COASTAL BIOGAS

Cluster On Anaerobic digestion environmental Services and nuTrients removAL

Primary Energy Recovery – Pre-treatment & Co-digestion Synergies

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Partners

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Preface

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Cover photo

Seaweed at Solrød Beach September 2020, Photo by Nanna Skov Larsen, Roskilde University

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Summary

The purpose of this report is to provide an overview of the different collection techniques and their costs as well as the effects on pre-treatment methods performed when separating sand from cast seaweed. Furthermore, the report includes how to use the nutrients in an optimal way and the problems with the seasonal changes in the organic content of seaweed when focusing on heavy metals.

Seaweed quality: The utilisation of cast seaweed in the biogas production is influenced by the quality of the seaweed collected. The seaweed quality depends on the seasonal changes, the seaweed species, the organic content, the period and location of harvest, the sand content and the pre-treatment method(-s).

The content of nutrients depends on the collection location, the seaweed species and the time of year. The changes in especially the content of heavy metals can have a negative effect for the biogas plant, as regulations determine if the content is too high.

Optimal use of nutrients: On average, the seaweed collected from Solrød Beach contains 4.8 kg N/t and 0.69 kg P/t. Further testing has showed that the levels of nutrients are higher in fresh seaweed than in older seaweed. Nutrients are mineralised and leached from the algae over time; which means that to recover most nutrients as possible the seaweed should be collected fresh.

Heavy metals in seaweed: Seasonal changes makes it uncertain when the content of heavy metals, especially cadmium, are below the limit value. When the content of cadmium is above 0.8 mg/kg dry matter (Danish limit value), the seaweed cannot be used as feedstock in the biogas production, and seaweed is to be returned to the sea, or pre-treated. Studies [1], [2] have shown that the cadmium content commonly is below the limit value from May to October and above the limit value from November to April. However, the cadmium content can change depending on month, temperature and water composition, which means that testing of heavy metals, needs to be performed on a regular basis. Furthermore, there is an indication of higher levels of cadmium in seaweed collected on the beach, compared to seaweed collected from the water.

Collecting techniques and collection cost: Different collection techniques have been investigated. The report suggests that due to the low sand up take, the speed and cost, the wheel loader with a grating bucket should be a preferred technique when collecting seaweed on the beach and in water. The technique has a collection capacity of 80 m^3 per hour, which makes it far quicker than other methods. Furthermore, the wheel loader is a cheap method, compared to the other techniques investigated.

Consequences for collection location: The location of collection can have an effect on the content of nutrients and sand. The sand content is shown to be higher for seaweed collected at the beach, which makes it more desirable to collect from the water. Studies have shown that the older algae can contain up to 32 - 77% sand, whereas the fresh seaweed can contain as low as 14% sand upon

collection. Furthermore, studies have shown higher levels of methane yield in fresh seaweed collected from the water, compared to seaweed, which has been laying on the beach for a longer period.

Pre-treatment methods: Pre-treatment of seaweed is a necessary process, due to the high levels of sand in the collected material, and to gain higher levels of methane. Pre-treatment methods can be mechanical, chemical, thermal, biological or a combination of the methods. A combination of mechanical and thermal pre-treatment has shown to reduce the sand content substantially in cast seaweed. However, the levels of nutrients have shown a decrease after the pre-treatment process. Testing has shown a great increase in the bio-methane production after thermal hydrolysis, and combined acid hydrolysis and mechanical disintegration.

Pre-treatment cost: The cost of pre-treatment depends on the method. It is desired that the pre-treatment costs are as low as possible and do not exceed the cost of other disposal of the seaweed.

Overall conclusion and recommendations: It is recommended to collect seaweed as fresh as possible to gain a high methane yield, higher levels of nutrients, lower levels of cadmium and lower levels of sand.

1. Introduction

This report focuses on nutrient recovery when utilising cast seaweed in the biogas production. It focuses on the former experiences from the use of cast seaweed at Solrød Biogas, highlighted through three themes: gas yield, nutrients and the circular thinking in COASTAL Biogas.

At Solrød Biogas plant, residues from nearby production sites as well as seaweed collected from Køge Bay are used as feedstock [3]. The collection and utilisation of seaweed contributes to the improvement of the marine environment, as well as the recirculation of nutrients.

The best collection techniques depend on the type of beach. Techniques for collecting seaweed at the beach and in shallow water are most developed, as well as being cost efficient. Furthermore, the colleting technique should have a sand uptake as low as possible due to the cost of transportation and the further pre-treatment.

The pre-treatment of seaweed is a necessity especially when the seaweed is collected on the beach. When the sand content is too high, it can have a negative effect on both the machinery at the biogas plant and the methane potential. The pre-treatment method has to be efficient enough to reduce the sand content, without having a negative effect on the methane potential and the levels of nutrients.

The different locations of collection, the seaweed species and season can have an effect on the methane yield, the sand content, levels of nutrients and heavy metals, and on the pre-treatment methods, which are most effective. These uncertainties and changes make it difficult to estimate the effect of the collection of seaweed, and the further utilization as feedstock in biogas.

The purpose of this report is to provide an overview of the different collection techniques and their costs as well as the effects on pre-treatment methods performed when separating sand from cast seaweed. Furthermore, how to use the nutrients in an optimal way and the problems with the seasonal changes in the organic content of seaweed when focusing on heavy metals.

2. Introduction to the utilisation of cast seaweed as feedstock in biogas

2.1. Production of biogas

The production of biogas contributes to the changeover of the energy system from fossil fuels to renewable energy. The production of biogas at Solrød biogas plant contributed to a reduction of 67,470 tonnes of greenhouse gases in 2020 [4]. Furthermore, the utilisation of cast seaweed has an impact on the marine and coastal areas, both when focusing on the environment and odour nuisances.

As seen in Figure 1 below, Solrød biogas plant utilise seaweed from the coast of Køge Bay, manure from nearby farms, pectin and carrageenan from the company CP Kelco and eluate from the company Chr. Hansen. Outputs from the production are methane, heat, electricity and bio-fertiliser for agriculture.

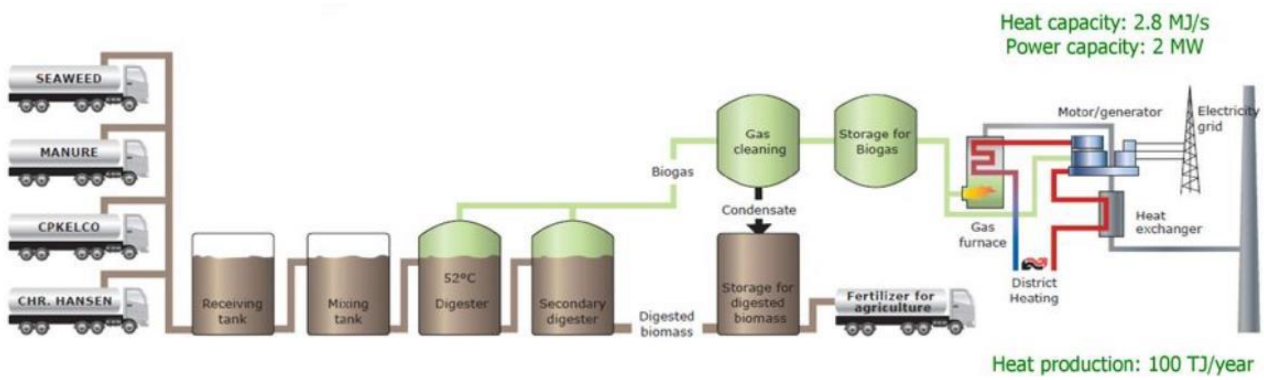

Figure 1: Biomass and biogas flow diagram of Solrød biogas plant [3]

Solrød biogas plant is currently receiving 226,000 tonnes of feedstock annually. As mentioned, the inputs consist of seaweed, manure and residual products from nearby companies. The majority of the feedstock are the organic residues from CP Kelco and Chr. Hansen, as seen in Table 1 below:

Table 1: Input and output at Solrød biogas plant [3]

Input
1,500 tonnes of seaweed
90,000 tonnes of organic residue from CP Kelco (pectin and carrageenan)
70,000 tonnes of organic residue from Chr. Hansen (eluate)
44,500 tonnes of manure
20,000 tonnes of other residual products from industries (biopulp)

Total: 226,000 tonnes
Output
18 mio. m^3 biogas or 11 mio. m^3 methane
Heat production for 4,000 households
Electricity for 5,400 households
220,000 tonnes of bio-fertiliser

The use of seaweed contributes to gas production and the removal and recycling of nutrients from the marine areas. The removal of cast seaweed at the coast of Køge Bay contributes to remove 62 tonnes of nitrogen/year and 9 tonnes of phosphorus/year [5].

Pectin and carrageenan mainly contribute to the production of gas. Pectin consists almost exclusively of organic, biodegradable material as well as consists of a high content of metabolic organic matter [6], which makes it suitable for gas production. Eluate and biopulp both contribute to the gas production and recycling of nutrients, and lastly the manure contributes to the gas production and process stability.

In a pre-feasibility study concerning the Solrød biogas plant, conducted by Solrød Municipality, it was discovered that pectin would be responsible for between 58% and 68% of the methane production [6], which makes this feedstock highly valuable for the biogas plant. However, it should be mentioned that pectin is not suitable for use alone due to the low pH level. The mixture of manure, pectin etc. is necessary to maintain an appropriate acidity in the biogas plant, to gain a level of methane as high as possible.

The production of biogas at Solrød biogas plant contributes to four significant environmental benefits [6]:

- Reduction of odour nuisances and other nuisances associated with cast seaweed on beach and coastal areas.
- Reduction in emissions of greenhouse gases.
- Improvement of the marine environment in Køge Bay.
- Utilization of nutrients in seaweed and residues from pectin production for fertiliser purposes.

2.2. Quality of raw material – seaweed quality

The quality of the seaweed depends on how long the seaweed has been laying on the beach as well as the species. When utilising cast seaweed in the production of biogas, a high gas potential, low sand content and a high level of nutrients are wanted. The biogas yield from anaerobic digestion of seaweed depends on the type of algae, their organic content, the period and location of harvest and the pre-treatment method.

To gain a high level of methane, studies have shown that the cast seaweed needs to be collected as soon and fresh as possible, either directly from the water edge or soon after reaching the beach [7].

The bio-methane potential (BMP) also depends on the seaweed species. An experiment from RUC tested the BMP of five different species of seaweed. The experiment shows that the seaweed species *Chorda filum* (dead man's rope) has a higher BMP than *Pylaiella littoralis* (sea felt), *Fucua vesiculosus* (bladder wrack), *Zostera marina* (eelgrass) and *Focus serratus* (type of brown algae (see Figure 2).

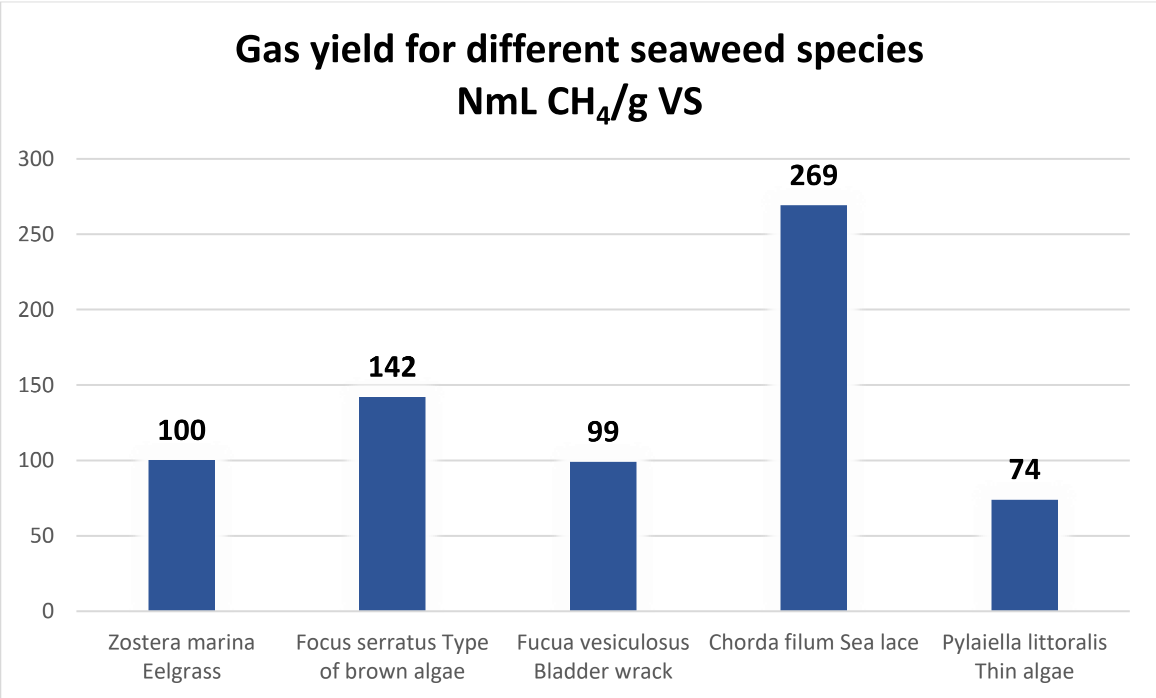

Figure 2: Gas yield for five different seaweed species [RUC]

The experiment showed that the methane yield for Sea lace (269 NmL CH4/g VS) where far higher than the other four seaweed species which were tested. The mix of different species will have an impact on the gas yield.

The quality of the seaweed in the biogas production also depends on when the seaweed is collected. A study showed the seasonal variations in the protein content in seaweed [8]. The seaweed type *Sugar kelp* (Saccharina latissima), which is a brown algae, had a maximum value of protein in May (150 g/kg DM) and minimum value of protein in August (73 g/kg DM). The seaweed recorded a higher methane potential in August with 256 L CH_4/kg VS, than in May (204 L CH_4/kg VS) [9]. Furthermore, it was found that the green algae *Ulva lactuca* (sea lettuce) produced more biomethane when being nitrogen starved, than nitrogen replete [10]. It was also concluded that a higher methane yield was gained from June to November, while from December to May the methane yield was lower [9].

Different studies have shown that the methane potential of the same type of seaweed shows varied results. The varied results are due to the different collecting places, different countries, different times of year, etc. [8].

Table 2: Methane yields obtained from brown seaweeds [8]

Seaweed type	BMP yield L CH4/kg VS	Country of collection	Reference
Brown Seaweeds			
Himanthalia elongata	261	West Cork, Ireland	[11]
	202	Brittany, France	[9]
Laminaria digitate	218	West Cork, Ireland	[11]
	246	Sligo, Ireland	[12]
Fucus serratus	96	West Cork, Ireland	[11]
Saccharina latissimi	342	West Cork, Ireland	[11]
	335	Sligo, Ireland	[12]
	223	Trondheim, Norway	[13]
	220	Norway	[14]
	209	Brittany, France	[9]

The green, red and brown seaweeds vary greatly in their composition, which can affect the methane potential [15]. *Sargassum spp.*, a brown seaweed, is found to be more recalcitrant to digestion, when compared to types of red and green seaweeds [16]. The fibre content in brown seaweed has been found to vary depending on the seasons, and a general overview of fibre content suggests that brown seaweed may generally have a higher fibre content compared to red or green seaweed [17]. The different composition in seaweed types means that pre-treatment methods may need to be tailored depending on the seaweed type and their structural composition [15]. The seaweed composition varies between species, seasons and geographical location due to the differences in temperatures, light intensities, as well as sea currents [18]. This can could mean that the eventual methane potential depends on the seaweed type, where it is collected and when it is collected.

A study has shown that brown types of seaweed can be difficult to degrade under anaerobic conditions and can inhibit anaerobic digestion, because the brown seaweeds are rich in polyphenols [8]. Furthermore, the protein concentrations in brown seaweeds were found to be lower than in red and green seaweeds, which had higher levels of polyphenols.

Experiments conducted by Gdańsk University of Technology (GUT) have tested the biogas and methane potential in the seaweed species *Enteromorpha compressa, Enteromorpha plumose, Potamogeton pectinatus* and a mixture of *Zostera marina* and *Enteromorpha plumose* as seen in Figure 3.

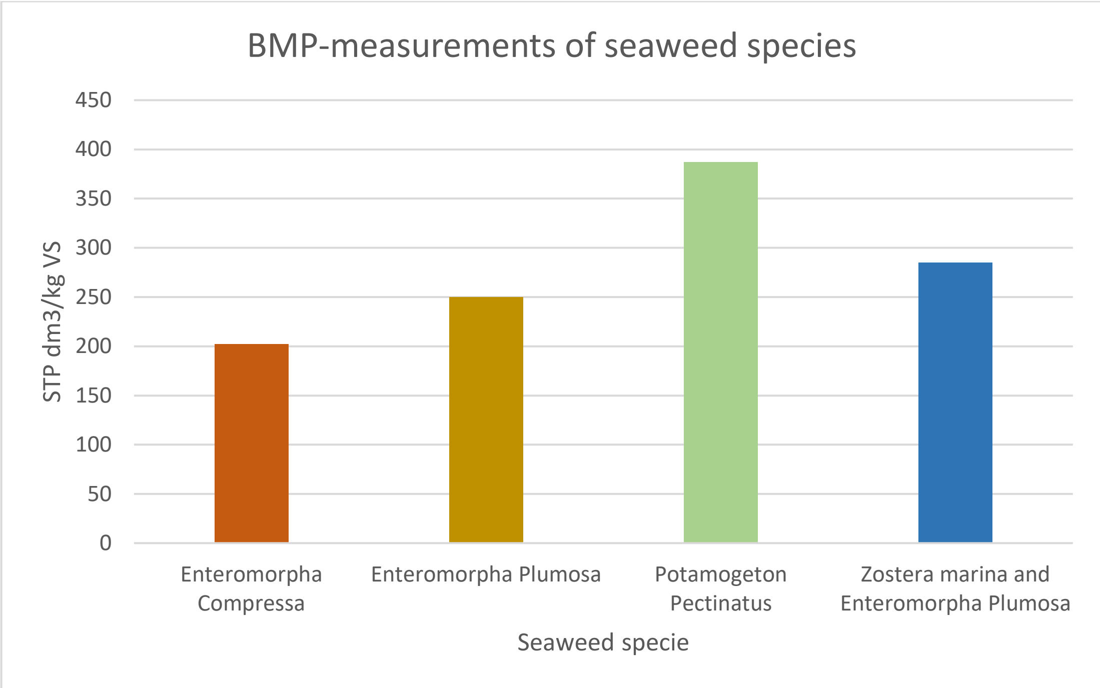

Figure 3: BMP-measurements of seaweed species conducted by GUT [GUT].

Of the seaweed species tested, higher methane levels were found in *Potamogeton Pectinatus* and the mix of *Zostera Marina* and *Enteromorpha Plumosa*. Furthermore, it shows an increase when *Enteromorpha Plumosa* is mixed with another species.

2.3. Nutrient recovery

An overflow of nutrients (nitrogen and phosphorus) in the Baltic Sea has a negative effect on the marine environment [19]. High levels of nutrients can result in eutrophication, which could lead to a decline in biodiversity, lack of oxygen, elevated levels of biomass (seaweed) etc. The collection of seaweed, which contains high levels of nutrients, can help to counteract eutrophication, as well as recycle nutrients. When nutrients are released near the shore, it gives nourishment to the growth of seaweed and microalgae. The new seaweed will grow in the nearshore environment and end back up on the beach by the currents. Overfeeding of nutrients to the nearshore environment can have the negative effects of muddied water, a decline of fish stock and a worsening of the seaweed smell. Nutrients released in the coast near water will contribute to a higher state of eutrophication in the area.

To prevent loss of nutrients and to prevent contributing to eutrophication, the seaweed should be collected as quickly as possible, either right after it is washed up on shore or while it is still in water. If the seaweed is not collected from the beach, the seaweed will start to decompose, and the nutrients in the biomass will leach out into the marine environment [20]. If the decomposition happens, the contained nutrients are released to the surrounding area, which is most likely the sea. In Solrød it is estimated that the removal of seaweed from the coast/beach prevents 62 tonnes of nitrogen from being released into the water, as well as 9 tonnes of phosphorus a year [7].

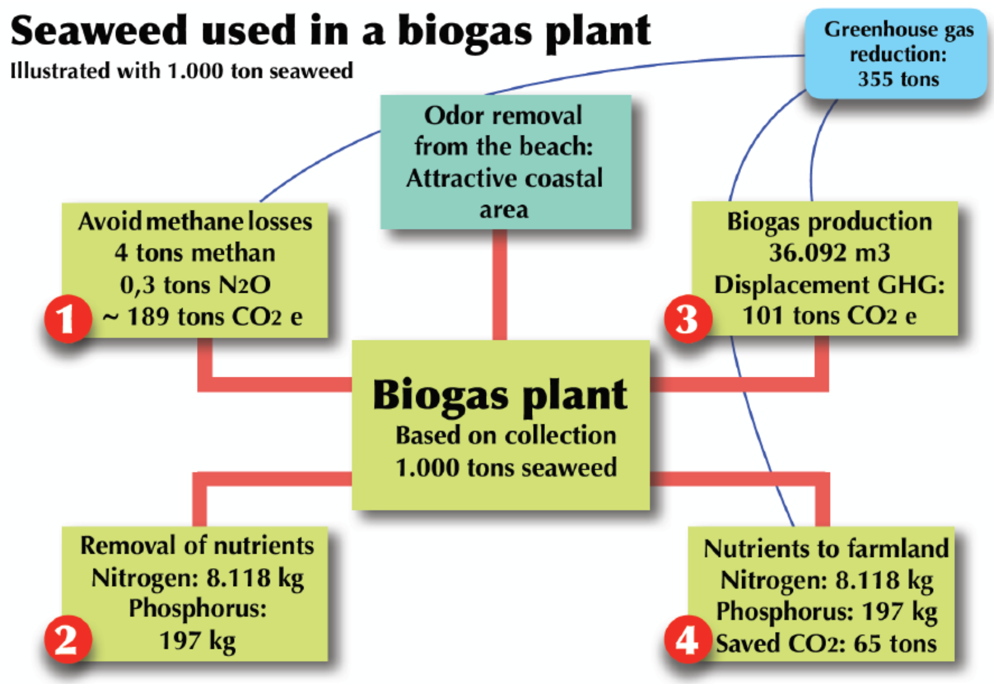

Figure 4: Benefits from removal of seaweed (illustration by Kjær, T.)

Based on the situation in Solrød, calculations by RUC show that the collection of 1,000 tonnes of fresh seaweed (wet and without sand), can recover 8,118 kg nitrogen and 197 kg phosphorus from Køge Bay.

The removal and recovery of nutrients in the Baltic Sea is important for improving the water quality and counteract eutrophication. A study from Solrød Municipality [6] shows that the fresh seaweed contains higher levels of nutrients than the seaweed, which has been laying for a longer period on the beach. Over time, when the seaweed are laying on the beach, the nutrients are washed out [21].

2.4. Pre-treatment

Pre-treatment is a necessary process when using cast seaweed as a feedstock in biogas. High sand content can have a negative effect on the gas yield, as well as transportation costs and abrasion on the machinery. The pre-treatment methods need to be assessable for the biogas plant, as well as being cost efficient. Furthermore, pre-treatment methods could improve the methane yield of the seaweed.

When collecting seaweed from the beach it is impossible to not collect sand as well. Depending on different collecting methods and collection location the sand content can vary, but will still have to go through some sort of pre-treatment to reduce the sand content. The pre-treatment can be mechanical, chemical, thermal, biological or a variation of the methods [22].

Table 3: Exampels for different pre-treatment methods

Mechanical	Chemical	Thermal	Biological
Mobile drum sieve Chopping/milling Beating Washing	Oxidation Alkali treatments	Heating at different temperatures	Enzymes Predators

Mechanical pre-treatment mainly affects the physical structure of seaweed [15]. The methods include size reduction by chopping, beating, washing etc. Mechanical pre-treatment methods can consist of a mobile drum sieve. This method sifts the seaweed in a drum sieve directly at the beach [6], [8]. An experiment with a drum sieve was performed in 2014 at Solrød Beach. The method was able to separate a high amount of sand from the collected seaweed.

Chopping or milling of the seaweed are commonly used to increase the surface area, which helps in the digestion process. However, the differences in the cell wall of seaweed can determine the beneficial value of mechanical pre-treatment [15]. This means that depending on the seaweed type, chopping or milling, can affect the methane potential.

Beating involves pounding the seaweed against a plate, enabling the production of seaweed pulp at different consistencies [15]. Comparisons between beating and milling of the seaweed species *Laminaria* spp. shows that beating was the most effective pre-treatment method to enhance the methane production [23]. However, other studies have shown only a marginal increase in methane yield from beaten seaweed compared to the seaweed, which were chopped or milled.

Washing is usually used to remove impurities such as sand, small stones and seashells [15]. The washing pre-treatment can also happen while the seaweed is being collected at the beach. In Solrød, the seaweed, which contains a visible high content of sand (more than 50%), is dumped back into the water, where it afterwards is collected again [24].

Thermal pre-treatment methods usually involve heating the biomass at different temperatures. Studies have shown that, thermal pre-treatment of some seaweed species, prior to anaerobic digestion, significantly increased the methane yield [8]. However, the optimum temperature depended on the microalgae species. Experiments at GUT tested thermal pre-treatment, where the collected seaweed first was thermally treated at elevated pressure, and afterwards diluted and moved to a hermetic high pressure laboratory heater and heated in a set temperature at 160°C for 30 and 120 minutes and 95°C for 60 minutes and 24 hours respectively. The pre-treatment showed an increase in the biogas production after thermal hydrolysis pre-treatment had been performed at 160°C for 30 minutes.

Experiments conducted at RUC tested a combination with washing and thermal pre-treatment methods, where the seaweed was washed in water with a temperature of 52°C, 54°C and 45°C, for different periods of time. The methods were tested on seaweed collected from different parts of the beach (in piles, water edge and fresh). The tests showed a high decline in sand content for all temperatures, but the best temperature and time depended on the location of collection (see 5.1: Sand separation laboratory test).

Experiments at GUT tested an acidic hydrolysis pre-treatment method to gain an increase in the methane potential. The seaweed was diluted after collection, and 2 M sulphuric acid was added until pH 2 was reached. Afterwards, the hydrolysis was performed for 1, 6.5 and 25 hours respectively. Further, sodium carbonite was added until the solution was fully neutralized to pH 7. The test showed an increase of the average biogas production after 1 and 6.5 hours of acidic pre-treatment.

Different stages of pre-treatment as well as a combination of different methods can greatly increase the quality of the methane yield, as well as remove the majority of the sand [22]. Experiments at GUT showed a higher methane production after conducting thermal pre-treatment methods, compared to mechanical pre-treatment, which showed the lowest methane production. However, a combination of acidic and mechanical pre-treatment showed higher levels of methane, when comparing to mechanical pre-treatment alone, which can be seen in Figure 5 below.

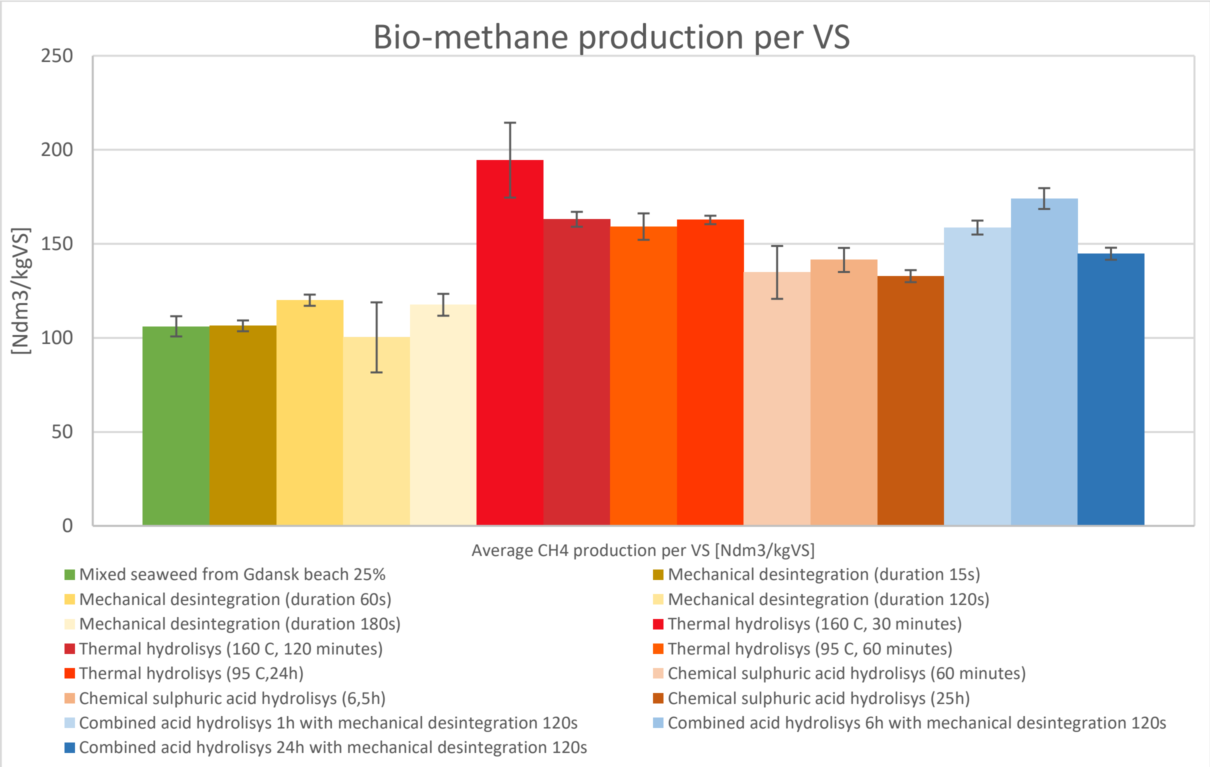

Figure 5: Average methane yield of algae pre-treatment methods, conducted by GUT [GUT].

However, the pre-treatment for processing seaweed is likely to vary with differences in seaweed chemical compositions [15]. This means that some seaweed species could benefit from some pre-treatment methods, when focusing on decreasing sand content and increasing methane yield, while others will not.

3. Nutrients and heavy metals in seaweed

3.1. Optimal use of nutrients

Cast seaweed contains levels of nutrients, such as nitrogen and phosphorus, which will add value for the use of residues from biogas production for soil improvement [1]. However, the levels of nutrients in cast seaweed depends on the location of collection, the seaweed species and the time of year. A study conducted by Solrød Municipality [6] tested the nutrient content of seaweed collected from Solrød Beach. On average, the seaweed contained 4.8 kg N/t and 0.69 kg P/t. Testing showed that fresh seaweed contained higher levels of nutrients, than seaweed which has been laying on the beach for a longer period [1]. The longer the seaweed is laying on the beach, the more nutrients are mineralized and leached from the algae. Especially the levels of phosphorus are washed out, when it reaches the coast. Figure 6 below shows the differences in nitrogen concentrations in cast seaweed depending on the collection area. When the seaweed is collected closer to the beach, lower levels of nitrogen, as well as methane levels, are detected.

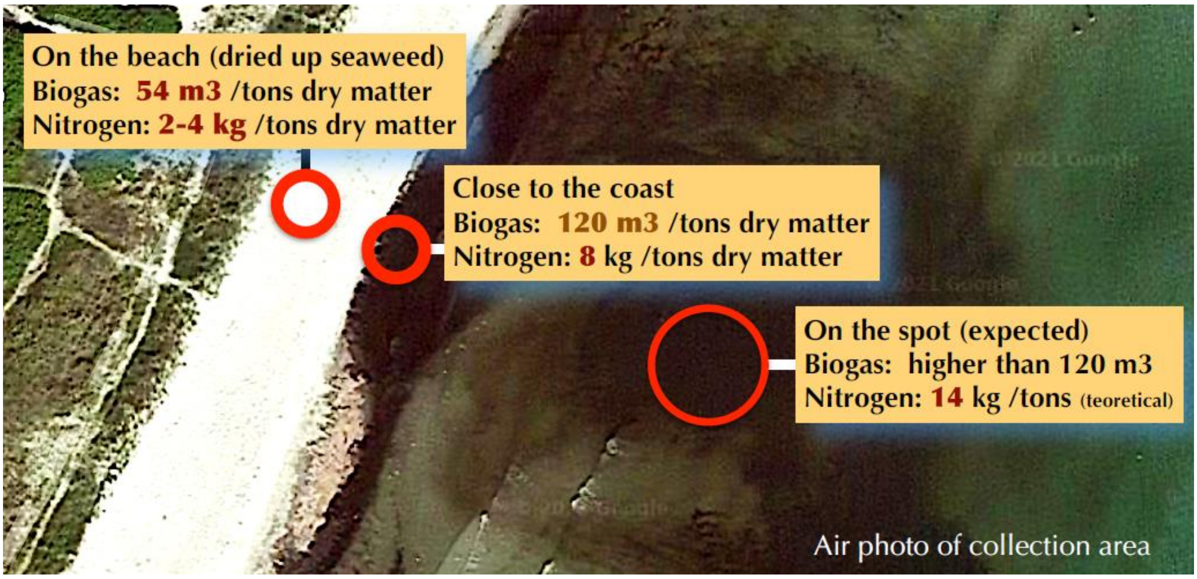

Figure 6: Nitrogen concentration in seaweed collected from the beach, close to the coast and in water.

In the pre-feasibility study, conducted by Solrød Municipality, it was found a decrease in the nutrient content, when the seaweed is mixed with sand [1].

In addition to the collection area, the nutrient content in cast seaweed can also depend on when during the year the seaweed is collected. In a former study [9], the seasonal variation in the nitrogen content of *Saccharina latissima* (sugar kelp) was tested from May to August. The tests showed a decline in nitrogen content during the summer months (June, July, August) as showed in Table 4.

Table 4: Seasonal variation of *Saccharina latissima* composition [9]

	May	June	July	August
DM dry algae (g/kg)	919	932	913	919
Volatile solid (VS) (g/kg DM)	541	605	618	639
Nitrogen (g/kg DM)	24	12	10	13

Measurements conducted by Solrød Municipality [1] show that the nutrient levels are higher during the winter months and lower during the summer months. However, batch tests collected from Solrød Beach (see Table 5: **Nitrogen and phosphorus content in seaweed collected at Solrød Beach** [1]) show no dependence in the nutrient content, when comparing to the months where the seaweed was collected.

Table 5: Nitrogen and phosphorus content in seaweed collected at Solrød Beach [1]

	Batch 1 January 2009	Batch 2 May 2009	Batch 3 January 2010
Nitrogen g/kg DM	7.1	4.1	3.1
Phosphorus g/kg DM	1.2	0.53	0.34

Even though the seaweed, which was collected in January 2009, contains higher levels of nitrogen and phosphorus, than the seaweed collected in May 2009, the seaweed collected in January 2010 contains less nutrients than Batch 1 and Batch 2 collected in January and May 2009. This shows an inconsistency in the nutrient levels for each month.

A study from Sweden tested the nitrogen and phosphorus concentration in seaweed collected five different places along Burgsviken Bay of Gotland in the Baltic Sea [25]. The results are presented in Table 6 below.

Table 6: Concentrations of phosphorus and nitrogen in seaweed collected in the Burgsviken Bay area [25]

Site	P (mg/kg DM)	N (mg/kg DM)
A1	3400	33000
A2	3500	38000
A3	3700	31000
B1	2400	20000
B2	2200	29000
B3	2000	21000
C1	1600	13000
C2	2100	16000
C3	1700	16000
D1	2600	34000
D2	2600	31000
D3	3300	32000
E1*	1900	25000
E2*	2100	28000
E3*	3000	24000

This removal of nutrients can help counteract eutrophication in the marine environment on a local scale. Collection of cast seaweed leads to removal of nutrients contained in the biomass, which would otherwise leak back to the marine environment during decay [20].

In a study conducted by the University of Greenwich, the nitrogen content was found in different types of seaweed species [26] (see Figure 7).

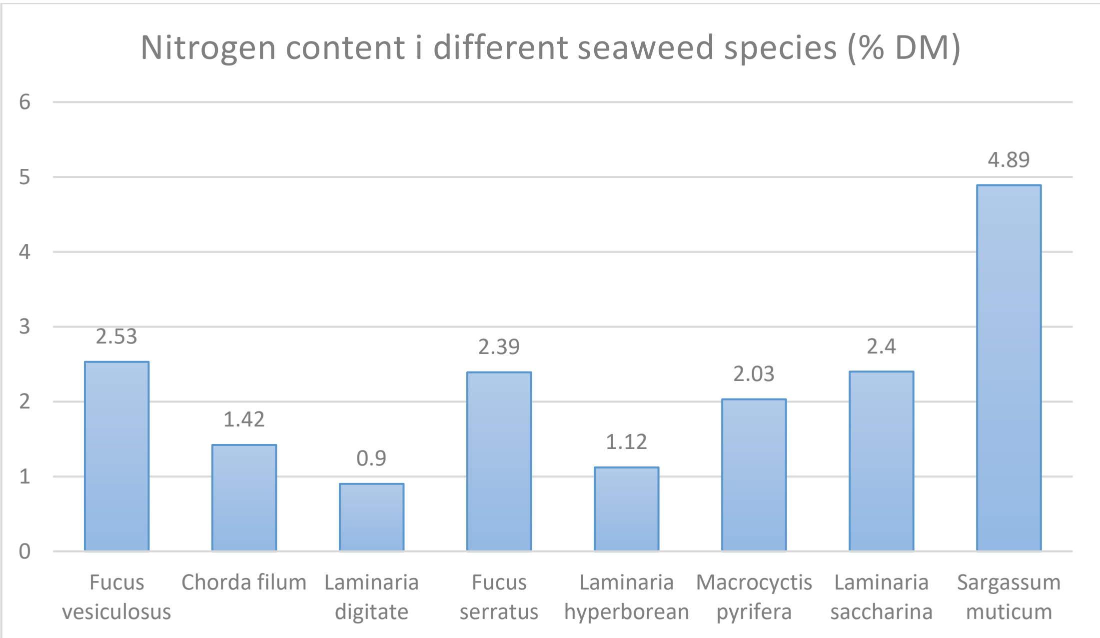

Figure 7: Nitrogen content in different seaweed species [26]

The seaweed species *Sargassum muticum* was found to have the highest concentration of nitrogen of all the species tested. *Fucus vesiculosus, Fucus serratus, Macrocyctis* and *Laminaria saccharina* all showed similar concentrations of nitrogen. *Laminaria digitate* showed to have the lowest concentration of nitrogen. The inconsistency in the nitrogen levels, can make it harder to estimate how much nitrogen is recovered from the sea.

The optimal use of the nutrients in seaweed is to recirculate the nutrients. This can be done by utilising the by-product in biogas as fertiliser on farmland. To use the by-product from the biogas production as fertiliser on farmland is a possibility due to the high values of ammonium, nitrogen, phosphorus and potassium after anaerobic digestion [27]. The recirculation of nutrients in cast seaweed, by utilising seaweed as feedstock in biogas production, can be seen as an optimal utilisation of the nutrients, as it firstly is included in the production of renewable energy, and afterwards as bio-fertiliser on farmland.

3.2. Heavy metals in seaweed

The content of heavy metals like cadmium depend on the beach-cast composition, location, seaweed species and when it is collected, as well as the uncertainties of nutrients in cast seaweed [25]. If the seaweed is to be used for anaerobic digestion and afterwards as bio-fertiliser, the uncertainties about cadmium pose a severe challenge. Too high levels of cadmium can limit the utilization of digestate on farmland. In Denmark, the seaweed cannot be used in the biogas production and afterwards as organic fertiliser if the cadmium content is over the limit value (0.8 mg/kg dry matter),[24]. The permitted content of heavy metals are subject to the Danish Waste to Soil Regulation [28], seen in Table 7 below.

Table 7: Limit values for heavy metals in residues according to the Danish Waste to Soil Regulation [28]

Heavy metals	Limit value (mg/kg DM)
Lead	120
Cadmium	0.8
Mercury	0.8
Nickel	30
Chromium	100
Copper	1,000
Zink	4,000

The seasonal variations of especially the cadmium content in seaweed is a challenge for the biogas plant, when utilising seaweed as feedstock in the biogas production.

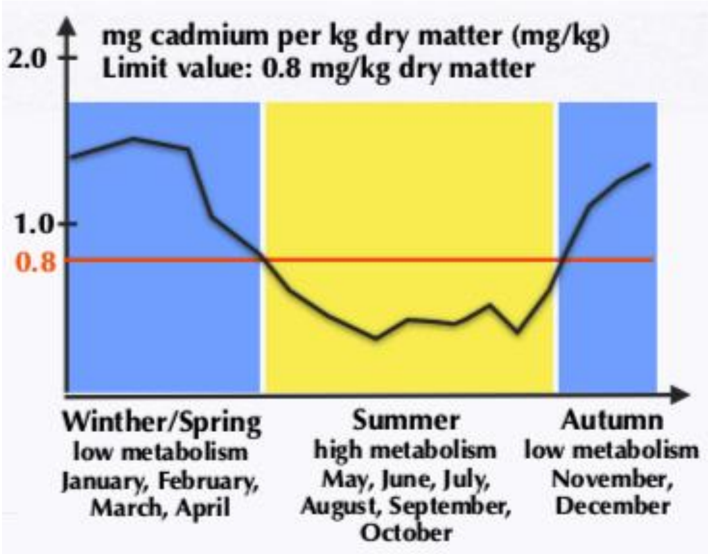

Figure 8: Cadmium content in seaweed collected at Solrød Beach [2]

Testing at Solrød Beach shows (see Figure 8) that the typical cadmium content is below the limit value during the summer months (May to October) and are above the limit value during autumn, winter and spring (November to April) [2]. This variation in the cadmium concentration means that the biogas plant can only use the seaweed collected from May to October.

In an analysis from RUC conducted by Højvang Laboratorier A/S from September 2020, the content of heavy metals was tested in cast seaweed collected from Solrød Beach (see Table 8).

Table 8: Heavy metals in seaweed collected in September at Solrød Beach [RUC].

Heavy metals	Damp seaweed from piles on the beach (mg/kg DM)	Wet seaweed from the water edge (mg/kg DM)
Lead	2.5	<2
Cadmium	0.44	0.17
Mercury	<0.03	<0.03
Nickel	3	1.76
Chromium	1.06	0.58
Copper	<5	<5
Zink	31.66	13.66

The seaweed did not exceed the limit values set by the Danish Waste to Soil Regulation [28] for any of the heavy metals included in the test. However, a study conducted by Solrød Municipality [1] showed an inconsistency in the cadmium content, when based on the seasonal changes (see Table 9). Three samples were collected January 2009, May 2009 and January 2010.

Table 9: Heavy metals in seaweed collected at Solrød Beach [1]

	Batch 1 12-01-2009	Batch 2 18-05-2009	Batch 3 18-01-2010
Cadmium mg/kg DM	2	0.25	0.46
Lead mg/kg DM	6	<3	2.5
Nickel mg/kg DM	0.9	8.9	1.4
Mercury mg/kg DM	<0.01	<0.01	0.1

Batch 1, which was collected in January 2009, shows far higher levels of cadmium than the samples collected in Batch 3, collected in January 2010. Of the three batches, only Batch 1 exceeded the limit values. In this case, it is shown that it is not possible to base the cadmium on the seasonal variations. The difference between Batch 1 and Batch 3 can be explained with water composition, temperature and the exact species, which the samples consisted of.

Some species of seaweed show a higher level of cadmium than other species. A study from Denmark [29] investigated the seasonal variation of the cadmium content in eelgrass (*Zostera marina*), from November 1979 to December 180. The samples of eelgrass were collected from three sampling stations by the Limfjord in the north of Jutland. The study showed a decline in the cadmium content during the summer months, where the cadmium concentration of eelgrass was below the limit value of 0.8 mg/kg DM). However, the cadmium concentration depended on the location of collection, as well as the seasonal changes (see Figure 9).

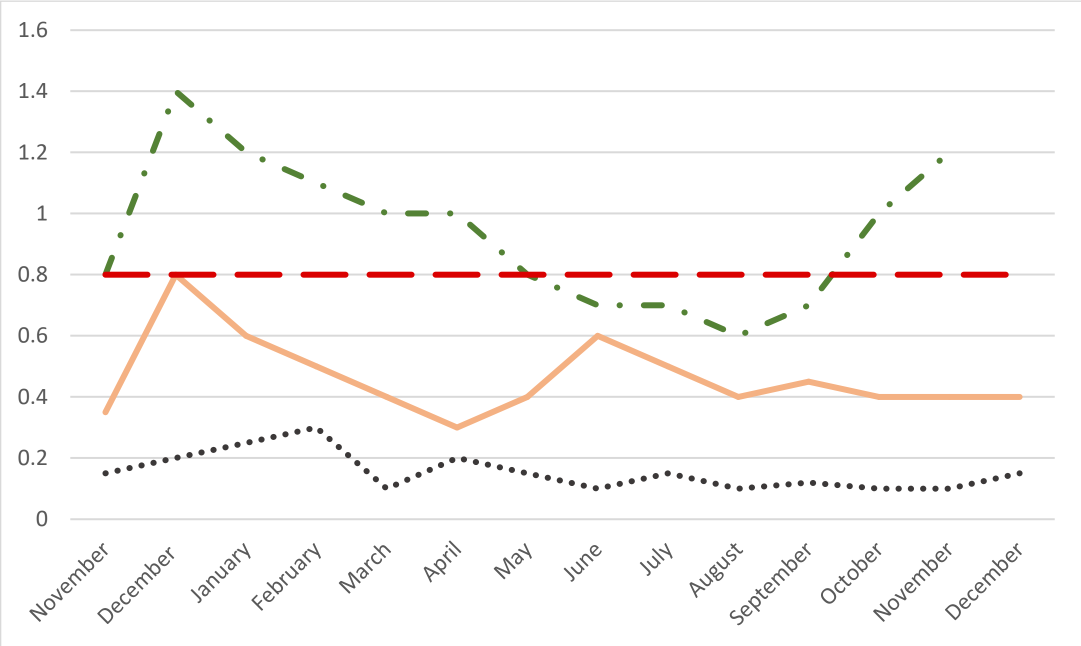

Figure 9: Seasonal variation of cadmium content in eelgrass from three locations, Rønbjerg (green, dashed line), Aalborg (orange line), Nibe (dotted line) and the limit value (red line) [29]

One of the locations, Rønbjerg, differs from the other locations, as the cadmium content is higher throughout the year. The locations Nibe and Aalborg show a cadmium content below the limit value during the whole year. The increase and decrease in cadmium also differs from location to location. As the cadmium content decreases from April to August for the eelgrass collected in Rønbjerg and Nibe, the cadmium content increases at the samples from Aalborg. However, there is a consistency since the cadmium content is higher during the winter months.

The study shows that the cadmium content depends on the season, the location of collection is important as well. Because of other factors, like water pollution, temperature etc., the cadmium concentration will vary from location to location.

Other studies have shown that location of collection and the seaweed species can have an effect on the cadmium content [25], [20]. A study from Sweden [25] tested the cadmium content from cast seaweed collected from Burgsviken Bay off Gotland, in the Baltic Sea. Fifteen samples were collected from five different places along Burgsviken Bay. The results revealed large variations in cadmium content, with levels ranging between 0.13 and 2.2 mg/kg DM as seen in Table 10.

Table 10: Cadmium consentration in seaweed collected at the Burgsviken Bay of Gotland in the Baltic Sea [25]

Site	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3
Cadmium (mg/kg DM)	2.2	1.8	1.3	1.4	0.77	0.71	0.75	0.67	0.67	0.16	0.21	0.13	0.13	0.23	0.14

Furthermore, the study showed a significantly higher cadmium content in eelgrass (*Zostera marina*) than in red algae species like *Ceramium* and *Polysiphonia* spp. Of the five seaweed species tested, *Zostera marina* showed a higher cadmium content than the limit value of 0.8 mg/kg DM. *Red algae, Potomageton pectinatus, Furcellaria lumbricalis* and *Fucus vesiculus* all showed significantly lower levels of cadmium than *Zostera marina.*

The difficulties of too high levels of heavy metals are that the collected seaweed cannot be utilised as biomass in the biogas plant. This means, that the collected seaweed can either be returned to the sea or a pre-treatment method to reduce the heavy metals content can be performed.

The inconsistency concerning the cadmium content can be a problem for the biogas plant using seaweed for anaerobic digestion. The further utilisation of residues as bio-fertiliser depend on the heavy metal (mainly cadmium) content in the seaweed. Methods for removing heavy metals, including the use of chemicals, have shown to be successful in reducing the content of heavy metals [27]. However, such methods could be questionable with respect to sustainability.

4. Collecting techniques for seaweed

4.1. Different methods for collecting seaweed

Seaweed collection is performed in different ways, depending on the type of coastal area. The challenge with the collecting techniques is to keep the sand content as low possible to have a minimal impact on the coastal nature and to be a cost-efficient option.

To collect seaweed on sandy beaches, most municipalities in the partner countries are opting for a tractor or wheel loader with a grate shovel or grid bucket. This technique offers to collect the seaweed quickly and minimise the sand content in the seaweed. This method also makes it possible to collect seaweed in shallow water as well as on the beach. Table 11 below shows the different collecting techniques used in the partner countries and on which coastal type the method can be used.

Table 11: Seaweed collecting techniques in the partner countries [27]**.**

Country	Collecting technique	Coastal type
Lithuania	BeachTech Marina	Sandy beach
Poland	Grip-claw loader with a dumper [30] Tractors with harrow	Sandy beach and shallow water
Germany	Wheel loader [30] Quad bikes/dune buggies	Sandy beach and shallow water
Sweden	Grid bucket (tractor with fork in form of rake)	Sandy beach and shallow water
Denmark	Wheel loader with grate shovel	Sandy beach and shallow water

The BeachTech Marina ( Figure *10*), which is a machine purchased by the municipality of Palanga, Lithuania, is a compact tractor and beach cleaner [31]. The machine can collect small to medium size debris, to a depth of 10 cm on the shore.

The grip-claw loader  Figure *11*), which is used in Poland, was tested during the WAB project [27]. The grip-claw was highly effective as it can collect the piles of seaweed from the beach and the shallow water at a high speed. Furthermore, the method resulted in a low sand content (1 – 2% of the total volume). The grip-claw loader can collect seaweed from shallow water. In Germany, the collection techniques vary depending on the municipality. However, most of the collection is done by wheel loader (Figure 12) or quad bikes/dune buggies. In Sweden, in the municipality of Trelleborg, the collection is done by using a grid bucket methods (a tractor with a fork in the form of a rake) (Figure 13). In Denmark, in the municipality of Solrød a wheel loader with a grate shovel (Figure 14) is used for raking the seaweed together on the beach, followed by collection of the material using a beach cleaner.

Figure 10: BeachTech Marina [31]

Figure 11: Grip-claw loader with a dumper [27]

Figure 12: Wheel loader with a pitchfork [30]

Figure 13: Grid bucket (tractor with a fork in the form of a rake) [photo: Trelleborg Municipality]

Figure 14: Wheel loader with an attached grate shovel [22]

Currently the partner countries are opting for collection techniques, which are suitable for sandy beaches and shallow water. Collection methods for rocky beaches and harbours are still under development and testing. A study from Trelleborg Municipality evaluated different collection methods for these types of coastal areas [27]. A pontoon machine (Figure 15: **Pontoon machine [photo: Trelleborg Municipality]**) and suction dredging (Figure 16) was tested for collecting seaweed at harbours. The pontoon machine was able to collect seaweed in the sea and underwater, up to a depth of 2 meters, but had no possibility to collect from deeper water. The method was considered very beneficial for harvesting of seaweed in smaller ports.

Suction dredging by using a pump would be able to collect sludge and mud from the sea floor. The technique was proposed for the use in areas such as ports and harbours, but not to act as a technology for large-scale algae collection. Furthermore, the method would need major moderation if it should be used for seaweed collection.

Figure 15: Pontoon machine [photo: Trelleborg Municipality]

Figure 16: Suction dredging machine [photo: Trelleborg Municiplity]

Dry suction with a collection barge and a water pressure pump with a collection barge was tested for collecting seaweed on coastal areas described as stony beaches. The dry suction method consists of a vacuum pump that could be used to suck up algae from the beach. However, to modify this method to seaweed collection, the nozzle would need to be broad (0.12-0.15 meters) to cope with large-scale algae collection. Furthermore, the nozzle needs to be fitted with a mesh on the underside to separate the algae from the material that is not wanted (stone/sand/sediment/debris) [27]. The water pressure pump with a collection barge is a similar method for the dry suction, where it is possible to vacuum algae up from the water. As for the dry suction, the nozzle should be supplemented with a sieve or mesh on the underside to prevent the collection of unwanted material. The machine would need moderate changes to be able to collect seaweed as required. As well as this method would be suitable for stony beaches, it could also be used to collect seaweed at deeper waters.

For collecting at sea with 5 – 12 meter depth, the Mammoth Suction was tested. With this method, a pneumatic pump sucks up the seaweed. Even though this method is very suitable for collecting seaweed at deep waters, the technique require moderate changes to the machine and furthermore the requirement of a diver.

4.2. Collection at shore, water edge and at the sea

The different collection techniques and the location can have consequences for the gas yield potential and the nutrient levels as described earlier (see 3.1: Optimal use of nutrients). When the seaweed is fresh, the methane potential and nutrient content are detected to be higher, than seaweed that has been laying on the beach, because the nutrients have not yet been released, as the degradation has not yet occurred.

Tests made by Højvang Laboratorier A/S shows the nutrient levels from seaweed collected in the water edge and damp seaweed collected from piles on the beach.

Table 12: Nutrient level for seaweed collected from water edge and piles on the beach [RUC].

Nutrient	Damp seaweed from piles on the beach mg/kg DM	Wet seaweed from the water edge mg/kg DM
Nitrogen	30,666	26,666
Phosphorus	763	633

As seen in Table 12 above, the test shows that the damp seaweed collected from piles on the beach contains more nitrogen and phosphorus than the wet seaweed collected from the water edge. This can be explained by the fact that the nutrient level is based on dry matter (DM). DM% will be higher in the seaweed collected from than beach than the seaweed collected from the water.

A study from RUC shows that the difference in the methane potential of damp seaweed collected from piles on the beach and wet seaweed collected from the water edge is almost in unison in the nutrient concentration. The damp seaweed is shown to have a slightly higher methane potential than the wet seaweed. It should be mentioned that none of the seaweed samples was completely dry, but earlier tests have shown that the methane potential for seaweed is decreasing over time, which means that dry seaweed, which has been laying on the beach for a long time, will contain a lower level of methane than wet and damp seaweed.

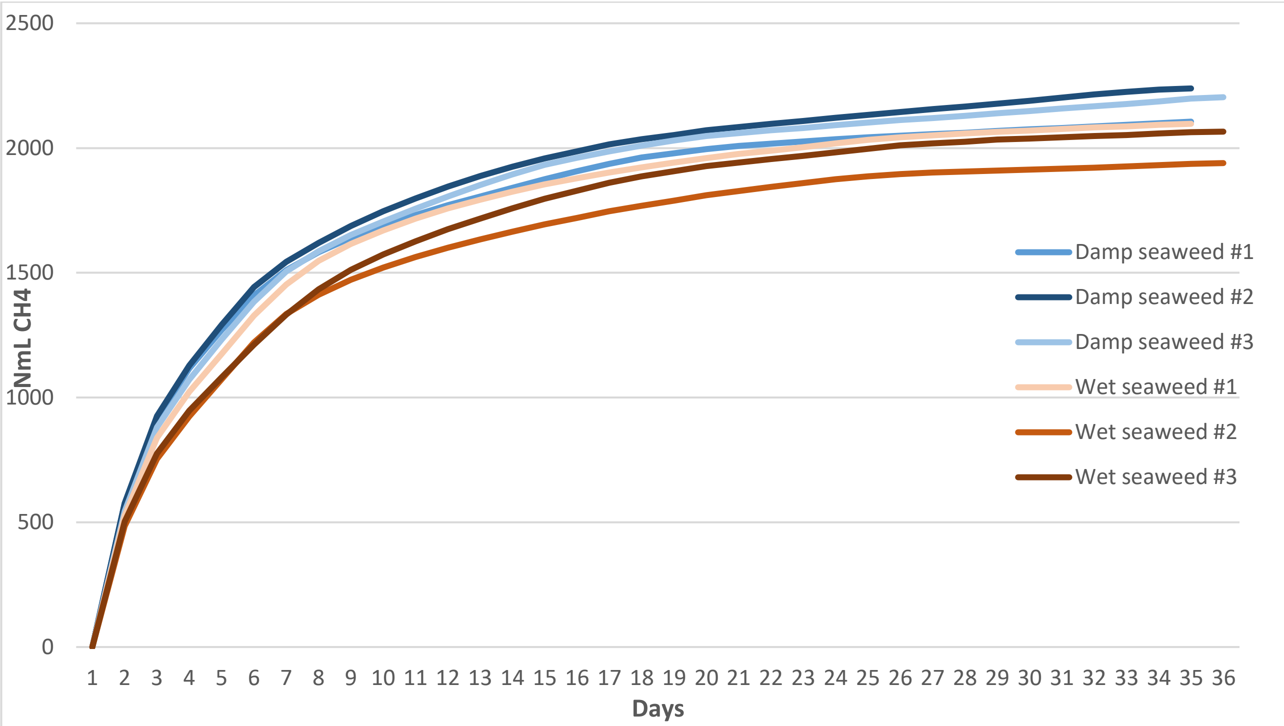

Figure 17: Methane potential of damp and wet seaweed [RUC].

This means that to gain a higher methane output at the biogas plant, the seaweed needs to be collected when it is still wet or damp at the beach, at the water edge and at sea. If it is not possible to collect the seaweed in water, the seaweed should be collected as soon as possible after it is washed up on the beach, to ensure as high a methane content and nutrient level as possible.

4.3. Collection cost

As mentioned the collection techniques should be as cheap as possible and be able to collect the seaweed quickly and without damaging the beach or coastal area. Table 13 below shows the collecting techniques, which was previously mentioned, the collection capacity per hour as well as the hourly cost.

Table 13: Collection techniques, where they can be used, the collection capacity and collection cost [27].

Collection technique/method	Coastal types where collection can be done	Collection capacity, m^3/hour	Collection cost, Euro/hour
Wheel loader with grating bucket/shovel	Sandy beach	80	97-145
Large and small beach cleaners	Sandy beach	2-10	145-242
Pontoon Machines	Harbour	4-12	145-194
Suction Dredging	Harbour	10-40	97-145
Dry Suction with Collection Barge	Sandy and stony beach	2-7	194-290
Water Pressure Pump with Collection Barge	Sandy and stony beach	2-12	194-290
Mammoth Suction	Sea/water	10-30	390-970

The collection technique where both the collection capacity is relatively high and the cost is low is by wheel loader and suction dredging. While the wheel loader is already an established technique in the partner countries for collecting seaweed by the coast and in shallow water, the suction dredging is not yet a feasible method. Most of the collection techniques currently used in the partner countries are suitable for sandy beaches and shallow water. Table 13 shows that the collection cost is higher for techniques intended to coastal areas described as stony, when compared to the collection capacity. Some collection techniques could still be suitable for seaweed collection (see Table 14), even though the collection cost is relatively high.

Table 14: Advantages and disadvantages of different collection techniques.

Collection technique	Advantages	Disadvantages
Wheel loader with grating bucket	Low sand uptake Quick Collection on the beach and in water Easy unload Cheap method	Low loading capacity leading to additional costs Size of the machine Wheel marks left on beach Moderate noise
Large and small beach cleaners	Quick collection if material is dry Collection on shore and in shallow water	Limited loading capacity Frequent unloading Sensitive to the type of beach Expensive Low collection capacity per hour
Suction dredging	No damage on beach and sea bed No turbidity is caused Moderate collection capacity per hour Suitable for harbours Cheap method	Major changes required
Pontoon machines	Collection in sea and underwater Low fuel consumption Possibility to equip with external cargo containers Suitable for harbours	Only useful for small size harbours Requirement of relatively good weather Collection to a maximum of 2 m water depth Expensive Low collection capacity per hour
Dry suction with collection barge	Suitable for most coastal types Simple technology Possibility to reduce undesirable materials	Moderate changes required Broad suction nozzle required Expensive Low collection capacity per hour
Water pressure pump	Suitable for deeper waters and stony beaches Easy adoption Possibility to reduce undesirable materials Suitable for most coastal types	Moderate changes required Broad suction nozzle required Expensive Low collection capacity per hour
Mammoth suction	Suitable at deep waters Moderate collection capacity per hour	Moderate changes required Requirement of diver Very expensive

Even though the large and small beach cleaners have a relatively high collection cost, the quick collection of dry materials makes it a suitable method for seaweed at the beach.

When comparing the advantages and disadvantages with the collection cost and collection capacity, the wheel loader with a grating bucket is the best collection technique for the collection of seaweed. However, the disadvantages could lead to further modifications, so the technique does not lead to additional costs, due to low loading capacity, leaving marks on the beach and moderate noise. Even though suction dredging is a cheap method with a relatively high collection capacity, and is suitable for collection in harbours, major modifications are required.

The two methods suction dredging and mammoth suction both have a relatively high collection capacity per hour. However, both techniques requires major or moderate changes, and the mammoth suction method is the most expensive technique of all the techniques mentioned.

In conclusion, the wheel loader with a grating bucket is the most suitable technique, when comparing to collection capacity and cost. The technique is already used in the partner countries, and can easily be modified.

4.4. Advantages and challenges

The study from Trelleborg Municipality [27] shows that a wheel loader or a grip-claw loader is to be preferred when collecting seaweed at the beach and in shallow water. They are both quick and cheap, compared to the other collecting techniques.

One of the main challenges with collecting seaweed with the intention to use it in biogas production is the high sand content. Even with the ideal collecting techniques, sand cannot be avoided in the seaweed. The sand content can be as high as 62% of the wet weight (WW) and 81% of the dry weight (DW) [30]. Studies from Solrød Biogas Plant have shown that the sand content normally is around 30% WW after collection, which has a negative effect on the machinery [31]. The sand content in the cast seaweed depends on how long it has been on the beach. Studies from Solrød show that fresh seaweed and seaweed that still flows in the water have a much lower sand content than the seaweed, which has been on the beach for a longer period. The study shows that the older algae can have a sand content of up to 32-77%, while the fresh seaweed contains as low as 14% when collected [4].

The advantages of collecting fresh seaweed are both the possibility for a lower sand content as well as a higher methane yield. However, the current collection techniques only make it possible to collect seaweed in shallow waters and on the beach. This means that to gain high methane yields, the collection techniques need to be modified so that seaweed can also be collected in deeper water.

Because of the high level of sand in the collected material, a pre-treatment process will be necessary before the seaweed is used in the biogas plant. Furthermore, a quick collection will be of help to lower the sand content in the seaweed and results in a higher methane yield.

High collection costs can further be a hindrance for the biogas plant and municipalities to start the collection of cast seaweed [22]. Therefore, it is preferred to collect seaweed of high value, which means high concentrations of nutrients and high methane yield.

5. Sand separation – experience and laboratory experiments

5.1. Sand separation laboratory tests

The high sand content had negative effects at Solrød Biogas Plant, the machinery were worn faster, which meant that they had to put the seaweed through some sort of pre-treatment, where the sand would be separated from the seaweed.

At Solrød Biogas Plant, the seaweed is put into a receiving tank, which contains a very strong stirrer. This pre-treatment of the seaweed is performed to separate the seaweed from the sand residue. Because of the stirring, the sand falls to the bottom of the tank. The receiving tank is emptied once a year of the sand, which is then taken back to the beach [32]. When the sand is removed from the receiving tank, the plant needs to shut down, which at Solrød Biogas plant costs around 13,300-20,000 EUR. The sand content in the seaweed collected on Solrød Beach is normally around 30% WW [33]. An objective for Solrød Biogas plant is to have a sand content under 10% DM after pre-treatment.

Due to the high sand content at Solrød Biogas Plant, tests at RUC have been conducted with the intention to minimize the sand content in the seaweed. Firstly, the seaweed has been treated with water – heated to 54°C, which then is blended for 15 seconds at high level. Afterwards the seaweed is transferred to a pot with 54°C hot water, where it is stirred through a sieve.

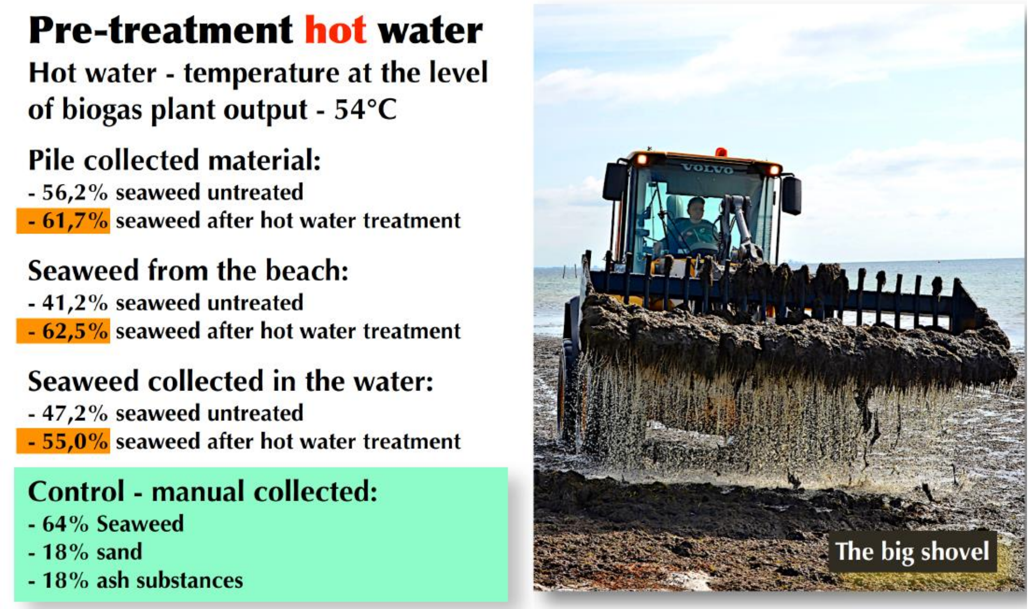

Figure 18: Results after hot water pre-treatment [RUC].

To further enhance the removal of sand, the hot water treatment was combined with centrifugation. The test was performed with a prototype, which consisted of an upside down bottle with an attached stirrer on top. Hot water (54°C) and seaweed was stirred at high speed for 2 minutes. During centrifugation, the sand was detached from the seaweed and fell to the bottom. However, the separation was only succesful when stirred at a continous high speed.

5.2. Sand separation pilot tests

Sand separation test performed by RUC mixed the use of mechanical (washing) and thermal (heating) pre-treatment methods. The experiment is based upon the terms, which is applicable at the biogas plant where the pre-treatment of the seaweed will be performed. Solrød Biogas plant has a thermophilic process with a process temperature of 54°C. This temperature will form the basis for the thermal pre-treatment, where the seaweed is heated directly with material from the digestion tank at the biogas plant. However, it is to be expected that the temperature will be lower than the process temperature (54°C), expected 45°C.

The experiment included three types of seaweed: dry seaweed collected form the beach, seaweed collected from the coastline (1-10 meters out in the water) and fresh seaweed. The seaweed was collected from Solrød Beach in July 2021 and consisted of a mixture of species, mostly brown algae and bladder wrack. The experiment consisted of three tests, where each type of seaweed was heated in water to 54°C for 4 minutes, 45°C for 4 minutes and 45°C for 20 minutes, as shown in Table 15.

Table 15: Test description for sand separation

Type of seaweed	Test 1	Test 2	Test 3
From the beach (dry seaweed)	54°C - 4 min.	45°C - 4 min.	45°C - 20 min.
From the coast (collected 1-10 meters out in the water)	54°C - 4 min.	45°C - 4 min.	45°C - 20 min.
Fresh seaweed	54°C - 4 min.	45°C - 4 min.	45°C - 20 min.

The purpose with Test 1 and Test 2 is to show the difference between the sand content when the seaweed is heated to 54°C and 45°C for respectively 4 and 20 min. The former laboratory test was based on the process temperature in the biogas plant (54°C), which as stated is expected to be at lower temperature.

The tests were performed with a HotmixPRO GASTRO [34]. The collected seaweed was transferred to the heated water, where a stirrer was set at low level. Afterwards the seaweed was collected by hand and set for draining in a sieve.

The test has shown that seaweed collected from the beach and fresh seaweed shows the sand content is decreased the most after test 3, 45°C for 20 minutes as stated in Table 16 below. This was compared to the sand content, which is applicable when no treatment is performed. Seaweed from the beach (dry seaweed) has a sand content of 46%, which is decreased to 23% after test 3. The fresh seaweed, which has the lowest sand content before treatment, shows that the sand content is decreased from 19% to 6% after test 3.

Table 16: Sand content in seaweed before and after pre-treatment based on dry matter [RUC]

Type of seaweed	Test 1	Test 2	Test 3	No treatment
From the beach (dry seaweed)	31%	38%	23%	46%
From the coast (collected 1-10 meters out in the water)	20%	41%	28%	45%
Fresh seaweed	11%	10%	6%	19%

Seaweed from the coast (collected 1 – 10 meters out in the water) shows the best results after test 1, 54°C for 4 minutes. After test 1, the sand content is decreased from 45% to 20%.

Test 2, 45°C for 4 minutes, shows the poorest results for both seaweed collected from the beach and seaweed collected from the coast. While test 1, 54°C for 4 minutes shows the poorest results for the fresh seaweed.

The test has shown that it will be a necessity to adjust the treatment to the type of seaweed (from where it is collected). Seaweed collected from the coast requires a higher water temperature, to decrease the sand content, than the dry seaweed collected from the beach and the fresh seaweed. Only pre-treatment of the fresh seaweed is reaching the objective set by Solrød Biogas.

5.3. Collection at shore, water edge and in the sea

Pre-treatment can have an effect on the gas yield in the seaweed. BMP experiments performed at RUC showed a higher methane yield in seaweed collected from the coast than fresh seaweed collected from water. However, when compared to the pre-treated seaweed collected from the coast, the methane yield decreased (see Figure 19).

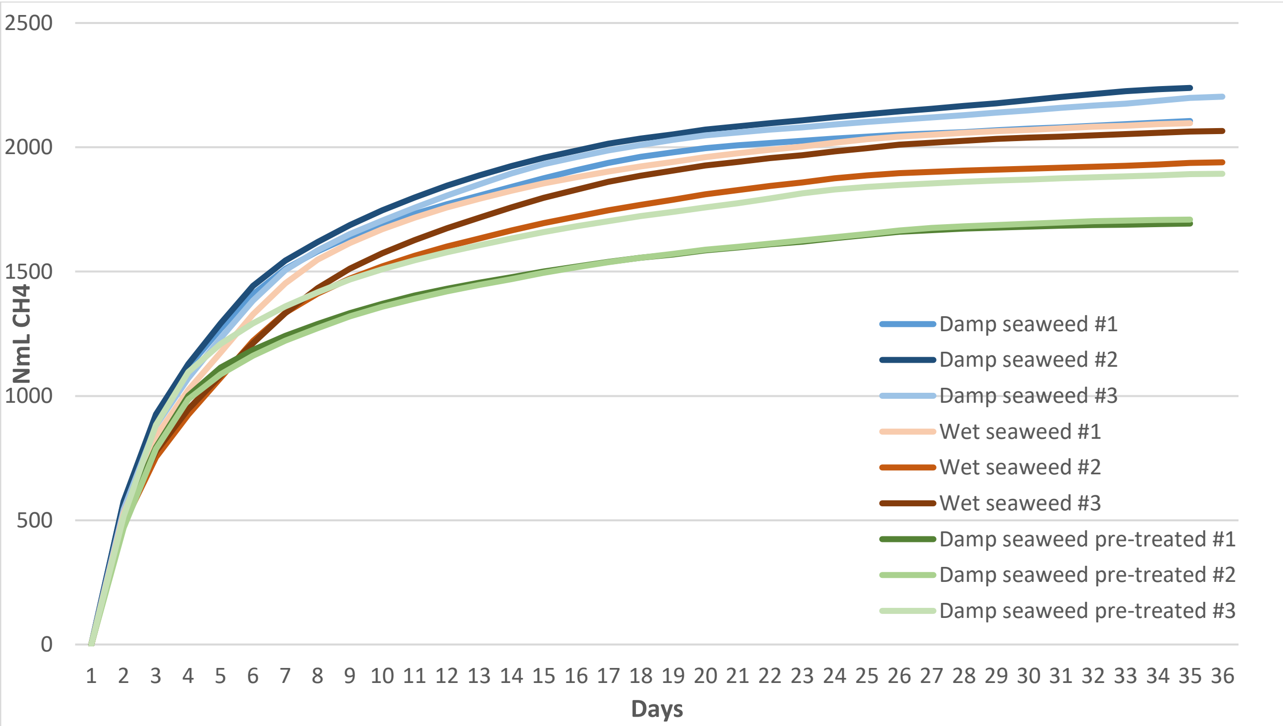

Figure 19: Methane potential for pre-treated seaweed compared to untreated seaweed [RUC].

The BMP experiment shows a decrease in methane potential after pre-treatment (mechanical and thermal) has been performed. The damp seaweed collected from the coast showed a high concentration of sand, which makes pre-treatment a necessity. The wet and fresh seaweed, which contained far less sand showed higher levels of methane than the seaweed, which went through pre-treatment.

This experiment shows that the performed pre-treatment method decreases the methane yield, in this case for damp seaweed collected at the beach. However, the pre-treatment is a necessity, which means the wet seaweed, which does not need excessive pre-treatment is a better option for gaining higher levels of methane.

Further testing conducted by Højvang Laboratorier A/S shows that the nutrient levels decrease after the pre-treatment process as shown in Table 17 below [35].

Table 17: Nutrient level for seaweed collected from the water edge and piles on the beach compared to the seaweed after pre-treatment [RUC].

Nutrients	Damp seaweed (mg/kg DM)	Wet seaweed (mg/kg DM)	Damp seaweed pre-treated (mg/kg DM)	Wet seaweed pre-treated (mg/kg DM)
Nitrogen	30,666	26,666	18,666	25,000
Phosphorus	763	633	553	530

The test shows that the nitrogen level is decreased by 39.13% after pre-treatment, and the phosphorus level is decreased by 27.51% for damp seaweed collected from piles on the beach. The nitrogen level for the wet seaweed is only decreased by 6.25% and the phosphorus level is only decreased by 16.32% for wet seaweed collected from the water edge. When comparing wet seaweed with pre-treated damp seaweed, the nutrient levels are higher for the wet seaweed.

Seaweed collected at Solrød Beach showed higher levels of cadmium in the seaweed collected on the beach, compared to the seaweed collected in water (see Table 18). Three batches were collected for each location (beach and water) and tested by Højvang Laboratorier A/S.

Table 18: Cadmium content in cast seaweed collected at Solrød Beach before and after pre-treatment [RUC]

Cadmium	Damp seaweed (mg/kg DM)	Wet seaweed (mg/kg DM)	Damp seaweed pre-treated (mg/kg DM)	Wet seaweed pre-treated (mg/kg DM)
Batch 1	0.50	0.19	0.54	0.20
Batch 2	0.28	0.11	0.22	0.11
Batch 3	0.54	0.21	0.67	0.20

The analysis shows no indication that the pre-treatment has an effect on the seaweed collected in water, regarding an increase or decrease in the cadmium levels. However, an increase can be recognised for Batch 1 and 2 after the pre-treatment of damp seaweed collected at the beach.

As stated earlier it is necessary to pre-treat the seaweed because of the high level of sand. The test from Højvang Labororatorier A/S shows that the nutrient levels are decreasing after pre-treatment, which means that nutrients get lost by conducting pre-treatments that consist of mechanical and thermal pre-treatment. The test also shows that there is a huge difference in nutrients loss depending on where the seaweed is collected.

5.4. Pre-treatment costs

The pre-treatment cost depends on the pre-treatment method. It is desired that the pre-treatment method is as low as possible and is not an inconvenience for the operators at the biogas plant. Furthermore, the cost of pre-treatment (as well as collection) should be lower than if the seaweed was disposed in other ways, e.g. by disposal on landfill.

In Dragør Municipality, Denmark, 611 tonnes of seaweed were collected in 2018. The collected seaweed was disposed on a landfill, which in 2018 caused an expense of 299,973 DKK (around 40,227 EUR) [36]. If converted to cost per tonne, Dragør Municipality spent 490.95 DKK or around 66.02 EUR to dispose the collected seaweed in a landfill. At Solrød Biogas, the collection and pre-treatment process costs 280 DKK (around 37.65 EUR) per tonne seaweed. Compared to the costs from Dragør Municipality, it can be concluded, that collection and pre-treatment of seaweed with the intension to utilize as feedstock, is by far cheaper than disposal of seaweed in landfills.

To keep the pre-treatment cost low, the sand content should be low upon collection, so no excessive pre-treatment is needed. Furthermore, seaweed species with a low concentration of sand and with high gas yield are to be preferred as they are of higher value for the biogas plant. However, it is not possible to collect certain types of seaweed species, as the variation of species are changing throughout the seasons [37].

5.5. Advantages and challenges

The sand separation tests showed that the collection location has an effect on when the pre-treatment is successful. Dry and fresh seaweed both shows the lowest levels of sand after 45°C for 20 minutes, whereas seaweed collected from the coast has the lowest sand content after 54°C for 4 minutes. However, only pre-treatment of fresh seaweed succeeded in achieve the objective set by Solrød of under 10% sand.

The pre-treatment needs to be as affordable as possible to be a possibility for the biogas plant to use seaweed for the production of biogas. The utilisation of cast seaweed (collection, transportation, pre-treatment and storage) needs to be cheaper than other methods of disposal.

A challenge when separating sand from seaweed is the difference with each species of seaweed. The seaweed (eelgrass and bladder wrack) collected from Odden, Denmark, was easier to separate from sand than the seaweed collected from the beach in Solrød (Pilayella littoralis and *Ectocarpus Siliculosus*). The seaweed collected from Solrød was stickier, which made it harder to remove the sand. This means that, depending on which type or species of seaweed, different types of sand separation methods will need to be considered [38].

If the sand content is low, it implies less cost for both collection, transport and the pre-treatment process. Again, the collection of fresh seaweed could be an advantage.

One of the challenges is to ensure the possibilities for collecting mostly fresh seaweed. This will require knowledge of when the seaweed is washed up on the beach, as well as regular supervision of the beach. Another challenge is to implement the pre-treatment facilities for all biogas plants, without it being an unaffordable cost.

6. Seaweed – Regional perspective

6.1. Estimated seaweed amounts in partner countries

Based on collected amounts of seaweed in the South Baltic Region, RUC has calculated the possible seaweed amounts for the region. The seaweed estimations are based on the Swedish collection figures, presented in *Deliverable 4.1: Report on beach cleaning and pre-treatment of seaweed* [39]. The maps presented in Figure 20 and 21 are based on the dataset *Eurosion* [40], and show the Natura 2000 areas in the South Baltic Region and areas which consists of sandy beaches.

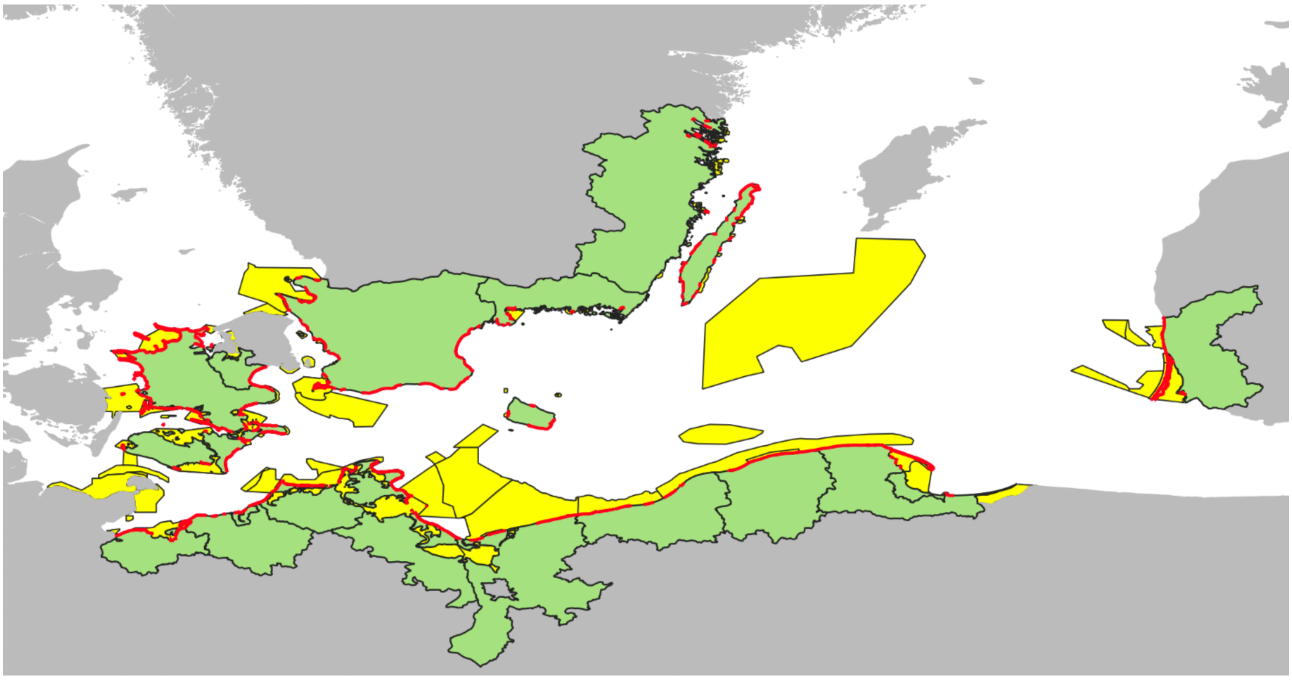

Figure 20: Map of sandy beaches (red lines) and Natura 2000 areas (yellow)

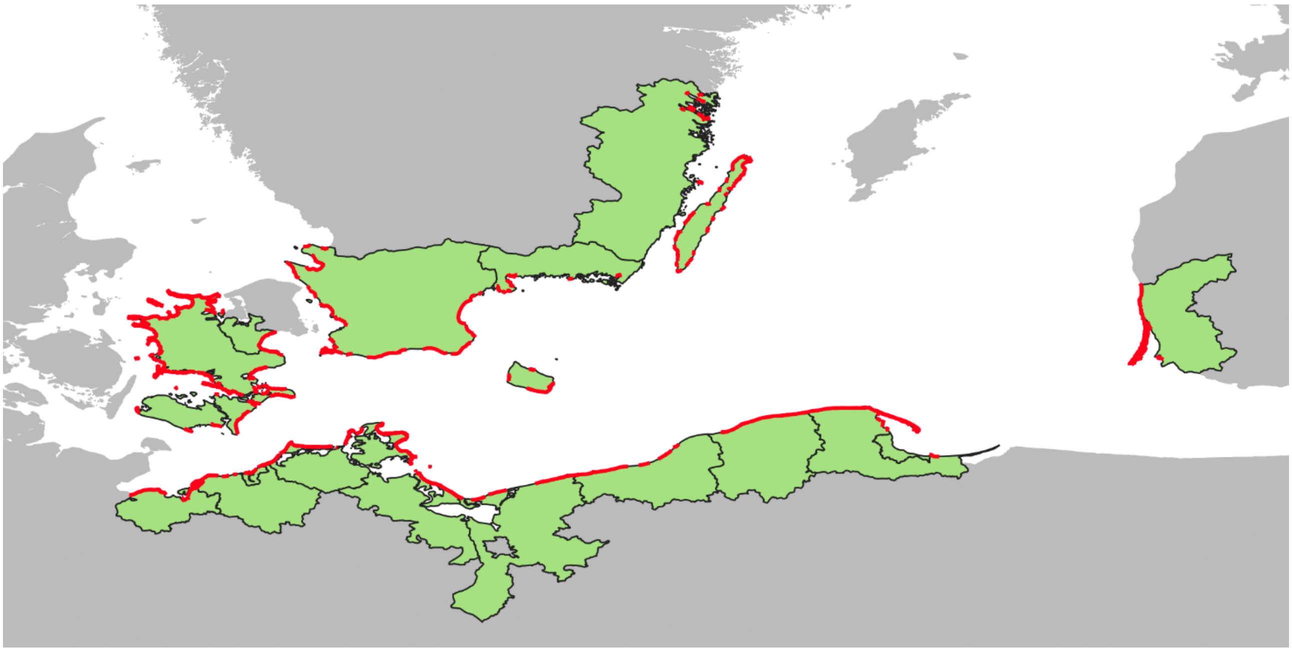

Figure 21: Map of sandy beaches in the South Baltic Sea

Based on the Swedish seaweed amounts (625 t/km), estimations have been calculated for the other partner countries, based on suitable coastline (sandy beaches). In Table 19, the seaweed estimations in the five partner countries are presented. It should be mentioned that the estimations will be higher or lower for some areas. The seaweed amounts stated are based on 625, 312.5 and 62.5 tonnes of seaweed per km.

Table 19: Estimations of the total amount of seaweed in the five partner countries

Region	Coastline within Interreg South Baltic (km)	Suitable coastline/sand beach (km)	Seaweed amounts, high estimate (t)	Seaweed amounts, middle estimate (t)	Seaweed amounts, low estimate (t)
Sweden	2,492	473	295,625	147,813	29,563
Denmark	1,455	328	205,000	102,500	20,500
Lithuania	257	153	95,625	47,813	9,563
Germany	1,633	327	204,375	102,188	20,438
Poland	914	312	195,000	97,500	19,500
SUM	**6,751**	**1,593**	**995,625**	**497,813**	**99,563**

Since the estimated seaweed amounts are based on the Swedish collection figures, the respective amounts could differ from area to area in the countries.

6.2. Estimated potential of collection, biogas production and nutrient recovery

Based on the estimations presented in Table 19, Table 20 shows the biogas production and the nitrogen and phosphorus removal based on Figure 4: Benefits of the removal of seaweed. The table is based on the seaweed amounts, middle estimates.

Table 20: Estimations of possible biogas production and removal of nutrients based on calculations made by RUC

Region	Seaweed amounts (t)	Biogas production (m^3)	Nitrogen (t)	Phosphorus (t)
Sweden	147,813	5,334,867	1,199,946	29,119
Denmark	102,500	3,699,430	832,095	20,193
Lithuania	47,813	1,725,667	388,146	9,419
Germany	102,188	3,688,169	829,562	20,131
Poland	97,500	3,518,970	791,505	19,208
SUM	**497,813**	**17,967,103**	**4,041,254**	**98,070**

To get more accurate estimations on the seaweed amounts, the biogas production and the removal of nutrients in a specific area, it will be necessary to gain an overview of the production of seaweed and where it is washed ashore.

7. Conclusion and recommendations

To collect and recycle high levels of nutrients, the seaweed should be collected as fresh as possible, while still in the water, or soon after reaching the beach. The longer time the seaweed is laying on the beach, the more nutrients are mineralized and leached back into the sea. The removal of nutrients can help to counteract eutrophication in the South Baltic Sea.

Fresh seaweed has shown to have a higher methane yield and nutrient levels than older seaweed. Furthermore, older seaweed has a higher level of cadmium, which can be a problem for the biogas plant to further use the seaweed as feedstock in their production.

The problem of high sand contents in the seaweed, especially in older seaweed, means that pre-treatment of the seaweed is necessary before it is utilised as feedstock. Of the pre-treatment methods tested, a combination of mechanical and thermal pre-treatment has shown to be successful to remove sand from seaweed. However, some pre-treatment methods can, besides being expensive, have a negative effect on the nutrient levels and the methane yield. Even though some pre-treatment methods have shown to be effective in increasing the methane yield, the seaweed species itself have a high impact.

The collection techniques should be cheap and effective and be able to collect seaweed both on the beach and in the water. Furthermore, the costs for the collection and pre-treatment should be lower than other disposal, like landfills.

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