COASTAL BIOGAS

Cluster On Anaerobic digestion environmental Services and nuTrients removAL

A report on operating biogas facilities utilising anaerobic digestion of cast seaweed

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Preface

The project receives funding by the Interreg South Baltic Programme 2014-2020 under the project "Cluster On Anaerobic digestion, environmental Services and nuTrients removAL (COASTAL Biogas)", STHB.02.02.00-DE-0129/17.

Cover photo

The Solrød biogas plant, a picture taken by Andrius Tamošiūnas

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4. Roskilde University (RUC), Denmark – project partner

5. University of Rostock (UROS), Germany – project partner

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Summary

The purpose of this report is to **summarise** information about the best practises of the existing or former biogas plants enabling to use various maritime substrates in anaerobic digestion (AD) process for continuous and stable biogas production. The report includes a whole aquatic biomass handling chain from substrate collection, storage and pre-treatment to mixing, biogas production and digestate utilisation of two separate biogas facilities in Denmark (Solrød biogas plant, https://solrodbiogas.dk/en/) and Sweden (Smyge pilot biogas plant) (Figure 1). Identification of various species of seaweed is outside the scope of the report.

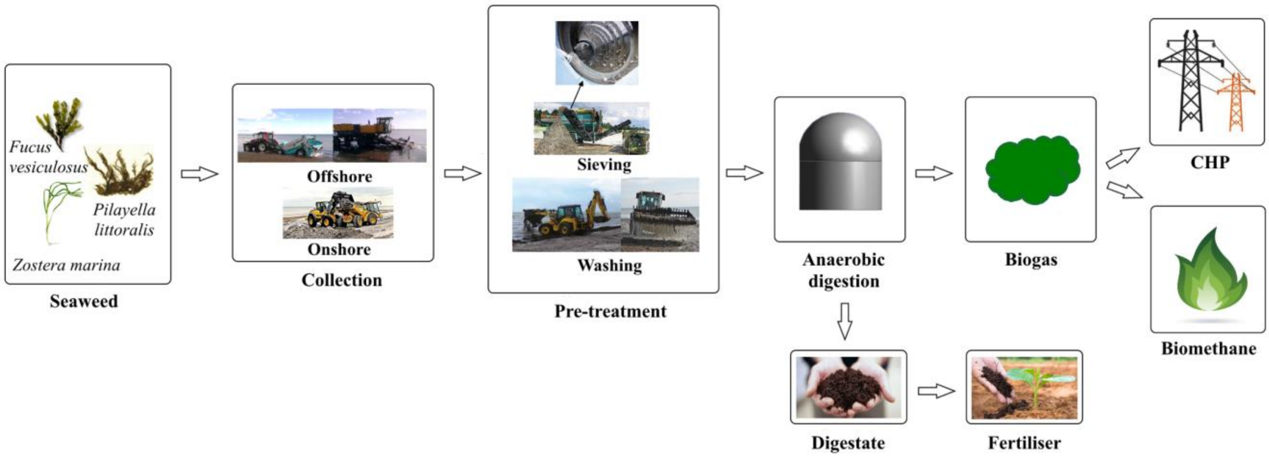


Figure 1: Aquatic biomass handling chain

Introduction

Nowadays, the need to find sustainable solutions towards a circular economy as well as climate change mitigation producing green energy requires consolidation of efforts of all stakeholders, such as politics, scientists, communities, business, industry, etc. The Baltic Sea area suffers from eutrophication due to past and present excessive discharges of nutrients (nitrogen and phosphorus) to the marine environment. As a result, eutrophication causes a threat to the biodiversity of the Baltic Sea due to elevated levels of algal and plant growth, increased turbidity, oxygen depletion, changes in species composition and nuisance blooms of algae. Moreover, the increasing volumes of maritime biomass, which is permanently discarded on beaches from day to day or after thunderstorms, has caused serious local odour problem by cast seaweed fouling on the beaches. Consequently, extra financial and human resources are required for municipalities to cope with this issue. Additionally, unpleasant odours impact not only the recreational coastal areas but also the value of property built near the coastline.

The quantities of discarded seaweed on the Baltic Sea coasts may differ from country to country. The biggest problem is faced in Denmark and Sweden, followed by Germany. A much smaller size of this negative phenomenon is seen in Poland, Lithuania, Latvia and Estonia. Therefore, Danish and Swedish local authorities together with communities have taken real action in the period from 2013 to 2015 trying to suppress the quantities of discarded seaweed on their shore. This was done by removing cast seaweed from beaches and utilising it for green energy production in two biogas plants. These attempts are helping to reduce eutrophication on the Baltic Sea area as well as to keep some recreational coastal areas clean and attractive for locals and tourists.

Further, two cases on handling aquatic biomass via anaerobic digestion process in biogas facilities will be presented. One is in Denmark (Solrød biogas plant) and another in Sweden (Smyge pilot biogas plant).

1. The case of Solrød biogas plant in Denmark

1.1. About the plant

The Solrød biogas plant is located in Solrød municipality, Zealand region, Denmark (Figure 2). Several factors contributed to the emergence of this biogas plant. First – community's odour problem caused by seaweed washed to the beach shore. Second – Solrød municipality's aspiration to produce green energy, thus fighting climate change. Third – local industries had challenges with proper utilisation of their by-products. Today, the Solrød biogas plant uses collected seaweed, organic residues (pectin, lactic acid and yeast slurry) and livestock manure for the generation of energy. This project shows how the endeavour to contribute to the development of sustainability by producing environmentally-benign energy and how cooperation between private and public partners can lead to new and advanced solutions [1–3].

The Solrød Biogas Plant was taken into operation in 2015. The plant was established and is operated by Solrød Biogas A/S, founded on May 28th 2014, with Solrød Municipality as a shareholder.

The biogas plant has a treatment capacity of 226,000 tons of feedstock per year. The biogas is used for Combined Heat and Power (CHP) generation in a large gas engine. The power is sold to the grid and the heat is supplied to the local district heating system, which is operated by Vestegnens Kraftvarmeselskab I/S and owned by 12 municipalities as stakeholders. The energy production of the biogas plant and the anticipated savings of CO_2 (equivalent) became part of the Solrød Municipality's Sustainable Energy Action Plan (SEAP), under the Covenant of Mayors [1]. Main input and output parameters of the plant as well as an investment are shown in Table 1 and Table 2, respectively. A picture of the plant and the process flow are shown in Figure 2 and Figure 3, respectively.

Table 1: Main input and output parameters of the Solrød Biogas Plant

Treatment capacity of biomass	226,000 tons/year
Methane production	6 million m^3/year
Electricity production	23 GWh/year
Heat production (District Heating)	28 GWh/year

Figure 2: The Solrød biogas plant [photo: Solrød Biogas A/S, 2018]

Table 2: Investment into the Solrød biogas plant

Investment	approx. 11.6 million Eur
CHP plant	approx. 4.2 million Eur
EU grant	0.5 million Eur
Annual revenues	approx. 4 million Eur

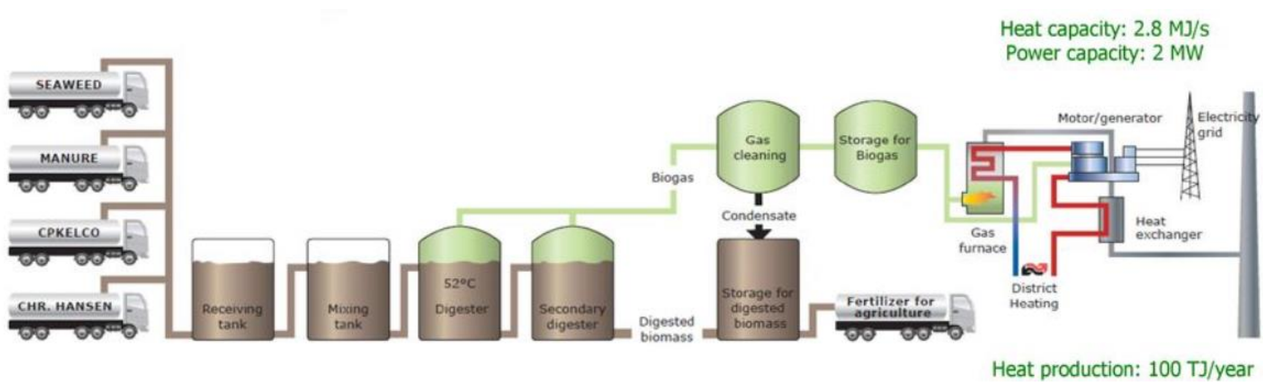


Figure 3: Simplified biomass and biogas flow diagram of the plant [1]

Benefits from the plant:

- 60 GWh/year renewable energy production
- 104 local jobs, of which 14 permanent
- 40,100 tons CO_2 saved per year (51% of the municipality target for 2025)
- Sustainable waste treatment and lower costs of waste transport
- Production of digestate as an organic fertiliser for farmers
- Reduced leaching of N to aquatic environment by 62 tonnes/year (70% of requirement for Køge Bay)
- Reduced leaching of P to the aquatic environment by 9 tonnes/year (100% of requirement for Køge Bay)
- Reduced odour nuisance from the beach/seaweed
- Improved sea water quality and higher recreational value of the maritime coastal area

1.2. Maritime substrate collection

1.2.1. Types of seaweed

The Solrød biogas plant receives seaweed (Figure 4), which consists of two types [1, 4]:

1. Green seaweed: eelgrass (*Zostera marina*)
2. Brown seaweed: *Pilayella littoralis, Ectocarpus sp.*

(a)

(b)

(c)

(d)


(e)


(f)

Figure 4: Seaweed at coastal line in Solrød municipality [photos (a) – Solrød Biogas A/S, 2018, (b-f) – Andrius Tamošiūnas, 2019]

1.2.2. Seaweed collection periods and quantities

The collection of seaweed along the Køge Bay coastal line in Solrød municipality (Figure 5) from 2016 to 2019 took place around the time of periods that are presented in Table 3. Furthermore, the collection of cast seaweed can proceed continually during the whole year except for several cases, such as bad weather conditions and/or the concentration of cadmium is above the limit (0.8 mg/kg dry matter) in the collected seaweed. This prevents the collected seaweed to be transported to and used in the Solrød biogas plant for biogas production [5, 7].

Figure 5: Seaweed collection area in Solrød municipality

Table 3: Collection periods for cast seaweed in Solrød municipality

Year	Seaweed collection period
2016	From May to October
2017	From August to October
2018	From November to December
2019	From April to October

According to a local entrepreneur, the amount of cast seaweed collected from the 3.7 km coastline in Solrød Municipality in 2009 was equal to 4,000 tons which corresponded to 1,081 tons/year km [5, 7]. Moreover, the annual average collection of cast seaweed from the entire Køge Bay coastline (38.6 km) has been estimated to be 42,000 tons/year, which conforms to 1,141 tons/year km. Recently, the annual quantity of cast seaweed collected from 1-2 km of Køge Bay coastline corresponded to 1,500 tons/year [5, 6]. Moreover, around 1,200 tons of seaweed were collected in 2019.

1.2.3. Seaweed collection and pre-treatment methods

The collected seaweed utilisation depends on the content of the heavy metal cadmium in the seaweed. Seaweed samples are taken once a month, and the results of the cadmium content become available in the middle of the month (it takes 7-8 working days to analyse the seaweed). If the cadmium content is below the limit value of 0.8 mg/kg dry matter, the seaweed is supplied to Solrød biogas plant. Otherwise, the seaweed is returned into the water. Correspondingly, works are carried out until the next measurement of the cadmium content in the seaweed. Typically, the cadmium limit value exceeds the threshold in the winter season (Figure 6) [6].

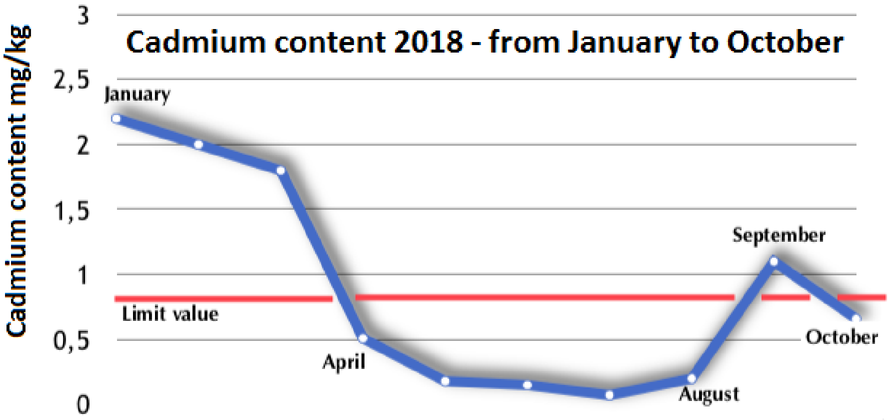


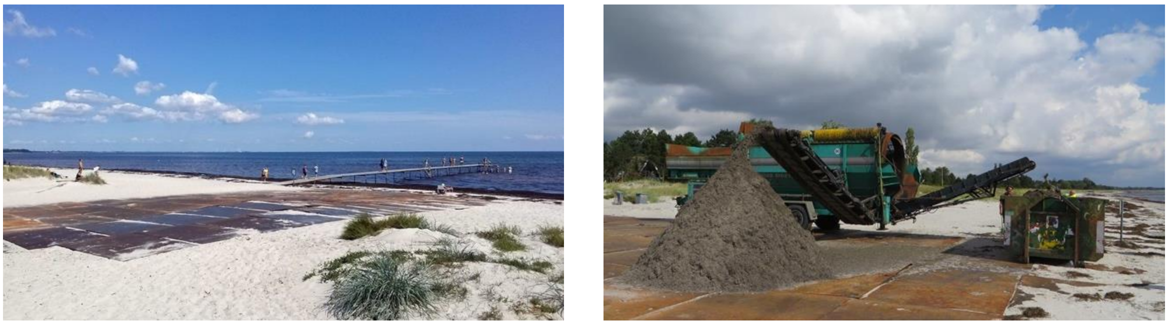
Figure 6: The cadmium content in the seaweed

During the feasibility study of Solrød biogas plant, the possibilities of seaweed collection were also studied. The prototype of a seaweed harvester was tested as a potential collection technique (Figure 7). It was found that this machine can collect approx. 30 m^3 of cast seaweed per hour while the sand content remains 23–40% w/w of dry solids. Hence, the harvester, which was invented in Halmstad Municipality, Sweden, has a great capacity for collecting seaweed on the shore. Unfortunately, Halmstad's machine can only be used in the water (near the beachfront). Thus, there is a need for additional techniques for onshore seaweed collection [8].

Figure 7: The prototype of seaweed harvester invented in Halmstad, Sweden [photo: Solrød Strands Strandrenselaug]

A significant challenge during the collection of seaweed was the high sand content. Therefore, the experiment with a very large mobile drum sieve (as the size of a truck) was performed in 2014 (Figure 8). The iron plates were laid on the sand on the beach. These plates ensured that the drum sieve, the trucks with the containers and all other equipment did not damage the beach or sank and got stuck on the sand. During the experiment, sandy seaweed was sifted in the drum sieve. The piles of separated sand were formed on the iron plates. Clean seaweed was collected in the containers, which were weighed before and after sifting [9].

Before the experiment, companies providing the mobile sieves showed some scepticism regarding the cleaning efficiency, as the material was not dry and it was expected that sand will stick to the seaweed as long as it is wet. Nevertheless, the mobile sieve managed to separate a high amount of sand from the collected seaweed [10, 11]. However, this pre-treatment method has some disadvantages, because every movement of the equipment to another place requires lying out the iron plates on the beach.



(a) (b)

Figure 8: (a) – iron plates; (b) – drum sieve [photos: Solrød Strands Strandrenselaug]

The development of the methods and tools, which are used to collect the seaweed, is still ongoing. Recently, seaweed has been collected and cleaned using a backhoe with a big shovel in front, a beach cleaning machine and a loader tractor (Figure 9 a-c). Also, a tractor with a giant rake and dump truck with iron bars (Danish: jernbjælke) are used to clear the ruts caused by collecting machines on the beach (Figure 10) [1, 3].

(a) (b) (c) (d)

Figure 9: (a) – a backhoe with a big shovel in front and dump truck; (b) – a beach cleaning machine; (c) – a loader tractor; (d) – a loader tractor and a dump truck [photos: Solrød Strands Strandrenselaug]

(a) (b)

Figure 10: (a) – a tractor (b) – a dump truck and a seaweed collecting machine clear the ruts of seaweed [photos: Solrød Strands Strandrenselaug]

Figure 11: A loader tractor forms a pile of the seaweed for collection [photo: Solrød Strands Strandrenselaug]

Generally, seaweed is kept in piles (Figure 11). During the collection, the seaweed, which visibly contains too high amounts of sand is dumped in the water using a backhoe or a loader tractor (Figure 12). From here, seaweed rinses and flows towards the beach where it is possible to collect it again, or the water currents carry it away. If the seaweed visually seems clean and contains less than 50% sand, a dump truck, which can hold 12–15 tons of seaweed, removes it from the beach and transports it to the Solrød biogas plant [5].

(a) (b) (c)

Figure 12: (a-b) – loader tractor, (c) - backhoe with a big shovel in front, rinsing of the sandy seaweed [photos: Solrød Biogas A/S, 2018]

This strategy allows collection around 90% of seaweed with less than 50% of sand [12]. Moreover, the seaweed is now delivered continuously to the biogas plant instead of lying on the beach. It means that unpleasant odour is being reduced and biogas production is improved, as the seaweed can be supplied in a continuous flow and is being provided fresher [13].

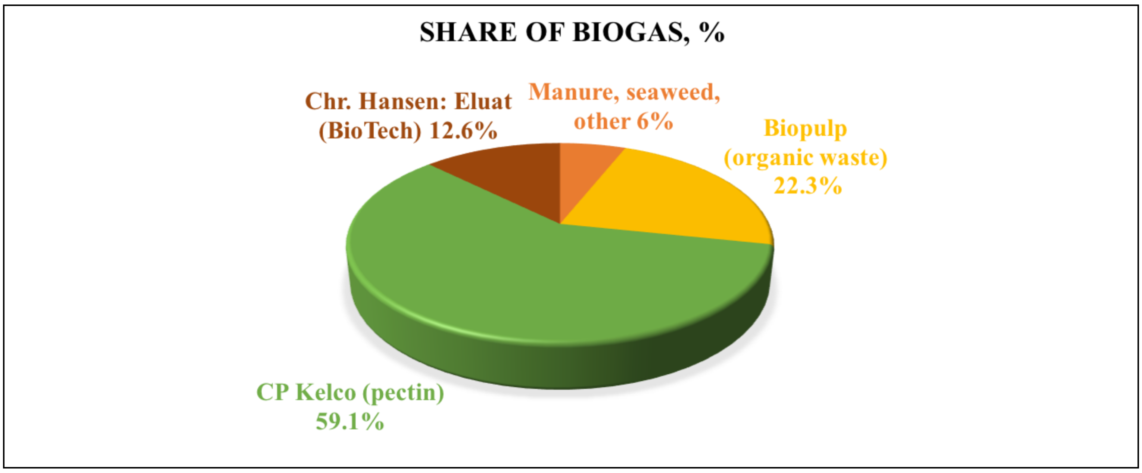
1.3. Feedstock transportation and its quantities

Currently, the Solrød biogas plant receives 226,000 tons of feedstock annually, as shown in Table 4 [13]. All the feedstock is transported to or from the biogas plant with trucks. The trucks have 28-30 tons of nominal and working load capacity. There are four main transportation paths [5]:

1. From seaweed collection place (beach coast) to the Solrød biogas plant.
2. From CP Kelco facilities to the Solrød biogas plant.
3. From the farmers to the Solrød biogas plant (manure supply).
4. From the Solrød biogas plant to the farmers (organic fertiliser supply).

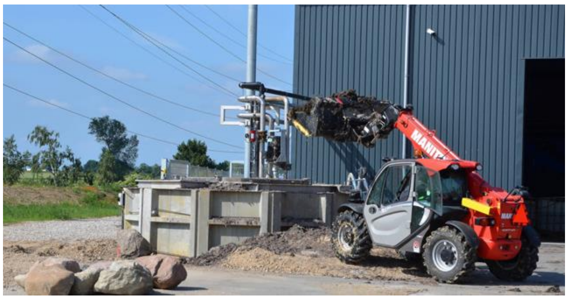
Table 4: Feedstock utilisation at the Solrød biogas plant

Feedstock	Quantity (tons)	Main contribution
Manure, seaweed, other	51,000	Gas production and process stability
CP Kelco: Pectin, carrageenan	95,000	Gas production
Chr. Hansen: Eluat (BioTech)	60,000	Gas production and nutrients
Biopulp (organic waste)	20,000	Gas production and nutrients
Total	**226,000**	



1.4. Seaweed pre-treatment in the Solrød biogas plant

Seaweed undergoes pre-treatment one more time at the biogas plant. Firstly, seaweed is put into a receiving tank with a very strong stirrer, which separates seaweed from the sand residue (Figure 13). The sand is removed from the bottom of the tank. Further, purified seaweed is chopped finely in a macerator and then mixed with another feedstock. Finally, feedstock composite is supplied via pipe systems into the biogas tank (digester) where gas formation takes place (Figure 14) [4, 6, 15].


(a)


(b)


(c)

Figure 13: Seaweed supply in a receiving tank with a stirrer [photos: Solrød Biogas A/S, 2018]

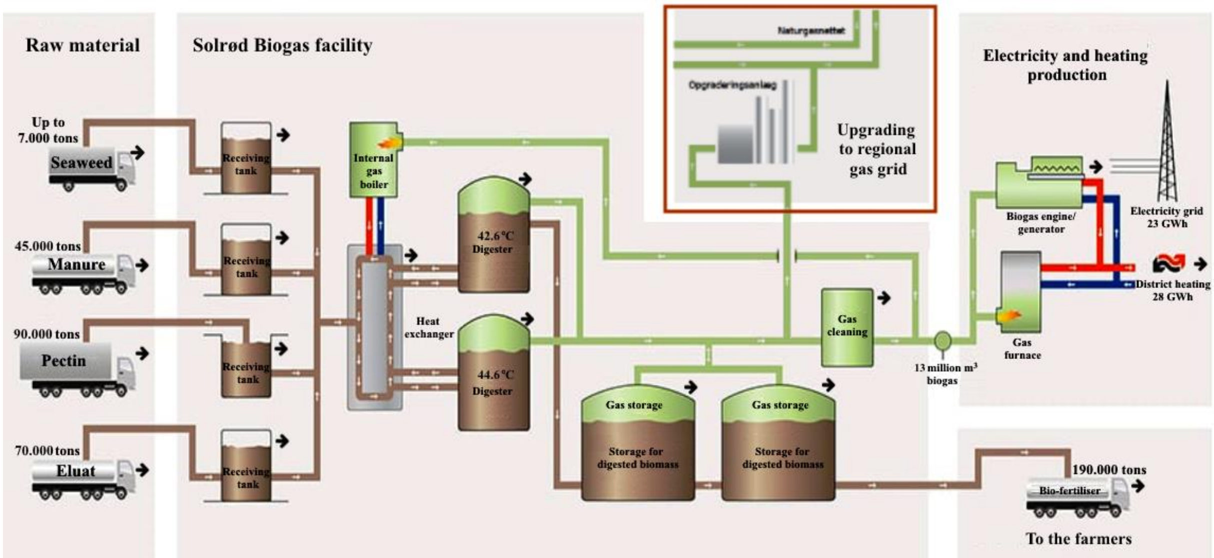


Figure 14: The scheme of biogas and organic fertiliser production in the Solrød biogas plant [16]

1.5. Biogas production in the Solrød biogas plant

1.5.1. Biomass digestion

The Solrød biogas plant has two digester tanks (Figure 15). The volume of each digester is 8,000 m^3. The temperature in the first digester is around 42.6 ^{o}C and in the second around 44.6 ^{o}C. The digestion process lasts around 30 days in an anaerobic environment and depends on the amount of raw materials running through the plant. Experiments performed at the Solrød biogas plant show that the highest biogas content is obtained after 25–30 days residence time. Also, is the following criteria are essential for the process [17]:

1. The right mixing ratio of the organic material;
2. A good mix of bacteria in the biomass;
3. The observed temperatures;
4. A stable and neutral pH of the mixture (7–8.5 pH);
5. Anaerobic (oxygen-free) mixture, environment.

Figure 15: The Solrød biogas plant digester tank [photo: Solrød Biogas A/S, 2018]

Under these conditions, different types of bacteria are capable of converting organic material into other compounds. For instance, methanogen bacteria turn organic material into methane (CH_4) and carbon dioxide (CO_2). Methane accounts for 2/3 of produced biogas, while carbon dioxide accounts for 1/3 of biogas. Also, small amounts of hydrogen sulphide (H_2S) and hydrogen (H_2) are formed during the anaerobic digestion process [17].
Hence, the bacteria are a prerequisite for producing biogas. They can produce biogas at temperatures between 10–60 ^oC. Bacteria convert the biomass as they grow (they multiply very rapidly). The bacteria in the digesters are mesophilic or thermophilic. The best living environment for mesophilic bacteria is at moderate temperatures (e.g. 42.6 ^oC as in the first Solrød biogas plant digester). Thermophilic bacteria live best at higher temperatures (e.g. 44.6 ^oC as in the second Solrød biogas plant digester). Thermophilic bacteria generally convert the organic material slightly faster than mesophilic bacteria. However, controlling the thermophilic process is more difficult [17].
Additionally, methanogen bacteria are the last link in the chain of a large number of bacteria that break down the biomass in digester tanks. Some bacteria break down carbohydrates, proteins and fats into carbon dioxide (CO_2) and hydrogen (H_2). Other bacteria break down the organic substances into acetic acid (CH_3COOH). Some methanogenic bacteria form methane from hydrogen and carbon dioxide. Other methanogenic bacteria break down acetic acid into methane and carbon dioxide. In simplified terms, the anaerobic respiration/combustion of methanogenic bacteria can be summarised as follows [17]:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2)$$

1.5.2. Biogas potential of the different feedstocks

During the feasibility study of the Solrød biogas plant, batch experiments were performed to measure methane potential of cast seaweed (mostly eelgrass – *Zostera marina*), pectin waste, carrageenan waste and pig manure. The methane potential of these feedstocks is shown in Figure 16. The average ultimate methane yields from seaweed, carrageenan waste, pig manure, and pectin waste are equal to 54, 120, 272, and 340 m^3/tons VS, respectively. Thus, seaweed has the lowest methane potential and pectin has the highest. However, due to inappropriate pH, pectin cannot be used as only feedstock in the biogas plant. Consequently, the feedstock mixture is appropriate for biogas production due to both high methane potential and suitable pH.

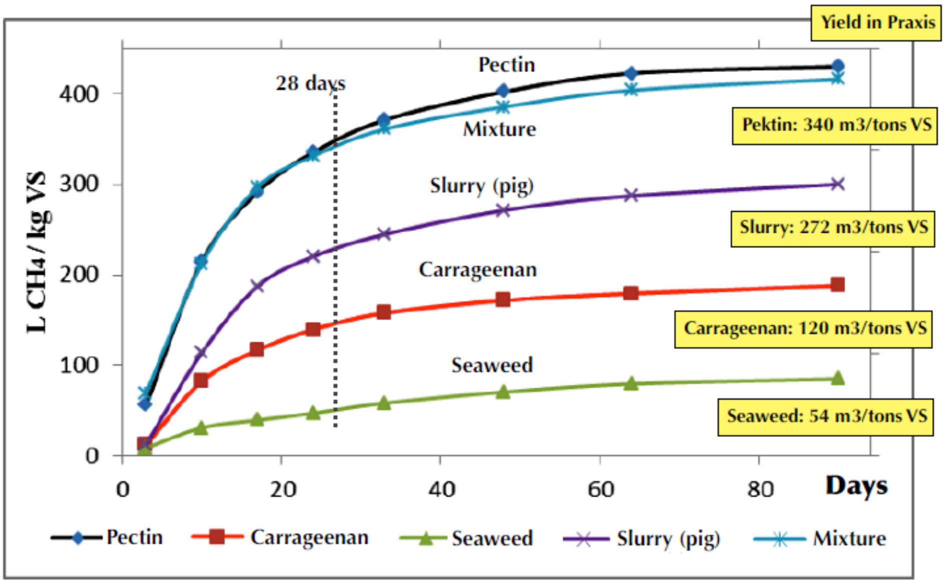


Figure 16: Methane production potential of seaweed, pectin, carrageenan, manure and mixture of these feedstocks

1.5.3. Biogas and degassed biomass storage

The Solrød biogas plant has two circular storage tanks for the degassed biomass (Figure 17). The volume of each tank is 1,700 m^3. In the storage tanks, there is a stirrer which ensures proper agitation of biomass. The tanks have an outside diameter of 19 m and an external height of 6 m. They are made of materials that can withstand various substances in the biogas, for example, hydrogen sulphide (H_2S), acids, moisture and siloxanes. At the top of the tanks is a gas-tight cover, which at the same time acts as gas storage and is connected to the gas system. In the tanks, there are level meters that measure biomass and biogas content in the tanks. The alert starts to sound when the tanks are getting close to being full. At the bottom of these tanks degassed biomass is stored, while the upper part of the tanks contains biogas [18].

Figure 17: Biogas (orange rectangular) and degassed biomass (green rectangular) storage tanks in the Solrød biogas plant [photo: Solrød Biogas A/S, 2018]

The most significant part of the biogas is produced in the two large digester tanks. In order to obtain even more biogas out of the biomass, a post-digestion takes place. About 95–97% of the biogas is produced in the digester tanks. The last 3–5% are produced in the post-digestion tank (one of the storage tanks) (Figure 18). The biogas from both digester tanks and the after-digestion tank is passed on to gas cleaning [18].

Figure 18: One of the storage tanks used for post-digestion [photo: Solrød Biogas A/S, 2018]

After the biomass is degassed in the digester tanks and the post-digestion tank, it is stored in a storage tank where it is mixed with sulfuric acid (H_2SO_4) and water (H_2O) from the gas purification. The degassed biomass contains many nutrients such as phosphorus (P), organic nitrogen (NO_3^-), ammonium nitrogen (NO_4^+) and potassium (K). Therefore, it can be used as an organic fertiliser. Most of the phosphorus (P) and organic nitrogen (NO_3^-) are found in the solid part of the biomass. Ammonium nitrogen (NO_4^+) is dissolved in the liquid. Consequently, the degassed biomass is delivered back to agricultural land in the form of organic fertiliser [18].

1.6. Organic fertiliser from the Solrød biogas plant

Every year, the Solrød biogas plant receives about 200,000 tonnes of residual products in the form of organic material from the food industry, agriculture and seaweed from the coast. In return, the Solrød biogas plant delivers 190,000 tonnes of degassed biomass (organic fertiliser) back to agriculture. The organic fertiliser can be used for all types of crops [19, 20]. Hence, from digested biomass (organic fertiliser) the following nutrients are provided (Table 5):

Table 5: Nutrients contained in organic fertiliser produced in the Solrød biogas plant [20]

Bio-fertiliser harvest 2018							
	Total Nitrogen (N), kg/ton	Ammonium (N), kg/ton	Phosphorus, kg/ton	Potassium, kg/ton	Copper, g/ton	Magnesium, g/ton	Sulphur, g/ton
August	4.45	3.15	0.58	0.99	2.45	143.00	161.00
September	4.60	3.23	0.68	1.38	2.15	151.00	160.00
October	4.90		0.78	1.38	3.08	170.20	
November	5.75	3.96	0.60	1.08	1.60	93.00	163.00
December	5.77	4.04	0.70	1.31	2.10	117.00	218.00
January	4.69	3.27	0.64	1.16	1.80	158.00	197.00
February	4.79	3.30	0.78	1.20	2.63	200.00	210.00
March	4.71	3.30	0.50	1.01	1.85	111.00	
April	3.94	3.00	0.57	0.95		133.00	178.60
May	4.33	2.85	0.67	1.03	1.85	80.00	175.00
June	3.86	2.80	0.64	0.91			
July	4.14	3.05	0.44	0.83	1.65	92.00	183.00
Average	**4.66**	**3.27**	**0.63**	**1.10**	**2.12**	**132.00**	**183.00**

Due to a higher content of ammonium nitrogen (NO_4^+), the degassed biomass has a higher fertiliser value than the manure that enters the biogas plant. The plant can absorb nitrogen easier when it is present in the form of ammonium nitrogen. Thus, NO_4^+ helps to promote plant growth [19].
Furthermore, the amount of slurry entering the biogas plant reduces during the digestion process as a proportion of the manure solids and the other residues are converted to biogas. This means that there is a smaller amount of dry matter in the degassed biomass than in the initial residues.

Respectively, all raw materials have an average dry matter share of 10% before the digestion, but the dry matter share drops to 4–5% after the digestion. Water (H_2O) and sulfuric acid (H_2SO_4) are added to the degassed biomass, which results in the fact that the volume of degassed biomass that is returned to agriculture is mostly the same as the amount of slurry and other residual products that entered the biogas production. The only differences are the distribution of liquid and dry matter, as well as the higher fertiliser value [19]. The degassed biomass is sanitised for one hour at 70 ^{o}C. This treatment ensures that diseases cannot transmit during organic fertiliser application in agriculture [5].

Degassed biomass (organic fertiliser) that is returned to agricultural lands has several advantages [1, 19, 20]:

1. The organic fertiliser penetrates the soil relatively quickly; thereby, the risk of evaporation of ammonium nitrogen is reduced.
2. The plants rapidly absorb organic fertiliser; thereby, the risk of nitrogen leaching into the environment is reduced. The nitrogen uptake of the crop increases by 10-25%.
3. Organic fertiliser results in a higher crop yield compared to manure.
4. The landowners can replace fertilisers produced using fossil energy with the environmentally friendly organic fertiliser produced during the biogas generation process.
5. The landowners become less dependent on fluctuating fertiliser prices, as the organic fertiliser forms a significant part of the fertiliser use.
6. Much less odour (up to -30%) is reported after the use of organic fertiliser compared to manure.
7. The organic fertiliser does not pose a risk of infection, as the biogas process has reduced the number of germs that could be in the manure.
8. The landowners receive a homogeneous fertiliser that covers a large part of the plant's nitrogen (N), phosphorus (P) and potassium (K) needs.

Spreading of the degassed biomass takes place in the same way as the slurry is spread today (with a slurry tanker or self-propelled slurry spreader) (Figure 19). Usually, it is spread in working widths up to 30 meters, in some cases even wider. The degassed biomass can also be deposited in the soil or laid out in the crop by towing hoses [20].

Figure 19: Spreading of the slurry on the field [photo: Solrød Biogas A/S, 2018]

1.7. Biogas cleaning

The biogas from the digester and the post-digestion tank contain the following gases: methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S). Hydrogen sulphide accounts for 0.1% of the total biogas. During the biogas burning process, sulphur dioxide (SO_2) forms from hydrogen sulphide. When SO_2 is emitted into the atmosphere, it reacts with water in the air and forms sulfuric acid (H_2SO_4), which falls as acid rain. Acid rain negatively affects terrestrial and aquatic ecosystems. Acid rain also supports the dissolution and break down of limestone in buildings and monuments. Consequently, it is essential to remove H_2S from biogas [21], which is done by a biological process. The uncleaned biogas is passed through filters and is bubbled with a liquid, containing bacteria. In an aerobic (including oxygen) environment, these bacteria convert sulphur to sulfuric acid (H_2SO_4) and water (H_2O). In other words, these bacteria use the energy of H_2S in building up the organic matter for their metabolism. In a simplified version, these chemical reactions occur as [21]:

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \quad (3)$$

$$2S + 3O_2 + 4H_2O \rightarrow 2H_2SO_4 + 2H_2O \quad (4)$$

The sulfuric acid (H_2SO_4) and water (H_2O) are passed on to the store of digested biomass. The sulphur in the sulfuric acid helps to improve the organic fertiliser value of the degassed biomass, as the crops on the field also need sulphur for their growth [21].

1.8. Combined heat and power generation in the Solrød biogas plant

Based on 2017 data, the Solrød biogas plant covered 5,826 household's electricity needs, equivalent to 64.73% of households in Solrød municipality, and the heat consumption of 1,920 typical households. Overall, it contributes to a CO_2 reduction of about 46,300 tons per year. In 2017, 23.8 GWh of electricity and 34.7 GWh of heat were produced. The production of electricity and heat increased by 17.10% and 14.04%, respectively compared to 2016. Also, 6,279,131 m^3 of methane were generated [22].

2. The case of Smyge pilot biogas plant in Sweden

2.1. About the plant

Prior to tests with algae as one of the substrates for biogas production, which were performed at the Smyge Pilot Biogas Plant, several EU-financed projects, such as "WAB – Wetlands, Algae and Biogas" (2010-2012[1], "BIOGASYSS" (2010-2015)[2] and "Bucefalos" (2012-2015)[3], had already been launched. These projects aimed at investigating the reduction of eutrophication via the pathway of removing maritime substrates from coasts and test aquatic biomass suitability for biogas production.
With this background and results, a new project started at Smyge trying to answer three main questions, which were raised as a result of previous experience:

- How to stabilise the biogas process without chemicals?
- Could the digestate be used as a fertiliser on agricultural land?
- How to find the most effective way to collect algae from the coast?

In this regard, the pilot biogas plant was constructed and operated by Norup AB in 2014, who also is the owner of the plant. The biogas plant consists of two parallel hydrolysis tanks, each of 150 m^3 in volume, methane filters, a buffer tank, and a gas boiler (Figure 20) [23].

Figure 20: Smyge pilot biogas plant [photo: Matilda Gradin, 2014]

This biogas plant was rented for a period of one and a half year (from 1st June 2016 to 31st December 2017) by the municipality of Trelleborg. The daily operation of the biogas plant was bought from Norup AB. However, the plant is no longer in operation. A final decision was made to dismantle the plant after the end of the project. Received investment from Nordic Investment Bank into the plant was close to 180,000 Euro. Around 80% of the total costs were used to hire and operate the plant.

[11] WAB project, http://wabproject.pl/index.php?ver=en
[2] BIOGASYSS project, https://www.biogassys.se/
[3] Bucefalos project, www.malmo.se/bucefalos

2.2. Maritime substrate collection

Aquatic biomass (algae) collection in Sweden is linked to the nutrient reduction potential, i.e. mitigation of eutrophication and additional secondary benefits, such as biogas production. Therefore, based on the experience of previously implemented projects (see section 2.1.) and other references [24], a number of technological solutions were tested in Trelleborg Municipality, Sweden, collecting algae both on shore and in the sea. The collection method also depends on the coastal type (sandy beach, stony beach, port, no beach, water of various depths) and collection technique availability/suitability (whether the technology needs engineering adaptation to use it for seaweed/algae collection, or its available for immediate use without significant change). Detox Biogas AB, which went bankrupt in 2011, had researched and evaluated different technologies for the collection of algae in different coastal types of Trelleborg Municipality, where they have defined two collection areas:

- collection area 1 represents the area from shore to 1 m depth into the sea;
- collection area 2 represents the area in the sea with 5-12 m depth.

It was stated that more technologies are available for the use in collection area 1 compared to collection area 2. According to this division, seven proven maritime biomass collection techniques were proposed for area 1 and only 2 for area 2 (Table 6) [24]:

Table 6: Maritime biomass collection methods (according to [24])

Area 1: along shore to 1 m depth into the sea					
No.	**Collection technique/method**	**Coastal types where collection can be done**	**Technology modification for algae collection**	**Collection capacity, m3/hour**	**Cost for collection, euro/hour**
1.	Grating Bucket	Sandy beach (beach & water)	No	80	97–145
2.	Pontoon Machines	Harbour	No	4–12	145–194
3.	Large and Small Beach Cleaners	Sandy beach (beach)	No	2–10	145–242
4.	Dry Suction with Collection Barge	Sandy beach (beach) Stony beach (beach)	Moderate	2–7	194–290
5.	Water Pressure Pump with Collection Barge	Sandy beach (beach) Stony beach (beach)	Moderate	2–12	194–290
6.	Skimmer Machines	Sea/water	Major	-	97–194
7.	Suction Dredging	Harbour	Major	10–40	97–145
Area 2: the sea with 5-12 m depth					
1.	Mammoth Suction	Sea/water	Moderate	10–30	390–970
2.	DM Truxor 4700b	Sea/water	Minor	-	-

2.2.1. Collection techniques for area 1

<u>Grating Bucket</u>

Algae has traditionally been collected and stored with a loader on the beach in Trelleborg (Figure 21). This collection is done only during the summer (2-3 months/year) and on five beaches that people use for bathing and sunbathing. The collected amounts vary from year to year, from 400 up to 1,400 m^3/year, for all beaches combined.

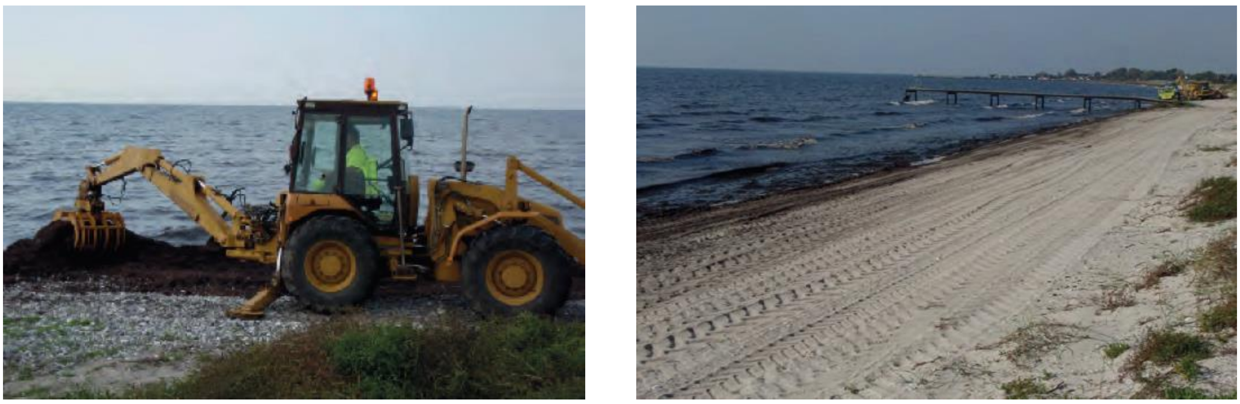
Currently, a wheel loader with a pitchfork or a bucket (with a mesh in order to minimise sand removal) is used for cleaning some of the beaches in Trelleborg. There are different types of mesh size that can be used. Dewatering takes place as soon as the bucket is above the water surface [24]. When the summer season is over, the collected and stored algae are usually delivered back into the sea.

Figure 21: A wheel loader with a pitchfork or bucket [photos: Trelleborg Municipality]

Advantages	Disadvantages
• Low sand take up • Quick and simple • Possibility to collect algae at the beach and in the water • Repetition of algae washing • Easy unload • Cheap method	• Low loading capacity leading to additional costs • Size of the machine • Wheel marks left on the beach • Moderate noise

<u>Grip-claw loader with dumper</u>

This method was tested during the WAB project [25]. The grip-claw collected the piles of seaweed from the beach and the shallow water (Figure 22). Thereafter, the power-rake pushed algae from the water to the beach and made the area plainer in order to facilitate the beach-cleaner to collect the finer materials. The dumper could load 6 m^3 of seaweed, and it took 6-9 minutes for the grip-claw to fill it, resulting in the effectiveness of about 45m^3/hour. The beach-cleaner collects smaller amounts and is more suitable for polishing the beach after removal of the large seaweed quantities. The amount of sand in the collected material was 1-2 % of the volume.



(a) (b)

Figure 22: (a) – a grip-claw loader; (b) – the beach after cleaning [photo: Trelleborg Municipality, 2010–2012]

Advantages	Disadvantages
• Low sand take up • Quick and simple • Suitable to collect algae on shore and in shallow water (less efficient) • Possibility of algae washing • Easy unloading	• Low loading capacity leading to additional costs • Size of the machine • More suitable for polishing the beach • Wheel marks left on the beach • Noise

Pontoon machines

These machines are built on pontoons and are powered by propellers or paddles. The machine includes a cutting table, which is adjustable in terms of depth. The Limnocombine (Figure 23) can lower the cutting table to a level of 2 m. In front of the cutting table, there is a horizontal knife. The Limnocombine has one horizontal and one vertical knife. The collected material is transferred by a conveyor into a self-emptying collection container in the back of the machine. The conveyor belt can be fitted with transverse ribs, depending on the composition of the material. Dewatering of the material takes place through natural runoff. This method is considered to be very beneficial for the harvesting of seaweed in smaller ports [24].

(a) (b)

Figure 23: Pontoon machine (Limnocombine): (a) – side view; (b) – backside view [photo: Trelleborg Municipality]

Advantages	Disadvantages
• Collection in the sea and underwater • Low fuel consumption • Collection capacity could be increased by 50% • Possibility to equip with external cargo containers	• Useful for small size harbours/ports • Requirement of relatively good weather • No possibility to collect from deeper water, collection up to a maximum of 2 m water depth • Boats need to be moved to allow the uptake of algae in ports

Large and Small Beach Cleaners

These techniques work either in the form of an individual machine or one attached to a tractor (Figure 24). Like a floating machine, these machines use conveyor belts with adjustable rollers. Brushes or small rakes address the material from the beach/sediment. The height of the brushes can, in most cases, be regulated. Some machinery can shake the material at the catchment board to minimise the uptake of sand. The collection of materials is done either just after the conveyor or above the conveyor on a flatbed [24].

(a) (b)

Figure 24: (a) – Monstret; (b) – Beachcleaner [photo: Trelleborg Municipality]

Advantages	Disadvantages
• Quick collection if material is dry • Possibility of shaking • Collection on shore or in shallow water	• Can stop if there is too much material or wet material on the catchment board • Limited loading capacity • Frequent unloading • Poor shaking if wet material • Sensitive to the type of beach

<u>Dry Suction with Collection Barge</u>

A vacuum pump could be used to "suck" up algae from the beach (Figure 25). The nozzle needs to be broad (0.12-0.15 meters) to cope with large scale algae collection. The nozzle needs to be supplemented with either a mesh or a metal with a fork-like design on the underside to separate the algae from the material that should not be collected (stone/sand/sediment/debris). However, some types of algae - particularly the Fucus brown algae - requires quite a large diameter of the nozzle (12.7–12.2 cm) in order to be collected. The material that is sucked up can be unloaded in two separate ways: onto a barge or into a tank. Unloading is done best via a barge that can be driven at sea but depending on the coastal type, land-based unloading (e.g. trailer) may be more suitable [24].

(c) (d)

Figure 25: (a) – Truxor with pump; (b) – close view of pump; (c-d) – sewage sucking trucks [photo: Trelleborg Municipality]

Advantages	Disadvantages
• Can be used in most types of coasts • Relatively simple technology • Easy adoption • Possibility to reduce undesirable materials (stones, debris) because of special type of nozzle • Possibility to place at several points along the coast	• Moderate changes required • Broad suction nozzle required • Extra-long hose requires more energy to suck

Water Pressure Pump with Collection Barge

In a similar way as for dry suction, one can apply a hydraulic pump, which has a larger orifice (0.12-0.15 meters), to "vacuum" up algae from the water. The nozzle could be supplemented with either a sieve/mesh network or metal with a fork-like design on the underside to prevent the collection of sand, stones and debris. No sieve/mesh should be used in the estuary where there is a risk that kelp can block the machine. Unloading is best done via a barge that can be driven at sea but depending on the coastal type, land-based unloading (via a trailer) may be more suitable [24].

Advantages	Disadvantages
• Can be used in most types of coasts • Relatively simple technology • Easy adoption • Possibility to reduce undesirable materials (stones, debris), because of special type of nozzle • Possibility to place at several points along the coast • More suitable for deeper waters	• Moderate changes required • Broad suction nozzle required • Extra-long hose requires more energy to pump

Skimmer Machines

This technique is frequently used in oil spill clean-up. Long arms collect material from along the surface of the water and from a short distance down below the surface. The machine can either push material to different locations or a brush in the machine can collect up the material and channel it through a tube to a small settling tank (Figure 26). The machine moves on continuous tracks and floats in deeper water. It could be used to complement other collection techniques (dry suction, water pump or floating machines), where the skimmer machine can bring materials to them [24].

Figure 26: A skimmer machine [photo: Trelleborg Municipality]

Advantages	Disadvantages
• Can be used in combination with floating, dry suction and water pump machine	• Severe changes required • A larger loading space is required to increase efficiency • The machine must be made heavier in order to become more stable in wind and wave conditions

Suction Dredging

Using a pump, sludge and mud can be collected from the sea floor. This technique is proposed for the use in areas such as ports or harbours and not to act as a technology for large scale algae collection (Figure 27) [24].

Figure 27: A suction dredging machine [photo: Trelleborg Municipality]

Advantages	Disadvantages
• No turbidity is caused • No damage on beach and sea bed • Can be used in combination with floating machine	• Major changes required

2.2.2. Collection techniques for area 2

Mammoth Suction

With this technology, the algae are sucked up by a pneumatic pump. The technique is used, for example, for marine archaeological studies (e.g. wrecks) and oil clean-up in deeper water (Figure 28). Mammoth suction consists of a suction tube that extends down to the sea floor. The air pressure is generated by a compressor located in a ship or barge. To facilitate handling, the nozzle needs to be anchored at the orifice. Power becomes stronger as the working depth increases. Therefore, this technology is most suitable for larger depths [25].

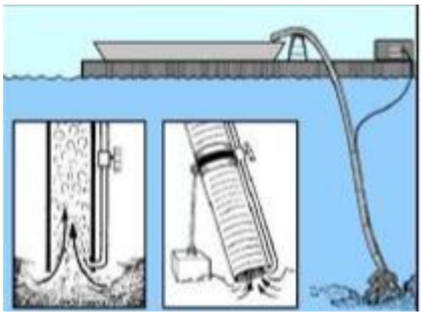


Figure 28: A scheme of a mammoth suction machine [photo: Trelleborg Municipality]

Advantages	Disadvantages
• Very suitable at deep waters	• Moderate changes required • Requirement of diver • Requirement of barges/vessels

DM Truxor 4700b

The DM Truxor 4700B is amphibious and therefore, can operate both on land and in water (Figure 29). It is primarily developed to harvest wetlands. The front fork attachment works very well, collecting algae almost completely free of sand, but the machine moves slowly, and the effectiveness was about 6 m^3 algae/hour. The DM Truxor is rather noisy in comparison with its effectiveness, making it unsuitable to use during recreation hours. The machine does not have the capacity to take up all algae because of the sparse front fork. However, other front attachments are available. The disadvantage of this model is that Truxor is developed for more calm water than the sea, and further improvements are necessary [23].

Figure 29: A DM Truxor 4700b [photo: Gabriaella Eliasson, 2016-2017]

Advantages	Disadvantages
• Possibility to collect both on shore and in water • Low sand take up • Cost effective	• Noisy • Developed for more calm water than the sea

Snow blower 'catamaran collector'

There is also one machine enabling to drive on snow, on pet soil, weak ice and on land. The principle is rather simple: rotating pontoons for floating and a screw for moving forward. This type of "catamaran" could be adapted for algae collecting (Figure 30). However, since it is similar to already described pontoon machines, it is only an idea.

Figure 30: Ford model of a snow blower [photo: Gabriaella Eliasson, 2016-2017]

Summary of aquatic substrates collection techniques

Despite a number of available algae collection methods tested in Trelleborg Municipality, many factors still influence the collection process:

- There is a need to examine and inspect every beach sediment bottom for some techniques prior to collection (large and small beach cleaners).
- If the loading capacity of the machines is not sufficient, this will lead to too many additional unloadings, and therefore, may become financially unsustainable. Therefore, most of the proposed prototypes require a change/modification to handle the large quantity of algae collected from the coastal area of Trelleborg Municipality.
- The salt in the sea water can affect the machines by corrosion and thus, can shorten their life expectancy. Periodic washing and checking of parts are required.
- No technique can deliver a substrate that is 100% clear of sand. The sand does not affect the biogas process, but it can cause wear on the equipment required for large-scale digestion and it builds up a depot in the digester reducing the available volume and therefore, the gas potential. It can also clog pumps and pipes.

For the particular case in the pilot Smyge Biogas Plant mostly two types of techniques were tested for harvesting and collection of algae: grip-claw loader with dumper and a Truxor. The future idea is also to use a modified version of snow blower 'catamaran collector' and algae should be preferable collected in the shallow water near the coastline to reduce sand contamination.

Moreover, despite the broadly presented seaweed/algae collection methods from the shore, or in the open sea, the implementers of the COASTAL Biogas project aims to harvest seaweed/algae that were cast to beaches by storms and currents. Additionally, not every described collection technique is allowed in each Baltic country. Thus, extensive description of seaweed/algae collection technologies will enable stakeholders to choose the most appropriate technology following the regulations of their country.

2.3. Storage methods of collected maritime substrate

For large amounts of collected aquatic biomass, storage could be required in order to ensure a continuous supply of material for digestion throughout the year. Consequently, some different methods for the storage of algae might be as follows [24]:

1. **Silage** - Silage means that lactic acid bacteria ferment the sugars of the material to form lactic acid in an oxygen free (anaerobic) environment. A rapid and vigorous lactic fermentation is of great importance for achieving good silage results. Good conditions for this are created by processing the biomass mechanically so that the cells are broken up. This provides lactic acid bacteria with access to the nutrition they need, and they quickly start to grow. Production of lactic acid decreases the pH, which prevents the growth of undesirable microorganisms. In this way, a crop is preserved and its energy and nutrients are recovered in a subsequent treatment process, such as anaerobic digestion for biogas production. A good ensiling process requires a sufficiently low pH (<4.2), an oxygen-free environment, the presence of lactic acid bacteria, available nutrients (sugars) and moderate humidity.
2. **Silage in Bunker Silos** - The bunker silo is the most common structure/silo for silage from a global perspective. The bunker silo can be adapted to many different conditions by adaptations of the design. What is needed is a structure with a base and three walls. A bunker silo can be located above the surface or buried. Silo caps/covers are used to prevent rain water from entering the silage. Care must be taken to ensure the silage is protected, for example, any sand used as a

weight on top of the plastic silage cover could be washed away, especially in winter and can thus expose the silage to rain. To succeed with silage in a bunker silo requires good packing and good coverage, in addition to basic requirements such as clean crops, enough good lactic acid bacteria and enough carbohydrates. Also, the crop should be chopped precisely to facilitate packing, speed up the fermentation and give a smooth surface on the removal of the silage. The bunker silo is an ideal silage storage technology and one of its main benefits is that it preserves large quantities of material. Disadvantages of ensiling algae in a bunker silo may be the low Total Solids (TS) levels (between 10-20%) in the material. This probably leads to a lot of pressure water (the hydrostatic pressures occurring when the silage became saturated with silage juice) being formed. Therefore, the construction of the silos and the handling of the material need to be adapted accordingly. To get a good ensiling process, the bunker silo also requires the material to be chopped up beforehand.

3. **Round Bale Silage** - The material needs to be placed in lines in a field, then with the use of a round baler, which has a capacity of about 20 bales per hour, round bales are formed and sealed with 12-13 layers of stretch film (silage plastic). The bales produced are usually about 160 cm high and weigh about 150 kg. A round baler is not as sensitive to sand pressure as a square baler. This also makes it suitable for crops with low TS (algae have TS of 15-20%). For the round bale, material, once baled, is held together with nets on the outside, which is also suitable for materials such as algae. Advantages of this technique include that the material can be stored for a long time and that both transport and storage are simple and cost effective. Additionally, the nutritional value of the material, and thus biogas potential, is maintained. The main disadvantage of the round baling method is that some form of thinning of the material is needed before ensiling. This is because the round baler is unable to process stones and other hard objects that are likely to exist in the collected algae material.
4. **Silage in Tower Silos** - Silage in a tower silo is usually made by the chopped crop being tipped on to a feeder table, which transports the crop to a fan. The fan then blows the crop up into the silo. No compaction of the crop is needed in the silo as the crop's weight is considered to be sufficient for a high degree of compaction to be achieved. The tower silo is probably the least labour-intensive system of silage management. Much of the movement, done by tractor and front loader in other systems, has been automated in tower silos.
5. **Silage in a Bag/Tube** - The technique consists of the chopped crop being packed tightly in a "tunnel" of silage plastic and combines some advantages of large bales and bunker silos. The fermentation of silage may be faster in the tube than in silage in a bunker silo or tower silo. In addition, this technology is also used for several types of crops. Since it does not require permanent structures in the form of silos, but only a paved surface, this is a cost-effective way to ensile [26]. Silage in the "tube" has consistently better values on several of the parameters usually used in the assessment of silage quality, such as pH value and concentrations of ammonia and butane diol. However, it is recommended that the TS content of the material should be approximately 30-40%, which is not the case for algae and seaweed.

2.4. Pre-treatment of collected maritime substrates

Prior to anaerobic digestion and algae mixing with other organics, it has to be pre-treated by removing sand and other coarse particles to as high a level as possible. This can be done mechanically by washing algae while collecting on shore or in the sea. Another pre-treatment solution is a sieve, which removes the sand (Figure 31). This method was also tested in Smyge Pilot Biogas Plant at Trelleborg Municipality. The sand fraction in the stored algae accounted for up to 80% of the volume. Sieves with different mesh sizes were tested. It was found that the optimal size dimension was 20 mm. The algae were treated twice through the sieve, but still, a small portion of sand was left in the algae fraction. It was estimated that about 90% of the sand fraction was reduced from the algae fraction with this pre-treatment method. The disadvantage of this pre-treatment is that there is still some sand left in the algae fraction and, of course, costs related to this pre-treatment are also important, if several cleaning cycles are necessary.

Figure 31: Pre-treatment of algae with a sieve [photo: Gabriaella Eliasson, 2016-2017]

Some thermal and/or chemical pre-treatment with further pulping to fluidise the fibrous matter may also be required.
The cost of collection, pre-treatment using the loader with a fork catcher in the front, and transportation of 15 km distance using a tractor with an attached wagon are estimated at 8.22 EUR/m^3 of algae mass [23].

2.5. Anaerobic digestion and biogas production

From the obtained results of earlier studies in Smyge [23], where algae were used as a biogas substrate, the process sometimes was unstable and measured sulphide caused a chemical dosage of iron chloride. Therefore, in order to reach process stability without adding chemicals while producing biogas from aquatic biomass substrates, to raise the gas exchange potential and the biogas production, the algae biomass was investigated to be co-digested with different decay products from the surroundings in the municipality of Trelleborg. Rejected tomatoes from the food industry, harvested grass from the municipality, horse manure and sugar beet residues were used as substrates in this project. Co-digestion of macroalgae with other organic substrates (manure, straw, grass, etc.) might also be needed to support the activity of microorganisms in the anaerobic decomposition process by reaching/increasing a proper C/N ratio [27]. Another option for co-digestion on a large scale is to mix macroalgae with a reed that is a very common species in wetland biomass and grows along the beaches of nutrient-rich lakes. Until recently, big investments have been made for the construction of new and restoration of existing wetlands in Trelleborg with the purpose to reduce the nutrients (N and P) inflow from arable land into the Baltic Sea [25].

The start-up of the biogas process in the Smyge Pilot Biogas Plant took about two months, and after two pH adjustments, the digestion process was stable through the whole project time from July 2016 to April 2017. The tests were separated into 3 stages, where 3 different batches of algae were used:

- For the 1st (start-up) batch, 50% of algae that had been stored for 8 months was used together with 50% ensilage received from Jordberga biogas plant, Sweden. Digestate volume exceeded 35 m^3. Since the mixture of organic material loaded in the start-up process was deliberately low and the sand content was high, the production of biogas was very low and is barely visible in Figures 32 and 33 from the period of July to October 2016. After the digestion process was over, the hydrolisation tank was emptied, and the digestate was analysed.
- The 2nd batch with a volume of 105 m^3 was loaded with pre-treated stored algae (the algae were the same as in the 1st batch, but this time the algae were twice sifted through a sieve to reduce sand content in it) and a mixture of residues from tomato industry in Trelleborg, harvested grass from the park department in the municipality of Trelleborg and small amounts of horse manure from horse farms in the surroundings of Trelleborg. The process started directly after loading (October 2016) and was stable, running with a high methane content of 70 %. The mix in this batch study showed a more immediate biogas production and was much higher compared to the first batch. According to Figure 32, gas was delivered from November 2016 until the end of December 2016.
- The 3rd batch was loaded in January 2017. A mixture of fresh algae, chopped sugar beets and stored harvested grass from the municipality was used. The digested volume was 110 m^3. The mixture of substrates was successful and processed for more than four months. The methane content was high and the process was stable during the whole period of digestion. The biogas production was high with a peak in March, a decline in April and finally stopped at the beginning of May 2017.

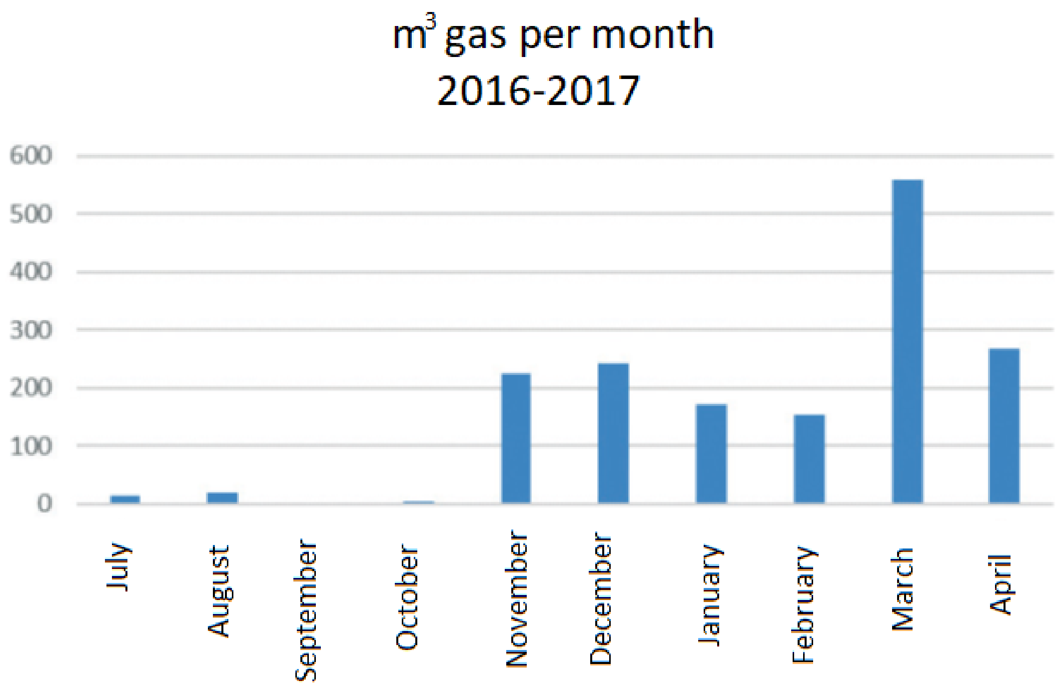


Figure 32: Biogas production during the project time [24]

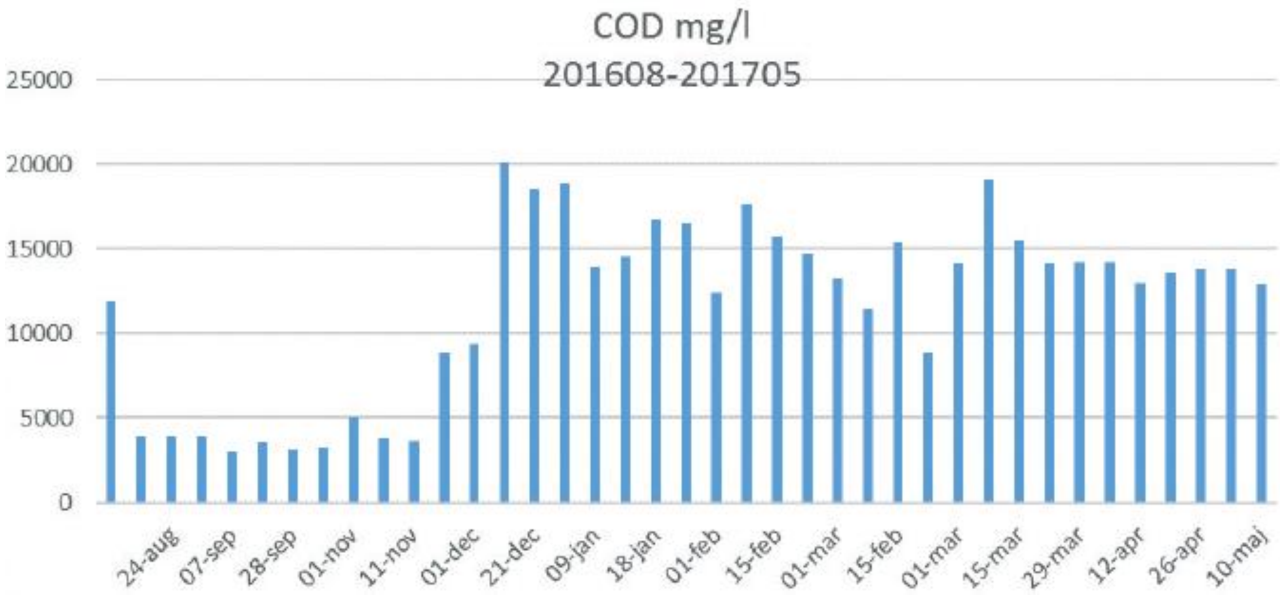


Figure 33: COD-content during the test time [23]

The biogas production studies at Smyge indicated that algae co-digested with easily degradable organic material resulted in a stable process with a high methane content (around 70%) and a high biogas production. No sulphides or smell were detected, and no chemicals were added [23].

As the whole amount of algae collected from the southern coast of Sweden could result in a maximum of 103 GWh/year, it is obvious that algae are going to be co-digested with other raw materials. In order to dilute the substrate, reach a proper C/N ratio to support the digestion and gain higher yields of biogas, algae should be co-digested with manure on a small-scale and wetland biomass, crops and household wastes in case of large-scale scenario [27]. Earlier co-digestion [28, 29] of macroalgae with manure and wetland biomass was experimentally tested for utilisation at the biogas plant. Results of co-digestion of macroalgae in combination with cow manure on the laboratory scale proved the viability of such a scenario with biogas yield in the range of 0.14–0.25 Nm^3 CH_4/kg VS.

The biogas yield from anaerobic digestion of macroalgae also depends on the type of algae, their organic content, the period of harvest and pre-treatment method. It is worth mentioning that laboratory experiments that were performed with the aim to investigate the potential of macroalgae as a substrate for biogas production are mainly focussed on one specific type of algae and not on their mixture as in the case of harvesting from the beaches [27].

2.6. Digestate

In the WAB project [25] digestate was not used as a fertiliser but only considered as a possibility due to its high values of ammonium (N) and potassium (K) after anaerobic digestion. In his thesis, O. Tatarchenko [27] stated that the digestate from anaerobic digestion of macroalgae has a good potential as fertiliser in terms of nutrient contents. However, the content of heavy metals, especially cadmium (Cd), can limit the utilisation of digestate on arable lands.

In the case of small-scale biogas production, the digestate is not treated for Cd removal and is used as a soil improver on energy forest plantation [27]. In this case, the digestate is subjected to standard treatment procedure such as dewatering. This is done to facilitate transportation as the residue

after anaerobic digestion has only 20% of dry matter, which makes it sticky. After dewatering, both liquid and solid fractions of digestate are used as a soil improver [27].
The whole digestate from the large-scale plant is used as organic fertiliser and spread on arable land. As far as algae are treated before digestion and heavy metals are removed, there will be no harm of using the digestate as organic fertiliser. As in the small-scale case, the digestate in this scenario is also dewatered using a screw-press or a centrifuge [27].
In order to make it safe for application on arable land, macroalgae should be treated for Cd removal before the digestion. The laboratory experiments of Cd removal from algae showed that ion exchange and adsorption could also be applied, resulting in a reduction of the Cd content of 94 to 95% m^3/TS [27, 30].
In Smyge pilot biogas plant digestate was indeed used as a fertiliser. Each of the three batches was investigated for their elemental composition and transported to a local farmer. The key elements concentrations are listed below in Table 7.

Table 7: Nutrient composition of digestate delivered to farm land [23]

Batch	m^3/TS	Nitrogen N, kg	Potassium K, kg	Phosphoros P, kg	Cadmium Cd, mg/kg TS	Cd/P, mgCd/kgP
Digestate 1	35/14.0	220	39	5	1.7	1666
Digestate 2	105/20.9	1317	1646	329	0.2	13.3
Digestate 3	110/50.6	837	483	873	0.5	31.9

The digestate of the 1st batch, in total 35 m^3, was transported to the farmer and had a content of 220 kg N, 39 kg K and 5 kg P and Cd content of 1.7 mg/kg TS. Since the cadmium and sand content was high, the digestate was composted together with manure and straw [23].
The digestate of the 2nd batch, in total 105 m^3, was transported to farm land with a content of 1317 kg N, 1646 kg K, 329 kg P, and a low Cd content of 0.20 mg/kg TS [23].
The digestate of the 3rd batch, in total 110 m^3, was transported to farm land with a content of 837 kg N, 483 kg K and 46 kg P. The cadmium content was 0.50 mg/kg TS [23].
The ratio of Cd/P, which shows the extraction of Cd relative to P, is different in the three batches caused mainly by different concentrations in the algae but also by the mix of the substrate. Cadmium is a naturally occurring, non-nutritive metal found in soil and minerals. Its persistence in the environment and its uptake and accumulation in the food chain makes Cd a public health concern.

Concluding remarks

The Solrød biogas plant

Since the Solrød biogas plant is the only known industrial scale plant where maritime biomass (cast seaweed) is used as a feedstock material for biogas production, this makes the plant attractive in terms of solving not only local community problems (bad odour, untidy beaches, dissatisfied tourists, decreased property value, etc.), but this also strongly contributes to closing nutrients (N, P) cycles, thus reducing eutrophication in the Baltic Sea region. Therefore, the experience obtained in Solrød is a good practice sharing knowledge with other communities and countries about the whole aquatic biomass handling chain in the most sustainable and economical way.

The Smyge pilot biogas plant

The conclusion after algae processing to biogas in the anaerobic digestion process at Smyge is that maritime substrate should be co-digested with other organic substrates to maintain a continuous and stable process. Also, maritime feedstock should be free of sand and preferably collected in the shallow water near the coastline. Recirculation of nutrients back to arable land from the sea closes nutrient cycles.

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