 10, 2021).

6. Applicability of Seaweed and its Beneficial Environmental Impacts

The applicability and demand of seaweed is ever expanding due to the rising interest in sustainable and healthy products with a high climate change mitigation potential (Sondak et al., 2016). Therefore, seaweed has a potential to play a large role in the shift towards a sustainable future. Currently, macroalgae are harvested for use in a range of products including: food, biofuel products, fertilizer, feed in agriculture and aquaculture, and cosmetics (Sondak et al., 2016). The topics discussed here are perceived to be best pathways for a decline in environmental problems. The pathways/uses of seaweed will be discussed, however some such as biofuels will not be discussed in depth because it is already in a higher state of maturity. Sustainable ingredients for animal/fish feeds are becoming an increasingly important and highly sought after (Swinscoe et al., 2019), with the potential use of seaweeds having recently gained popularity and as such will be discussed. Using seaweeds in fertilizers have been around for a while but it was not until recently that their full potential has been realized.

6.1 Fish Feed

Aquaculture, mainly fish farms have come under fire for being environmentally damaging, through water pollution and spread of disease (Chu et al., 2020). In this section we will focus on the environmental degradation fish feeds cause and the potential mitigation opportunity that seaweeds could hold.

The type of fish that is farmed is generally higher up the food chain. Therefore, these fish require a diet high in protein and fatty acids, which mainly comes from wild caught fish (Kok et al., 2020). These feed-species are generally caught in an unsustainable manner and sustain overfishing (Hutchings, 2000). With the depleting ocean resources and higher demand for sustainable aquafarms, many fish feed producers have moved towards plant-based substitutes. However, this increases the pressure on essential agricultural resources (Kok et al., 2020). The transport of fish meal and the added pressure on agricultural systems could be reduced using seaweeds. Additionally, seaweeds in fish diets have shown to improve immune and antioxidant response of the fish (Ferreira et al., 2020). Thus, less synthetic additives or medicines is needed in the fish feed, reducing the risk that these would leak into the surrounding ecosystem if farmed in an open system (Peixoto et al., 2016).

Currently, seaweed is often used as a binder in fish meal (Aslamyiah et al., 2017). However, seaweeds can also form a sustainable source of essential nutrients and proteins (Swinscoe et al., 2019). The quantity of amino acid, vitamins and minerals in seaweeds is 10 to 20 times higher than in terrestrial plants (Aslamyiah et al., 2017). However, there are problems with the digestibility of large quantities of seaweed for many species of fish as the macroalgae contain high levels of crude fiber and other substances that are different from the raw material in animal protein (Aslamyiah et al., 2017).

There are options to overcome the high fiber content. One is the fermentation of seaweed as outlined by Aslamyiah et al. (2017). The fermentation increased the dry matter and organic matter digestibility, protein content, and decreased the crude fiber, fat, and ash within the seaweed. Another already operating option is using insects and feeding them seaweed. Insects have emerged as a sustainable option for fish feed after

being approved by the EU in 2017 (Swinscoe et al., 2019). Insects and their larvae can partially sustain fish with no nutritional deficiencies (Lock et al., 2016). However, Swinscoe et al (2019) noted that carnivorous marine fish (such as Salmon) still require essential fatty acids which come from marine sources such as smaller fish. They discovered that when Black Soldier Fly larvae is fed seaweed, it can provide missing long chain polyunsaturated fatty acids in a safe manner. Black Soldier Flies are highly efficient at converting organic matter into high value protein and fats. Therefore, this could provide a sustainable solution, and a commercially attractive and viable alternative. (Swinscoe et al., 2019).

Thus, linking Delta21's seaweed production to sustainable fish feed for Dutch fish farms would reduce the pressure on (wild-)fish stocks and agricultural land, reduce the risk of non-natural compound leakage and would indirectly reduce the carbon footprint of Dutch fish farms.

6.2 Soil Fertilizer

Over the past couple of years, seaweed has emerged as a product that can improve agriculture on various levels. The use of seaweeds in fertilizers is not new. For centuries coastal areas have used seaweed in compost heaps for agricultural farming (Mukherjee & Patel, 2020). Recently, seaweed (in the form of liquid fertilizers) has emerged as Economically and environmentally sustainable, and cost-effective option (Vijayakumar et al., 2019). Some studies have pointed out the benefits of integrating seaweed fertilizers alongside synthetic fertilizers, with both increased quantity and quality of yields (Pramanick et al., 2020).

Seaweed is extremely beneficial for organic farms, containing all of the beneficial nutrients without the need for chemical or animal fertilizers (Kaur, 2020). Yet, the use of seaweed is not confined to organic farms nor to a certain crop type. Some studies have pointed out the benefits of integrating seaweed fertilizers alongside synthetic fertilizers, with both increased quantity and quality of yields (Pramanick et al., 2020).

Seaweeds are a good source of organic matter and fertilizer nutrients (Bulgari et al., 2019), offering a wide spectrum for agricultural inputs in the form of biofertilizers, enhancers and bio stimulants (Kaur, 2020). They contain high amount of macro- and micro-nutrients, vitamins, amino acids, and growth regulators (Kaur, 2020; Mukherjee & Patel, 2020; Craigie, 2011). These nutrients, such as cytokins, gibberellins and phyco colloids, are of great commercial value (Kaur, 2020). They also contain large sums of magnesium and potassium which is extremely beneficial for the soil and crop (Vijayakumar et al., 2019).

In addition to replacing chemical and animal fertilizers, they can replace other synthetic products in agriculture such as chemical foliar sprays (Kaur, 2020). In fact, these seaweed foliar sprays have been shown to improve the quality and quantity of yield (Kaur, 2020; Pramanick et al., 2020; Garai et al., 2021; Gutiérrez-Gamboa et al., 2020; Daniel & Fabio, 2020), better water and nutrient use efficiency (Garai et al., 2021), and enhance resistance towards fungi, bacteria and virus' (Sharma et al., 2014).

The negative externalities that arise from intensive use of fertilizers and foliar sprays form an ever-present threat. With agricultural inputs having reached an all-time high, a shift must be made towards a "less for more" mind-set to reduce eutrophication and associated risks (Michalak et al., 2017) (Daniel & Fabio, 2020). Seaweed fertilizers form a solution. It is seaweeds bio-stimulant capacity that is looked at most when focusing on increasing output with less inputs (Michalak et al., 2017). Daniel and Fabio (2020), found that depending on the yearly climate conditions, primary nutrient and total fertilization units applied in a pear orchard decreased by 35-46% and 13% respectively when seaweed-based extracts are applied. Additionally, there was a significant improvement in the average weight of fruits (5%) and total yield (19-55%). These results are supported and explained by other studies: they highlight the high amounts of bio-stimulants in seaweed fertilizers and their importance as abiotic stress alleviators and subsequently nutrient use efficiency enhancers (Bulgari et al., 2019; Van Oosten et al., 2017).

Seaweeds can also benefit compost piles and provide an interesting tool for nitrogen and phosphorus recycling (Cole et al., 2016). The addition of seaweed into compost piles increase the thermophilic temperature and enzyme activities, additionally enhancing the utilization capacity of carbon sources of the microbial community and the diversity of beneficial microbes within a compost pile (Zhou et al., 2019). Composting is one to the lowest cost approaches to nutrient stabilization and leaching reduction (Cole et al., 2016), thus could be a low-cost option to benefiting the sea and terrestrial agriculture.

This has been proposed as a solution in areas that suffer high levels of eutrophication. However, as stated previously, the North Sea is no longer eutrophicated. Therefore, the nutrient recycling mechanism may not be as effective as a pathway.

6.3 Animal Feed

Seaweeds in agricultural feeds have seen an increased attention recently. Seaweeds have been found to (1) reduce the need for antibiotic usage (Morais et al., 2020), (2) improve cattle performance (Xue et al., 2019), (3) reduce methane in ruminants (Vijn et al., 2020), (4) reduce the reliance on soy and other feed crops, and (4) decrease feed conversion ratio (Abudabos et al., 2013).

6.3.1 Reduce Antibiotic Usage and Improving Cattle Performance

Marais et al (2020), state that seaweeds are very rich in useful metabolites and minerals, making seaweed a highly value commodity which can substitute the need for antibiotic usage in various livestock feeds. Additionally, feeding kelp (brown seaweed) has been found to improve cattle performance (yields). Trials in lactating dairy cows yielded reductions in multiple ruminal compounds, which effects have been shown to improve milk yield (Xue et al., 2019).

6.3.2 Reducing Methane in Ruminants

The main climate change mitigation potential of seaweed in agriculture besides substitutions for other products is methane inhibition in ruminants (Vijn et al., 2020). Seaweed has been found to reduce methane output from ruminants by inhibiting the CH₄ biosynthesis within methanogens (Abbot et al., 2020). *Asparagopsis Taxiformis* is a seaweed species that is known to reduce methane and that has been researched in numerous in vitro and in vivo studies. Appendix C goes into more detail with regards to this topic.

Sadly, *Asparagopsis Taxiformis* grows in tropical waters, and the water temperatures on the Dutch coast cannot support this species. In addition, there are too little in vivo trials with species that can be grown in the ESL. Production of *Asparagopsis Taxiformis* does occur on land under controlled conditions. A trending topic is the use of cooling water to mimic the warm conditions needed for *Asparagopsis Taxiformis* (The Seaweed Company, 2021). However, this would probably not be possible in the ESL, because of the Natura 200 legislation.

There has been some research into other seaweed species beside *Asparagopsis Taxiformis*, but these are mostly in vitro studies and none on in vivo studies. Therefore, within this report, the use of seaweed from the ESL to reduce methane from ruminants will be excluded. However, the use of seaweed from the ESL to reduce the impact of ruminants in the Netherlands on climate change does not stop here.

6.3.3 Reducing the Feed Conversion Ratio and Reliance of Soy

Besides using seaweeds for methane inhibition in ruminants, seaweed can still be used for food additives in ruminants to benefit carbon mitigation (Xue et al., 2019). As stated preciously, they are rich in useful metabolites, minerals (Morais et al., 2020) and some species high in protein (Makkar et al., 2016). The uses and beneficial outcome of seaweed for feed outlined in the fish feed section are similar to that of agricultural feeds. The main focus is on decreasing feed conversion ratio and increasing food use efficiency of animals using seaweed supplements. This would decrease the import of soy from overseas and move towards a degree of farming requiring less inputs, both reducing the carbon footprint of agriculture and land use needed to support the number of animals. Results between papers differ heavily relating to the addition of seaweed as a supplement. Some of the side effects that are mentioned about seaweed addition in papers are: Increase in feed conversion rate, no increase in feed conversion rate, increase in body weight, and an increase in product yield (Abudabos et al., 2013; Costa et al., 2021; Bikker et al., 2020). However, there is no academic consensus on what the exact side-effects are and within which species. Some papers suggest the benefits in both monogastric and ruminant species whilst others suggest one or the other.

The effect on feed conversion rations are mostly apparent within poultry. Most of the poultry feed is corn (60-75% in broiler chickens), with the remaining percentages being made up of mostly soy (Abudabos et al., 2013; Costa et al., 2021). Substituting these two sources of feed of which have adverse effects on the environment, particularly soy, could reduce the reliance and need for these high carbon emitting and environmentally damaging crops. Abudabos et al (2013) found that broiler birds' fed on a 3% *Ulva Lactuca* diet performed better than the control, although seasonal variations in the nutrient composition of the seaweed

could yield different results. Therefore, there would be 3% less feed from corn and soy being required to grow broiler chickens. A meta-analysis and systematic review by Andi et al (2020), supports the use of seaweed in poultry with seaweed supplements having a beneficial impact on body weight gain and the food conversion ratio of broiler chickens. Other research also outlined the potential for seaweeds in improving performance and food conversion ratio of laying hens and geese (Andi et al., 2020).

6.4 Biofuels

Seaweeds are useful for bioethanol and biodiesel due to their high levels of carbohydrates which can all be utilized as a feedstock for these biofuels (Bikker et al., 2016). The whole crop can be utilized with the residual biomass being used as fertilizer, or as a feedstock for other kinds of biofuels (Osman et al., 2020), maximizing the total energy yield from the biomass. Biofuels are produced from biomass, which is renewable and reduces the dependence on fossil fuels (Osman et al., 2020). A large sum of biomass used for biofuels (first generation biofuels) comes from food crops, which raises the food vs fuel debate and competition with land for food (Elshobary et al., 2020). Seaweeds have been discussed as a good option that can surpass the concerns raised by the three generations of biofuels (Osman et al., 2020; Elshobary et al., 2020; Michalak, 2018). They do not compete with arable land, leftover wastes can be utilized in arable lands, have lower pre-treatment costs than terrestrial biomass residues, and do not take up precious freshwater resources like microalgae do (Osman et al., 2020; Elshobary et al., 2020). Seaweed is easier to harvest than their microalgae counterparts which require the use of more technological procedures than seaweed (Osman et al., 2020).

6.5 Conclusion

Seaweed has a high potential to reduce (non-)local environmental impacts, although this is dependent on the species and use. Using each species to maximize its carbon offsetting is crucial to increasing the role of the ESL to mitigate climate change. Using the seaweed for just one of these uses may not be enough but incorporating a zero-waste system/circulatory system, could potentially be the key to maximizing the mitigation potential of the ESL. An example of this would be using seaweed for biofuels and the waste material could be incorporated into fertilizers.

Ideally reducing methane from cattle would be highly beneficial. The most potent GHG could potentially be eliminated from Dutch cattle farms, especially if the same results as seen with *Asparagopsis Taxiformis* are recreated. However, in vitro studies did show a decline of 45-50%, which if replicated in in vivo studies is still a significant drop in methane. More research is required on this. However, with regards to animal feeds, sea lettuce appears repeatedly throughout the literature. Although recent studies have looked into sugar kelp in animal diets and have showed signs of having good potential (Rey et al., 2019). In fish feeds, both seaweed species have the potential to be used with beneficial effects on the fish and carbon offsetting being present. These two pathways provide opportunities to substitute highly emitting and unsustainable sources of feed. There are not just singular benefits of each of these pathways, but the benefits are seen throughout including on the animal themselves; benefitting the producers (cost of production), animal (health), environment (fewer synthetic additives), and in terms of this report the mitigation capacity.

7. the Carbon Footprint of each Pathway

7.1 Methodology

To determine the emissions of CO₂ to global warming or the mitigation potential of each pathway in the ESL this study has conducted a carbon footprint (CFP) study. By analyzing a series of life cycle assessment (LCA) studies in the vicinity of the Netherlands regarding the cultivation of seaweed and mussels we have determined the CFP and mitigation potential of each pathway in the ESL (according to ISO 14067¹). The CFP of a product is the sum of GHG emissions and removals within a product system (as described by LCA) expressed as CO₂ equivalents using the single impact category of climate change. The CFP is calculated based on the methodology of an LCA which consists of the four phases (Figure 6) of an LCA, 1) the goal & scope, 2) the LCI (life cycle inventory), 3) LCIA (life cycle inventory assessment), and 4) the life cycle interpretation to estimate the environmental impact during all stages from raw material extraction to the end-of-life (ISO 14040²).

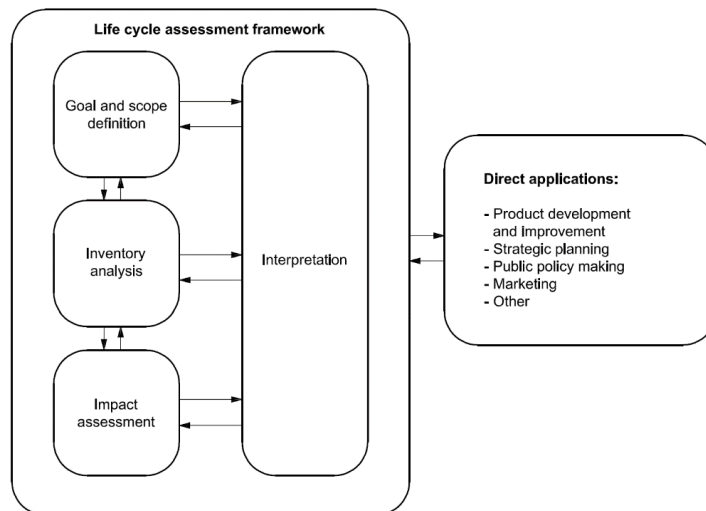


Figure 6 Stages of an LCA (ISO, 2006)

The biggest difference with an CFP compared to a regular LCA is that it only uses the impact category climate change. In phase 4) the life cycle interpretation, the mitigation potential of each concerning aquaculture activity with mitigation potential is included.

Carbon Footprint (CFP) Software

For the CFP analysis we have used the open-source open LCA software from the company Nexus (version 1.10.3). OpenLCA Nexus is an online archive for LCA data which combines data offered by world leading LCA data providers such as Ecoinvent and ELCD. This is open-source software that contains tens of thousands of datasets, from which some of them are free (openLCA Nexus, 2020a).

Assessment Method

For the impact assessment method regarding the results of the LCI this study has chosen to use the Environmental Footprint (mid-point indicator) method which is a baseline model of the IPCC 2013 report (radiative forcing as global warming potential (GWP100 in kg CO₂ eq). The mid-point indication was chosen because this study focuses on a single environmental problem and the IPCC 2013 report was chosen since it is the latest accessible report of the IPCC.

Datasets

For the datasets of the materials and productions processes regarding the LCI of the cultivation systems and mitigation efforts, the Product Environmental Footprints (PEF) developed by the European Commission was used. This dataset, originating from the European Commission its Single Market for Green Products initiative (SMGP) was chosen because it is a common method for the assessment of environmental impacts of products, especially in the environmental footprint sector (openLCA Nexus, 2020b).

¹ Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification

² Environmental management - Life cycle assessment - Principles and framework

Goal & Scope

This research project aims to provide Delta21 and its contributors with constructive options and insight into the carbon mitigation potential of the ESL. The product system to be studied is a series of mitigation pathways regarding the cultivation of seaweed and mussels which have the potential to actively- or passively mitigate carbon. The functional unit is kg CO₂-eq per kg of the concerning aquaculture activity using the impact category climate change. Mitigation pathways that are included in this CFP study are:

I. CO₂ addition for enhanced productivity (from industries), II. Mussel cultivation for food production (raw at packaging), III. Seaweed for fish feed production (protein rich fish feed ingredient), IV. Seaweed for fertilizer production (fertilizer supplement), V. Seaweed for biogas production (energy generation), VI. Seaweed for fodder production (maize substitute).

7.2 Life Cycle Inventory (LCI)

The data concerning the LCI and LCIA for CO₂ addition for enhanced productivity (from industry) in this study was based on the LCA study of Wildbolz (2007) that assessed technologies of CO₂ transport and sequestration in Zurich, Switzerland. Data concerning the LCI for mussel cultivation in this study were based on the LCA study of E. Tamburini et al. which cultivated Mediterranean mussels (*Mytilus Galloprovincialis*) in the Northern Adriatic Sea, Italy (Tamburini et al. 2020). The data concerning the LCI for seaweed cultivation in this study were based on the LCA study of Seghetta et al. (2017) which cultivated seaweed (*Saccharina Latissima*) in Limfjorden, Denmark. Detailed results of the LCI can be found in Appendix D.

7.3 Life Cycle Impact Assessment (LCIA)

Based on the LCI and LCIA (Appendix D) we can see that pathway I. CO₂ addition for enhanced productivity (from industries) and pathway II. Mussel cultivation for food production (raw at packaging) have the highest emission, followed by V. Seaweed for biogas production (energy generation). The other activities have a similar environmental impact (Figure 7).

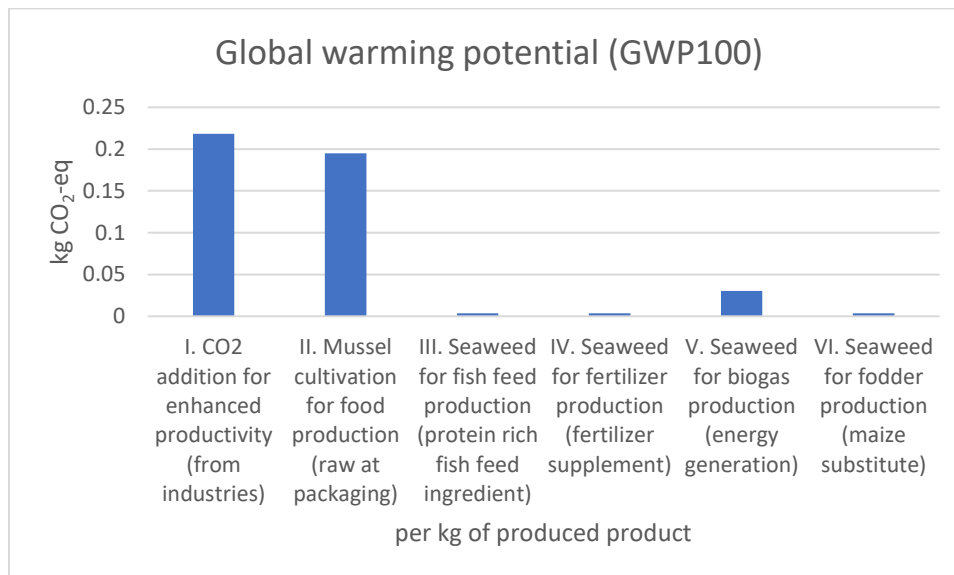


Figure 7 Global warming potential (GWP) of the potential aquaculture activities: I. CO₂ addition for enhanced productivity (from industries), II. Mussel cultivation for food production (raw at packaging), III. Seaweed for fish feed production (protein rich fish feed ingredient), IV. Seaweed for fertilizer production (fertilizer supplement), V. Seaweed for biogas production (energy generation), VI. Seaweed for fodder production (maize substitute)

7.4 Life Cycle Interpretation (mitigation potential)

To determine the mitigation potential of each aquaculture activity we have taken the results of the LCIA and looked at the emissions of the concerning activities such as the production of the protein rich fish feed ingredient and the emissions concerning preparation of biomass for biogas and the emissions that are concerned with burning it.

Table 4 III. Seaweed for fish feed production (protein rich fish feed ingredient)

per kg of produced seaweed for protein rich fish feed ingredient

Conversion ratio biomass to protein-rich fish feed ¹	13	%
Protein rich fish feed ingredient	0.13	kg
Protein substitution ratio	1:1	-
Protein rich fish feed ingredient	0.13	kg per kg product
Production of soy	4.75E-01	kg CO ₂ -eq per kg soy
Production of soy per kg of produced seaweed (ratio 13%)	6.18E-02	kg CO ₂ -eq per kg seaweed
Mitigation potential	6.18E-02	630
Seaweed cultivation	3.00E-04	kg CO ₂ -eq
Fish feed production pathway	3.40E-03	kg CO ₂ -eq
Climate change	- 0.0581	kg CO ₂ -eq

¹ (Seghetta et al., 2016)

Firstly, we have looked at the conversion ratio of biomass to protein-rich fish feed which is 13%. This means that per kg of *Saccharina Latissima*, 0.13 kg of protein-rich fish feed ingredient can be produced. This was multiplied by the emissions of soy of 4.75E-01 which means a mitigation potential of 4.75E-01 * 0.13 per kg of produced seaweed of 6.18E-02. The emissions of the seaweed cultivation and fish feed production pathway were extracted from the mitigation potential to come to the final negative emission of -0.0581 kg CO₂-eq per kg used kg of seaweed (Table 4).

Table 5 IV. Seaweed for fertilizer production (fertilizer supplement)

per kg of produced seaweed for fertilizer supplement*

Fertilizer supplement (% phosphorus fertilizer of DW biomass) ³	0.35	%
Phosphorus fertilizer production per kg	350	mg P / kg biomass
Phosphoric acid_fertiliser grade, dihydrate process_at plant_EU-28+3_S	1.01255	kg CO ₂ -eq per kg P
Phosphorus fertilizer production (emission) ¹	1.01E-06	kg CO ₂ -eq per mg P
Undecomposed carbon (biofertilizer) per kg fertilizer	10	%
Carbon content per kg DW seaweed	3	%
Undecomposed carbon (biofertilizer) per kg fertilizer ²	3.50E-03	kg CO ₂
Carbon mitigation potential (alternative fertilizer production)	3.54E-04	kg CO ₂ -eq
Seaweed cultivation	3.00E-04	kg CO ₂ -eq
Fertilizer production pathway	3.40E-03	kg CO ₂ -eq
Climate change	- 0.00015	kg CO ₂ -eq

*Protein recovery was set at 100% in the biorefinery process to produce protein rich fish feed which means there was no nitrogen left in the liquid fertilizer (Seghetta et al., 2016).

¹ (Smol, 2020), ² (Seghetta et al., 2016)

Firstly, we have looked at the phosphorus content per DW biomass *Saccharina Latissima* which is 0.35%. This means that per kg of *Saccharina Latissima*, 350 mg phosphorus can be produced for producing phosphorus fertilizer. The emissions of producing phosphorus fertilizers are 1.01E-06 kg CO₂-eq per mg produced P which means that the mitigation potential of this pathway is 1.01E-06 * 350 = 3.54E-04 kg CO₂-eq. For applying biofertilizers, about 10% of the carbon is considered undecomposed after 100 years. Therefore, we looked at the 10% of the fertilizer that was produced by the biomass and counted this as undecomposed mitigation potential. By subtracting the emissions of the cultivation cycle and the fertilizer production pathway with the mitigation potential of the substituted phosphorus fertilizer and the containing undecomposed carbon we come to a negative emission to climate change of – 0.00015 kg CO₂-eq per used kg of seaweed (Table 6).

Table 6 V. Seaweed for biogas production (energy generation)

per kg of produced seaweed for biogas production

Biogas production from 1kg of <i>Saccharina Latissima</i>	2.62E-02	m ³ per kg product
Calorific value of biogas ¹	2.23E+01	MJ per m ³
Calorific value per kg product	5.85E-01	MJ per kg product
Biogas CHP plant efficiency ²	4.30E+01	%
Calorific value per kg product (usable energy)	2.52E-01	MJ per kg product
Electricity production (emission)	2.70E-01	kg CO ₂ -eq per MJ
Carbon mitigation potential (alternative electricity production)	- 6.79E-02	kg CO ₂ -eq
Seaweed cultivation	3.00E-04	kg CO ₂ -eq
Biogas production pathway	2.99E-02	kg CO ₂ -eq
Climate change	- 0.0376	kg CO ₂ -eq

¹ (Frazier, 2019), ² (Clarke Energy, 2013)

Firstly, we have looked at the biogas that could be produced from 1 kg of *Saccharina Latissima* which is 2.62E-02 m³ per kg of product. Then we have taken the calorific value per volume of produced biogas to calculate the calorific value per kg of used seaweed. From the calorific value per kg of used product we have accounted for the CHP efficiency to get a more reliable result. Subsequently, we used the emission of electricity production in kg CO₂-eq per MJ of produced electricity to see which emission this pathway could mitigate. By subtracting the emissions of the cultivation cycle and the biogas production pathway we come to a negative emission to climate change of – 0.0376 kg CO₂-eq per used kg of seaweed (Table 6).

Table 7 VI. Seaweed for fodder production (maize substitute)

per kg of produced seaweed for fodder production

Maize (corn grain) production; , at farm, technology mix, production mix,	5.46E-01	kg CO ₂ -eq per kg
Maize to seaweed substitution ratio	1:1	-
Seaweed cultivation	3.00E-04	kg CO ₂ -eq
Fodder production pathway	3.45E-03	kg CO ₂ -eq
Climate change	- 0.5427	kg CO ₂ -eq

Since seaweed can be used as complementary to fodder, we have looked at the emissions of maize production because feeding chickens 3% of seaweed can thus mitigate the otherwise produced maize. Maize production has an emission of 5.46E-01 and because maize is directly replaced for seaweed the substitution ratio is 1. By subtracting the emissions of the cultivation cycle and the fodder production pathway we come to a negative emission to climate change of – 0.5427 kg CO₂-eq per used kg of seaweed (Table 7).

7.5 Mitigation Potential

To account for the carbon that was taken up by the cultivation of both the seaweed- and mussel species we have assumed an uptake (by passive absorption) of 1.17 kg CO₂ per kg of cultivated seaweed and 0.22 kg CO₂ per kg of cultivated mussel (Table 8).

Table 8 Mitigation potential including the absorption of carbon by each of the six aquaculture activities

Mitigation pathway	emission	local carbon uptake	non-local carbon mitigation	mitigation potential
I. CO ₂ addition for enhanced productivity (from industry)	0.2182	0	1.17	0.9518
II. Mussel cultivation for food production (raw at packaging)	0.195	0.22	0	0.025
III. Seaweed for fish feed production (protein rich fish feed ingredient)	0.0037	1.17	0.0581	1.2244
IV. Seaweed for fertilizer production (fertilizer supplement)	0.0037	1.17	0.00015	1.1664
V. Seaweed for biogas production (energy generation)	0.0302	1.17	0.0376	1.1774
VI. Seaweed for fodder production (maize substitute)	0.0037	1.17	0.5427	1.7089

Based on the results of the mitigation potential (Table 5, 6, and 7) and the results of the LCI and LCIA (Appendix D) we can see that II. Mussel cultivation food production (raw at packaging) has the lowest mitigation potential (Table 8). Pathway I. CO₂ addition for enhanced productivity (from industry) has the second lowest mitigation potential of 0.9518 kg CO₂-eq. With this pathway we consider that all carbon is supplied from non-local sources such as the industry. Therefore, the local carbon uptake is assumed to be 0, since the seaweed is already saturated with the externally sourced carbon. Thirdly, IV. Seaweed for fertilizer production (fertilizer supplement) and V. Seaweed for biogas production (energy generation) have an almost equal mitigation potential of 1.1664 and 1.1774 kg CO₂-eq respectively. The pathways III. Seaweed for fish feed production (protein rich fish feed ingredient) and VI. Seaweed for fodder production (maize substitute) have the highest mitigation potential with a carbon mitigation potential of 1.2244 and 1.7089 kg CO₂-eq (Figure 8).

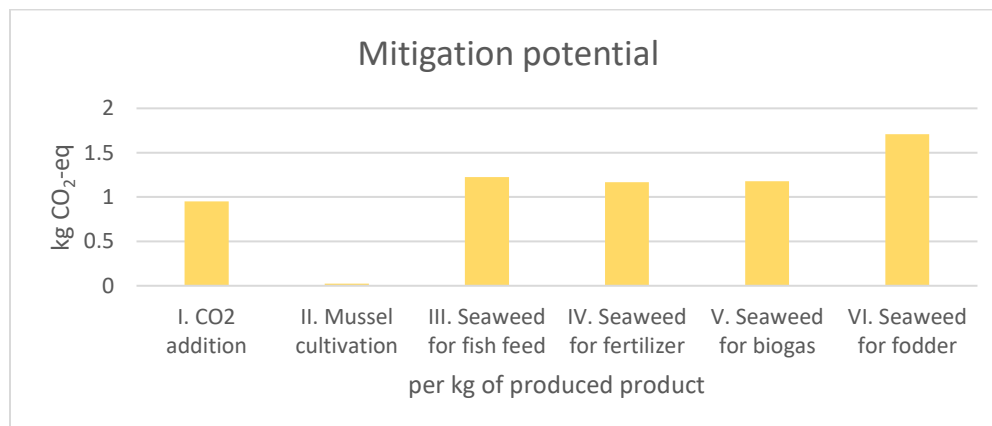


Figure 8 Carbon mitigation potential of the potential aquaculture activities: I. CO₂ addition for enhanced productivity (from industry), II. Mussel cultivation for food production (raw at packaging), III. Seaweed for fish feed production (protein rich fish feed ingredient), IV. Seaweed for fertilizer production (fertilizer supplement), V. Seaweed for biogas production (energy generation), VI. Seaweed for fodder production (maize substitute)

7.5.1 Mitigation Comparison

The carbon mitigation potential per kg of produced product might not say much. Therefore, we have estimated the carbon mitigation potential for the whole ESL (19 km²) expressed in amount of carbon mitigated by wind turbines. As an example, we used pathway III. Seaweed for fish feed production (protein rich fish feed ingredient). This pathway has an annual mitigation potential of 62234.83 ton CO₂-eq, which equals a CO₂ displacement of a set of wind turbines with the capacity of 55MW and a carbon price (EU ETS) of €3,228,120.63 (Appendix E).

7.6 Conclusion

Pathway I. CO₂ addition for enhanced productivity (from industries) has a relatively high emission due to the use of steel, rockwool, and diesel that is being used for production and installment of the pipelines. Especially, considering that this highly emission intensive infrastructure must be replaced approximately every 30 years. In this pathway we consider that all carbon is supplied from non-local sources, so it contributes to mitigation but not to local uptake. Since the emissions of this pathway are relatively high compared to the non-local carbon mitigation potential its final mitigation potential is mediocre.

Pathway II. Mussel cultivation for food production (raw at packaging) is relatively CO₂ intensive due to the use of machinery such as a socking machine, a de-clumping machine, and a grading machine which are made of steel. Moreover, the mitigation potential is relatively low since mussels do not sequester that much carbon, to compensate for their emissions.

Pathway III. Seaweed for fish feed production (protein rich fish feed ingredient) has a relatively low emission because the process of seaweed cultivation is not CO₂ intensive. Also, the hydrolysis steps taken to valorize the product into high protein substance for fish feed are not intensive. Because this pathway is off setting import of soy (which is CO₂ intensive) its mitigation potential seems promising.

Pathway IV. Seaweed for fertilizer production (fertilizer supplement) has a relatively low emission since equal data as pathway III has been used. The mitigation potential is also relatively low because the product has a low concentration of phosphorus, and this pathway looks at substituting phosphorus fertilizer.

Pathway V. Seaweed for biogas production (energy generation) seems like a promising technique to mitigate carbon but burning biogas will still emit (biogenic) carbon emissions into the atmosphere. However, it could mitigate emissions in current electricity generation.

Pathway VI. Seaweed for fodder production (maize substitute) has a relatively low emissions since the seaweed cultivation is not energy intensive and the product can almost directly be fed to chickens. Because the seaweed is replacing maize production, which is relatively CO₂ intensive the mitigation potential of this pathway seems most promising. Altogether, it seems like either valorizing the physical product or using the raw material directly will be most promising to mitigate carbon emissions.

Altogether, it seems like either valorizing the product (of seaweed in this case) or using the raw material directly will be most promising to mitigate carbon emissions.

7.8 Discussion

Data from the LCA studies regarding the CO₂ from industry pathway and seaweed cultivation have assumed a yield of 16585 kg per ha of seaweed (*Saccharina Latissima*) according to the study of Seghetta et al. (2016) to come to a functional unit of emissions per kg of product. The LCA on mussel cultivation already had a functional unit of 1kg produced product. This means that if the yield changes, the emissions will change as well which could lead to a different CFP result. However, other studies show similar results of emission per kg of produced seaweed so the calculations used can be assumed to be correct.

Pathway I. CO₂ addition for enhanced productivity (from industries), for this pathway we have assumed a distance of 100 km from industry to the ESL but this could obviously change or current OCAP systems could be used. This means that the emissions regarding the pipelines can be lower. However, if the pipelines will have a distance more than 100 km this will also increase the emission.

Pathway II. Mussel cultivation for food production (raw at packaging) has a relatively high emission due to the use of steel in various equipment. So if they would use less of this kind of equipment or substitutes, the emissions would be much lower. Also, the cultivation practice will probably be much more efficient and

controlled in the ESL which means that this mussel cultivation system can possibly be much more sustainable. Especially considering that the emissions are mainly caused by the steel equipment and the diesel, future plans for the ESL would probably be consisting of boats powered by electricity.

Pathway III. Seaweed for fish feed production (protein rich fish feed ingredient) is based on the seaweed species *Saccharina Latissima* and using other species might result in a different protein content and biomass yield which will also have an influence on the mitigation potential.

Pathway IV. Seaweed for fertilizer production (fertilizer supplement), this pathway was determined based on the fish feed production because the hydrolysis and the microalgae growth are similar for producing the fertilizer supplement. However, if these activities will have practical differences, it could be the case that these data are not completely correct.

Pathway V. Seaweed for biogas production (energy generation), for this pathway the emissions of NH₃, H₂S, H₂O, and NO_x during combustion were not being accounted for because of the lack of proper datasets within the openLCA software. Therefore, the actual emissions could be much higher than currently assumed.

Pathway VI. Seaweed for fodder production (maize substitute) was based on the fact that 3% of the feed by chicken can be substituted by seaweed. However, the effectivity of feeding seaweed to chickens or other animals is highly dependent on the animal and the seaweed species that is being used. The seaweed species used in the study regarding chicken feed is *Ulva Lactuca*. This also means that the effectivity with the species that is advised for the ESL might not have the same results.

8. Multi Criteria Analysis

8.1 Methods

Multi-Criteria-Analysis (MCA) are conducted to better compare different options with each other based on different selected criteria (Strager & Rosenberger, 2007). In this section, the different criteria will be elaborated upon, furthermore certain criteria will weigh more towards the final score than others to ensure that the priorities of the commissioner are incorporated into the report.

For conducting the MCA, the program *Definite* (Decisions on a finite set of alternatives) will be used. The program is also known as BOSDA. In *Definite*, four distinct phases are outlined: (1) Setting up of the MCA, (2) Standardizing the effect scores, (3) MCA results and (4) conducting a sensitivity analysis.

8.2 Phase 1: Setting up the MCA

The first phase of the MCA is the set-up phase. The end goal, the different categories, the different criteria and their indicators will be explained and elaborated upon in this section and are shown in Table 9 and Figure 9.

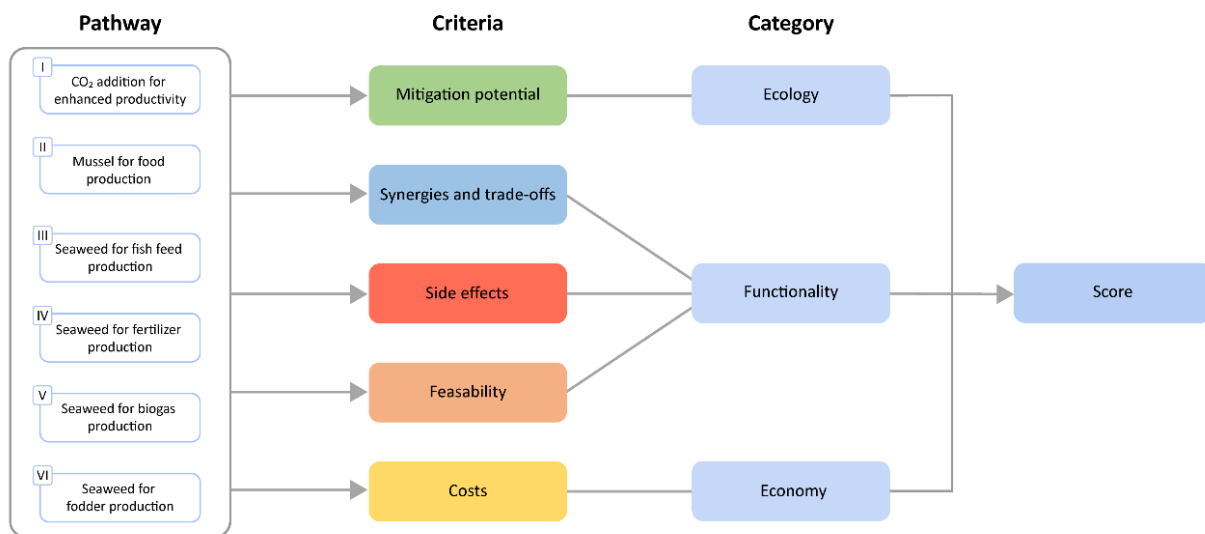


Figure 9 Pathways and criteria that were used in the MCA

Firstly, the end goal of the MCA is to assess how effective each pathway is for the Delta21 project, with this end goal we can advise the most effective pathway for the Delta21 project. Secondly, to assess effectiveness, the MCA was subdivided into three categories: ecology, functionality, and economy (Windapo, 2014; Hwang & Tan, 2012; Hua 2011; Tánczos & Kong, 2001). These categories were chosen because they all play a vital role for a successful project. Thirdly, from these categories one or multiple criteria were determined each with their own (multiple) indicators. Appendix F2 shows why each category and indicator is important.

The carbon mitigation potential of each pathway determines the ecological impact. The carbon mitigation potential will be based upon three indicators: how much carbon can be sequestered, how much carbon is emitted during its life cycle, and how much carbon it mitigated. The carbon mitigation potential was calculated in section 7, and the results from it will be used in the MCA.

For functionality, the following three criteria were used: feasibility, Synergies and side effects. The criteria feasibility has four indicators: how long has this pathway been used (*Maturity*), does the pathway require high or low technical requirements (*Technical requirements*), how much innovation is needed for the implementation of the pathway (*Innovation*) and how much cooperation is needed (*Cooperation*)? The combination of these sub indicators shows a good holistic representation of how difficult it would be to implement a pathway. The criteria synergies will look at whether the pathway has positive or negative synergies when combined with the other pathways. Lastly the criteria side effects will look at unintentional

positive and negative side effects that this pathway can have, the severity of the side effects and the spatial and temporal scale of the side effects.

For economy the criteria "cost" was. An ordinal scale was used to give an indication which pathway might be more expensive than the others relatively. These predictions will be based upon literature from similar projects.

Table 9 The different criteria, indicators and units that were used in the MCA

Criteria	Indicators	Units
1. Carbon mitigation potential	Mitigation pathway (+)	kg CO ₂ -eq
	Global warming potential (+)	kg CO ₂ -eq
	Emissions (-)	kg CO ₂ -eq
2. Synergies and tradeoffs with other pathways	Negative tradeoffs with other pathways (-)	Ordinal (1, 2, 3, 4, 5)
	Positive synergies with other pathways (+)	Ordinal (1, 2, 3, 4, 5)
3. Side effects	On what scale do the side effects operate (-)	Ordinal (1, 2, 3, 4, 5)
	How severe are the negative side effects (-)	Ordinal (1, 2, 3, 4, 5)
	How influential are the positive side effects? (+)	Ordinal (1, 2, 3, 4, 5)
	How long will the side effects remain after the initial pathway is stopped? (-)	Ordinal (1, 2, 3, 4, 5)
4. Feasibility	Amount of cooperation needed (-)	Ordinal (1, 2, 3, 4, 5)
	Maturity of the pathway (+)	Ordinal (1, 2, 3, 4, 5)
	Technical requirements needed (-)	Ordinal (1, 2, 3, 4, 5)
	Level if innovation needed (-)	Ordinal (1, 2, 3, 4, 5)
5. Costs	Amount of monetary resources needed to implement the pathway. (-)	Ordinal (1, 2, 3, 4, 5)

As highlighted in Table 9 many criteria's will be assessed on an ordinal scale, to minimize subjectivity evaluative questions were formed with five different answers (Appendix F2). Based on the literature explored during this project (See section 4,5,6) and the evaluative questions, the pathways got a grade on an ordinal scale of 1-5. It is important to distinguish that for certain sub-criteria it is optimal that they score high (e.g. positive side effects) and for certain criteria it is preferred that they score low (e.g. costs). Sub-criteria that want to score high will be labelled with a "+" sign in Table 9 sub-criteria that want to score low will be labelled with a "-" sign in Table 9.

8.3 Phase 2: Standardizing the Results

As shown in Table 9 different units will be used for the MCA to better compare these different results it is important to standardize the results from each criteria. As previously highlighted, some criteria are positive, meaning that you would want a higher number whereas other criteria are negative, thus you want a lower number. To ensure that in the end the final grade makes sense, two different equations will be used to standardize. The interval technique *Maximum* was used, this method ensures that the scale between the scores stays proportional.

For negative criteria

$$-\left(\frac{\text{Score}}{\text{Highest score}}\right) + 1 = \text{Grade}$$

For positive criteria

$$\frac{\text{Score}}{\text{Highest score}} = \text{Grade}$$

Equation 1: The formula for negative criteria

Equation 2: The formula for positive criteria.

After using this method, all the scores will range from 0 to 1, which makes it easier to determine which pathway is best suited for the Delta21 project. Next, the different weights will be added. Since certain criteria will have a higher priority than other criteria, weights will be allocated accordingly. Based on comments from the commissioner and other experts the following weights were determined (Appendix F3). For example, the commissioner stated the *carbon mitigation potential* is their number one priority, and *costs* was the least important. Additionally, each criterion will have a certain weight, and the sum of all criteria will equal to 100%. Each indicator for its criteria will also be assigned a certain weight, and these will also equal to 100%.

8.4 Phase 3: Results of the MCA

In Figure 10 the results of the MCA are presented, it shows that seaweed cultivation for the use of fodder feed is the optimal pathway based on the criteria chosen. This is likely due to it being able to directly substitute corn for fodder (Abudabos et al., 2013; Costa et al., 2021), whereas for example fish feed the seaweed first needs to be adjusted to have higher protein level (Aslamyah et al., 2017).). Thus, making the life cycle more complicated and emitting additional carbon. But in general, the seaweed cultivation in the ESL scores relatively high.

Mussel production in the ESL is relatively low, this is due to the expensive and large machinery needed for mussel production, these machineries are made of steel and require a lot of electricity to work. Thus, making the life cycle of mussel more carbon intensive.

CO₂ implementation also scores low, due it is having negative synergies when implemented with other pathways, being harder to implement and having severe negative side effects on other ecosystems.

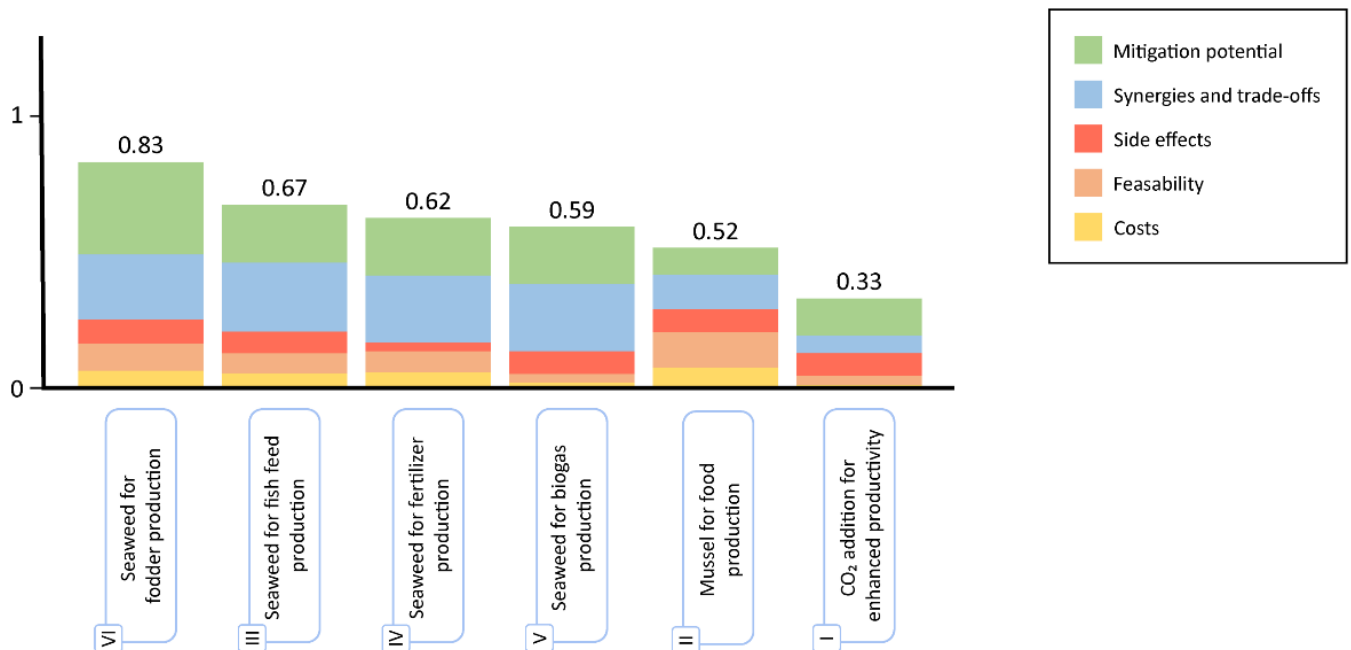


Figure 10: The final outcome of the MCA

8.5 Conducting the Sensitivity Analysis & Discussion

When conducting an MCA, data is utilized from different places which can create uncertainty in the results (Ligmann-Zielinska et al., 2012). Furthermore, the Delta21 project deals with very innovative and new ideas, this means that even more uncertainty arises. Due to this uncertainty, it could happen that the pathway the original MCA scored as the number one option, in some cases should be scored as a number two. For example, for calculating the carbon mitigation potential for mussels, a LCA was conducted that calculated this. But if mussel production were to be implemented in the ESL, it could be done more sustainable, this is something that remains uncertain and could change the ranking of mussel production in the ESL. In Appendix F3 the

allocated uncertainties are displayed, cost was given an exceptionally high uncertainty, due to the difficult nature of predicting that accurately based on preliminary literature.

To this end a sensitivity analysis was conducted, where certain scores were allocated a certain percentage of uncertainty. In Table 10 these results are shown and there is relatively low uncertainty. For example, we can conclude with 92% certainty based on this MCA that seaweed- cattle feed is the best choice for the ESL. There are some cases where seaweed-fertilizer is better than seaweed-fish feed but in almost all cases is seaweed-cattle feed the optimal choice, this is due its high carbon mitigation potential.

Table 10 Uncertainty analysis

Alternatives/positions	1	2	3	4	5	6
Seaweed – cattle feed	92%	8%	0%	0%	0%	0%
Seaweed – fish feed	8%	68%	9%	13%	3%	0%
Seaweed -fertilizer	0%	24%	75%	0%	0%	0%
Seaweed – biogas	0%	0%	15%	82%	3%	0%
Mussel production	0%	0%	1%	5%	94%	0%
CO ₂ implementation	0%	0%	0%	0%	0%	100%

It is crucial to keep in mind that while trying to be as objective as possible, there are certain biases inherently related to the MCA. It is based on certain chosen criteria, if one were to do a different MCA with different criteria the ranking as shown in Table 10 might be different. Furthermore, by using evaluative questions as highlighted earlier, this report tried to improve objectivity and transparency, but it is impossible to remove subjectivity completely. But even with these uncertainties in mind, since cattle feed scored significantly higher than the other options it is still this reports recommendation to implement that in the ESL.

9. Further Research

During the conduction of this report many new questions arose in this section these are shortly covered, and it could prove beneficial to conduct further research into these topics prior to implementing the pathways.

Active 3D ocean farming is becoming more prominent around the world and can increase productivity, resiliency and biodiversity (Flannery, 2017). This type of farming would be suitable for the ESL, and by increasing productivity even more carbon could be sequestered (Steppe 2021).

This report shortly touched upon the topic of nutrient balance in the ESL. This is, however, a rather difficult topic because the ESL is an open system, and has a connection to the North-Sea. This means that what happens in the ESL could influence the North-Sea both in a positive and/or negative way. Further research is needed to explore whether (1) the aquaculture in the ESL could temporarily deplete the surrounding ecosystems and (2) in case of fertilization, how the extra nutrients should be added.

Adding onto the point above, if nutrient uptake is maximized, then carbon pumping can be investigated. However, this requires modelling, research and more expert input into the level and the best approach to minimize the consequences of pumping carbon into the ESL.

One of the findings of this report is that the combination of seaweed and mussel in the ESL could prove great improvements. Further research should be conducted whether this idea could be expanded upon further, by making a more intricate ecosystem here that could include shrimps, crabs or other species (Figure 11).

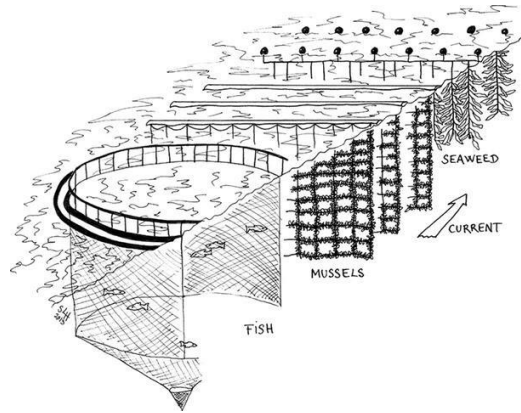


Figure 11 Example of an integrated multi trophic system (Holdt & Edwards, 2014)

This report showed the multiple ways seaweed could be used after harvesting from the ESL, but it was not within our scope to look into the details such as which stakeholders should be included in this production chain. This however will be imperative to make this process as efficient as possible in the end.

Appendix A. Detailed information regarding ESL

A1. Material characteristics

The walls of the ESL will mostly contain fine sand and silt that originates from deepening of the ESL. This sand has a fine particle size and consists of silt (Berke & Lavooij, 2017). However, currently it is unclear whether the sand layer will be stable enough because the sand layers are alternated by silt layers. Possibly, there will also be some peat involved in strengthening the bottom layer (LEDTA7, 2019). Additionally, when the slopes appear not to be stable enough, a layer of gravel might be added to strengthen the slope. Due to the large daily fluctuations in water level, it is estimated that silt will accumulate at the bottom of the ESL.

A2. Expected time of Drought Exposure

Because the ESL is constantly pumping water in- and out for the generation of electricity there is always a difference in the height of the water column. There is a maximum increase or decrease of the water level of 1.2 meters every hour. For example, there will be no water present for 15.7 hours a day consecutively at a depth of -5.5 below the highest point, for a depth of 17.5 below the highest point this will only be 1.4 hours a day (ConsultanSEA, 2020).

A3. Chemical Conditions of the ESL

The ESL contains mainly seawater. However, once every 5-10 years fresh water will enter the ESL with high river discharge. Based on information that was obtained by the previous ACT group, which used official reports and datasets from the Dutch Water Authorities (DWA) and the OSPAR commission the mean chemical conditions of the ESL are described (Table 11) below (ConsultanSEA, 2020).

Table 11 Chemical conditions (after ConsultanSEA, 2020)

Variable	Mean	Unit
Temperature	6-17	°C
Salinity	31.30	psu
Oxygen	246.9	µm / L
pH	8.05	-
Nitrogen	0.84	mg / L
Phosphorous	0.06	mg / L
Chlorophyll-a	8.9	µg / L

The nitrogen and phosphorus content are variable throughout the year. In summer, these nutrient concentrations decrease. Bioavailability may threaten optimal growth of algae. In Figure 12 below, the average and std of the total concentration N and P 6 km of the coast off Goeree shown per month.

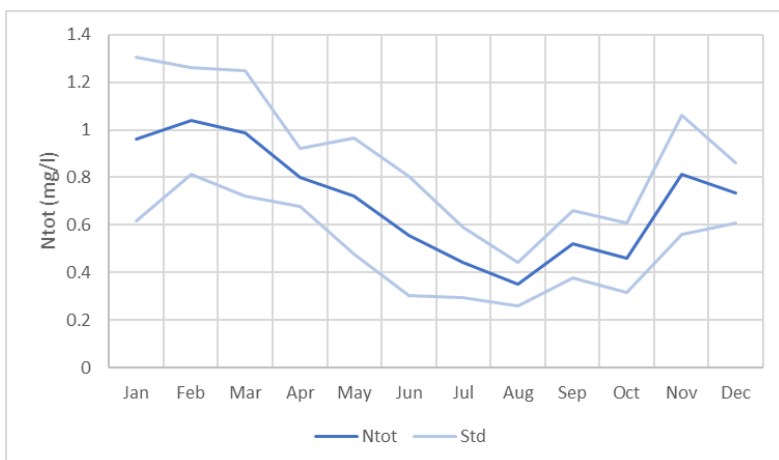


Figure 12a: The average monthly concentration of N

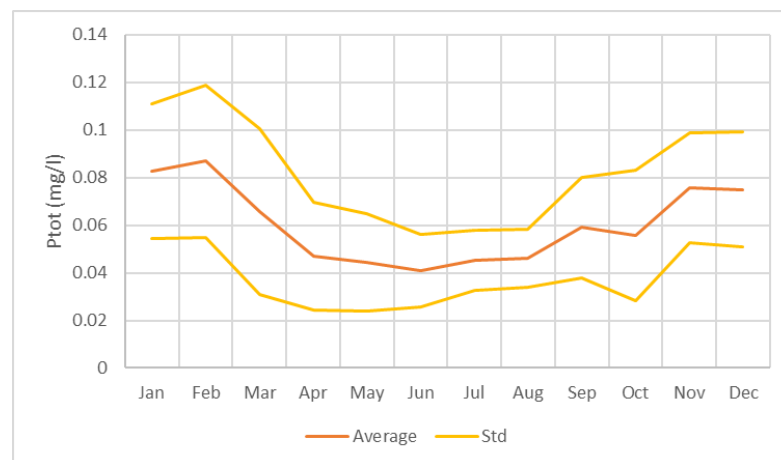


Figure 12b: The average monthly total P

Nutrient concentrations are also relevant for the surrounding ecosystem. Too high values result in unwanted eutrophication with algae bloom and hypoxia (lack of O₂). This may not only threaten biodiversity, but human health as well. Most oceans have currently been identified as eutrophic due to (indirect) input of nutrients of anthropogenic origin (OSPAR, nd), which in the Netherlands caused periodic hypoxia (Irigoiien, 1997). However, nowadays, the water quality of the disembarking rivers has greatly improved. Instead of eutrophication, nutrient depletion now forms a threat. Already in the Oosterschelde aquaculture farmers are hesitant to implement building-with-nature techniques because of nutrient competition between nature and farming (T. Murk, personal communication, May 10, 2021).

Appendix B. Passive Adsorption Pathway

B1. Sugar Kelp (*Saccharina Latissima*)

Sugar kelp is a perennial species that favours a cold temperate climate. It has been cultivated in the Atlantic Ocean for half a decade now, but is widely used in Asian countries (Wang et al. 2014). It favors colder temperatures, because heat stress causes the kelp to release its nutrients and results in an increased mortality rate and a decreased plant-tissue quality (Redmond et al. 2014). Growth-rate is impeded when temperatures exceed 17 degrees and death is immediate above 23 degrees Celsius (Kain, 1991). Thus, Sugar Kelp should be cultivated during the winter months and harvested before summer.

The total yield will increase the earlier sugar kelp is seeded; with the earliest being September (Boderskov et al., 2021). Harvesting can best occur mid-March until May, when growth rate peaks (Handå et al., 2013). Regarding cultivation practice, the yield was twice as high when using longlines than frames (Sanderson et al., 2012). Sugar kelp has successfully been grown at 0.5 and 1 m depth (Augyte et al., 2017). At greater depth, yield decreases exponentially, see Figure 13 (Sanderson et al., 2012)

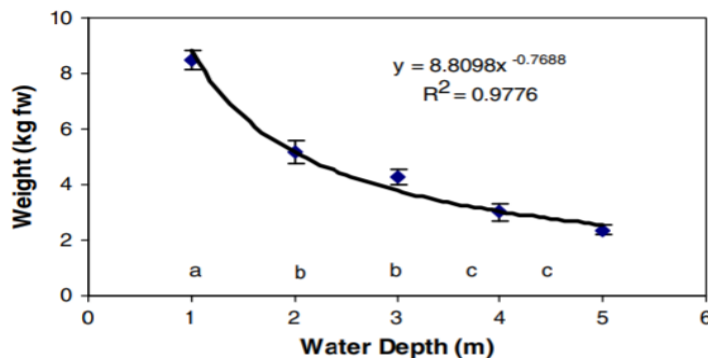


Figure 13: Mean yield of Sugar Kelp harvested per bundle from longlines against harvest depth (Sanderson et al., 2012)

The yield from longlines differs over various experimental set-ups and locations. Experiments in the Netherlands at De Wiederij, resulted in a dry-weight yield of 15 ton/ha per growing season (Groenendijk et al., 2016). This yield falls within the range of other experiments with Sugar Kelp on longlines. Wet yields ranged between 13.3 and 24.1 kg/m with an average of 17 (+- 4.5) kg/m. The dry weight % of was rather constant ranging from 10 to 12%. Assuming a longline spacing of 1.5m and a average dry weight % of 11% this leads to a dry weight yield of 11 (+- 3) ton/ha (Augyte et al., 2017; Kim et al. 2015; Peteiro and Freire, 2013; Sanderson et al., 2012). In addition, J. Wouters (J. Wouters, The Seaweed Company, personal communication, May 3, 2021) mentioned that with a linespacing of 4m resulted in a dry weight yield of 5 kg/m. That results in a dry weight yield of 12.5 ton/ha. In further computations, we will the estimate given by J. Wouters.

Based on multiple studies, the average percentage C, N and P in Sugar Kelp amounts to: 28%, 1.5% and 0.6% respectively (Augyte et al., 2017; Kim et al. 2015; Peteiro and Freire, 2013; Sanderson et al., 2012)

The daily fluctuation of the water level in the ESL generate turbulence which is favored by Sugar Kelp and seaweed in general (J. Wouters, The Seaweed Company, personal communication, May 3, 2021). In Spain, moderately exposed sites result in higher Sugar Kelp yields than sheltered sites (Peteiro & Freire, 2013). This is because the higher velocities increase light and nutrient availability, and thus growth rate of the seaweeds (Hurd, 2000). The turbulence limits the settlement of epiphytic plants and encrusting animals on the seaweed (Sanderson et al., 2012). Also, the constant flushing of the ESL will inhibit accumulation of dead organic material of which the decomposition can create hypoxic conditions (Merks, T., 2021). It must be noted that too high velocities will inflict damage to the crop (Sanderson et al., 2012). Thus, Sugar Kelp will flourish in the ESL as long as it's not cultivated in proximity of the pumps.

The proximity of the ESL to Rotterdam and its industries, might increase the risk of chemical spills. Luckily, Sugar Kelp is very robust regarding oil and chemical pollution (White and Marshall, 2007). In addition, the N- and P-concentration in the ESL do not drop below the required minima for Sugar Kelp to grow: 0.014 mg N/l (Wald, 2010). 0.0157 mg P/l (McCulla, 2013).

The only problem with growing Sugar Kelp in the ESL is that it cannot survive salinity levels below 8 PSU. Although its minimal required salinity range is quite broad: 23-55 PSU (e.g., Gerard et al. 1987; Karsten 2007; Peteiro and Sanchez 2012), it will die within one day when submerged in water with low salt concentrations. As Sugar Kelp is grown in winter when storm frequency is largest, the discharge of excess river water in the ESL will interfere with sugar kelp cultivation. Worst case scenario would be that the long lines must be reseeded once every 10 years.

B2. Sea Lettuce (*Ulva Lactuca*)

Sea Lettuce has thin, bright green leaves that are 30 cm long (Wald, 2010). It favors warmer conditions and is a fast-growing species that can increase its dry matter weight with 40-50%/day under optimal conditions (van den Burg et al., 2013). Like microalgae, Sea Lettuce can thus form 'blooms' under warm and eutrophicated conditions (Wald, 2010). Due to its warm loving nature, the growing season is from April till the end of August (Bikker et al., 2016). Below temperatures of 15 °C, growth is limited. Of the investigated species, Sea Lettuce is the only one that can be cultivated during the summer, therefore it can be grown consecutively with Sugar Kelp, Dulse and/or Oarweed.

Growth is optimal at the following nutrient concentrations: 0.31-3.1 mg -P / L, 2.24-15.4 mg N /L (Wald, 2010). Even the lower end of these nutrient requirements is never met in the ESL, see appendix A3 Figure 12a & b. However, because the ESL is refreshed daily, the flux of N and P is high. Therefore, the growth rate is less impeded lower nutrient concentrations. An experiment with water from the Yerseke and a flow velocity of 2.5l/min resulted in a reasonable growth rate of 23% (instead of the before mentioned 50%) (Groenendijk et al., 2016). Nonetheless, to reach maximum growth capacity, nutrients must be added, especially to avoid depletion of nutrients outside the ESL, see 4.3.1

In experiments in the Yerseke, dry weight yields of 20 ton/ha have been obtained using raceways. However, in other studies over the world, dry yields between 6-14 ton/ha were found (Groenendijk et al., 2016). In the ESL, the sea lettuce will not be cultivated in raceways. Therefore, the yield obtained in the Yerseke is a too high estimate for the ESL. Yet, as the ESL is a semi-closed system, we think a higher end yield of 15 ton/ha might still be obtainable. Of this yield, 32.7%, 2.5% and 0.13 % consists out of C, N and P respectively (Bikker et al., 2016; Roleda et al., 2021; Zertuche-González et al., 2021)

Sea Lettuce can be harvested multiple times during the growing season. The frequency of harvest (once a week or every three weeks) does not change the total yield but does impact the protein levels in the plant tissue. Based on experiments in raceways, the protein levels increase with maturity of the weed. Nonetheless, Sea Lettuce has relatively high protein levels (Groenendijk et al., 2016) and a higher %dry weight than sugar kelp: 17.5 % vs 11%.

Because Sea Lettuce is a free-floating species, it will have to be cultivated in nets or some sort of mesh construction (J. Wouters, The Seaweed Company, personal communication, May 3, 2021). Also, the water velocities should not exceed 0.4 m/s (Knits, 2019), so it should not be cultivated next to the pumps.

Sea Lettuce is more tolerant regarding changes in salinity as it survives in both salty and brackish waters. Optimal salinity has been found to be 30 PSU, but it may survive semi-freshwater conditions (Malta et al, 1999). If the ESL needs to be used in summer to store excess river water, the crop damage will likely be less extensive as opposed to Sugar Kelp.

B3. Dulse (*Palmaria Palmata*)

Dulse is a seaweed commonly consumed as snack in Scotland. It has gained attention over the years for its 'bacon-like' flavor. Sadly, it has not yet been successfully utilized as a meat-substitute. Although it is commonly found in European waters, Dulse is not native to the Netherlands. It has a higher N% than the previously discussed seaweeds. This means the biofiltration capacity of Dulse is higher and therefore Dulse is useful in a multi-trophic aquaculture system (IMTA) (Lüning, 2001). In addition, it can not only filter out nutrients from aquaculture waste, but Dulse can be used as fishfeed (Corey et al., 2013).

Dulse should be harvested prior to summer as it experiences bleaching in summer months caused by to the higher water temperatures and nutrient depletion (rapid algae growth). The latter won't be a problem as minimum N-requirements are often met: 0.042-0.42 mg N/L Wald, 2010). For the former, Anderson et al., suggest lowering the longlines in summer, where temperatures will be lower. In the ESL however, the daily replacement and mixing of the water may lead to a constant temperature with depth. In addition to bleaching, epiphyte settlement also poses a threat in summer. These plagues reduce the quantity and quality of the harvest. Therefore, it is still best to harvest dulse before summer.

Current stems come from wild plants, due to commercial cultures being absent (Grote, 2019). Yields, as a result, are low ranging from 0.08 to 1.24 kg/m long line (Sanderson et al., 2012; Browne, 2001), which equals a dry weight yield of ~0.5 ton/ha. Growth is optimal on longlines at a depth of 1 m (Browne, 2001). Like Sugar Kelp, Dulse performs better when planted in autumn. The lines can be deployed as early as August/September (for Scottish waters) or when the threat of the crop to epiphytes or larva settlement is reduced (Sanderson et al., 2012). Earlier seeding may also enable multiple harvests.

Dulse areas very sensitive to synthetic compounds and hydrocarbon contamination; although, the data on this is scarce (Hill, 2018). Similar to Sugar Kelp, Dulse can only tolerate small changes in salinity. The optimum is at 31 PSU but still high growth rates down to 21 PSU (Hill, 2018).

Dulse is similar in many aspects to Sugar Kelp. However, because Dulse is non-native, has a ~25 times lower yield and a higher sensitivity towards chemicals, Sugar Kelp is a better match for the ESL.

B4. Oarweed (*Laminaria Digitata*)

Oarweed is also a brown seaweed and thus similar characteristics as Sugar Kelp. It can grow 2-3 m long, with the number of leaves and their length increasing under turbulent conditions. Unlike Sugar Kelp, Oarweed has a lifespan of 3-6 years with reduced growth in fall and accelerated growth in spring/summer (Bikker et al., 2016). However, in the Dutch climate, the growing season is from September to march/may because above 18 degrees Celsius the thallus starts to degrade (van den Burg et al., 2013). Therefore, Oarweed can be cultivated together or instead of Sugar Kelp (Bikker et al, 2016). Sugar Kelp, however, will outcompete Oarweed when nutrient availability is limited (Lubsch & Timmermans, 2019). Additionally, cultivation of Oarweed in the ESL is tricky as it is often grown at a depth of 6 m (Edwards & Watson, 2011); making it unfeasible for the ESL. Thus, the ESL is better suited to grow Sugar Kelp.

B5. Risk of Depletion: Calculation

- Compute average N and P concentrations of sea water for the growing season of Sugar Kelp and Sea Lettuce: Nov-Apr and May-Okt. For this, data 6 km off the coast of Goeree was used.
- Compute the quantity of water pumped in and out each day:
 $17.5 \times (19 + ((26-19)/2)) \times 10^6 = 3.9 \times 10^{11} \text{ dm}^3$
- Compute total amount of N and P that pass through the ESL in the two periods:
nutrient conc. $\times (365/2) \times 3.9 \times 10^{11}$ (keeping in mind all the units)

Table 12 Results from above calculations

	Average conc. Nov-Apr (mg/l)	Average conc. May-Okt. (mg/l)	Total nutrients Nov-Apr (tons)	Total nutrients May-Okt. (tons)	% taken up by Sugar Kelp	% taken up by Sea Lettuce
N	0.73	0.69	52183	49283	0.70%	1.45%
P	0.06	0.06	4430	4381	3.14%	0.85%

B6. Sequestration through Seagrass

Seagrass is one of the most productive ecosystems in the world, with astonishing high rate of carbon sequestration (Costanza et al., 1997; Duarte et al., 2004). The Netherlands is home to two types of seagrass *Zostera Noltii* (*Z. Noltii*) and *Zostera Marina* (*Z. Marina*) (van Katwijk, 2000). With how potent seagrass is at sequestering carbon and with its other beneficial ecosystem services, we analyzed whether it could be a fit for the ESL.

However, seagrass requires an ecosystem with relatively low turbidity, where it can grow without being disrupted (Giesen et al., 1990a, 1990b; Hoeksma, 2002; Reise et al., 1989; van Katwijk, 2000). With the constant pumping of the ESL there will be too much turbidity for seagrass to grow ultimately, and thus it is not advice to utilize seagrass for the ESL.

B7. Microalgae

A CO₂ mitigation pathway that has been excluded from this topic is culturing microalgae within the ESL. Microalgae is perceived as a sustainable renewable biofuel feedstock, among other sustainable products (Osman et al, 2020; Elshobary et al., 2020). The microalgae used as feedstock for biofuels are generally freshwater microalgae species (Elshobary et al., 2020), although marine species are cultivated as well (Greene et al., 2016). It is more efficient to grow microalgae on land where everything can be controlled to keep productivity at its highest (Naumann et al., 2012). Generally, microalgae are cultivated in open raceways and ponds, and closed photobioreactor systems where everything can be controlled (Greene et al., 2016). But even under controlled conditions, microalgae cultivation is a complicated procedure (J. Wouters, The Seaweed Company, personal communication, May 3, 2021).

Thus, cultivating and harvesting microalgae in a semi-controlled system like the ESL would be extra difficult and presumably costly. In addition, we believe it will prove difficult to contain the microalgae within the boundaries of the ESL. The organism being so small, can easily be pumped out and/or obstruct the pumps. The former would endanger the surrounding ecosystem, whereas the latter would clash with the production of energy. Therefore, we have decided that cultivation of microalgae is not a viable option to increase the carbon mitigation potential of the ESL.

Appendix C. Methane Inhibition

Each seaweed species inhibits and reduces methanogens differently and therefore effectiveness of each species differs. The main compound that inhibits methane production is bromoform, although there is research indicating that there are potential adverse effects. The positive and adverse effects of *Asparagopsis Taxiformis*, are dose-dependent and operate in a dynamic form (Muñoz-Tamayo et al., 2020), making it difficult to summarize effects from multiple seaweed species. However, there is a consensus and some friction between both companies and researchers on the side-effects of *Asparagopsis Taxiformis*. Overall, there is a clear indication that when animals are solely fed with seaweed, it has adverse effects on the animal's health (Marais et al., 2020).

Even within the same species there is a large level of uncertainty and variability of CH₄ reduction. One reason for this variability is the inability to measure CH₄ emissions in experiments with dozens of individuals (Abbot et al., 2020).

Table 13 In Vitro studies

Species	CH4 decrease	Area of Growth
<i>Asparagopsis Taxiformis</i>	74% - 5% dry matter (Brooke et al., 2018) 98.9% (Machado et al., 2014) 98% - 1% dry matter basis, inclusion rate (Abbot et al., 2020)	Tropical to warm waters
<i>Zonaria Farlowii</i>	11% (Brooke et al., 2018)	Widespread but says shallow subtidal of rock reefs
<i>Dictyota Bartayresii</i>	92.2% (Machado et al., 2014)	tropical western Indo-Pacific region and the Gulf of Mexico
<i>Gigartina Spp</i>	49% (2% dose) (Abbot et al., 2020)	
<i>Ascophyllum Nodosum</i>	15% (11.1 % dose) (Abbot et al., 2020)	Northern Atlantic
<i>C. Patentiramea</i>	66.3% (Machado et al., 2014)	
<i>Cystoseira Trinodis</i>	73% (3.8% dose) (Abbot et al., 2020)	Temperate regions of the northern hemisphere such as Mediterranean, Indian and pacific oceans
<i>Ulva Spp</i>	50% (16.6 % of dry matter) (Abbot et al., 2020) 45% (25% of dry matter) (Abbot et al., 2020)	Global
<i>Ulva Ohnoi</i>	45% (16.6% dry matter) (abbot et al., 2020)	Global
<i>Padina Australis</i>	51% (16.6% dry matter) (Abbot et al., 2020)	

Table 14 In Vivo studies

Species	CH4 decrease + dose rate	Area of Growth
<i>Asparagopsis Taxiformis</i>	Emissions: 65% (dose : 0.5%) (Stefenoni et al., 2021) Yield: 55% (dose : 0.5%) (Stefenoni et al., 2021) 9% (dose 0.05%) (Kinley et al., 2020) 40% (0.10%) (Kinley et al., 2020) 98% (0.20%) (Kinley et al., 2020) 67% (Roque, 2019a) 80% decrease in sheep (Li et al., 2018)	Tropical to warm waters
<i>Ascophyllum Nodosum</i>	Limited effect on rumen microbiome	

Many papers within the literature state that there is promise for multiple species particularly based on in vitro studies but very little research on in vivo studies outside of *Asparagopsis Taxiformis*.

Globally there are already multiple companies whose sole focus in the reduction of CH₄ emissions in ruminants, see Table 14. As seen the main focus is on *Asparagopsis taxiformis*, with the additional use of *Asparagopsis aramata*.

Table 15 Seaweed cultivation companies focusing on CH₄ in ruminants (Abbot et al., 2020)

Company	Location	Activities
Symbrosia	USA	Production techniques for <i>Asparagopsis</i> spp. seaweeds
Volta Greentech	Sweden	Production of <i>A.s taxiformis</i> species
Taighde Mara Teo	Ireland	Production of <i>A. aramata</i>
DúlaBio	Ireland	Production of seaweed “blends” for CH ₄ reduction
BMRS	Ireland	Production of <i>Asparagopsis</i> spp.
CH ₄ Global	Australia	Global supply of <i>Asparagopsis</i> spp.
SeaExpert—Consultoria na Área das Pescas, Lda.	Portugal	Sustainable harvest and supply of <i>Asparagopsis</i> spp.
Acadian SeaPlants Ltd.	Canada; Ireland and UK	Sustainable harvest and supply of a range of different seaweeds
SeaLac Ltd.	Ireland	Supply of sustainable seaweeds

DúlaBio, a start-up who produce a Irish seaweed supplement (blend of different seaweeds) that have been shown to reduce methane emissions from livestock (DúlaBio, 2020). Methane emissions from cows are generally detected in short lived what DúlaBio are calling eruptions (of 1-10 seconds), that can be detected when sampling methane up to 1m of a cows nostril during feeding or rumination. They have published their results of their first trial, 25th May 2020 (DúlaBio, 2020). This trial took place over 11 weeks where mostly beef cows (Hereford, Angus and Shorthorn breeds) where their feed was supplemented 0.5% of their seaweed blend. The results showed a decline in peak methane emissions by 37.5% (4 week mark) and 79.6% (11 week mark). According to DúlaBio (2020) there was high variance between cows with some individuals responding to the seaweed supplementation more than others.

Appendix D. LCA

D1. Life Cycle Inventory (LCI)

The data concerning the LCI for seaweed cultivation in this study were based on the LCA study of Seghetta et al. (2017) which cultivated seaweed (*Saccharina Latissima*) in Limfjorden, Denmark. This LCA study has looked at the main features of the cultivation system of artificial growing seaweed. Seaweed farming always starts with the seed line production where kuralon ropes are seeded with seaweed spores (incubated in a cold room). Afterwards, the seeded kuralon ropes are coiled around 8 mm ropes which act as support and surface for the seaweed that is necessary for its growing phase. To prevent the lines from floating iron weights are attached to the support ropes. The seeded lines are deployed in September and harvested in spring (Seghetta et al., 2017). Table 16 describes the life cycle inventory (LCI) of materials needed for the cultivation cycle together with the datasets used and the location of the dataset.

I. CO₂ addition for enhanced productivity (from industries)

The data concerning the LCI and LCIA for CO₂ addition for enhanced productivity (from industry) in this study was based on the LCA study of Wildbolz (2007) that assessed technologies of CO₂ transport and sequestration in Zurich, Switzerland. However, the study was done in Zurich, most data was based on the production of CO₂ pipelines in the USA. The authors looked at the development of the infrastructure such as resources and materials that are needed to build such pipelines. They looked at the construction and land use, dismantling and disposal, monitoring and assembly drawing, all topics that were necessary for the production of these CO₂ and maintaining them. Materials used are sand, diesel (for the building machine), steel for the pipes, rock wool for isolation of the pipes, transport by various type of transport for transport of materials but also for regulatory monitoring (Table 17). This study also looked at the disposal of materials

but since other LCA studies in this report did not do this we have not used this data for a more reliable comparison (Wildbolz, 2007).

II. Mussel cultivation for food production (raw at packaging)

The data concerning the LCI and LCIA for mussel cultivation in this study were based on the LCA study of E. Tamburini et al. which cultivated Mediterranean mussels (*Mytilus Galloprovincialis*) in the Northern Adriatic Sea, Italy (Tamburini et al., 2020). This LCA study has looked at the main processes of cultivation, the seed procuring and socking, growing and re-socking, harvest and transport, and depuration and packaging. Mussel farming always starts with a rearing cycle, which starts in fall by collecting wild seeds on the hard infrastructure of mussel farms. These are usually cabling and buoys, where early seeds can attach. After the rearing cycle the seeds are removed and placed in plastic mesh socks with a socking machine (installed on the boat) to be attached to suspended long-lines and kept at depth with buoys. These buoys are anchored to the seabed by concrete blocks with the help of ropes. To avoid overcrowding in the socks, a second and third socking operation is usually needed. In this process mussels are re-seeded in double-mesh socks (made from plastic and cotton). Mussels are harvested when they reach market size, which takes approximately 9-12 months (Tamburini et al., 2020). Table 18 describes the life cycle inventory (LCI) of materials needed for the cultivation cycle together with the datasets used and the location of the dataset.

III. Seaweed for fish feed production (protein rich fish feed ingredient)

The data concerning the LCI and LCIA for the protein rich fish feed ingredient production pathway in this study was based on the LCA study of Seghetta et al. (2017) which cultivated seaweed (*Saccharina Latissima*) in Limfjorden, Denmark. The first step in processing the seaweed for protein production is hydrolyzation of the biomass, in which the carbohydrates break down into sugars that are used by microalgae as growth medium. Enzymatic hydrolysis subsequently releases available glucose with a 80% conversion efficiency. This hydrolysis takes place in a heated tank where water and additional nutrients are added (LCI Table 19). The hydrolysate was used as growth medium for the heterotrophic algae *Chlorella Protothecoides*. This pathway also considered the dewatering and the eventual transport to nearby companies that use this product as raw material for producing fish feed.

IV. Seaweed for fertilizer production (fertilizer supplement)

The data concerning the LCI and LCIA for the fertilizer supplement production pathway in this study was based on the protein rich fish feed ingredient production pathway (as described above) because the process is similar (Table 20).

V. Seaweed for biogas production (energy generation)

The data concerning the LCI and LCIA for the biogas production pathway in this study was based on the LCA study of Seghetta et al. (2017) which cultivated seaweed (*Saccharina Latissima*) in Limfjorden, Denmark. This biogas production pathway was based on basic knowledge on anaerobic fermentation of biomass in which 60% contains of methane, 38% carbon dioxide, 0.5% ammonia, 1.2% hydrogen sulfide and 0.3% water. Additionally, a digestate is produced in this process which this study will not consider. Biogas yields in this study are based on lab analysis of the species *Saccharina Latissima*. The energy and material consumption for the biogas production process is based on a literature study on biogas plants. This pathway also considered the dewatering and the eventual transport to nearby companies that use this product to produce electricity (Table 21).

VI. Seaweed for fodder production (maize substitute)

The data concerning the LCI and LCIA for the fodder production pathway in this study was based on the protein rich fish feed ingredient production pathway (as described above) because the process is similar. However, only the electricity used and transport by boat and car were considered because for this pathway the plain seaweed is used as raw material.

Table 16 LCI of Seaweed Cultivation (*Saccharina Latissima*) for food with partial drying at cultivation site. (Seghetta et al. 2017)

Material		Dataset	Amount / kg	Unit	Location ³
Diesel	fuel for car (collection of fertile material)	Diesel at refinery, production mix, at refinery, from crude oil, 10 ppm sulphur	2.10E-06	L	RER
Natural gas	not specified	Natural gas mix, consumption mix, to consumer, technology mix, medium pressure level (< 1 bar)	5.70E-07	kg	RER
Electricity	autoclave, refrigerator, air pump, sand filter, UV filter	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV	1.40E-05	kWh	DE
Iron	screw anchors, iron bars	Ferrite (iron ore), production mix, at plant, iron ore mining and processing, 5.00 g/cm ³	5.60E-05	kg	GLO
Nylon	black buoys	Nylon 6 granulate, production mix, at plant, reaction of caprolactam with water, 1.08 g/cm ³	2.76E-05	kg	RER
PP	ropes, headlines, 8mm rope, mechanical filters, industrial bags	Polypropylene glycol, Production mix, at plant, Technology mix,	3.20E-05	kg	GLO
PET	tank for seawater, spray bottle	PET granulates, amorphous, production mix, at plant, Polymerisation of ethylene, 0.91- 0.96 g/cm ³ , 28 g/mol per repeating unit	2.45E-06	kg	RER
Polyvinyl	kuralon twine	Polyvinyl acetate dispersion, Production mix, at plant, Technology mix, 51% in water	6.50E-06	kg	GLO
Sand	not specified	Silica sand production, production mix, at plant, technology mix, 100% active substance	1.30E-06	kg	RER
Concrete	concrete block, block rope	Concrete C20/25 (Ready-mix concrete) , production mix, at plant, technology mix, C20/25	2.51E-04	kg	DE
Boat	transport by boat	Barge, consumption mix, to consumer, technology mix, diesel driven, cargo, 1500 t payload capacity	4.20E-06	tkm	RER

 Table 17 LCI CO₂ addition for enhanced productivity (from industries) (Wildbolz 2007)

Material		Dataset	Amount / kg	Unit	Location ⁴
Sand	for installing the pipes	Silica sand production, production mix, at plant,	4.65E-01	kg	RER

³ GLO = global, RER = Europe, and RoW = rest of the world

		technology mix, 100% active substance			
Diesel	machinery used for production and installment of pipelines	Diesel at refinery, production mix, at refinery, from crude oil, 10 ppm sulphur	3.50E-01	MJ	EU-28+3
Steel	housing of pipelines	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel	2.86E-02	kg	ROW
Rock wool	Isolation of pipelines	Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3	5.41E-04	kg	EU-28
Transport lorry	transport of machinery and materials for production, installment and monitoring of pipelines	Articulated lorry transport, Total weight 12-14 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, 12 - 14t gross weight / 9.3t payload capacity	3.33E-02	tkm	ROW w/o EU-28+3
Transport rail	transport of machinery and materials for production and installment of pipelines	Freight train, diesel traction, consumption mix, to consumer, diesel driven, cargo, average train, gross tonne weight 1000t / 726t payload capacity	5.83E-03	tkm	EU-28+3

Table 18 LCI Mussel (*Mytilus Galloprovincialis*) cultivation food production (raw at packaging) after Tamburini et al. 2020

Material		Dataset	Amount / kg	Unit	Location ⁴
Diesel	diesel for boat	Diesel at refinery, production mix, at refinery, from crude oil, 10 ppm Sulphur	2.00E-02	L	RER
Steel	socking machine, de-clumping machine, grading machine	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel	8.00E-01	kg	ROW
Nylon	long-lines	Nylon 6 granulate, production mix, at plant, reaction of caprolactam with water, 1.08 g/cm ³	9.30E-03	kg	RER
HDPE	buoys	HDPE granulates, production mix, at plant, Polymerization of ethylene, 0.91- 0.96 g/cm ³ , 28 g/mol per repeating unit	2.77E-02	kg	RER
PP	long-lines	Polypropylene glycol, Production mix, at plant, Technology mix,	6.80E-03	kg	GLO

PVC	diving vests, gloves, boots	PVC granulates, low density, production mix, at plant, polymerization of vinyl chloride, 62 g/mol per repeating unit	8.00E-04	kg	RER
Rubber	boots	Natural rubber, at plant, production mix, per kg	1.00E-03	kg	GLO
Concrete	anchoring blocks	Concrete C20/25 (Ready-mix concrete) , production mix, at plant, technology mix, C20/25	1.73E-01	kg	DE

Table 19 LCI seaweed (*Saccharina Latissima*) for fish feed production (protein rich fish feed ingredient) after (Seghetta et al. 2017)

Material		Dataset	Amount / kg	Unit	Location ⁴
Boat	transport by boat, protein distribution	Barge, consumption mix, to consumer, technology mix, diesel driven, cargo, 1500 t payload capacity	3.67E-02	L	RER
Truck	not specified	Natural gas mix, consumption mix, to consumer, technology mix, medium pressure level (< 1 bar)	2.01E-02	kg	RER
Electricity	(agitators, feeding system, pump, heat, CHP control, compartment fan, heating circuit, cooler fan, cooler pump, compressor, chopping, hydrolysis)	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV	1.49E-03	kWh	DE
CaCl ₂	microalgae growth	calcium chloride production, production mix, at plant, technology mix, 100% active substance	2.32E-09	kg	RER
Ca(NO ₃) ₂	microalgae growth	Calcium ammonium nitrate at plant_EU-28+3_S	4.93E-09	kg	RER
MgSO ₄	microalgae growth	Magnesium sulfate at plant_EU-28+3_S	1.22E-08	kg	RER
H ₃ BO ₃	microalgae growth	Boric acid, powder production, production mix, at plant, technology mix, 100% active substance	5.80E-10	kg	RER
NaNO ₃	microalgae growth	sodium nitrate production, production mix, at plant, technology mix, 100% active substance	1.91E-08	kg	RER

Table 20 LCI seaweed (*Saccharina Latissima*) for fertilizer production (fertilizer supplement) after (Seghetta et al. 2017)

Material		Dataset	Amount / kg	Unit	Location ⁴
Boat	transport by boat, protein distribution	Barge, consumption mix, to consumer, technology mix, diesel driven, cargo, 1500 t payload capacity	3.67E-02	L	RER
Truck	not specified	Natural gas mix, consumption mix, to consumer, technology mix, medium pressure level (< 1 bar)	2.01E-02	kg	RER
Electricity	(agitators, feeding system, pump, heat, CHP control, compartment fan, heating circuit, cooler fan, cooler pump, compressor, chopping, hydrolysis)	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV	1.49E-03	kWh	DE
CaCl ₂	microalgae growth	calcium chloride production, production mix, at plant, technology mix, 100% active substance	2.32E-09	kg	RER
Ca(NO ₃) ₂	microalgae growth	Calcium ammonium nitrate at plant_EU-28+3_S	4.93E-09	kg	RER
MgSO ₄	microalgae growth	Magnesium sulfate_at plant_EU-28+3_S	1.22E-08	kg	RER
H ₃ BO ₃	microalgae growth	Boric acid, powder production, production mix, at plant, technology mix, 100% active substance	5.80E-10	kg	RER
NaNO ₃	microalgae growth	sodium nitrate production, production mix, at plant, technology mix, 100% active substance	1.91E-08	kg	RER

Table 21 LCI seaweed (*Saccharina Latissima*) biogas production (energy generation) after (Seghetta et al. 2017)

Material		Dataset	Amount / kg	Unit	Location ⁴
Boat	transport by boat	Barge, consumption mix, to consumer, technology mix, diesel driven, cargo, 1500 t payload capacity	2.10E-06	tkm	RER
Truck	not specified	Natural gas mix, consumption mix, to consumer, technology mix, medium pressure level (< 1 bar)	7.53E-04	tkm	RER
Electricity	(agitators, feeding system, pump, heat, CHP control,	Electricity from fossil unspecified, production	1.49E-02	kWh	RER

	compartment fan, heating circuit, cooler fan, cooler pump, compressor, chopping, hydrolysis)	mix, at plant, AC, technology mix, 1kV - 60kV			
CH ₄	emissions to air (biogas production + use)	IPCC 2013	4.19E-04	kg	GLO
N ₂ O	emissions to air (biogas production + use)	IPCC 2013	1.00E-06	kg	GLO
CO	emissions to air (biogas production + use)	IPCC 2013	1.94E-04	kg	GLO

D2. Life cycle impact assessment

Table 22 Seaweed cultivation food production (partial drying at cultivation site)

per kg of produced seaweed

process	amount	unit
Concrete	2.28E-05	kg
Diesel	1.10E-06	kg
Electricity	1.36E-05	kg
Ferrite (iron ore)	1.31E-06	kg
Natural gas mix	3.49E-07	kg
Nylon	1.99E-04	kg
PET	5.42E-06	kg
Polypropylene	9.25E-05	kg
Polyvinyl	7.43E-06	kg
Silica sand	4.47E-08	kg
Boat use	8.00E-08	kg
Climate change (emissions in terms of CO₂-eq)		
	0.0003	kg CO ₂ -eq

Table 23 I. CO₂ addition for enhanced productivity (from industries)

per kg of produced seaweed

process	amount	unit
Sand	1.60E-02	kg
Diesel	4.27E-03	kg
Steel	1.97E-01	kg
Rock wool	1.06E-03	kg
Transport lorry	4.82E-07	kg
Transport rail	7.39E-07	kg
Climate change (emissions in terms of CO₂-eq)		
	0.2182	kg CO ₂ -eq

Table 24 II. Mussel cultivation for food production (raw at packaging)

per kg of produced mussel

process	amount	unit
Concrete	1.58E-02	kg
Diesel	1.05E-02	kg
HDPE	5.73E-02	kg
LDPE	1.05E-02	kg
Natural rubber	1.73E-05	kg
Nylon	7.10E-02	kg
PVC	1.76E-03	kg
Polypropylene	1.97E-02	kg
Stainless steel	8.61E-03	kg
<hr/>		
Climate change (emissions in terms of CO ₂ -eq)	0.1950	kg CO ₂ -eq

Table 25 III. Seaweed for fish feed production (protein rich fish feed ingredient)

per kg of produced seaweed for protein rich fish feed ingredient

process	amount	unit
Transport by boat	7.00E-04	kg
Transport by truck	1.30E-03	kg
Electricity	1.45E-03	kg
CaCl ₂	1.42E-09	kg
Ca(NO ₃) ₂	2.27E-08	kg
MgSO ₄	2.91E-09	kg
H ₃ BO ₃	5.93E-10	kg
NaNO ₃	9.34E-08	kg
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Climate change	0.0034	kg CO ₂ -eq

Table 26 IV. Seaweed for fertilizer production (fertilizer supplement)

*per kg of produced seaweed for fertilizer supplement**

process	amount	unit
Transport by boat	7.00E-04	kg
Transport by truck	1.30E-03	kg
Electricity	1.45E-03	kg
CaCl ₂	1.42E-09	kg
Ca(NO ₃) ₂	2.27E-08	kg
MgSO ₄	2.91E-09	kg
H ₃ BO ₃	5.93E-10	kg
NaNO ₃	9.34E-08	kg
<hr/>		
Climate change	0.0034	kg CO ₂ -eq

*Because the hydrolysis and the microalgae growth are similar for protein rich fish feed ingredient and the fertilizer supplement the same data from E) was used

Table 27 V. Seaweed for biogas production (energy generation)

per kg of produced seaweed for biogas production

process	amount	unit
Transport by boat	3.04E-03	kg
Transport by truck	6.23E-05	kg
Electricity	1.45E-02	kg
CH ₄	1.17E-02	kg
N ₂ O	2.98E-04	kg
CO	3.04E-04	kg
Climate change	0.0299	kg CO ₂ -eq

Table 28 VI. Seaweed for fodder production (maize substitute)

per kg of produced seaweed for substituting maize

process	amount	unit
Transport by boat	7.00E-04	kg
Transport by truck	1.30E-03	kg
Electricity	1.45E-03	kg
Climate change	0.00345	kg CO ₂ -eq

Appendix E. Mitigation comparison

The carbon mitigation potential per kg of produced product might not say much. Therefore, we have estimated the carbon mitigation potential for the whole ESL (19 km²). Considering the sequestration of CO₂ by passive absorption and the mitigation potential of the activity fish feed production from the produced seaweed the mitigation potential for the ESL was determined to be 62234.83 ton CO₂-eq, which equals a CO₂ displacement of a set of wind turbines with the capacity of 55MW and a carbon price (EU ETS) of €3,228,120.63 (Table 29). If we compare this with the first wind farm in the Netherlands (Egmond aan Zee, OWEZ) in Table 30 below we can see that the ESL has the mitigation potential of CO₂ which is equal to half the wind farm in Egmond aan Zee, which has a capacity of 108 MW with 36 wind turbines. Half of the wind farm thus means approximately 18 wind turbines.

Table 29 Mitigation comparison (annual mitigation potential)

	Sugar kelp	Sea lettuce	
C	3.5	4.9	ton/ha
Conversion ratio	3.67	3.67	
Sequestration of CO ₂	12.845	17.983	ton/ha
Mitigation potential CO ₂ (fish feed production)*	0.9635	0.9635	ton/ha
total		32.755177	ton/ha
ESL		19	km ²
1 km ²	=	100	ha
Mitigation potential		62234.83	ton CO ₂ -eq / ESL
Carbon price ²		51.87	€ / ton
Value regarding the carbon price (02-06-2021)		3,228,120.63	€ / ESL
Wind turbine CO ₂ displacement ¹	1130 ton CO ₂	per	MW
Equal to wind turbine CO ₂ displacement of		55	MW / ESL

¹ (Community Windpower Ltd, 2014), ² (Ember, 2021)

*for the mitigation potential of fish feed production pathway we have assumed that cultivation of sea lettuce is similar to cultivation of sugar kelp.

Table 30 From "existing wind farms in the Netherlands (RVO 2021)"

Windfarm	Number of wind turbines	Power per windmill (in MW)	Wind farm capacity (in MW)	In use since
Egmond aan Zee (OWEZ)	36	3	108	2007

(RVO, 2021)

Appendix F: MCA

F1: Evaluative questions

F1.1 Side effects

(Scale) **Evaluative question:** On what type of scale will the side effects have effects?

1. The side effects are on local scale
2. The side effects are on ecosystem scale
3. The side effects are on regional scale
4. The side effects are on national scale
5. The side effects are on international scale or larger

(Negative side effects) **Evaluative question:** To what extent has the technique negative side effects?

1. The side effects could cause disastrous problems, by for example resulting in the collapse or severe degradation of a local or non-local system.
2. The side effects could cause severe problems, by for example negatively impacting the local population of organisms.
3. The side effects could cause medium problems, by for example disrupting processes in the food chain.
4. The side effect could cause minor problems, by for example causing stress to local or non-local organisms.
5. There are no negative side effects

(Positive side effects) **Evaluative question:** To what extent has the technique positive side effects?

1. There are no positive side effects.
2. The side effect has small upsides, by for example improving resiliency of a local or non-local system
3. The side effects have medium upsides, by for example removing waste and cleaning the system.
4. The side effects have major upsides, by for example improving local nutrient distribution.
5. The side effects have tremendous upsides, by for example greatly improving the biodiversity

(Duration) **Evaluative question:** How long will the side effects remain, after the initial technique is stopped.

1. The side effects will stay for a very short time (months)
2. The side effects will stay for a short time (1-5 years)
3. The side effects will stay for a medium amount of time (5-14 years)
4. The side effects will stay for a long time (15-34 years)
5. The side effects will stay for a very long time (35+ years)

Table 31: MCA scores for side effects

	Seaweed-cattle feed	Seaweed-fish feed	Seaweed-biogas	Seaweed-fertilizer	Mussel production	CO ₂ implementation
Scale	3	5	4	4	3	3
Negative side effects		3	3	3	3	1
Positive side effects	4	4	3	4	4	2
Duration	1	1	1	1	1	3

F1.2 Feasibility

(maturity) **Evaluative question:** How long has this pathway been around?

1. The pathway has been around 75 years

2. The pathway has been around for 50-74 years
3. The pathway has been around for 25-49 years
4. The pathway has been around for 10-24 years
5. The pathway has been around for 0-9 years

(Technical requirements) **Evaluative question:** How much technical requirements are necessary for the implementation of this pathway

1. Almost no technical requirements are needed for the implementation of the pathway, and the technical parts are very simplistic.
2. Very little technical requirements are needed for the implementation of the pathway, and the technical parts are relatively simple
3. Some technical requirements are needed for the implementation of the pathway, and the technical parts are advanced
4. There is a great number of technical requirements needed for the implementation of the pathway, and the technical parts are very advanced
5. Extensive technical requirements are needed for the implementation of the pathway, and the technical parts are all state-of-the-art

(Innovation) **Evaluative question:** To what extent is innovation necessary for the implementation of the pathway

1. No innovation is needed, the pathway has already been done and needs no adjustment
2. A small amount of innovation is needed, the pathway has already been done but small adjustments are needed.
3. Some innovation is needed, the pathway has been done before, but has never been implemented in this specific way.
4. Quite some innovation is needed, the pathway in general requires innovation, and implementing it in this way has never been done.
5. A great deal of innovation is needed, there is no similar project to this.

(Amount of cooperation needed) **Evaluative question:** To what extent does the pathway rely on cooperation of other stakeholders

1. The pathway is completely independent and needs no cooperation of other stakeholders.
2. The pathway is relatively independent, but functions better with the addition of a small amount of other stakeholders
3. The pathway is relying on a group of small/medium size of other stakeholders
4. The pathway is dependent on a medium size of other stakeholders
5. The pathway will not work without the help of a great number of other stakeholders.

Table 32: MCA scores for side effects

	Seaweed-cattle feed	Seaweed-fish feed	Seaweed-biogas	Seaweed-fertilizer	Mussel production	CO ₂ implementation
Maturity (Benefit)	4	3	3	3	5	1
Technical requirements (Cost)	2	2	3	2	1	4
innovation (Cost)	1	2	4	2	1	3
Amount of cooperation needed (Cost)	3	2	4	2	1	3

F1.3 Synergies

Evaluative question: If the pathway is implemented along another pathway to what extent does it have positive interactions for both pathways.

1. The pathway has no positive interactions
2. There are small benefits between the two pathways, for example increasing resiliency
3. There are decent benefits for the pathway for example a small increase in growth
4. There are great benefits for the pathways, for example increasing nutrient availability
5. There are incredible benefits for the pathways, for example greatly increasing productivity

Evaluative question: If the pathway is implemented along another pathway to what extent does it have negative interactions for both pathways.

1. There are no negative interactions between both pathways
2. There are small negative interactions between the two pathways, for example competition for the same nutrients
3. There are decent negative interactions between the two pathways, for example causing problems growth
4. There are severe negative interactions between the two pathways, for example inhibition of productivity.
5. There are disastrous negative interactions between the pathways, making them completely unfit to be implemented in the ESL together.

Table 33: MCA scores for synergies

	Seaweed-cattle feed	Seaweed-fish feed	Seaweed-biogas	Seaweed-fertilizer	Mussel production	CO2 implementation
Positive interactions	4	4	4	4	3	2
Negative interactions	0	0	0	0	3	4

F2. Motivation

Table 34: MCA argumentation

Criteria	Motivation	Indicators	Motivation
1. Carbon mitigation potential	Negative pathways that can contribute to reducing CO2 levels is imperative. (IPCC 2014; Minx et al., 2017)	Mitigation pathway (+)	Calculating how much CO2 is mitigated by the pathway is vital.
		Global warming potential (+)	How much CO2 eq is taken up during growth is important to assess, since here CO2 is already being sequestered
		Emissions (-)	When calculating the pathways it is important to also account for the GHG that they emit
2. Synergies and tradeoffs with other techniques	Knowing how well the different pathways work together is vital if Delta21 doesn't want to implement a monoculture.	Negative tradeoffs (-)	Negatively influencing other pathways is a non-desirable trait in a pathway.
		Positive Synergies (+)	Positively influencing other pathways is a preferable trait in a pathway.
3. Side effects	Assessing for side effects from pathways gives a more clear image whether a pathway is viable. (Jung & Han, 2017)	Spatial scale	
		Negative side effects	
		Positive side effects	
		Temporal scale	

4. Feasibility	A project has to be feasible and be able to be implemented in order to be effective.	Amount of cooperation needed	When reliance and number of stakeholder increase, it becomes harder to implement a project successfully (Di Maddaloni & Davis, 2017; Radigues-escales et al., 2018).
		Maturity of the technique	How long a project has already been established and used, how much easier it becomes to implement; (Rodrigues-Escales et al., 2018)
		Technical requirements needed	When higher levels and more advanced technical machinery is needed it becomes also more difficult to implement (Van der panne et al., 2003)
		Level if innovation needed	Innovative projects are more likely to fail (pinto & Mantel 1990).
5. Costs	Wrong assessment of how important monetary resources are can cause projects to fail (Akintoye, 2000 ;Rodrigues-Escales et al., 2018))	Monetary resources needed.	Wrong assessment of how important monetary resources are can cause projects to fail (Akintoye, 2000)

F3. Weights & Uncertainties

Table 35: MCA weights

Criteria	Weights	Indicators	Weights
1. Carbon mitigation potential	35%	Mitigation potential (+)	40%
		Global warming potential (+)	30%
		Emissions	30%
2. Synergies and tradeoffs with other pathways	25%	Negative tradeoffs	50%
		Positive synergies	50%
3. Side effects	15%	Spatial scale	15%
		Negative side effects	40%
		Positive side effects	30%
		Temporal scale	15%
4. Feasibility	15%	Amount of cooperation needed	25%
		Maturity of the pathway	25%
		Technical requirements needed	25%
		Level of innovation needed	25%
5. Costs	10%	Monetary resources needed.	100%

Table 36: MCA uncertainties

Criteria	Uncertainty
Carbon	
Carbon mitigation pathway	20%
Carbon uptake	20%
Emissions	30%
Synergies and trade offs	
Positive interactions	20%
Negative interactions	20%
Side effects	
Spatial scale	20%
Negative side effects	20%
Positive side effects	20%
Temporal scale	10%
Feasibility	
Amount of cooperation needed	20%
Level of innovation needed	25%
Technical requirements	25%
Maturity	20%
Costs	60%

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