COASTAL BIOGAS

Cluster **O**n **A**naerobic digestion environmental **S**ervices and nu**T**rients remov**AL**

Report on case studies including feasibility studies and ecosystem services benefits

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Preface

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Authors

Patrycja Makoś-Chełstowska, Gdańsk University of Technology, Poland
Konrad Smolarczyk, Gdańsk University of Technology, Poland
Robert Aranowski, Gdańsk University of Technology, Poland
Iwona Cichowska-Kopczyńska, Gdańsk University of Technology, Poland
Karolina Kądziela, Gdańsk University of Technology, Poland

Project partners:

1. Agency for Renewable Resources (FNR), Germany – project coordinator
2. Gdansk University of Technology (GUT), Poland – project partner
3. Baltic Energy Innovation Centre (BEIC), Sweden – project partner
4. Roskilde University (RUC), Denmark – project partner
5. University of Rostock (UROS), Germany – project partner
6. Lithuanian Energy Institute (LEI), Lithuania – project partner

Summary

Eutrophication threatens the flora and fauna of the Baltic Sea. It has environmental, social and economic consequences. The use of cast seaweed in an anaerobic digestion process offers many opportunities of particular relevance to the Baltic Sea region as it transforms a natural resource, often considered a waste, into a high quality renewable fuel and natural fertiliser (digestate), enabling the recovery of nutrients from the water and resulting in the mitigation of eutrophication. This solution can contribute to the transition to a circular bioeconomy and can bring many economic, social and environmental advantages. The report discusses the current state and feasibility of using algae for nutrients removal and related ecosystem services benefits. The potential of marine biomass has been analysed in each partner country. Feasibility studies of selected cases on existing and new biogas plants in the partner countries and the possible use of cast seaweed including collection, pre-treatment and use in commercial biogas plans is presented within the report.

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Introduction

Due to the inflow of huge amounts of nutrients, mainly of agricultural origin the quality of water deteriorates. The intensification of agriculture results in use of larger and often excessive doses of mineral fertilisers in order to provide higher yields. However, crops are not able to absorb such amounts of nutrients, so the excess nitrogen in the form of nitrates, nitrites and ammonium and phosphorus, mainly phosphates flow to river waters and further to the seas. This is especially harmful to the closed seas with big inflows, like for example Baltic Sea. The over fertilisation of surface waters results in explosive growth of algae, which causes disruptive changes to the biological equilibrium (including fish deaths). This is true both for inland waters (ditches, rivers and lakes) as well as for coastal waters.

The proposal in the COSTAL Biogas project (Cluster On Anaerobic digestion, environmental Services and nuTrients removal) is to utilise seaweed and algae to fertilise soil in order to contribute to reducing the demand of artificial fertilisers, while simultaneously decreasing the eutrophication problem in the Baltic Sea.

The goal of this report is to provide a comprehensive overview on the feasibility, potential and benefits of the anaerobic digestion process as a way to utilise huge amounts of seaweed. Furthermore, methods of processing marine plants to obtain biogas and, above all, a solution to recover nutrients from the water and transfer them to land, thus contributing to the reduction of eutrophication problem, are part of the report.

1. Policy and frameworks

The energy sector is strongly dependent on the policy frameworks. Decision-making processes are based on strict procedures, principles and specified goals. In the following section, the legal framework conditions in each project partner country are presented. They are discussed in regard to several areas that affect the feasibility of the solutions covered by the project.

1.1. Legal framework for the energy sector in Poland

1.1.1. The Energy Policy of Poland until 2040

The Energy Policy of Poland until 2040 (EPP 2040) was issued by the Ministry of Economy and focuses on improving energy security, efficiency and competitiveness.

In the EPP 2040 in the field of renewable energy sources (RES), Poland declares:

- 15% share of renewable energy sources in final energy consumption in 2020,
- 10% market share of biofuels in transport fuels in 2020 and 14% in 2030, while striving to make greater use of second-generation biofuels,
- reaching a 21% share of renewable energy in the total energy consumption in 2030,
- protection of forests against excessive exploitation, in order to acquire biomass and sustainable use of agricultural areas for RES purposes,
- support for RES development (while ensuring network safety),

- reduction of CO_2 emissions by 30% by 2030 [1].

Figure 1 demonstrates the forecast structure of the coverage of demand for electricity production by the electric power sector as a result of the implementation of EPP 2040.

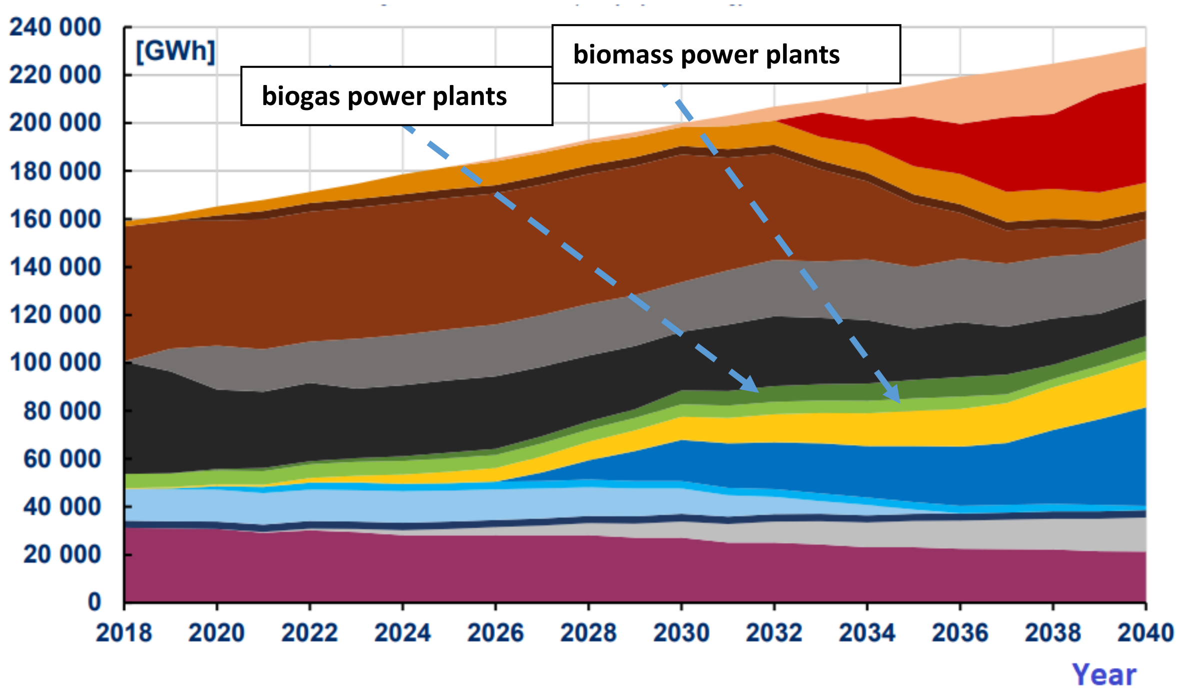

Figure 1 Electricity generation by technology until 2040 [1]

black – optimal use of own energy resources, red- development of the electricity generation and transmission infrastructure, orange- diversification of gas and oil supply and network infrastructure development, yellow- development of energy markets, gray- launch of nuclear energy, green- development of renewable energy sources, blue- development of heating and cogeneration, violet- improving energy efficiency of the economy.

1.1.2. Directions for the development of agricultural biogas plants in Poland for 2010 – 2020

This document defines several goals and effects of biogas plant development:

- building 2000 installations producing agricultural biogas;
- developing preliminary changes in the law to facilitate the construction of biogas installations,
- supporting financing as well as educational programmes;
- increasing the supply of renewable energy carriers produced from national resources, i.e. wind, solar, aero-thermal, geothermal, hydrothermal, wave, sea currents, river, biomass etc.,
- increasing the share of agricultural biogas as a transport fuel;
- increasing employment in the local communities and economic entities of the agriculture and RES energy industries;
- improving the energy infrastructure;
- generating significant heat and power energy from renewable resources;
- acquiring significant quantities of environmentally friendly, high quality, organic fertilisers as post-fermentation substrate waste of agricultural origin;

- acquiring significant quantities of organic fertilisers as post-fermentation substrate waste of agricultural origin.

1.1.3. National Action Plan for renewable energy

The National Action Plan is a strategic document developed by all EU member states, characterised by ways to achieve the quantitative objectives set out in the EU climate and energy package. The National Action Plan indicates further directions of legislative work, aimed at a more efficient use of biomass resources in the form of waste from agricultural production, food, sewage sludge and the service sector. Tables 1 and 2 present assumptions regarding the expected contribution of energy from individual technologies, to the overall energy balance (from 2018 to 2020), for electricity and heating [2].

Table 1 Forecast of power demand and production of electricity from RES up to 2020.

	2018	2019	2020
Installed Power [MW]	480	730	980
Energy production [GWh]	1968	2993	4018

Table 2 Forecast of energy production from RES in heating and cooling up to 2020.

	2018	2019	2020
Energy production [kt_{oe}]	364	408	453

1.2. Legal framework for the energy sector in Denmark

The most important framework for the energy sector was developed in 1996. The Energy Action Plan “Energy 21” includes medium and long-term scenarios until 2005, 2020 and 2030. The basic assumptions for the scenarios included a doubling of biogas production between 1996 (2.2 PJ) and 2000, and a further doubling before 2005. The new Energy Agreement for the period 2020-30 was prepared in 2017.

Currently, the government’s energy and climate goals are the following [3]:

- In 2030 Denmark will meet at least 50% of its energy needs with renewable energy;
- In 2030 coal will be completely phased out of electricity production;
- In 2050 Denmark will be a low-emission society and independent of fossil fuels;
- Renewable energy must account for 20% of the EU’s energy consumption (Danish target at 30%);
- Increase in energy efficiency by 20% for the whole of EU (The annual Danish target is to save 1.5% of energy consumption);
- The EU must reduce carbon dioxide emissions by at least 40% by 2030;
- The EU must reduce total emissions in the EU’s quota trading system by 43% in 2030, compared to 2005;
- By 2030, Denmark must reduce emissions in the non-quota sectors by 39% compared to 2005.

1.3. Legal framework for the energy sector in Germany

In Germany, energy regulation is mainly subject to the Energy Industry Act (Energiewirtschaftsgesetz – hereinafter “EnWG"), which is Federal Law. Renewable energy sources are favoured under the Renewable Energy Act of 29 March 2000 and the Combined Heat and Power Act of 12 May 2000. According to § 3 of the Renewable Energy Act, grid owners are obliged to access energy suppliers producing energy exclusively by water, wind, solar, geothermal, natural gas, marsh gas or biomass and to purchase the electricity generated in such plants at certain minimum rates as provided for in § 4 - 8 Renewable Energy Act [4].

In Mecklenburg-Western Pomerania, the Climate Action Plan of March 2010 formulated the targets for the use of bioenergy by the year 2020 (Potenzialatlas_Bioenergie_Mecklenburg-Vorpommern 2013). Bioenergy can provide electricity, heat and fuel. As an economical engine for the region, it is very lucrative. The federal states support this development with funding programmers.

According to the federal government’s energy policy, by 2025 the renewable energy share of electricity generation should be between 40% and 45%. By 2035, renewable energies should have a share between 55% and 60%, and at least 80% by 2050. These targets have been included within the Renewable Energies Act and therefore, are legally binding on the government [5].

1.4. Legal framework for the energy sector in Sweden

The main regulatory body for the Swedish energy markets is the Swedish Energy Markets Inspectorate (the Inspectorate), an authority under the Ministry of Enterprise, Energy and Communications. A climate and energy policy was adopted by the Swedish parliament in 2009. It set a target for the consumption of energy from renewable sources, which by 2020 should account for at least 50% of total energy consumption, as compared to the 20% target that applies at the EU level. In 2045, Sweden shall have no net emissions of greenhouse gases and will thereafter achieve negative emissions. The goal in 2040 is 100% renewable electricity production.

In Sweden, there is a program supporting investments that produce biogas. The payment can amount to 40% in investment aid, and in northern Sweden, the aid may be as much as 40% in certain cases. The investment aid is a part of the Rural Development Programme 2014–2020. The Swedish government introduced also special support for gas from manure, a methane reduction compensation [6].

1.5. Legal framework for the energy sector in Lithuania

The Lithuanian Law on Energy from Renewable Sources entered into force on 12 May 2011. The Law establishes the legal framework for administration, regulation and control over the renewable energy sector in Lithuania. The Law sets following mandatory energy targets to be achieved by 2020:

- 20% of gross annual energy consumption must come from renewable sources;
- at least 20% of energy consumption in transport sector must be sources from renewables;
- 60% of district heating energy must be derived from renewable sources.

Lithuania supports initiatives to increase the use of biomass in heat production (both by installing bio-boilers and constructing bio-combined heat and power (CHP) facilities) and promotes the use of waste for heat production. The goal is to enable renewable energy to account for 60% of centralised heat production by 2020 [7].

1.6. EU Renewable Energy Directive

The original Renewable Energy Directive (2009/28/EC) established a set target of 20% total energy consumption from renewable sources by 2020 [8]. However, the European Union recently introduced a new renewable energy directive (2018/2001), which established a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023. The directive is part of the clean energy for all Europeans package, aimed at establishing a new stable legislative framework, which will facilitate the clean energy transition and help the EU to meet its Paris Agreement commitments on reducing greenhouse gas emissions [9].

1.7. Environmental protection regulations

In order to obtain full benefits from the proposed solutions, it is necessary to develop a common position in the field of legal regulations. Environmental laws, including marine, coastal and coastal environments, differ in each country and are presented in this section.

POLAND

In Poland, a large part of the coastal area is located in the protected area Natura 2000. The legal act regulating the functioning of the Natura 2000 network in Poland is the Nature Protection Act of 16 April 2004 (Dz.U. z 2004 r. Nr 92, poz. 880). According to this act, the Natura 2000 does not apply any specific list of prohibitions. The construction of new biogas plants on Natura 2000 sites may involve the need to prepare an environmental assessment report. Depending on the type of the Natura 2000 site, responsible for functioning are:

- the director of the national park where the Natura 2000 site overlaps with the park area;
- the director of the maritime office – in marine areas outside national parks;
- the regional director of environmental protection – in land areas outside national parks.

Directors of maritime offices perform the supervision of marine areas outside the borders of national parks.

DENMARK

The main relevant policies in force in Denmark are Natura 2000, the Danish Marine Strategy and Coastal Protection Act.

GERMANY

In Germany, the Federal Nature Conservation Act (Gesetz über Naturschutz und Landschaftspflege BNatSCHG, 2009) and Flora-Fauna-Habitat Directive (92/43/EEC) deal with nature protection.

SWEDEN

Normally, permission to clear seaweed within nature reserves or national parks is not granted from the county administrative board, but in some cases, exceptions are granted. In Vellinge municipality, for example, all bathing beaches are located within nature reserves, but seaweed cleaning may still be carried out.

LITHUANIA

According to Lithuanian hygiene standard HN 92:2018 "Beaches and Bathing Water Quality" approved by the Order of the Minister of Health, macro-algae and (or) phytoplankton on the beaches and bathing areas need monitoring and removal from bathing areas after each storm. Further management of marine biomass is not covered in any legal act.

1.8. Post-fermentation waste management

POLAND

Detailed conditions for the use of post-fermentation sludge are described in the Waste Act of 27 April 2001 (j.t. Dz.U. z 2007 r. Nr 39, poz. 251, z późn.zm.) and the Act on fertilisers and fertilisation of 10 July 2007 (Dz.U. Nr 147, poz. 1033). Post-fermentation residue has parameters that enable its use as a natural fertiliser, however, biogas plant owners can only apply post-ferment residuals to their own fields. Currently, there is no possibility to sale post-fermentation sludge as fertiliser to other farmers. In the Act on fertilisers and fertilisation, post-fermentation material is not included in the definition of manure. The introduction of post-fermentation material as a fertiliser on the market requires obtaining the consent of the minister competent for agriculture and is associated with the implementation of the attestation procedure. According to the definition in the Act on waste, biogas plants are installations for waste recovery. Therefore, it imposes an obligation on the investor to obtain a permit for recovery and generation of waste.

DENMARK

Baltic Sea Action Plan and EU Nitrates Directives allow to use digestate as fertiliser. However, these documents do not contain specific information on the use of seaweeds digestate as fertiliser. Seaweeds can be used as fertiliser as long as they do not contain heavy metals and comply with basic parameters set out in the Fertiliser Act.

GERMANY

It is advantageous to use the digestate as fertiliser. However, it is essential to carry out a fertiliser application in accordance with the requirements of the Fertilisers Ordinance (DüMV) and the Fertilisation Ordinance (DüV). In accordance with federal and state regulations, no landfill of fermentation residues from biogas plants in which only conventional substrates are fermented is permitted on areas of organic farming [10]. Accordingly, only such areas of conventional agriculture are available for using digestate as fertiliser.

SWEDEN

Baltic Sea Action Plan and EU Nitrates Directives allows the use of digestate as fertiliser. However, these documents do not contain specific information on the use of seaweeds digestate as fertiliser. Seaweeds can be used as fertiliser as long as they do not contain heavy metals, comply with basic parameters set out in the Fertiliser Act and the digestate must be certified.

LITHUANIA

National law allows digestate to be used as fertiliser, but not from seaweeds.

2. Market analysis

In addition to meeting legal requirements, the solutions developed by the project are justified to be implemented in the regions where there is a market and social need. Resources and possibilities are further discussed.

2.1. Region potential

POLAND

The total length of the coast in Poland is 770 km (Figure 2). This length takes into account the Vistula and Szczecin Lagoon as well as the Gdansk and Puck Gulf. However, the total length of the coast without protected areas is 410 km. Sandy beaches dominate the Polish shore. Stony beaches, which are common in other European countries, cannot be found. The width of the beaches does not exceed 100 m, and their total area is 20 km^2. Beach sand mainly consists of small grains of quartz with a diameter of 0.1-2 mm. They are often covered with minerals, *i.e.* magnetite, ilmenite, rutile, monocyte, and even semi-precious grenades and zirconium. There are also single igneous rocks (containing granites, porphyrites, and basalts) or sedimentary rocks (limestones and red pisses).

Figure 2 The length of Polish borders.

DENMARK

The total length of the coastal in Denmark is 8,750 km of which almost 1,800 km are protected.

GERMANY

The German Baltic Sea Coast measures 2,582 km in total, of which 1,945 km belong to the federal state of Mecklenburg-Western Pomerania. This coastline can be divided into inner and outer coastline as well as into flat coast and steep coast (see Figure 3). 60% of the Mecklenburg-Western Pomeranian coast belong to a multitude of islands – the four largest ones are Rügen, Usedom, Hiddensee and Poel. According to the EU Water Framework Directive (WFD) and the implementation of its requirements at federal and state level, a direct access to the shore at the German Baltic Sea area is due to nature protection only possible on limited stretches of beaches or harbors. Only 309 km of its outer coast are reported as tourism beaches [13]. These beaches also have a good infrastructural connection and are therefore suitable areas for a removal of seaweed.

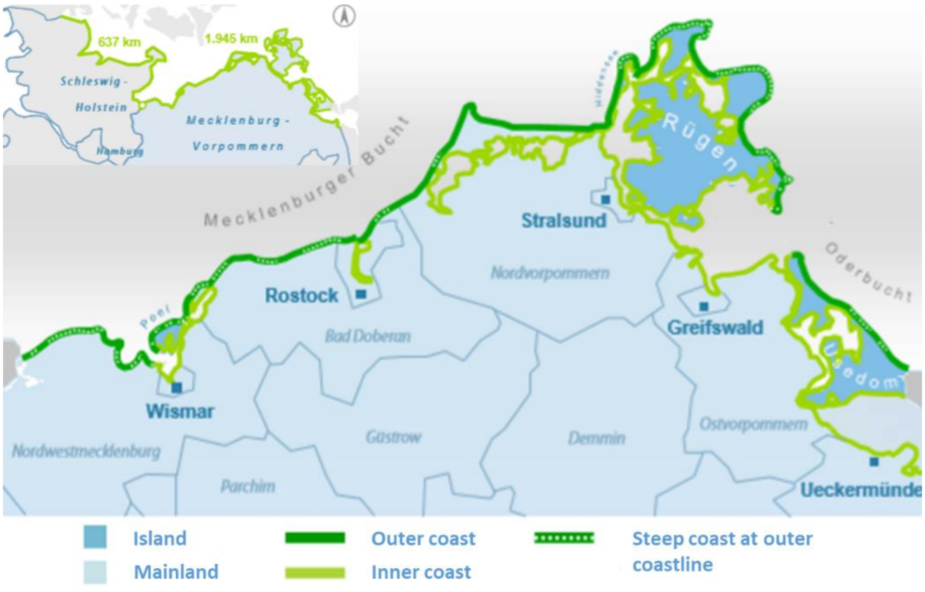

Figure 3: Coastline of Mecklenburg-Western Pomerania, Germany [12]

SWEDEN

Sweden is located in Northern Europe, in the eastern part of the Scandinavian Peninsula. The eastern and southern coasts of Sweden lie at the Baltic Sea (approx. 2,150 km). There are vast archipelagos (over 220,000 islands) in the southeast of Sweden. Marine and coastal biotope complexes along the Swedish South Baltic coast mainly consist of rocky coasts and cliffs, sandy and moraine coasts, bays and lagoons. The sandy coasts are especially characteristic to Skåne (east coast and the southeastern part), to the coasts of large islands in the Baltic Sea (Öland and Gotland) and to archipelagos along several parts of the coast. In Sweden, the potential for cast seaweed in Scania (the southernmost province in Sweden) was estimated to 83,106 tons/year, or rather 63,628 tons/year when excluding nature reserves and natural parks. This assessment was performed using extrapolation of existing data, since not every municipality had available data.

LITHUANIA

The study area is located on the west of Lithuania and encompasses the eastern coast of the Baltic Sea. The Lithuanian Baltic coast relief consists of a sandy plain, which has emerged from the seabed when its coastline/shore has retreated, i.e. when Lithuanian coast has lifted. At present, the coastline of Lithuania, including the Baltic Sea coast of Curonian Spit, consists of sandy or pebble beach stretches. Lithuania has around 91.1 km long coastline of the Baltic Sea. It consists of the continental coast (from the Latvia – Lithuania border in the north of Lithuania to the northern breakwater of Klaipėda Harbour entrance), which stretches around 38.7 km, and the Curonian Spit coast (from the southern breakwater of Klaipėda Harbour entrance to the border with Kaliningrad Oblast, Russia in the south), which stretches around 51.4 km. The Curonian Spit (from 0.4 km to 4.0 km width) almost cuts off the Curonian Lagoon from the Baltic Sea. The Klaipėda Strait connects the Curonian Lagoon with the Baltic Sea. The distance between the continental coast and the coast of Curonian Spit is around 1 km. The total area of sandy beaches of the Lithuanian coastal zone is around 10.6 km^2. The area of beaches of continental coast is around 3.6 km^2, whereas the area of the beaches of Baltic Sea coast in Curonian Spit measures around 7.0 km^2. The width of beaches varies from 16 to 500 m. The average width in the continental zone is around 92 m, while in the Curonian Spit it is 136 m.

Table 3 List of basic information about the coastal region in individual countries

Parameter	Poland	Denmark	Germany	Sweden	Lithuania
Total length of the coast	770 km	8750 km	2582 km	3400 km	122 km
Length of the coast without protected areas	410 km	-	309 km	-	95 km
Type of beaches	sandy beaches	sandy and stony beaches	sandy and stony beaches	sandy and stony beaches	sandy and pebble beach
Width of the beaches	>100 m	-	-	-	16-500 m

2.2. Resources potential

2.2.1. Types of seaweed

POLAND

The seaweed collected from Polish beaches consists of 22-75% of green algae, 17–71% of red algae and 0–50% of brown algae as well as a small proportion of seagrass - *Zostera marina* (Figure 4). Among the algae present on the Polish coast, the following species can be identified:

- Green algae: *Cladophora glomerata, Enteromorpha spp., Ulotrix spp., Stigeoclonium spp., Ulva flexuosa, Ulva clathrata,*
- Brown algae: Pilayella littoralis, Ectocarpus spp.,
- Red algae: *Ceramium spp., Polysiphonia fucoides, Phyllophora brodiaei.*

Figure 4 Seaweed at coastal line in Poland [11].

DENMARK

The Solrød biogas plant receives seaweed (Figure 5), which consists of two types [1,2]:

- <u>Green seaweed:</u> eelgrass (*Zostera marina*)
- <u>Brown seaweed:</u> *Pilayella littoralis, Ectocarpus spp.*

Figure 5 Seaweed at coastal line in Solrød municipality [16].

GERMANY

The seaweed meadows of the German Baltic Coast are populated mainly by green seaweed eelgrass (*Zostera marina*), but *Fucus* species can also be found washed ashore. The seaweed provides many services for the ecosystem. Their roots serve as natural erosion protection for the sediment. Furthermore, they are of high importance as a food and breeding habitat for a number of animals and they can absorb excess nutrients [17-18].

SWEDEN

Macro algae are very common along the coast of Skåne and usually occur in three groups: green, brown, and red algae. Algae are usually associated with the negative algal bloom, but they also have an important role in the ecosystem. Bladder wrack (*Fucus vesiculosus*) is naturally found in the Baltic Sea and, due to its size, contributes to creating complex bottom structures that function as nursery for many of the sea animals. Eelgrass (*Zostera marina*), which is not an algae but a seed plant, also occurs in abundant amounts on sand bottoms along certain stretches along the coast of Skåne.

LITHUANIA

At the Lithuanian Baltic Sea coast, the following algae species occur:

- Green algae: *Cladophora sp.*
- Brown algae: *Fucus vesiculosus*
- Red algae: *Furcellaria lumbricalis*

2.2.2. Seaweed collection dates and its quantities

POLAND

In Poland, seaweed can be collected from May to October. However, the largest amount of seaweed on the beaches is observed in August. Currently, cast seaweeds are collected from beaches in all cities in Poland exclusively for clearing them.

Due to the lack of biogas plants producing biogas from seaweed, there is no accurate information on the amount of seaweed collected from Polish beaches. According to MOSiR (Gdańsk, Gdynia, Sopot) it is possible to collect 180-796 tons of fresh mass from beaches and up to 700 tons (Zakład Oczyszczania Miasta 2010) from the sea during one season.

IO PAN estimated this number at 220-440 tons per season. The average value for seaweed collected from beaches is 550 tons/season, from city beaches in Gdansk, Gdynia and Sopot. There is no information on the amount of algae collected from other beaches in Poland. It can be estimated that approximately 9,500 tons/year of algae can be collected from Polish beaches.

DENMARK

Until 2016, the collection of seaweed along the Køge Bay coastal line in Solrød municipality (Figure 5) due to the environmental permit was performed three times per year from 1 May to 1 September by Solrød strand Beach Cleaning Laug. The collections approximately lasted one week each and took place around the dates that are presented in Table 3. Since 2016, the collection of cast seaweed can proceed continuously during the whole year except for several cases, such as bad weather conditions and/or too high concentration of cadmium (>0.8 mg/kg dry matter) in the collected seaweed [3–5]].

Figure 6 Seaweed collection area in Solrød municipality [4].

Table 4 Typical collection dates for cast seaweed in Solrød municipality [3].

Collection	*Dates*
1st	From 1 of June to 23 June
2nd	From 1 August to 7 August
3rd	From 24 August to 31 August

Based on information from a local entrepreneur, the amount of cast seaweed collected from the 3.7 km coastline in Solrød Municipality in 2015 was equal to 4,000 tons, which corresponds to 1,081 tons/year/km [3,6]. 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 with 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 [3,4].

GERMANY

A density and biomass estimation of the recent seaweed population in the German Baltic Sea showed that seaweed with a total dry matter of 11,595 tons is growing along the coasts of Mecklenburg-Western Pomerania and Schleswig-Holstein. At the end of a vegetation period, dead and torn-off plant components are flushed to the coasts by wind and flow-induced hydrodynamic processes [19]. The amount of seaweed washed ashore highly depends on location and exposure of the beaches as well as acute weather events [20]. According to the state parliament of Mecklenburg-Western Pomerania, an average of 50 tons per km coastline per year wash up at the beaches. The organic material is classified as biological waste and contrary to their value for nature; biomass at beaches is a problem within tourist areas because of the appearance and the smell. That is why tourist beaches are being cleaned during the main tourist season (April-October) [13].

SWEDEN

The potential for cast seaweed in Scania (the southernmost province in Sweden) was estimated to 83,106 tons/year wet weight or 63,628 tons/year wet weight if nature reserves and natural parks are excluded. The collecting period is from 15 May-15 September. Note as well that biomethane production is not the primary target but rather the nutrients removed from the sea, i.e. mitigation of eutrophication.

To calculate the biomethane potential, an average value of TS (Total Solids content) was assumed to be 12.8% and the VS (Volatile Solids content) 79% of TS. The methane potential was assumed to be 210 Nm^3 CH_4/ton VS.

This gives an annual biomethane potential of 1,764,772 Nm^3 CH_4 corresponding to 17.6 GWh (including nature reserves and natural parks).

However, there are several ways to increase this number:

- Extending the period of collection.
- Collecting seaweed from beaches not categorised as sand (then collection probably has to be done from the sea and not from land, e.g. rocky beaches).
- Collecting seaweed in the water and not only on the beaches.

LITHUANIA

In Lithuania, according to data of Palanga municipality, 50 tons of seaweed were collected from the beaches in 2018. As the length of a supervised coastline is 25 km, an average amount of collected seaweed is 2 tons per km coastline during the recreational season. However, some information found online statistics that in 2010 over 400 tons of seaweed were removed from the approximately 1 km long Palanga beach section.

2.2.3. Seaweed collection and pre-treatment methods

A summary of the most important information about coastal regions in selected countries are presented in table 5.

Table 5 A summary of the basic information about coastal regions of partner countries.

Parameter	Poland	Denmark	Germany	Sweden	Lithuania
Type of seaweed	Green, brown and red algae	Green, brown algae	Green algae	Green, brown and red algae	Green, brown and red algae
Seaweed collection dates	May -October	1 May – 1 September	April-October	15 May – 15 September	?
Reason for the collection of seaweed	purification of beaches	biogas production / purification of beaches	purification of beaches	biogas production is not the primary target but mitigation of eutrophication	purification of beaches
Quantities of collected seaweed	9,500 tons/year	42,000 tons/year	11,595 tons/year	63,628 tons/year	?

2.3. Investor potential

There are several groups than can be profiteers of the solutions developed within the project. These are local habitants and tourists, biogas plants, energy sector and agriculture. The investor potential estimated on the basis of the products receivers is discussed in this section.

POLAND

Agricultural land (as percentage of land area) in Poland was reported at 46.93% in 2015, according to the World Bank collection of development indicators, compiled from officially recognised sources [26]. In Poland, the total area of agricultural land is 14.6 million ha and an average of 2 million tons of mineral and chemical fertilisers are consumed. In 2016, the total fertiliser consumption for Poland was 172.8 kg/ha (17% of phosphorous (P) fertilisers, 57% of nitrogenous (N) fertilisers and 26% of potassium (K) fertilisers). Though Poland's fertiliser consumption fluctuated substantially in recent years, it tended to increase through 2002-2016 period resulting in 172.8 kg/ha in 2016. However, due to the high transport costs, farmers from four voivodships (Pomorskie, Zachodniopomorskie, Kujawsko-pomorskie and Warmińsko-mazurskie) may be interested in buying natural fertilisers (fermentation residue). Table 6 demonstrates an area of agricultural land and production and consumption of mineral and chemical fertilisers in Poland by voivodships in 2017 [27].

Table 6 An area of agricultural land and production as well as consumption of mineral and chemical fertilisers in Poland by voivodships in 2017.

Parameter	Voivodships				Poland
	Zachodnio-pomorskie	**Pomorskie**	**Kujawsko-pomorskie**	**Warmińsko-mazurskie**	
Area of agricultural land [ha]	812,920	748,236	106,556	943,184	14.6 M
Production of mineral or chemical fertilisers [t]	-	-	-	-	9.2 M
Production of mineral or chemical fertilisers in terms of pure ingredient [t]	-	-	-	-	3.0 M
Consumption of mineral or chemical and lime fertilisers in terms of pure ingredient [t]	214,579	101,944	109,312	109,883	2.0 M
Consumption of mineral or chemical and lime fertilisers in terms of pure ingredient per 1 ha of agricultural land [kg/ha]	134.5	136.2	201.4	116.5	140.2

DENMARK

Agricultural land (as percentage of land area) in Denmark amounted to 62.18% in 2015, according to the World Bank collection of development indicators, compiled from officially recognised sources. In Denmark, the total area of agricultural land is 2.6 million ha and fertiliser consumption is 132 kg/ha of arable land [28]. Agricultural consumption of N, P and K was in 2011/2012 (as pure nutrients): 187,024 tons N, 12,804 tons P and 42,616 tons K.

GERMANY

In Germany, in 2015 47.96% of the land area were used for agricultural purposes, according to the World Bank collection of development indicators, compiled from officially recognised sources. The total area of agricultural land amounts to 16.7 million ha and fertiliser consumption is 202 kg/ha of arable land [29]. The total agricultural land of 2.3 million ha (2017) can be divided over Mecklenburg-Western Pomerania with 1.3 million ha and Schleswig-Holstein with 1 million ha. The mineral fertiliser consumption in 2013/2014 was 2.4 million tons. The level of mineral fertiliser consumption per 1 ha of agricultural land in 2013/2014 was 144 kg (12% of P fertilisers, 69% of N fertilisers and 19% of K fertilisers) [30].

SWEDEN

In Sweden, in 2015 the agricultural land was 7.46% of the land area, according to the World Bank collection of development indicators, compiled from officially recognised sources. The total area of agricultural land amounts to 3.1 million ha and fertiliser consumption is 96.69 kg/ha of arable land [31]. The total consumption of mineral fertilisers in terms of pure ingredient in 2016 was 240,400 tons (27,500 tons of K fertilisers, 198,000 tons of N fertilisers and 14,400 tons of P fertilisers).

LITHUANIA

Agricultural land (as percentage of land area) in Lithuania was reported at 47.98% in 2015, according to the World Bank collection of development indicators, compiled from officially recognised sources [32]. Arable land and permanent crops cover around 4 million ha, 2 million ha are under forest and 0.5 million ha are permanent pasture. Organic agricultural area of 234,133 ha (in 2017) 68% consists of arable land, 27% is grassland, and 3.4% permanent crops. The total fertiliser consumption is 122 kg/ha of arable land. Nitrogen fertiliser consumption by agriculture in 2017 exceeded 167,100 tons. Phosphorus (P_2O_5) consumption 53,700 tons; Potash (K_2O) 75,700 tons [33-34].

Comparison of the amount of fertilisers used in various countries is shown in Table 7.

Table 7 Comparison of the amount of fertilisers used in various countries.

Parameter	Poland	Denmark	Germany	Sweden	Lithuania
Area of agricultural land [ha]	14,6 M	2,6 M	16,7 M	3,0 M	0,2 M
Total fertiliser consumption [kg/ha] of arable land	172.8	132.0	202	96.7	122.0
Fertiliser consumption (% of fertiliser production)	82.1	328	86.1	264	22.4
Consumption of mineral	2.0 M	187,000	2.4 M	240,400	296,5010

fertilisers in terms of pure ingredient [t]					
Consumption of mineral fertilisers per 1 ha of agricultural land [kg]	140.2	71.6	144.0	79.1	64.2

A list of advantages and disadvantages of market analysis in individual countries is presented in Table 8.

Table 8 Advantages and disadvantages of coastal market in individual countries

Country	Advantages	Disadvantages
Poland	- Sandy beaches make seaweed collection easier - Relatively large agricultural land area - Large fertiliser consumption	- Large part of the coastal areas is located in the protected area - Relatively small amount of algae in Poland compared to other countries - Algae is collected for cleaning beaches only and there are no commercial biogas plants that could use algae for methane production - No technology to remove algae from beaches without the addition of sand
Denmark	-Long coast with large potential of seaweed amounts - Already developed collection technology minimising the sand content	- Some of the beaches are stony and therefore seaweed collection is difficult
Germany	- Long coast with large potential seaweed amounts - large agricultural land area - large fertiliser consumption	- Large part of the coastal areas is located in the protected area - Some of the beaches are stony and therefore seaweed collection is difficult - Cast seaweed is characterised as bio-waste, which makes utilisation in biogas plants difficult
Sweden	-Long coast with large potential of seaweed amounts	- Some of the beaches are stony and therefore seaweed collection is difficult
Lithuania		- Short coast - Some of the beaches are stony and therefore seaweed collection is difficult

3. Technical potential

3.1. State of the art

3.1.1. Collection of cast seaweed

The seaweed collection method depends on the coastal type (sandy beach, stony beach, port, or no beach, from water of various depths) and availability/suitability techniques. It may be necessary to modify existing techniques for algae collection.

The collection of seaweed and seagrass on sandy beaches is usually carried out by tractors that collect large piles together with sand etc. The material is loaded into a trailer and taken to another area where it is left for a period of time in order to dry. The loss of water and volume saves transport cost to the further facility. The collecting technique could be improved by modified machinery. For example, attaching a grapple fork to the loader helps with the drainage of the trapped water. Other methods include combining grip-claw loader, power-rake and Beach Cleaner, which gives an effectiveness of ca. 45 m^3/hour and approximately 262 kg/minute of fresh material. Other methods will make use of remastered machines, such as a pea combine harvester, with effectiveness of around 500 kg/minute. The collection by hand could serve as a support for other techniques, for example for places, that bigger machinery cannot reach or where it is permitted. In addition, it is easier to separate rubbish and sand at the first step by hand.

The grating bucket consists of a wheel loader with a pitchfork or a bucket in different sizes and shapes and can be adjusted to seaweed collection. The machine weights approximately 10 tons and uses ca. 16 l/h of fuel. The shaking helps reduce the sand intake. The Beach Cleaner comes as an individual machine or one attached to a tractor. It uses conveyor belts with adjustable rollers to take up the material. Brushes and shakers are constructed to reduce the sand uptake.

Table 9 Advantages and disadvantages of different collecting methods

Method	Advantages	Disadvantages
Hand picking	-proper selection from other rubbish -possibility of washing from the sand at the place of gathering -less impact on the coastline	-low efficiency -high labour cost -slow process
Wheel loader with a grating bucket	-relatively low sand intake -quick and simple	-average cost of operating -takes other residues like rubbish -sensitive to holes or rocks
Beach cleaners	-collecting material relatively quick if it is dry -shaking reduces the sand intake to minimum (from dry material)	-low capacity -sensitive to holes or rocks -fresh and wet algae might not be a suitable material

POLAND

Due to the collection of algae only for the purpose of cleaning the beaches and transferring those for utilisation, no advanced tools and methods are used in Poland. Usually, backhoe loaders are used. In

Figure 7, the backhoe is depicted on the left and the shovel excavator on the right. Before the utilisation process of seaweed, it is not necessary to remove impurities from the biomass (water, sand, sticks, plastic etc.). Therefore, no additional pre-treatment methods are applied in Poland.

Figure 7 Removal of algae using a backhoe loader on the beach in Świnoujście [25].

DENMARK

The utilisation of collected seaweed depends on the heavy metal cadmium content in the seaweed. A seaweed sample is taken once a month and the results are available 7-8 working days later. If the cadmium content is below the limit value of 0.8 mg/kg in dry matter, then 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.

Seaweed is pre-treated at the biogas plant. Firstly, the seaweed is put into a tank with a strong stirrer, which separates the seaweed from sand residue. The sand is removed from the bottom of the tank periodically. Further, the purified seaweed is chopped finely in a macerator before being mixed with other feedstock. Finally, feedstock composite is supplied into the biogas tank (digester) via pipe systems, where gas formation takes place during the anaerobic digestion process.

GERMANY

In Germany, cast seaweed is mainly removed from beaches because of recreational reasons. The collection is carried out with excavators or wheel loaders at the waterline but methods vary in different municipalities. In most cases, the collected material is transported to landfills. Only a few surrounding municipalities collaborate with a local enterprise, where cast seaweed is utilised for compost production.

In Germany, due to environmental protection cast seaweed can only be collected at the waterline and on the beach, as a collection from the water is not legal.

SWEDEN

Note as well that biomethane production is not the primary target but rather the nutrients removed from the sea, i.e. mitigation of eutrophication.

LITHUANIA

Collected and stored on shore; left on the beach, expecting that the sea will take it back.

Table 10 Methods of cast seaweed treatment by countries.

Country	Method
Lithuania	Collected and stored on shore, expected to be taken back to the sea
Poland	Collected by hand and machinery, taken and stored at the landfill or deposed and composted on a dedicated land
Denmark	Collected from the shore with machines, co-digested in biogas plants, used for soil improvement
Sweden	Collected from the shore with machines, co-digested in biogas plants, used for soil improvement, deposed and composted
Germany	Collected from the shore with machines, decomposed and composted

3.1.2. Pre-treatment

The core function of different pre-treatment approaches is to make the organic matter more accessible to the microorganisms by breaking down the complex biopolymers, enhancing the bio-digestibility of the algal biomass through accessibility of microbial enzymes, disruption of cell walls and bringing out the chemical substances from polymers into more available compounds to ultimately improve fermentation and therefore the biogas yield. Due to the high sand content, the seaweed should be firstly washed. This pre-treatment is conducted with a float/sink separator and reveals the main by-products water and sand, which can be returned to the beach.

There are several methods to increase biodegradability of seaweed. With different levels of effectivity mechanical (cutting, drying), thermal (heating), alkaline (NaOH), acidic (HCl) pre-treatment or enzymatic hydrolysis (cellulose or hemicellulose) can be applied. In addition, combinations of pre-treatment methods can significantly increase the methane production.

3.1.2.1. Chemical pre-treatment

For chemical pre-treatment, the most common acids and bases are sodium hydroxide, sulphuric, nitric, hydrochloric, phosphoric, citric, lactic, acetic and oxalic acid. The biomass is treated with different dilutions where the lower ones need less substance for neutralisation and higher concentrations might increase the production of inhibitory compounds toxic to microorganisms, which might stop the process.

3.1.2.2. Thermal pre-treatment

The goal of the process is to disrupt the chemical structure of the biomass while preserving their constituents and minimising the hydrolysis of monosaccharides. The pre-treatment temperature varies from 80 to 130°C with retention time from 1-120 minutes. Usually the higher temperature and longer retention time the better are the results.

3.1.2.3. Physical pre-treatment

Mechanical treatment can significantly enhance accessibility for the microorganisms to the surface of biomass. It can be carried out by simply using blender milling in order to obtain a particle size of <1 mm.

3.1.2.4. Biochemical pre-treatment

Enzymatic hydrolysis seems to be a more economical and environmental friendly method than the others. It does not lead to creation of inhibitory compounds and does not require the use of corrosive chemicals. The hydrolysis is performed for a period of 24 hours. For the process the following enzymes are used e.g. Cellulase from *Trichoderma longibrachiatum*, Alginate Lyase from *Flavobacterium* and Celluclast®.

3.1.3. Fermentation process

The fermentation process can run in different temperature ranges: psychrophilic (15-25°C), mesophilic (35-37°C) and thermophilic (45-60°C). However, the majority of applications is provided in a range of 30°C to 45°C. Another important parameter is the hydraulic retention time during which the substrate has time to decay. Depending on the feedstock composition, it may vary from 20 to 60 days. The proper mixing is crucial for an optimal fermentation process as it keeps the temperature evenly distributed. The pH should be maintained at neutral level. Drops of the pH value to 6.2-6.5 level might cause slowing down or even stopping of the process. Efficiency of the process is measured several times during the fermentation. It is calculated through different parameters, such as loss of the dry matter, biogas and methane yield from 1 kg of the dry organic matter and hydraulic retention time in which 90% of methanogenic substances is converted to biogas. Anaerobic digestion does not require beach cast to be dried; instead, the high water content (around 80-90%) makes it suitable for wet anaerobic digestion. Green and red algal species contain high levels of easily fermented sugars, which increases the anaerobic digestion processes. The co-digestion of the cast seaweed is usually conducted with different organic residues, such as manure, communal organic waste or sewage sludge. Best methane yield was obtain in ratios combining different sources, for example 80% cattle manure and 20% cast seaweed or 80% cattle manure, 10% sugar beet pulp an 10% cast seaweed [1].

3.1.4. Fermentation residues

The composition of the fermentation residues strongly depends on the substrates used in the first place. Use of different pre-treatment methods might also influence the digestate composition (decrease of NH_4^+ and increase of phosphate concentration [1]). The digested effluents could be potentially valuable as fertiliser. Although owning high potential, the material needs to be examined first due to possibly high level of heavy metals or different contaminations. It is assumed that 50 kg of bio-fertiliser can replace 1 kg of synthetic fertiliser. Currently, the most popular methods of digestate use is spilling on agricultural fields, separation for the solid and liquid fraction or further processing such as drying, composting and palletising.

Table 11 Summary of the current cast seaweed management in project partner countries

Country	Cast seaweed management	Collection methods	Further biomass management	Technological process	Obtained product
Lithuania	Collection and removal only from recreational areas, at others it is left and washed back into the sea	A compact tractor and beach cleaner all in one	Composting together with other biodegradable waste	Municipal waste composting plant	Natural fertiliser (after composting)
Poland	Collection and removal from	Mainly with grip-claw	Disposal in landfills or	Municipal waste	Natural fertiliser

	recreational areas in May-October	loader or by hand	composting together with other biodegradable waste	composting plant	(after composting)
Denmark	Collection and removal only from sandy beaches in April-September	Front loaders, beach cleaning machines, backhoe with a shovel	Transportation to biogas plant and fermentation or storage, composting and utilisation as fertiliser	Municipal waste composting plant, industrial scale biogas plant, where maritime biomass is used as feedstock	Biogas and natural fertiliser (digestate)
Sweden	Collection and removal during summer season	Grip-claw loader or wheel loader with a pitchfork	Transportation to biogas plant and fermentation	Pilot scale biogas plant, where maritime biomass is used as feedstock	Biogas and natural fertiliser (digestate)
Germany	Collection and removal from sandy beaches during touristic season	Wheel loaders, quad bikes/sand buggies	Mostly composting and utilisation as fertiliser or disposal in landfills	Municipal waste composting plant	Natural fertiliser (after composting)

3.2. Technical indicators

3.2.1. Biomass characterisation

Macroalgae are classified into three major groups, brown algae, red algae and green algae. All of these contain high amounts of carbohydrates (up to 60 %), medium to high amounts of proteins (10–47 %) and low amounts of lipids (1–3 %) with a variable content of mineral ash (7–38 %) [2, 3]. Various seaweed species can be found among the wreck washed ashore. The ones frequently found at the Baltic Sea coast are *Zostera marina* (eelgrass), *Pilayella littoralis* and *Ectocarpus spp.* (filamentous brown algae). The C:N ratio of collected seaweed (average of 17.8:1) is slightly lower than the optimal range for anaerobic digestion, which is between 20:1 and 30:1 C:N.

Table 12 Composition of macroalgae regarding carbohydrate, protein, lipid and ash content [4]

Compound	Green Algae	Red Algae	Brown Algae
Water	70 %–85 %	70 %–80 %	79 %–90 %

Ash	18 %–53 %	26 %–48 %	33 %–55 %
Total organic	47 %–82 %	52 %–74 %	44 %–66 %
Carbohydrate	25 %–50 %	30 %–60 %	30 %–50 %

Table 13 Composition of various seaweeds % TS [5]

Algae	Lipids	Proteins	Carbohydrates
Green algae			
Codium fragile	1.8	10.9	32.3
Enteromorpha linza	1.8	31.6	37.4
Ulva Lactuca	6.2	20.6	54.3
Red algae			
Gelidium amansii	0-3.1	15.6-16.3	61.0-67.3
Porphyra tenera	4.4	38.7	35.9
Gracilaria verrucosa	3.2	15.6	33.5
Brown algae			
Laminaria japonica	1.8–2.4	9.4–14.8	51.9–59.7
Hizikia fusiforme	0.4–1.5	5.9–13.9	28.6–59.0
Saccharina japonica	0.5	19.9	44.5
Sargassum fulvellum	1.6	10.6	66.0
Ecklonia stolonifera	2.4	13.6	48.6

To optimise the process it is advised to use different feedstock sources for co-digestion. It can improve the C/N ratio and balance the dry matter content.

Table 14 Methane yield potential from various species of macroalgae and seaweed

Organic substrates	Methane yield (Nm^3/tons VS)
Brown algae	
Brown macroalgae	140-410
Laminaria spp.	260-280
Sargassum spp.	120-190
Red algae	
Mixture of red filamentous beach cast algae	130-200
Mixture of *Polysiphonia focoides* and other filamentous red algae	80-200
Red filamentous algae	210
Green algae	
Ulva lactura	162-271
Seagrass	
Zostera marina	150
Terrestrial biomass	
Tops of sugar beets, maize, timothy, clover forage	270-370
Pig manure	310

3.2.2. Biogas use

Due to the presence of different undesirable components, the biogas needs purification in form of desulphurisation, drying and if needed CO_2 removal. Hydrogen sulphide is a product of protein breakdown and the concentration usually varies from 0.1-2%. It can be removed by biological desulphurisation. Elimination of moisture from the gas can be done by cooling down and water condensation. There is a variety of ways of CO_2 removal such as absorption, chemisorption, adsorption or membrane separation. Afterwards, the biogas can be used in CHP, biofuel or it could be transferred to the gas network.

4. Case studies

The case studies were performed in each partner country. The main goal was to find out if it is feasible to use cast seaweed in existing biogas plants as a co-substrate to the biomass usually used in the plant. The case studies focused on technological and environmental aspects to provide specific and realistic solution to the eutrophication problem that will not negatively affect the processes conducted at biogas plants. The case studies were essential in finding the problems and issues that could stand in the way to use cast seaweed and to address them precisely.

The analysis highlights the opportunities and obstacles of using seaweed as a feedstock for anaerobic digestion based on the existing practices in biogas plant. It enables proposal of the appropriate strategy that will contribute to solving long-duration problems such as climate change, biodiversity loss and diminish the pressure to the environment.

Figure 8 presents the forces that were identified during the case studies.

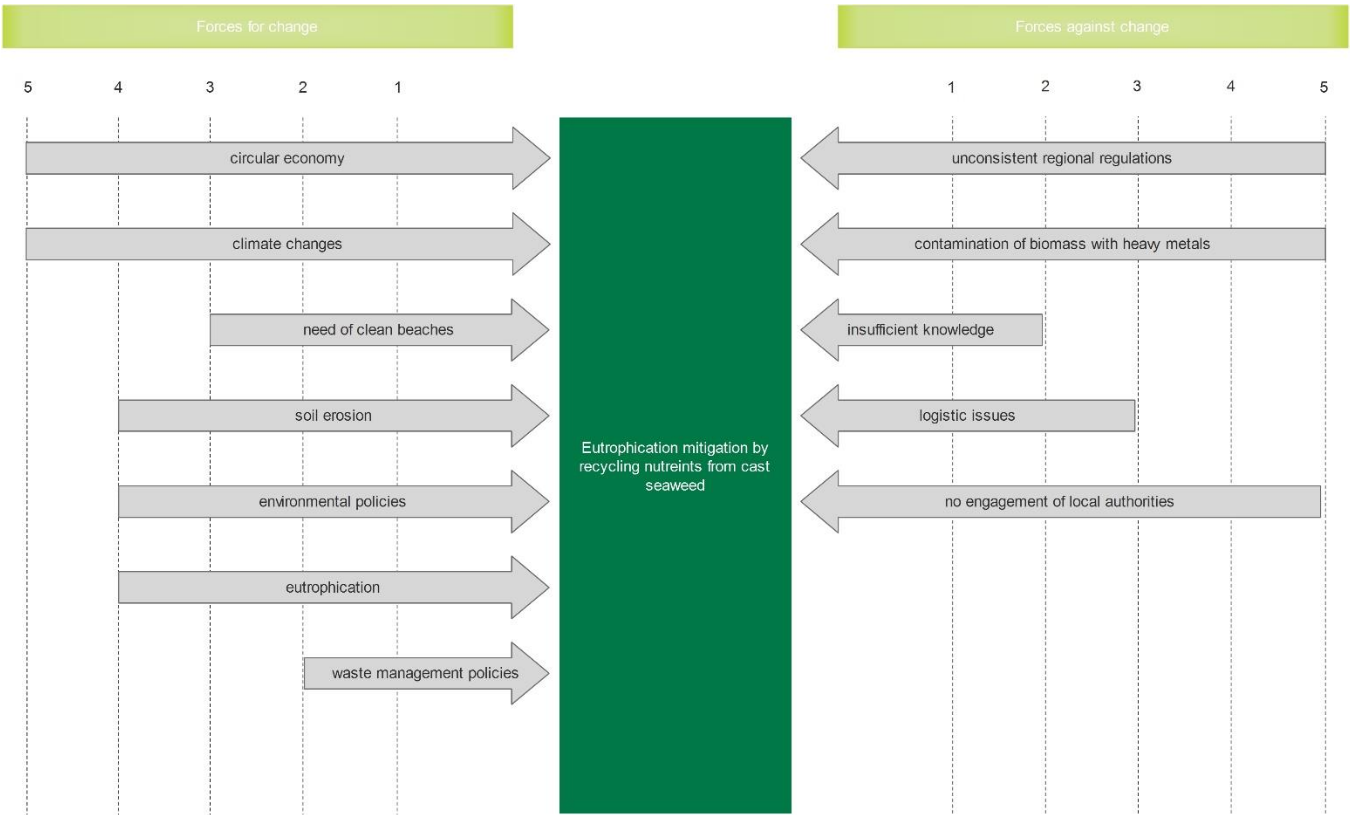

Figure 8 Force Field Analysis

Case Study 1: Wastewater treatment plant in Swarzewo, Poland

Case study partner: Gdańsk University of Technology

Location of the case study: Swarzewo, Pomerania, Poland

Aim of the case study: Assessment of cast seaweed applicability in anaerobic codigestion with sewage sludge

1. Introduction

The wastewater treatment plant (WWTP) “Swarzewo” was established in 1980. The facility was thoroughly modernised in 2014-2016. The technological processes were improved and the plant has been equipped with the new installation for sewage sludge digestion with the electricity and heat recovery system. Implemented solutions significantly reduced the amount of waste and emission of odours that can be produced along the wastewater treatment process. Additionally, the discharge of the pollutants to the Baltic Sea waters was minimised. Modernisation also contributed to an economic development of the facility and surrounding municipalities.

Figure 9 Fermentation tanks

The digestion system is based on a mesophilic fermentation process and is conducted using two closed anaerobic digesters. The substrates that are used for the digestion are organic fractions from other industrial wastewater treatment plants, local fish factories or food factories and two substrates that originate from the sewage treatment process: sewage sludge and fats that are separated from the sewage. The process provides a sufficient amount of biogas to fully cover the energy demand of the facility and electric energy that in excess can be fed to the electrical grid. Moreover, the company produces and sells agricultural fertiliser that is obtained by composting green waste and the digestate.

2. Wastewater treatment

WWTP “Swarzewo” processes around 14,000 m^3 of sewage daily during the summertime and around three times less during the rest of the year. The treatment plant is equipped with an installation that enables the collection of sewage from other wastewater treatment plants, which is around 5% of the total amount of sewage processed in the facility. Three stages of wastewater purification process can be distinguished: mechanical, biological and chemical treatment. Screens and rotary sieves are installed on the sewage inlet in order to separate larger solid particles, part of fats and sand from the raw wastewater. Sewage is then directed to the grit chamber, where sand with mineral fractions are removed and fatty fractions are collected. Initially treated sewage is directed to the first stage sedimentation tank, where primary sludge is separated. The collected sludge is partially dewatered in gravity thickeners and undergoes an anaerobic digestion process, while screened material is landfilled. Subsequently, biological treatment is performed inside of the six sequencing batch reactors that provide cyclic flow of

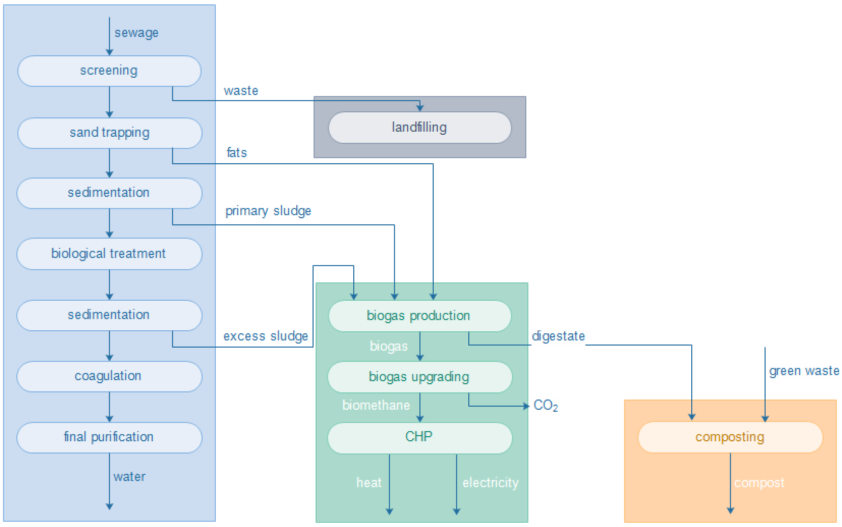

Figure 10 Flow chart at WWTP Swarzewo

wastewater through the installation. Sewage is mixed with an activated sludge that decomposes organic material. After the treatment, activated sludge is separated from the excess water by sedimentation and decantation with simultaneous discharge of excess sludge. Excess sludge is thickened, mixed with primary sludge and added to fermentation batch. Phosphorous compounds are removed from the wastewater by coagulation with iron (II) sulphate solution produced on the site. Emerging iron phosphate salts are removed together with an excess sludge. Remaining excess sludge and other impurities are finally removed in the wastewater clarifier tanks. After the treatment, clear sewage can be discharged into the open sea by pipelines.

Figure 11 Sequencing batch reactors

The wastewater treatment plant is equipped with modern automation and control system that provides optimal conditions at each stage of the sewage treatment process.

3. Anaerobic fermentation technology

Precipitate formed in the primary sedimentation tanks is thickened with gravity thickeners and recirculated to intensify volatile fatty acids production. It is mixed with the excess sludge collected from the sequencing batch reactors. Agitator pumps pump the feedstock stream, consisting of sewage sludge, to the digester. Another types of substrates utilised in an anaerobic digestion are: sewage sludge from five different wastewater treatment plants and organic waste produced locally. Fish industries and other food processing facilities provide high-energy waste, rich in grease and proteins, improving an overall biogas production. Plant's capacity for organic waste of external origin is 26,000 tons annually. For the biogas production, organic pulp is dissolved with digestate in winter, while with excessive sludge during summer. It is grinded in a macerator, pumped into the intermediate storage tanks and dosed periodically to the digesters.

Figure 12 Organic waste intake to the pre-treatment chamber

Two main feedstock streams introduced to the digester can be distinguished: primary with excessive sludge and organic pulp from external substrates. Dry matter for the entire feedstock is around 2%. The installation consists of two fermentation chambers with total volume of 7600m^3 operating at 38°C. Recuperation of heat is provided in the external spiral cross-flow heat exchanger powered by digestate. Average retention time is 30 days, but can reach up to 60 days, depending on the organic waste content in the utilised feedstock. Wastewater treatment plant processes around 4,000 tons of sewage sludge annually with addition of the equal amount of organic fractions from the outside sources.

Figure 13 Macerator used for organic waste pre-treatment

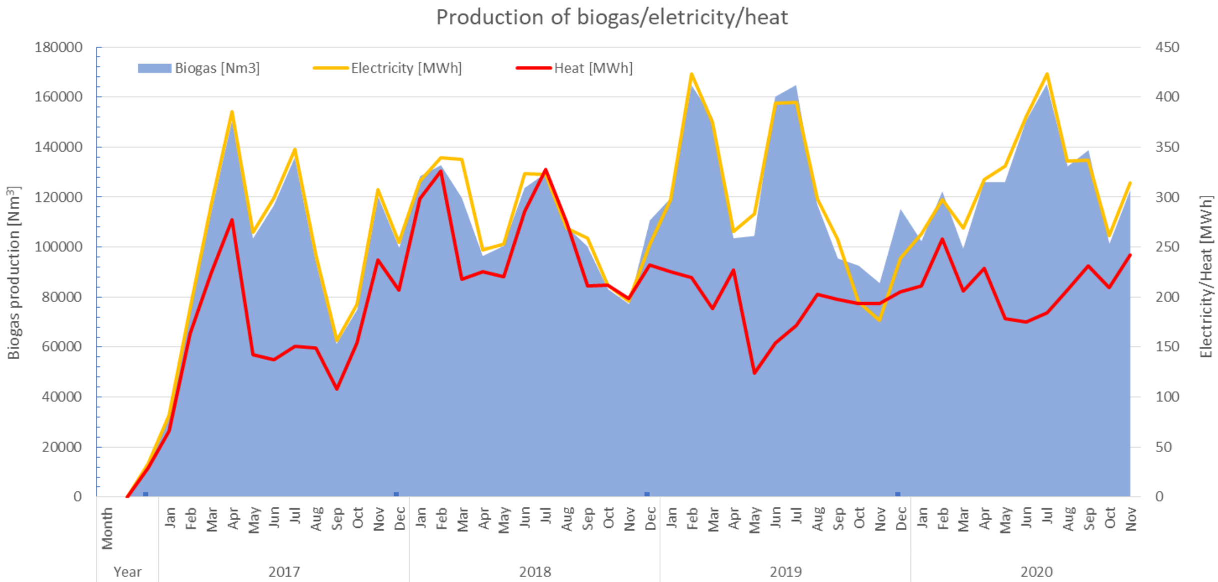

Figure 14 Biogas, electricity and heat production

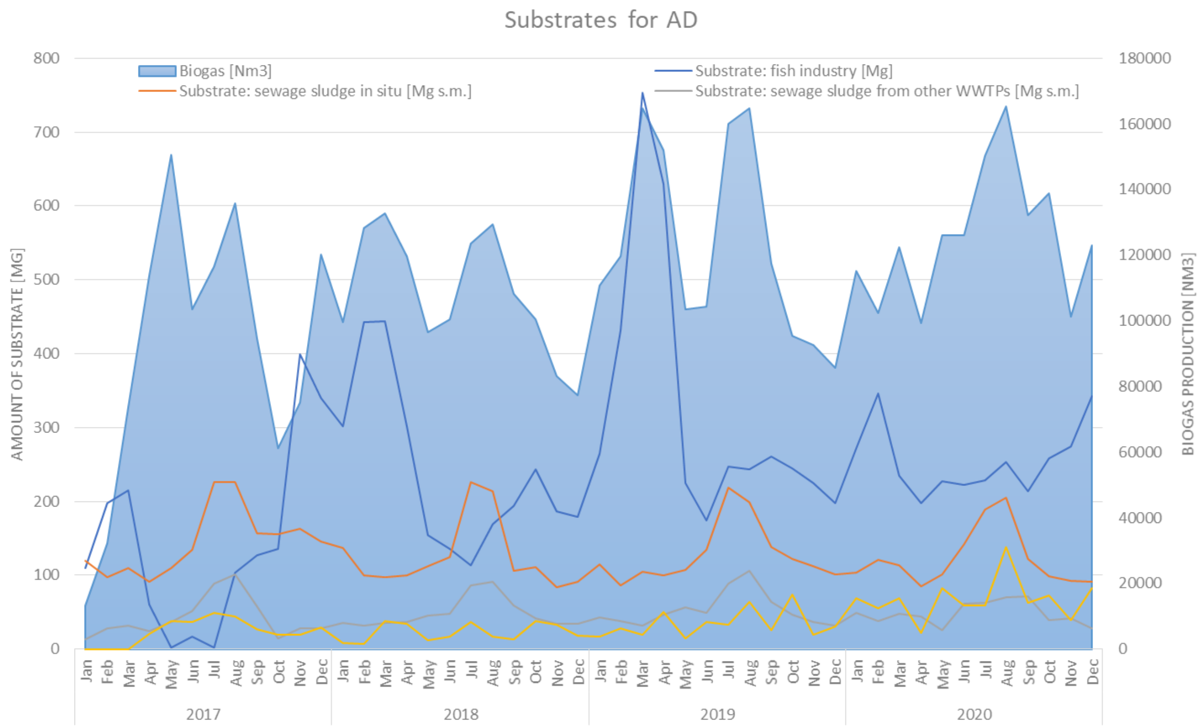

Figure 15 Substrates used in anaerobic digestion

4. Electricity and heat regeneration

The facility produces an average of 4,000 m^3 biogas daily, 65% of which is methane. Biogas undergoes chemical desulphurisation on an iron bed and siloxanes are removed in the columns packed with activated carbon. After the purification, it is dehydrated, cooled down to the room temperature and stored in the high-pressure tank.

Biogas is converted into the heat and electricity in 1:1 ratio by two electric generators, located on the plant's area, with power of 400 kW each. Total electricity and heat produced by combined heat and power system covers energy requirements of the facility and surplus is subjected to the electrical grid, making the WWTP "Swarzewo" energetically self-sufficient.

Figure 16 Biogas storage tank

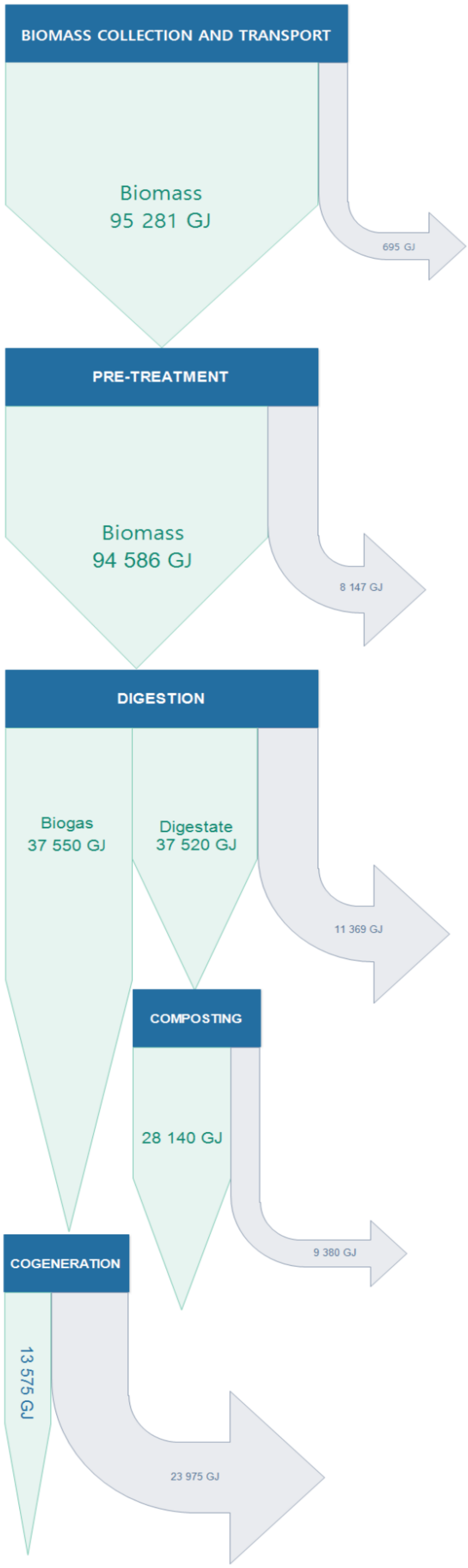

Figure 17 Energy balance

Figure 18 Generator for heat and electricity production from the produced biogas

5. Digestate processing

The digestate is dewatered with decanter centrifuges. Leachate is reused in the process for the organic pulp dilution, while solid fractions of digestate together with green waste like grass or leaves as a structural material, are utilised for the compost production. Compost heaps are formed with specially designed heavy equipment. Material is stored in a roofed yard where it can be easily mixed and aerated to maintain favourable composting conditions. Composting section is equipped with: dynamic composting system with forced negative pressure and pressure aeration of compost piles, an aerated maturation area, biofilter and automatic process control. Produced compost meets the requirements stated by the decision of the Minister of Agriculture of Poland and has been sold on the local market under the name of "Ulkomp", since 2006. Fertiliser is rich in carbon and other valuable substances, due to the diversity of substrates utilised as a feedstock for an anaerobic digestion.

Figure 19 Roofed compost yard equipped with aeration channels

Figure 20 Maturing compost and structural material for the compost

6. Conclusions

WWTP Swarzewo could share digester and biogas upgrading system for biogas production from cast seaweed. The number of residents and tourists in the region would provide sufficient amount of sewage to produce sludge for co-digestion. The most important issue that should be considered in the use of seaweed is to collect and prepare biomass. The transportation cost would be low due to the close neighbourhood of the coast. Moreover, mostly asphalt road are advantageous for the seaweeds transportation. The pretreatment infrastructure is sufficient to deal with marine biomass. The digestate produced during anaerobic digestion is used for composting to produce off-class compost. Since the amount of the liquid substrates is high and a lot of the co-composting material is used, possible heavy metals present should not exceed the threshold.

Case Study 2: Klaipėda's Wastewater treatment plant, Lithuania

Case study partner: Lithuanian Energy Institute

Location of the case study: Uosių g. 8, Dovilų sen., Dumpių km., Klaipėda County, Lithuania

Aim of the case study: Assessment of cast seaweed applicability in anaerobic codigestion with sewage sludge

1. Introduction

The Klaipėda's Wastewater treatment plant (WWTP) was established in 1998. The plant is located approx. 12 km from the nearest beaches (fig. 21). Wastewater is treated using mechanical and biological methods. Wastewater enter the plant through pressure networks from Klaipėda, Gargždai cities and Priekulė, Rimkai, Jakai, Kalotė, Slengiai, Karklė, Agluonėnai, Dovilai, Stragnai settlements. Since 2000, the facility has been periodically modernised. Seeking to improve the biological treatment process, the company reconstructed aeration tanks in 2003. After reconstruction significantly improved the treatment efficiency. Over the last 10 years, the efficiency is 98-99% in terms of BOD7 concentration, 85-92% in terms of nitrogen and 93-97% in terms of total phosphorus. Closed sewage sludge digestion tanks (fig. 22) were built in 2009, enabling biogas and thus electricity/heat production.

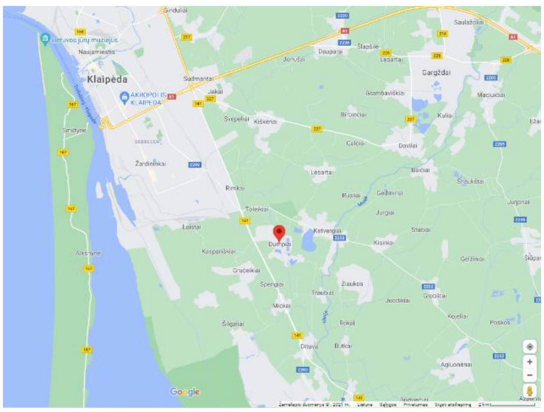

Figure 21 Location of the Klaipeda's WWTP

Figure 22 Fermentation tanks with biogas storage tank (photo: Klaipėda's WWTP)

In 2013, the sewage sludge drying facilities were built. This allowed to reduce the volume of the sludge and to stabilize it. Besides many more modernisation steps taken on a way such as air cleaning from unpleasant odours using bio-filters, sand separation, scrubbers, etc., the plant was also equipped with an automatic disinfection and odour neutralization system using ozone in 2017. The latest modernization in 2019 was related to the development of a system of remote control and management of the technological process with the help of advanced algorithms.

2. Wastewater treatment

The Klaipėda's WWTP processes around 141,720 m^3 of sewage sludge annually, which is the main process feedstock. The first stage of wastewater treatment is a mechanical treatment, i.e. a primary treatment of wastewater before biological treatment. At this stage, large sediments, mineral (sand, slag, etc.) impurities, leachate (fats, etc.), suspended solids and various other substances that are undesirable in other stage are removed. Such equipment as manual grating, mechanical automatic gratings, aerated sand traps, sand separators, primary settlers are used for mechanical wastewater treatment. About 732 kg of sorting and about 85 kg of sand waste are detained every day. Detained sand and sediments are periodically taken to a household waste landfill.

The next secondary treatment stage is biological. In the part of biological wastewater treatment, wastewater is treated with the aid of activated sludge and microorganisms present in it.

3. Anaerobic fermentation technology

The technological scheme of Klaipėda's WWTP is shown in figure 23.

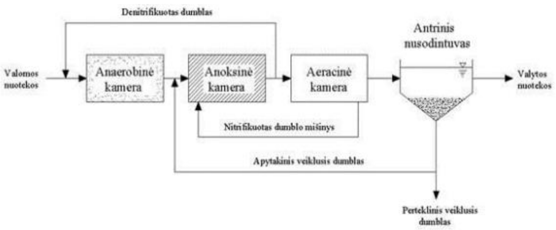

Figure 23 Technological scheme of biological treatment of wastewater at the Klaipėda's WWTP (photo: Klaipeda's WWTP)

The sludge is digested in two digestion tanks. The digestion process is carried out on mesophilic stage, maintaining a temperature of 35-37ºC. Organic matter is metabolized into ammonia, carbon dioxide and methane gas under the anaerobic conditions by methane bacteria. In sludge digesters, the retention time is kept to about 22 days. Such methane digestion obtain rotted, black, almost odourless sludge. The biogas during the digestion process is collected at the top of the sludge digestion towers and supplied, after gas purification, to the gas storage tank. This biogas is used as fuel in cogeneration plants or boiler house. Just before the digestion process, the sludge is cut. Primary sludge composition: dry matter 4-5%, organic matter 80-82%. Excess (secondary) sludge: dry matter 0.8-1.0%, organic matter 80%. Digested sludge: dry matter 3.15%, organic matter 63-67%. The digesters of WWTP usually decompose only local sludge generated in sludge removal process. Digested and dried sludge is normally not stored. All dried sludge is transported to a waste incineration plant situated in Klaipėda or cement production plant in Akmenė.

4. Electricity and heat regeneration

The facility produces an average of 2,063,546 m^3 biogas annually, 65% of which is methane (carbon dioxide 32-35%). Just before storage at the biogas storage silo, the biogas is cleaned from moisture and sulphur compounds. The produced biogas is used as fuel in cogeneration unit (combined heat and power production) or boiler house to cover energy requirements both thermal and electrical. Three biogas generators (2 in operation, 1 as reserve) generates about 91.5% of the electricity required for the entire wastewater and sludge treatment process of the plant. The excess heat from the generators is used for sludge drying. Additionally, a 600 kW generator operating on natural gas is used for sludge drying.

5. Dried sludge (digestate) processing

The digested sludge is further dried (using dry-type flocculants) in centrifuges (remaining at about 75% moisture) and fed to a belt-type low temperature (up to 85ºC) sludge dryer. After, the dried sludge, which contains no more than 10% moisture, is crushed and enters a 150 m^3 dried sludge storage tank, where is stored until it is unloaded. Finally, the dried sludge is loaded into containers and handed over to the final waste manager. No further utilisation of the dried sewage sludge to be used as an organic fertiliser or compost is reported.

6. Conclusions

Klaipėda's WWTP might have a possibility to utilise cast seaweed in its technological process, including biogas production.

The number of residents and tourists in the region would provide sufficient amount of sewage to produce sludge for co-digestion. The most important issue that should be considered in the use of seaweed is to collect and prepare biomass for co-digestion. The transportation cost would be low due to the close neighbourhood of the coast.

The pre-treatment infrastructure could be sufficient to deal with marine biomass. The only issue could be additional sand content present in the collected seaweed, which would require separation. This needs to be checked if currently available sand separation system would be able to effectively cope with extra portion of sand present in the seaweed. Moreover, how effective the system to remove the major part of sand is unknown. This would also slightly increase the energy requirement. However, the quantities of cast seaweed on Lithuanian beaches are not high and therefore the energy penalty would be of minor effect.

There is a possibility to better manage the digestate produced after anaerobic digestion. The plant could financially benefit (extra incomes) in case of selling the digestate, which could be used as an organic fertiliser. Prior to this, the examination needs to be carried out if the quality of the produced digestate is good enough, especially heavy metal content, which excess above the threshold values might limit its utilisation potential.

Case Study 3: Hagelsrum Biogas plant in Hagelsrum, Sweden

Case study partner: Baltic Energy Innovation Centre

Location of the case study: Hagelsrum, Småland, Sweden

Aim of the case study: Assessment of cast seaweed applicability in anaerobic codigestion with agricultural waste

1. Introduction

Hagelsrum Biogas plant was established in 2011/12 by the Birgersson family, owner of the Hagelsrum farm. The farm has 650 dairy cows, raises calves and grows fodder crops, and has a total area of 500 hectares. The main idea behind the biogas plant was to produce power and heat to cover the farms own consumption and sell the excess electricity to the grid. However, just a few a months after biogas production began the electricity prices went down. The Birgersson family decided to upgrade the biogas and sell it as vehicle fuel instead. In 2018, a bigger digester and the upgrading plant were ready for operation.

Figure 24 Hagelsrum Biogas

The digestion system is based on a one-step mesophilic fermentation process in two serial CSTR (Continuous Stirred-Tank Reactor) reactors. The first reactor is a 4,500 m^3 glass enamelled steel reactor operating at 40°C, with a top-mounted agitator.

The second reactor is a 2,100 m^3 glass enamelled steel reactor operating at 37°C, with three submersible agitators.

Figure 25 One out of three submersible agitators in the second reactor.

The reactors have double membrane roofs. The maximum capacity is 250 m^3/day of substrate corresponding to approx. 20 GWh of biogas. The substrates that are used for the digestion are cow manure (78-83%), straw bedding (15-20%) and scrap fodder (~2%). The dry matter in the ingoing substrate is 8% and small cutting pump is used for pretreatment. The biogas plant is currently processing 130 m^3/day of substrate and the retention time is approx. 30 days. The produced biogas contains 57% methane and the digestate is used as fertiliser on farmland. The biogas is upgraded and designated as transport fuel. The production corresponds to 2,700 m^3/day of pure methane.

Out of the 45,000 m^3 of substrate processed annually, 25,000 m^3 are produced onsite and 20,000 m^3 are gathered from surrounding farmers within a radius of 20-40 km. The digestate is transported back to surrounding farms. The trucks are always full. Picking up substrate and returning digestate. Hagelsrum Biogas has a buffer storage of substrate for a few days of operation and concrete tanks as digestate storage for 8 months.

The upgrading is delivered by DMT Environmental Technology (NL) and is based on membrane separation. The upgraded biogas meets the Swedish standard that requires a methane content of 97% for the biogas to be used as transportation fuel or injected into the natural gas grid. The upgraded biogas is piped to the mother station in Mållilla through a 5 km long pipeline, and from there trucked to additional three daughter refuelling stations in Vimmerby, Hultsfred and Högsby.

Figure 26 One of four refuelling stations owned by Hagelsrum Biogas.

The pipeline that connects Hagelsrum Biogas and the refuelling station in Målilla operates at ~4 bar (max 10 bar). The biogas is compressed to 200 bar in Målilla.

2. Energy balance

Hagelsrum Biogas produces 10 GWh of upgraded biogas from 45,000 m^3 substrate annually. 2-2.5 GWh of heat are used for heating of the substrate and 0.7 GWh of electricity is used for agitators and pumps per year. The power consumption for the upgrading is in the same range as for the biogas plant, i.e. 0.7 GWh per year. The energy needed for transport of substrate and digestate is estimated to 250 MWh per year.

3. Economy

The total investment for the biogas production plant including the upgrading was 40 MSEK, with a 40% support by public funding. The 5 km pipeline costed 5 MSEK and it was supported by 50% through public funding. The four refuelling stations costed 10 MSEK each and the total investment of 40 MSEK for these was supported by 70% through public funding.

4. Lessons learned

It has been an advantage to have only one owner who supplies most of the substrate and handles the biogas production, upgrading and distribution including refuelling stations. In order to keep the costs down, the owner has done as much work as possible. It has been a lot of administrative work to get permissions and the challenge has been to find end users willing to pay a good price. In Sweden, the transportation sector is primarily willing to pay the cost. There is a tough competition from the imported Danish biogas due to the high Danish feed-in tariff that makes it profitable to produce the biogas in Denmark (get the feed-in tariff) and export it to Sweden where there is a tax exemption, if the biogas is used as vehicle fuel.

The European Commission´s view on the future transportation sector, where electricity and hydrogen are favoured, gives a high uncertainty for the future development of biogas as vehicle fuel.

5. Conclusions

Hagelsrum Biogas is currently running the facility below the maximum capacity, and cast seaweed or any other aquatic biomass could potentially contribute to a higher capacity utilisation of the biogas plant. The most important issues that should be considered in the use of cast seaweed are collection, transport, storage and pre-treatment of the biomass. The transportation cost would be rather high due to the 60 km long distance to the coast. Moreover, storage and pretreatment of the cast seaweed need to be constructed. It would probably be of more interest to co-digest biomass from nearby lakes, rivers and wetlands instead. In this way, nutrients from leakage and run-off from agricultural land in these water systems are returned to the farmland. The digestate produced during anaerobic digestion is used as a fertiliser on farmland that belongs to Hagelsrum Biogas or its neighbours. Possible heavy metals present in the seaweed or biomass from lakes, rivers and wetlands would not exceed the threshold for using the digestate on farmland since these additional biomasses would constitute a small fraction of the total processed biomass.

Case Study 4: Municipal organic waste plant in Borgstedt, Germany

Case study partner: Rostock University

Location of the case study: Borgstedt, Schleswig-Holstein, Germany

Aim of the case study: Assessment of the feasibility of using cast seaweed as a feedstock in a municipal organic waste fermentation plant

1. Introduction

The municipal waste AD plant in Borgstedt is located around 20 kilometres from the coastal area of the town of Eckernförde. It went into operation in 2008 with a capacity of 30,000 tons/year with two CHP units for electricity and heat supply. The plant was expanded in 2019 to include BB2 and a further CHP unit (CHP 3). Up to 60,000 tons/year of organic municipal waste could be treated per year. With further expansion, the capacity will be around 80,000 tons/year.

The AWR site in Borgstedt has a total area of 32.2 hectares. The waste management centre itself currently covers around 10 ha. Due to building restrictions (for the area under a power line) it consists of two fermentation plants (BBA1 and BBA2), which are separated and both have their own reception and mixing areas as well as percolate tanks. To the west of BBA2, an expansion area is currently being developed.

The amount of organic waste, which the plant receives, varies significantly between the summer and winter months. The difference is typically around 2,500 tons/month with up to 8,000 tons/month in the warmer months (May through October) and as little as 4,000 tons/month in the colder months. This leads to different retention times, which along with the somewhat different composition of the waste, results in different monthly biogas yields. The typical retention time is 30 days.

When the fermentation capacity is exceeded, the excess waste is treated aerobically in the rotting boxes.

Figure 27 Location of the municipal organic waste treatment plant

Figure 28 Layout of the municipal organic waste treatment facility

2. Anaerobic fermentation technology

The AD plant is a one-stage dry fermentation plant with 18 fermenter boxes (also called garage fermenters).

BBA1 is run mesophilic while BBA2 is run thermophilic. BBA 1 consists of ten fermenters, seven rotting boxes, two post-rotting halls (including an extension) and a bio filter. BBA 2 consists of eight fermenters, four rotting boxes, three post-rotting halls and a biofilter. The fermenter volume is 16,500 m³. Currently, 10,500 m³ of which is used in equal parts by BBA1 and BBA2.

Both AD treatment plants share a gas storage facility along with a compost storage facility. The gas storage facility, which, in addition to raw gas storage, is also used for lean gas utilisation, has a usable area of 233 m² and offers a storage volume of 2,000 m³.

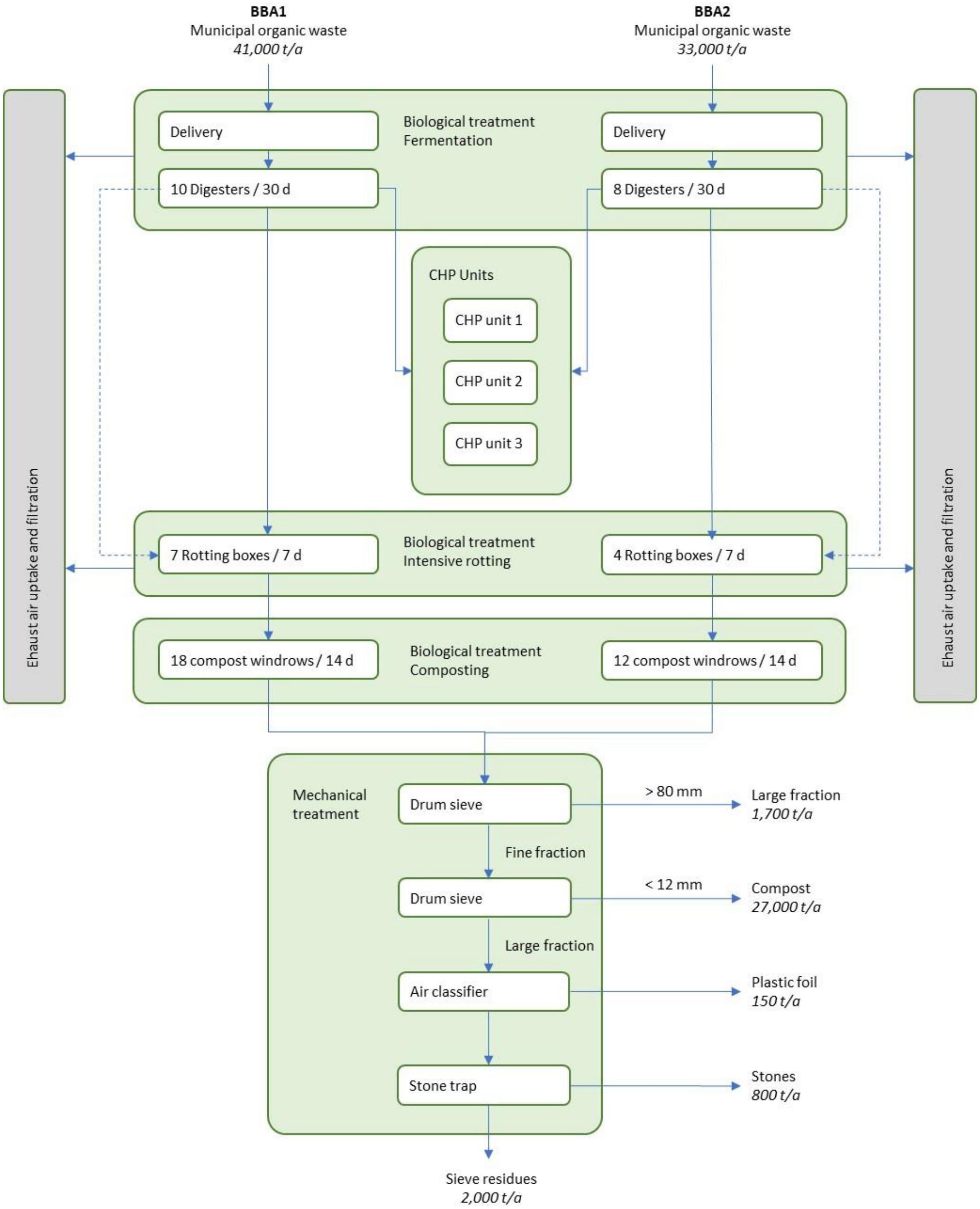

Figure 29 Flow diagram of the municipal organic waste treatment plant

3. *Electricity and heat generation*

Three CHP modules are responsible for converting the biogas into electricity and thermal energy – 625 kW (2008), 550 kW (2008) and 1,203 kW (2019). The electricity produced by the CHP units is mostly fed to the grid, but a portion is also used on-site. The facility has a capacity to produce nearly 25,000 m^3 of biogas daily, around 60% of which is methane. Part of the heat and power generated in the CHP units is used for the energy supply of the facility. The surplus generated electricity is fed to the grid, for which the plant currently receives a feed-in tariff. Surplus thermal energy is sold to neighbouring industrial facilities. The potential for heat production after the expansion of the facility also makes it possible to provide thermal energy for local households.

4. *Digestate processing*

After fermentation, the digestate is sent to aerobic intensive rotting boxes for 7 days, followed by 14 days in windrow composting. The compost is then sorted with a rotating drum filter. The compost is sold to various agricultural customers.

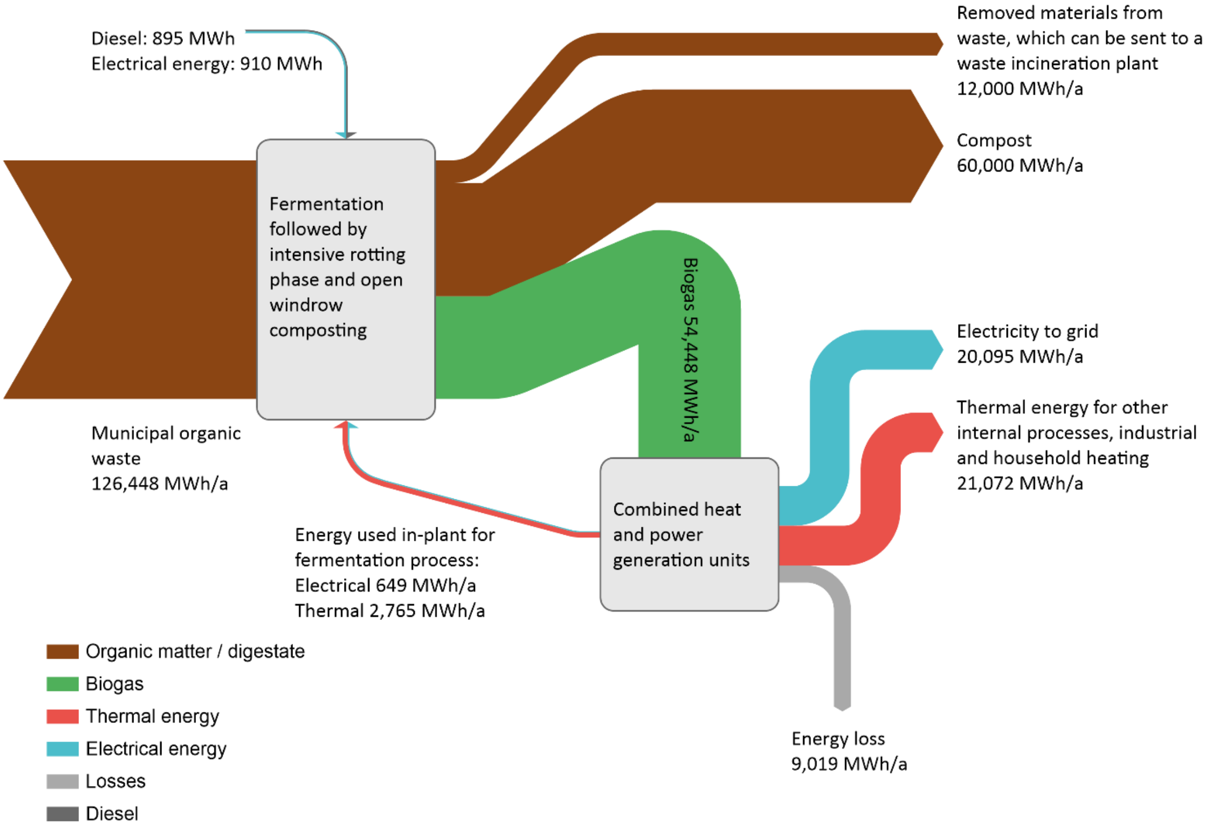

Figure 30 Sankey diagram of energy balance[1]

[1] Material flow data based on Figure 3. Energy content of municipal organic waste based on values from Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL). Energy content for compost and removed foreign material based on Ramke, H., Plausibilitätskontrollen in der Analytik von Zuordnungsparametern fester Siedlungsabfälle from Fachgespräch Feststoffuntersuchung 2008. Electrical and thermal energy generation based on CHP specifications. In-plant electrical and thermal energy use for fermentation based on Knauer, T., Scholwin, F. & Nelles, M. Maximizing the Energy Output from Biogas Plants: Optimisation of the Thermal Consumption of Biogas Systems. *Waste Biomass Valor* **9,** 103–113 (2018). https://doi.org/10.1007/s12649-017-9920-2

5. Conclusions for cast seaweed treatment

The plant attempted to use cast seaweed as a substrate in 2009 and was not convinced that it should be further pursued due to the large amounts of sand and water it contained. In addition, the input feedstock increases significantly in spring and summer months, which coincide with the time that more seaweed is collected. Therefore, a solution, which concentrates the organic fraction and reduces the amount of non-organic fraction being transported, is desirable. One possibility may be the collection and storage of the cast seaweed with protection from rain, in order to allow it to ferment (butryic acid fermentation) and collect the leachate. The leachate can then be used in the biogas plant. It is mostly free of inorganic material and can achieve a gas yield similar to maize. The nutrients can also be recycled.

In the nearby town Eckernförde (about 20 km from the AD site) an average of 1,300 tons/year of cast seaweed are collected, which are currently composted. The composting plant is closer to the beach. If the storage option is implemented it would make the most sense economically for the municipality (beach cleaner) to investigate if they have a site near the beach for this purpose. The municipality currently has a yearly cost of around 40,000 Euros for disposal, which could be used as a basis to determine the economic feasibility.

Case Study 5: Municipal residual waste plant in Rostock, Germany

Case study partner: Rostock University

Location of the case study: Rostock, Mecklenburg Vorpommern, Germany

Aim of the case study: Assessment of the feasibility of using cast seaweed as a feedstock in a municipal residual waste treatment plant

1. Introduction

The AD plant, which went into operation in 2007, is located approx. 12–15 km from the nearest beaches. It is part of a facility that includes the mechanical-biological treatment of residual municipal household waste. The waste is separated into different fractions and treated accordingly. The residual household waste is sorted at the plant for a <60 mm organic fraction. The kitchen and canteen waste is cut to 1 cm and pressed to obtain the liquid fraction. The canteen waste is sent to the AD plant along with the fraction <60mm from the municipal residual waste. Afterwards, it is combined with other fractions and treated in intensive rotting tunnel. Finally, the waste is composted in windrows and then dried to be disposed of as derived fuels.

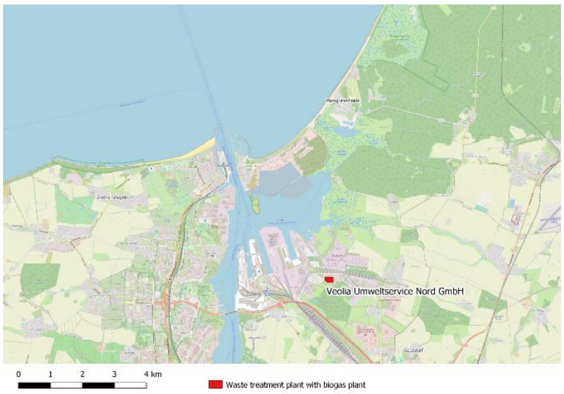

Figure 31 Location of the municipal residual waste treatment plant

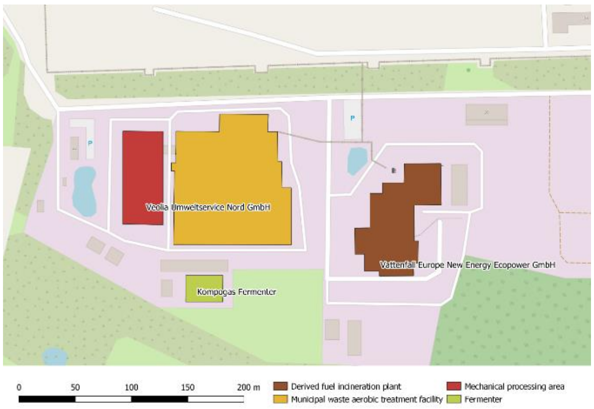

Figure 32 Layout of the municipal residual waste treatment facility

2. Anaerobic fermentation technology

The waste is fermented in three single-stage, Kompogas fermenters, each with a net volume of 1,200 m³ and typical plug-flow stirrers distributed lengthwise in the horizontal fermenter. The feedstock is considered "dry" (average around 35% total dry matter content) and consists of 40,000 tons/year mechanically-processed waste (fine fraction <60mm from residual household waste) and wet waste (canteen waste). The dry matter content of the fine fraction is between 45% and 55%, the canteen waste has a dry matter content between 15% and 25%. The thermophilic dry fermentation fermenters operate at approx. 50°-55°C and the feedstock has a retention time of 12-16 days.

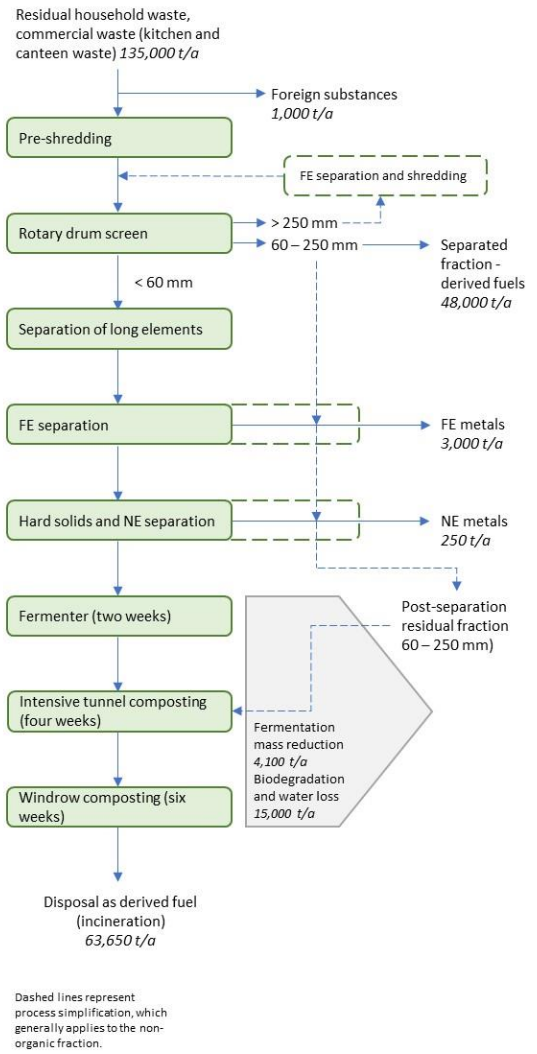

Figure 33 Flow diagram of the municipal residual waste treatment plant

3. Electricity and heat generation

The facility produced 4,753,464 m³ biogas in 2020. Veolia oversees the process up to the production of raw biogas and is obligated to deliver biogas with an average annual methane content of 55%. The gas upgrading unit is designed for a nominal output of 350 m³/h in standard conditions and the plant operators try to distribute the gas production as evenly as possible. The upgraded biogas (biomethane) is stated as having >95% methane content, but it can be assumed to be more since the upgrading plant is an amine scrubber, which typically has the highest levels of methane purity (over 99%) and very little methane losses (less than 0.1%). In 2020 12,828 MWh or around 1,286,660 m³ of biomethane were fed to the gas grid.

Since the feedstock includes the organic fraction of residual household waste, the digestate is considered contaminated and is incinerated (see below under digestate processing).

4. Digestate processing

After intensive tunnel composting along with the rest of the residual waste, windrow composting and drying the output (not only digestate) approx. 63,650 tons/year refuse-derived fuel is delivered to the immediate neighbouring plant, EBS-HKW Rostock, for incineration.

Due to the fact that the biogas plant is part of a mechanical biological treatment plant, which means that it processes waste, which is not source separated, it is not possible to use the digestate as fertiliser.

5. Conclusions for cast seaweed treatment

The AD plant does not have sufficient storage space or facilities for the cast seaweed. The feedstock could theoretically be used directly in the plant, but the sand would be mixed with the contaminated waste and would not be suitable for redistribution on the beach. On the other hand, digestion at the plant may remain an option for cast seaweed with high levels of cadmium.

Another possibility is the collection and storage of the cast seaweed with protection from rain, in order to allow it to ferment (butyric acid fermentation) and collect the leachate. The leachate can then be used in the biogas plant. It is mostly free of inorganic material and can achieve a gas yield similar to maize. Once the sand is drier and free of most of the organic fraction it can be redistributed at the beach.

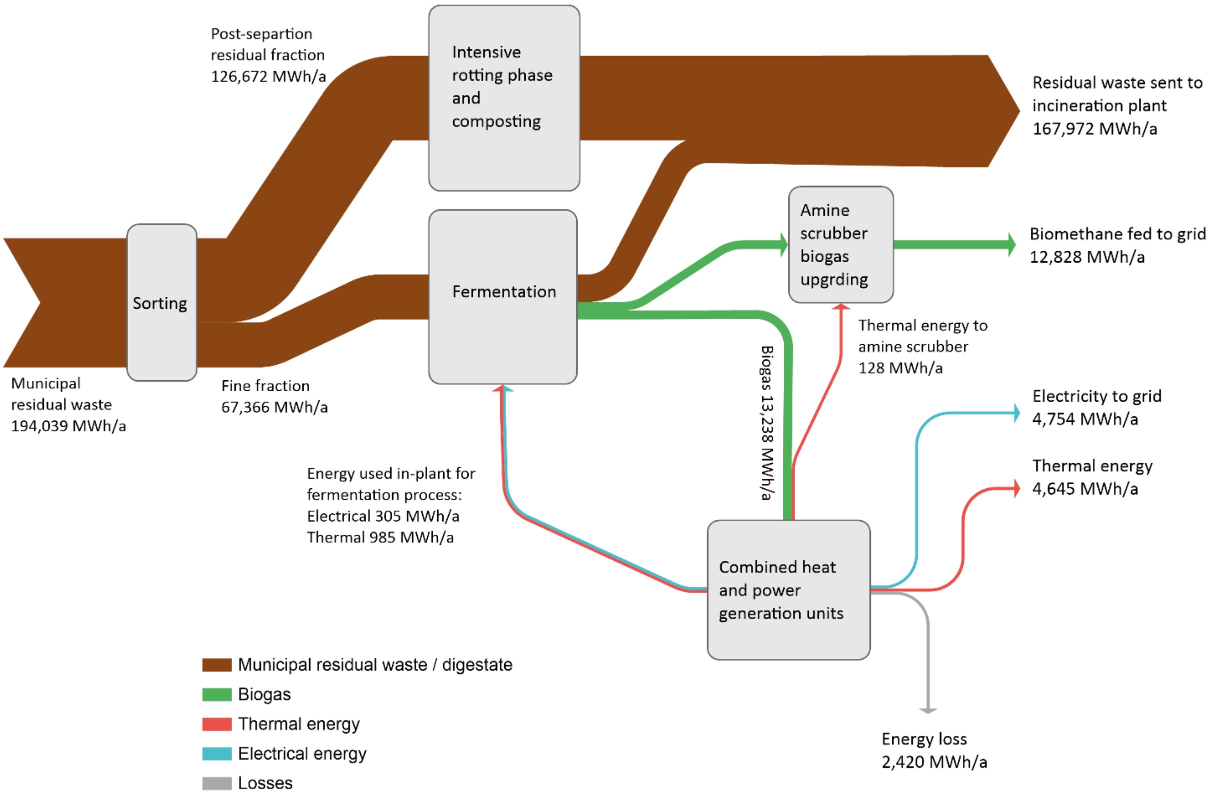

Figure 34 Sankey diagram of energy balance[2]

[2] Material flow data based on Figure 3. Energy content of municipal organic waste based on specific values from 2020 (approx. 58 m3/t organic fraction). Energy content for compost and removed foreign material based on Ramke, H., Plausibilitätskontrollen in der Analytik von Zuordnungsparametern fester Siedlungsabfälle from Fachgespräch Feststoffuntersuchung 2008. Electrical and thermal energy generation based on CHP specifications. In-plant electrical and thermal energy use for fermentation based on Knauer, T., Scholwin, F. & Nelles, M. Maximizing the Energy Output from Biogas Plants: Optimisation of the Thermal Consumption of Biogas Systems. *Waste Biomass Valor* **9,** 103–113 (2018). https://doi.org/10.1007/s12649-017-9920-2. Assumption thermal energy use amine scrubber 0.6 kWh_th/m3 biogas according to BMEL Bundesministerium für Ernährung und Landwirtschaft, 2019. Schlussbericht zum Vorhaben Effiziente Mikro- Biogasaufbereitungsanlagen (eMikroBGAA)

Case Study 6: Biogas Plant in Solrød, Denmark

Case study partner: Roskilde University

Location of the case study: Solrød, Region Zealand, Denmark

Aim of the case study: Assessment of cast seaweed applicability in anaerobic digestion with domestic households and manure

1. Introduction

"Solrød Biogas" plant was built in 2014-2015. The investment was made by public-private cooperation, between Solrød Municipality, suppliers, outlets and research institutions. The main idea of the facility was to reduce the problems of odour nuisances at the beach caused by decomposing seaweed and algae by removing the material and using it for biogas production and thereby reduction of nutrient content in the Baltic Sea. The facility reduces the use of fossil energy for electricity and heat production to cut down greenhouse gas volumes, in this way contributing to solving the climate problem. Residual products can be used for fertiliser on farms to replace synthetic fertilisers, typically produced by means of fossil fuels.

Figure 35. Solrød Biogas

The digestion system is based on one stage mesophilic fermentation process (42-44°C), using closed anaerobic digester.

The substrates that are used for the digestion are organic fractions from domestic and agricultural waste (around 90%), seaweeds (around 0.5%), and manures (around 9.5%). Dewatered digestate is further mixed with 15% pectin, and the final product is pellet, which goes to the farms. The biogas produced consists of CH_4 (55%), CO_2 (45%) and SO_4^{2-} (8ppm).

Figure 36 ***Fermentations tanks***

The process provides sufficient amount of biogas used for CHP generation. 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. In Denmark, only the biogas of methane content of 99-100% can be injected into the gas grid.

Figure 37 ***CHP generator***

2. Biogas plant

The "Solrød Biogas" processes around 220,000 tons/year of biomass. Biogas plant is equipped with installations that enable organic wastes, seaweeds collection and transporting. The manure, farm, sea and domestic wastes, in the proper ratio (mostly in liquid state) are introduced into tank where biomass is heated in 70°C for 1 hour and next is cooled down to 45°C. The mixing speed is 15 rpm and the solid particles are cut into smaller particles below 12 mm. The pretreated mixture is introduced to three fermentation tanks, where the mesophilic process of fermentation lasts 35 days. Each of the tanks is 8,000 m^3. Sulphates present in the obtained biogas are separated using iron chloride. The cleaned gas can be stored in concrete tank of 2,000 m^3 or combusted. Produced energy is converted into electricity (by a gas engine) or heat (by heat exchangers). Biogas plant can produce 6,000,000 m^3 of methane, 23 GWh of electricity and 28 GWh of heat yearly. For that, 20,000 m^3 of water is consumed for seaweeds washing. No heat loss from bioreactors is observed.

Figure 38 Gas cleaner (contain Iron Chloride)

Solrød Biogas has five employees and their annual maintenance costs are 420,000 DDK. They are responsible for overseeing the operation of the biogas plant, collecting and transporting seaweeds (about 4 km from coast), distribution of energy and heat, mixing digestate with pectin and distribution as an organic fertiliser (CP Kelo).

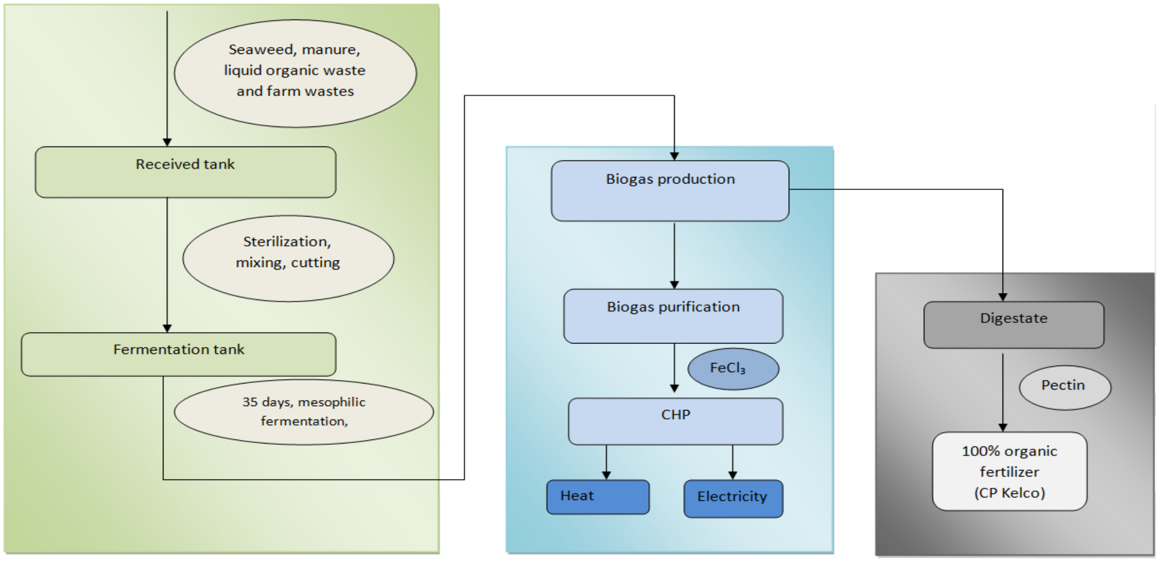

Figure 39 Flow chart at "Solrød Biogas

3. Biogas production

Biogas plant consists of 3 reactors (each 8,000m^3), 2 raw material tanks (each 2,000 m^3), gas cleaning system, 1 heat exchanger (1,900kWh), 2 concrete storage tanks for raw materials (around 1,700 m^3), 1 CHP generator with gas engine, chimney and air filters. The additional element is hall, where organic fertiliser is produced.

The main reason why the biogas plant was established was unusual problem of seaweeds on the coast.

Figure 41 Seaweeds washed ashore at low tide

This specific raw material is collected from coast by tractors, transported into biogas plant, washed from sand and introduced to the tanks. Sometimes, seaweeds are stored in receiving tanks. The ratio of biomass introduced into the tanks depends of amount of seaweed. Collected seaweeds cannot be stored longer than 3 days to prevent from decomposition. For that reason, the investor decided to process other organic waste. The amount of seaweeds in processed material is only 5%.

Figure 40 Organic waste stored in concrete tanks before fermentation process

Figure 42 ***Biogas stored tanks***

4. Management of marine biomass

Marine biomass is collected from the coast following a local vision. When medium amounts of seaweed are observed, the collection of biomass starts. Along with the collection of biomass, samples for elemental analyzes are collected from 20 places.

Table 15 Results of elemental content of seaweeds in 2009-2013

Parameters	**Average [mg/Kg dry matter]**	**Limit value [mg/Kg dry matter]**
N (total)	46, 340	Non
P (total)	732	Non
Pb	< 3.58	120
Cd	0.52	0.80
Cr	<2.40	100
Hg	0.01	0.80
Ni	3.5	30
Zn	38	4, 000
DEHP	<0.50	50
Nonylphenol	0.64	10
PHA (sum of 9)	2.41	3
LAS	<40	1, 300

There are three steps for the collection of marine biomass:

- seaweeds are picked up by tractor with grate grad directly from water,
- dewatering collected biomass,
- transport to the biogas plant.

Biomass treatment at the biogas plant takes place in four steps:

- Seaweed is put in a tank with very strong stirrer.
- The stirrer separates sand and seaweed.
- The sand is removed from the bottom of the tank.
- Seaweed is decomposed and diluted with additional material from the biogas reactor to make it pumpable and pumped into the biogas reactor.

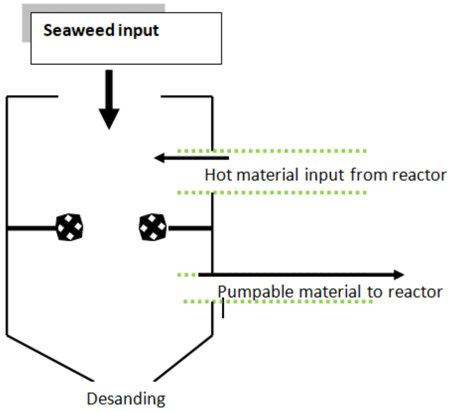

Figure 43 ***Scheme of seaweed treatment***

If too much marine biomass is collected in a windy day, it is stored in tank up to 3 days.

5. Electricity and heat regeneration

Facility produces 12,000,000 m^3 of methane, 25,000 MWh of electricity, 32,000 MWh of heat. Heat is transferred by pipes (around 15 km) to the local heat supply.

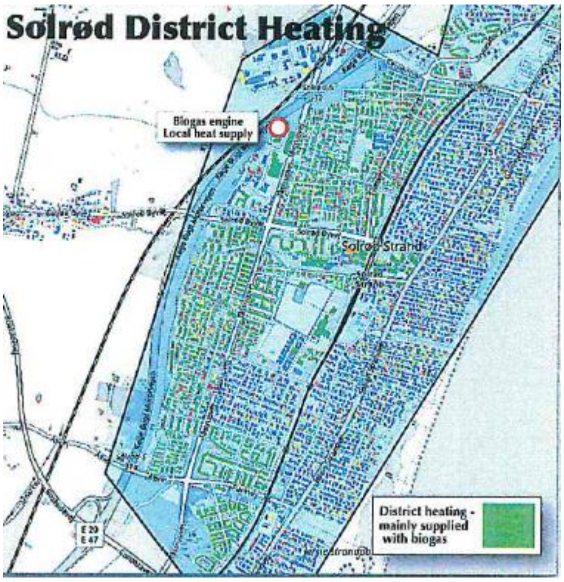

Figure 44 Solrød heating and electric district

Solrød Biogas plant:

- produces 50,040MWh,
- input energy: 53,100MWh,
- efficiency: 94%,
- raw materials: waste/residues,
- water consumption: 0 tons/year,
- residues in dry matter: 185.000 tons,
- Used as fertiliser: 100%,
- Green house: 40,100 tons,
- Recycled carbon: 8,440 tons,
- Recycled nutrient: 1,180 tons,
- Externality costs (water, landfill and greenhouse gases): + 1.1 million $

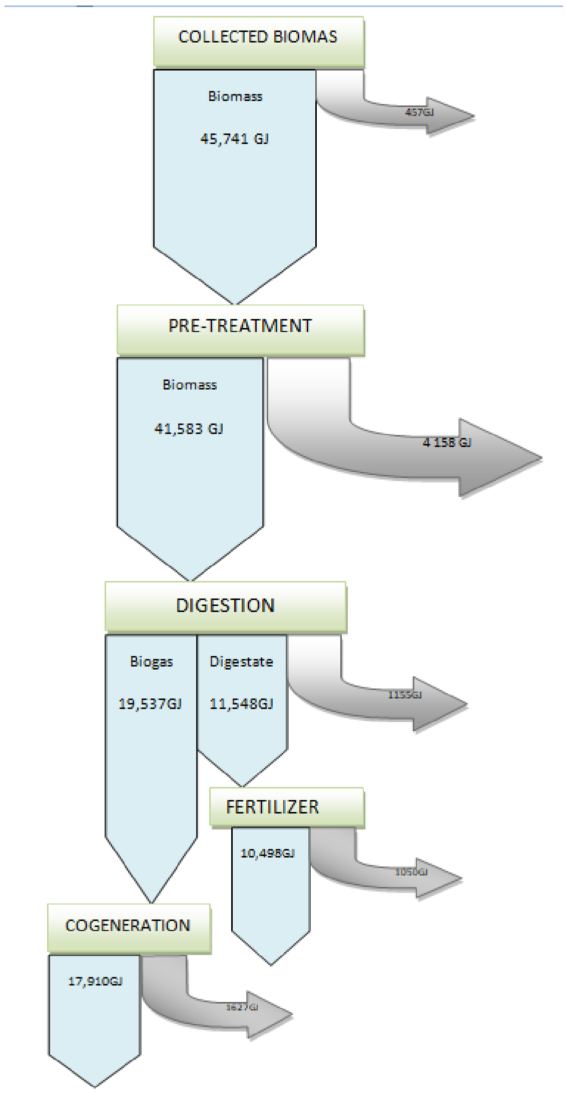

Figure 45 Algae energy balance

6. Digestate processing

Digestate, the second product of an anaerobic digestion, is mixed with pectin. The blinded material comes from fried lemon peels and it is transported do biogas plant by trucks. The material is unloaded and fed into the feeder by excavated bucket in covered hall. During the blending process, lemon peel adsorbs the liquid digestate. Then, this pulp is transferred into the pellet-producing machine. The pieces of the final product are lover than 12 mm. "CP Kelo" is 100% organic fertiliser, which is stored in plastic bags before comes to farmlands. In one year, the "Solrød Biogas" generates 107,000 tons of pellets. Produced plant food meets the requirements started by the decision of the Danish Government and has been sold by "Huber

Company”. Fertiliser is rich in carbon and other valuable substances, due to the diversity of substrates utilised as a feedstock for an anaerobic digestion.

Figure 46 Fried lemon peels transported to biogas plant

Figure 47 Pellet conveying with an excavator bucket

Figure 48 Pectin feeder before mixed with liquid digestate

Figure 49 Cutting machine used for producing organic pellet

Figure 50 Organic fertiliser stored in plastic bags before sale

7. Conclusions

“Solrød Biogas” produces digestate and biogas from cast seaweed. The seaweed is a problem to a number of residents in the region. The most important issue that should be considered in the use of seaweed is to collect and prepare biomass for the process. The transportation cost would be low due to the close neighbourhood of the coast. Moreover, mostly asphalt road are advantageous for the seaweeds transportation. Investment in biogas plant has brought benefits for environment:

- Solve problem with odours from seaweed and algae by removing the seaweed and use it in biogas,
- Contribution to solve the climate problem: using seaweed and organic waste from Kelco in biogas plant will contribute to reduce the use of fossil fuels in the energy consumption in the area,
- Contributing to solve problems with marine pollution. Removing the seaweed of the Køge Bay will diminish the load of nutrients, which today is a major problem of the aquatic environment,
- Contribute to useful nutrients recovery. The residues from the gas plant will be use for fertiliser to replace chemical fertiliser.

5. Environmental ecosystem benefits

Costal and marine ecosystems deliver a wide range of services. They are affected by the solutions developed within the project. The changes are estimated and discussed in this chapter.

5.1. Current status

One of the main problems in the Baltic region is eutrophication. This is a result of excess input of nutrients into the sea that causes several negative effects, such as elevated growth of sea plants, turbidity, changes in biodiversity and low oxygen level. The annual loss of benefits resulting from these effects is assessed to be almost 4,500 million Euros in the Baltic Sea Region.

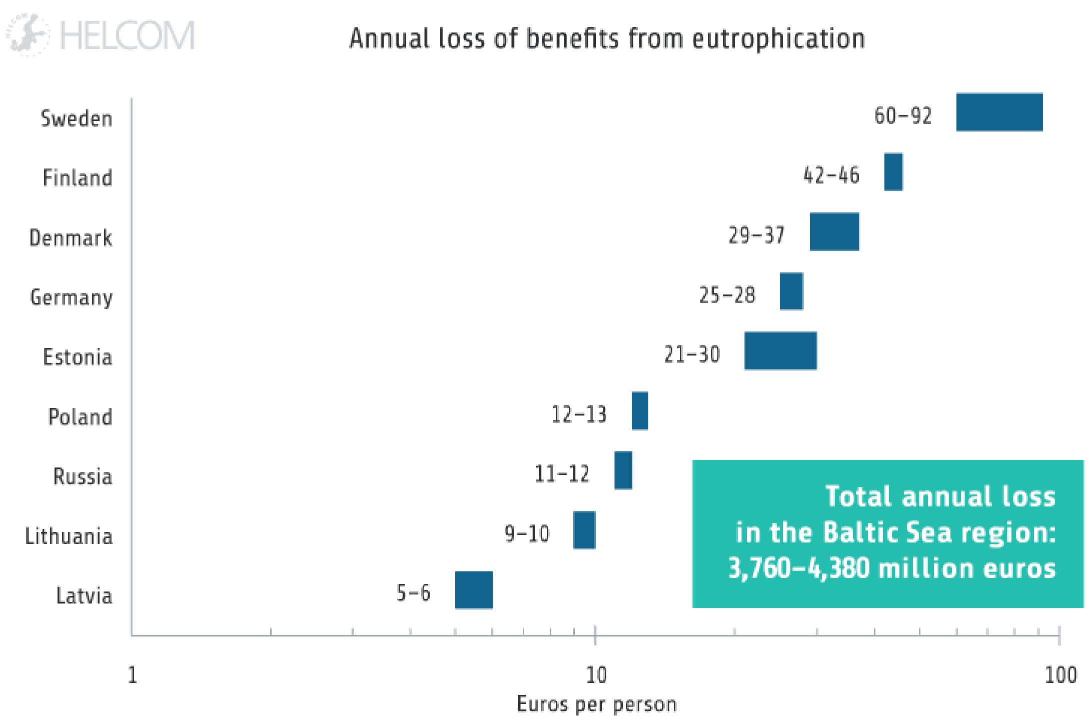

Figure 51 Economic costs of eutrophication [7]

According to the HELCOM integrated status assessment for 2011-2016, 96% of the Baltic Sea area suffers from eutrophication. In most of the South Baltic countries, the status of both open sea and coastal areas is considered as “not good” completely. The assessment includes three groups of criteria: nutrient levels, direct and indirect effects. Among the direct effects, water clarity, cyanobacterial bloom index and Chlorophyll-a concentrations are taken into account. Whereas indirect effects cover oxygen debt and macrofauna state indicator.

In Table 16 eutrophicated area in each country is given

Table 16 Eutrophicated areas in South Baltic region *[8]*

Country	Open sea [km^2]	Coastal [km^2]	Total [%]
Germany	11,300	4,200	100
Denmark	29,000	17,317	99
Lithuania	6,200	600	100

Poland	27,000	2,600	100
Sweden	117,000	26,100	100

The total input of nutrients into the Baltic Sea estimated by HELCOM in 2014 was 825,825 tons of nitrogen and 30,949 tons of phosphorus, of which 529,583 and 22,273 originated from rivers, respectively. Riverine input focuses mainly on the seven biggest rivers. About 55 million people live within their catchment area. In southern regions, the agricultural activity is more intense resulting in higher nutrients input. The rivers Nemunas, Vistula and Oder show the highest nutrient input as almost 50% of their catchment area is cultivated. Detailed analysis was performed by HELCOM [9]. If the current status is preserved, further nutrients income is expected.

5.2. Ecosystem services

Ecosystem services are all the goods material and non-material that human benefit from ecosystems for free. Marine ecosystem services (ES) can be divided into provisioning, cultural, supporting and regulating. There are 24 ecosystem services classified in the UN Millennium Ecosystem Assessment that are used in the analysis.

Provisioning:

P1	food – fish, algae, etc.
P2	non-food goods – rocks, sand, industrial water
P3	energy – waves
P4	waterways and area – shipping, platforms, wind turbines
P5	chemical substances – medicine, biotechnology, cosmetology
P6	other resources – amber, seashells
P7	genetic resources - DNA

Regulating:

R1	climate and air – oxygen production, CO_2 absorption
R2	sediment retention – sediments reduce risk of erosion
R3	eutrophication – N and P uptake by organisms
R4	biological regulation- balance between species , cohabitation and symbiosis
R5	pollutants – degradation or storage in the sediments

Supporting:

S1	geochemical cycles – N, P, C, O, H_2O
S2	production – algae from sunlight and nutrients
S3	food chain – formation of phytoplankton, decomposition of dead biomass
S4	biodiversity – variety of microorganisms, plant, animals
S5	habitats – environment of living for all the species
S6	resilience – ecosystem resistance to changes

Cultural:

C1	recreation – swimming, sports, fishing, tourism
C2	aesthetics – water, beaches, scenery
C3	education and science – data for environmental studies and museums
C4	cultural heritage – historic finds, wrecks, villages
C5	inspiration - art, music, film, literature
C6	legacy – for future generations

5.3. Drivers of change and scenarios

Drivers of ecosystem services are defined as human-induced factors that cause change in ecosystem and resulting services.

The main direct driver of activities proposed in COASTAL Biogas project in eutrophication that is a major concern in the Baltic Sea. Eutrophication though is a result of a surplus of nitrogen and phosphorus in water originating from emissions mainly from agriculture. Another driver is therefore improper fertiliser and land use as well as growing resource consumption. This is not only a result of population growth, but rather of technology changes, economic, social, cultural and political changes and most of all welfare and economic prosperity. All those factors cause increase in energy use and climate changes. Therefore, research on new effective methods of energy production and on new resources is extensively conducted.

Environmental services benefits assessment was performed for three scenarios. Scenario 1 presents current state when excessive marine biomass is not used for biogas production. This is the initial state to which scenarios 2 and 3 are compared. Scenario 2 is based on the seaweed use for biogas and fertiliser production, whereas in Scenario 3 biomass is utilised in anaerobic digestion producing biogas however, digestate is gasified instead of used as fertiliser. The Scenario 3 is relevant when the digestate cannot be used in the field according to high heavy metals content.

Table 17 Summary of scenarios

Scenario 1	Scenario 2	Scenario 3
Eutrophication	Eutrophication reduced	Eutrophication reduced
Cast seaweed	Clean beaches	Clean beaches
Smell	Clean air	Clean air
Touristic value	Tourism increased	Tourism increased
Use of renewable resources	Biogas produced	Biogas produced, syngas produced
Consumption of mineral fertilisers	Mineral fertilisers replaced with digestate	Mineral fertilisers used

5.4. Environmental services benefits in the Baltic Sea

Besides improvement of environmental services directly in the Baltic Sea that are described below, there are additional benefits resulting from scenarios in a wider perspective of Baltic region.

Table 18 Estimation of environmental services benefits in the Baltic Sea

Ecosystem service		Scenarios		
		1	2	3
Provisioning	P1	↓	↑	↑
	P2	✗	✗	✗
	P3	↑	✗	✗
	P4	✗	✗	✗
	P5	✗	✗	✗
	P6	✗	✗	✗
	P7	↓	↑	↑
Supporting	S1	↓	↑	↑
	S2	↓	↑	↑
	S3	↓	↑	↑
	S4	↓	↑	↑
	S5	↓	↑	↑
	S6	↓	↑	↑
Regulating	R1	↓	↑	↑
	R2	↓	↑	↑
	R3	↓	↑	↑
	R4	↓	↑	↑
	R5	↓	↑	↑
Cultural	C1	↓	↑	↑
	C2	↓	↑	↑
	C3	✗	✗	✗
	C4	✗	✗	✗
	C5	✗	✗	✗
	C6	↓	↑	↑

⬆	- Increase in service
⬇	- Decrease in service
✕	- No impact

PROVISIONING

Food – fish, algae, etc.

The consequences caused by increased nutrient load in the Baltic Sea are broad. Enhanced pelagic primary production decrease secchi (photic) depth, thus low oxygen conditions can be found in both: water column and seafloor. This phenomenon affects marine habitats and the fish stocks negatively. The dominating fish species in the Baltic Sea are cod, herring, sprat and they constitute around 80% of the total fish biomass. Those species provide important environmental services, they are human source of food and constitute significant element of marine environment [10].The number of Total Allowable Catches (TAC) was proposed by European Commission basing on the scientific advice. Fish stock of Baltic Sea is in alarming situation, the fishing opportunities are decreasing especially for the main target fishing species such as cod, herring. For 2020, TAC proposed for Western Cod is 3,065 tons and was reduced by 68% comparing to 2019, western herring catch total is 2,651 tons and has decreased by 71%. Eastern cod can only be by-catch. For herring reduction come to 25% [11]**.** Using the cast seaweed for biogas production, could decrease the number of algae in coastal areas and lowering the hypoxic level in the water reservoir, providing the fish more suitable living conditions.

Non-food goods – rocks, sand, industrial water

Eutrophication or seaweed collection does not influence rock or sand sources.

Energy – waves

Since waves are mostly dependent on wind ant its direction, algae blooms does not have an impact on it.

Waterways and area – shipping, platforms, wind turbines

The excessive phytoplankton blooms mosly occure in the coastal areas, so they don't impact shipping. Seaweed does not affect platforms or wind turbines.

Chemical substances – medicine, biotechnology, cosmetology

Chemical substances produced by algal blooms in the Baltic Sea are not commonly use in medicine or in biotechnology. Algae used for these purposes are sourced by specialized cultivations.

Other resources – amber, seashells

Excessive marine biomass does not affect amber, seashells resources.

Genetic resources – DNA

The extensive algal biomass load in the Baltic Sea diminishes DNA resources and alter biodiversity. Habitat deterioration associated with oxygen depletion, poor lighting conditions and increased nutrient load disrupt biological conditions of the Baltic Sea. Eutrophication contribute to species die off and as a result exert a negative impact on ecosystem, lowering the DNA variation. Genetic diversity is crucial for adaptation of ecosystem to changing conditions [12]. Reducing algae biomass in coastal areas would improve water conditions of Baltic Sea.

SUPPORTING

Geochemical cycles – N, P, C, O, H2O

Natural nitrogen removal process is microbially mediated and leads to N_2 gas formation, allowing nitrogen to escape the water column to the atmosphere. In the process both oxic and anoxic conditions that are needed, so usually denitrification takes place in the sediments. Sediments in hypoxic areas release and accumulate nitrogen as ammonium instead of removing the nitrogen. Eutrophication increases inorganic and organic carbon content and ratio of total dissolved organic carbon to microbial available organic carbon increase [4]. It is assassinated that in 20th century the pelagic primary production increased by 30-70%, and sedimentation of organic carbon by 70-190% [5]. Increased primary production also impact oxygen cycle, the deposition of organic material and its decomposition leads to higher oxygen consumption at the seafloor. Oxygen debt increased from around 8mg/l in 1952 to 12mg/l in 2010 and has a tendency to increase, indicating deteriorating oxygen conditions. In anoxic condition phosphorous can be released from sediments, increasing its concentration in the water body and leading to further eutrophication advance [6]. Removing algae biomass could improve geochemical cycles, by increasing the oxygen availability and by removing nutrient content in coastal areas. Moreover, using digest from biogas production as a biofertiliser could close the nutrient cycle environment, by reducing usage of mineral fertilisers.

Production – algae from sunlight and nutrients

High availability of nitrogen and phosphorous increases the supply of organic matter in the sea, which stimulates the growth of primary producers and causes excessive phytoplankton blooms. Such water condition provides all important factors for algae to grow like: sunlight avalibility in the top water layer, carbon dioxide or nutrient fertilisers. The algae production can be expressed through increased chlorophyll-a concentrations in the water as a proxy of phytoplankton biomass. Baltic Marine Environment Protection Commission evaluated the average chlorophyll-a concentration in surface water between 2011 and 2016 and determined threshold values. For most of the Baltic Sea regions the threshold value of chlorophyll-a was failed, hence the status of Baltic Sea is not good. For example, chlorophyll-a concentration value in Gdansk Basin for 2011 was above 2 µg l^{-1} and had increased to above 5 µg l^{-1} in 2016 with threshold value 2.20 µg l^{-1}. The good status was achieved only in Kattegat which is the one of 17 assessment units [13]. Removing algae from coastal areas could improve the status of Baltic Sea and mitigate the consequences of phytoplankton blooms.

Food chain – formation of phytoplankton, decomposition of dead biomass

Eutrophication distrupt food chain system. Diatoms and dinoflagellates, as primary producers, have an essential role in food web dynamics of the Baltic Sea. The changes in amount and in ratio of those phytoplankton groups may affect the nutrition of zooplankton and have an impact on the productivity of higher trophic levels in all pelagic habitats. Extensive phytoplankton blooms inhibit large zooplankton grazing, causing mass mortality of zoobenthos and consequently reducing food availability for different fish species, such as cod. The long-term trend of zooplankton biomass and mean size in the Western Gotland Basin was assessed as a useful measurement of the status of the pelagic food web. This biodiversity core indicator evaluates the zooplankton community structure and asses the status of the pelagic habitats. Zooplankton biomass decreased from 600 mg/m^3 in 1989 to below 200 mg/m^3 in 2016, mean size of zooplankton was also reduced below the threshold value [14]. Using seaweed as a biogas could improve coastal water quality and reducing zoobenthos mortality.

Biodiversity – variety of microorganisms, plant, animals

Due to extraordinary salinity gradient, Baltic Sea consist various habitat types and the diversity of species is higher than expected in such low salinity conditions. Nitrogen-fixing cyanobacteria blooms in summer are a natural phenomenon in the Baltic Sea. However, the phytoplankton blooms occurs more often and are more extensive. The biological diversity of coastal ecosystems decreases with increasing nutrient enrichment process and there are a few species that can benefit from eutrophication. Blue-green algae take an advantage of high nutrient content, most of other aquatic the species are in danger due to habitat deterioration caused by excessive phytoplankton blooms.

The number of zoobenthic species in the Gulf of Finland was assessed. Species richness and abundance of benthic animals significantly decreased from around 6,500 individuals per m^2 in 1996 to below 1,000 in 2014. The biodiversity core indicator 'State of the soft-bottom macrofauna community' was evaluated that accounts proportion of sensitive and tolerant species, species richness and abundance of benthic animals. The rapid decrease of benthic quality index can be noticed in 1994 [15]. Benthic communieties are negatively affected by eutrophication, algal blooms makes water less transparent, and reduces light intensity in the bottom water causing a larger perennial macroalgae disappear and lower their growth. The benthic community on hard substrates is dominated by brown and red seaweeds and the abundance of benthic community have decreased, contributed to habitat loss of zoobenthos population. Lost in essential spiecies like bladder wrack macroalgae, that transforms bare rock into living environments, influence other aquatic species altogether [15]. Reducing the opportunist algae from coastal area could enable other species to develop and to survive, hence improving the biodiversity of Baltic Sea.

Habitats – environment of living for all the species

Exceed algal blooms enhance the oxygen consumption at the seafloor followed by increase deposition of organic material. The oxygen deficiency and production of toxic gases (like hydrogen sulphide), produced by phytoplankton species, can result in oxygen depletion areas in the bottom water, so-called dead zones. Poor bottom conditions lead to the abundance loss of habitat-forming species such as: bladder wrack, eelgrass, stonewort. This phenomenon changes the oxygen and light conditions and reduces the availability of benthic habitats. Benthic macrofauna provide important ecosystem services, they are a common component in the fish diet, they have an ability to form habitats for fauna and facilitate the mineralization of settling organic matter [16]. Oxygen-depleted bottom water contribute to habitat loss and decline of population of benthic macrofauna. In the Baltic Sea dead zones areas (i.e. concentrations of oxygen below 2 ml l^{-1}) increased from around 5,000 km^2 to over 60,000 km^2 in over past century [17]. Removing seaweed from seashore could reduce the hypoxic zones of Baltic Sea and improve quality of benthic habitats in coastal areas.

Resilience – ecosystem resistance to changes

Algal blooms reduce water circulation and increase sedimentation of organic matter. Reduced circulation influence the natural nitrogen removal process, which is ecosystem service mitigating eutrophication and has significant impact on species abundance. Biodiversity losses and genetic diversity make Baltic Sea more vulnerable to changing environments, since homogenic ecosystems are less resilient to changes. The dependence between number of species, ecosystem productivity and stability over time is undeniable. Variety of species is important for ecosystems function effectively, since lack of highly specialized and key species can negatively influence ecosystem function, increasing its sensitivity to anthropogenic and natural perturbations [18][12]. Reduced amount of algae in shore areas could improve water circulation and water self-purification processes, reducing biodiversity losses and making Baltic Sea more resistance to changes.

REGULATING

Climate and air – oxygen production, CO2 absorption

Phytoplankton constitute the largest biomass responsible for oxygen production through photosynthesis [19]. However, due to eutrophication, the consumption of oxygen in the water body significantly increase. The increased nutrient load, thus increased organic matter production and reduced water exchange lead to the oxygen deficiency in the water body. Bacteria responsible for dead plants digest, use oxygen for digestion purposes and release the carbon dioxide. Before industrialization the water partial pressure of carbon dioxide, which is proportional to the CO_2 concentration, were slightly above atmospheric values. With increasing industrialization Baltic Sea, the emissions were above the CO_2 absorption and in 2002, the annual release was evaluated to be around 30% higher than uptake. Following years confirm that the net effect is a net release of CO_2 to the atmosphere. However, there are large variations between years and the Baltic Sea alternates between being a sink and a source [20]. The CO_2 distribution depend on seasonal variation in light availability, weather conditions and alkalinity. CO_2 dissolves in water, forming weak acid, decreasing the pH value of the Sea. CO_2 production of Baltic Sea caused by eutrophication contributes to the global warming problem and sea acidification [21]. Algae collection could decrease deposition of organic matter and oxygen uptake by microorganism, responsible for algae digestion. CO_2 emissions from Baltic Sea would be reduced and its impact on global warming would be lower.

Sediment retention – sediments reduce risk of erosion

Soil erosion is a natural process responsible for shaping the physical landscape through the distribution of weathered materials produced by geomorphic processes. However, when soil erosion occurs in an accelerated rate due to anthropogenic activities, wind or water, deterioration or loss of the natural soil functions is likely to ensue. Soils perform a range of key functions, including food production, storage of organic matter, water and nutrients cycling, and habitat quality for a huge variety of organisms. Preserving soil resources through erosion prevention is a safeguard procedure to protect the ecological environment and the ability of soils to contribute to ecosystem functioning. Reduction from water additional amount of algae could help prevent the coastal before erosion.

Eutrophication – N and P uptake by organisms

Nitrogen and phosphorous are limiting nutrients for phytoplankton to growth, some algal species can benefit with increased nutrient concentrations that alter primary production. The nitrogen and phosphorous loads increased and the peak was noticed in 1980. In consequence, the nitrogen and phosphorous uptake by phytoplankton increased 6.5 and 6 times, respectively. Internal fluxes of nitrogen and phosphorus increased, due to high nutrient uptake by primary producers and intensified pelagic nutrient regeneration [22]. Excessive algae blooms disrupt nutrient cycling in coastal areas and causes the nitrogen and phosphorous to be more available for marine organisms. By lowering the algae number in the shore, the better nutrient cycling would be achieved. Reducing nitrogen and phosphorous availability for organisms would reduce nutrient uptake in the long-term.

Biological regulation- balance between species, cohabitation and symbiosis

Ongoing coastal eutrophication has significant influence on variability among living organisms in the Baltic Sea, including species that are responsible of maintaining ecosystem structure. Domination of diatoms and dinoflagellates during annual algae bloom, disrupt functioning of other coastal species like mussels or benthic seagrass. Marine species relay on benthic species abundance that are responsible for providing habitats and suitable conditions for adult and juveniles organisms. Seagrass meadows also provide suitable living conditions and enhance growth of microbial community that is responsible for nitrogen and phosphorous cycling. Proper nutrient regeneration is crucial for seagrass to grow and survive. The symbiosis between seagrass and bacteria plays important role in marine ecosystem dynamics, this relationship is also responsible for organic matter flow in the marine food chain [23]. However, benthic communities are highly vulnerable for changing conditions and hard to recover once lost. Occurring hypoxia in coastal area causes anaerobic bacteria to dominate in bentho-pelagic processes and leads to deterioration of bottom sea level. The abundance of seagrass decreased significantly, macroalgal species. In the HELCOM report, integrated biodiversity status for benthic habitats was assessed and only 31 % open sea areas show good status for soft-bottom habitats [14]. Algae in coastal areas disrupt the biological regulation, so its collection would help to maintain the natural balance between species.

Pollutants – degradation in the sediments

Increased growth of short-lived macroalgae enhance its sedimentation. Marine sediments are rich in organic matter, which is degraded by microbial activity, leading to high consumption of the oxygen in the bottom waters. Absence of oxygen facilitate the release of phosphorous from the sediments that stimulate further primary production. In addition, the contaminant sedimentation can occur during algae blooms, increasing contaminants uptake in the marine food chain. This extensive sedimentation affects natural processes of water purification by affecting the ability of sediments of bounding the contaminants. Hydrogen sulfide is produced in anaerobic processes and can be found in the bottom waters in highest concentrations. Usually, Fe(II) in sediments is responsible for binding the sulfides, produced by microbial activity. In anoxic regions and low reactive iron concentrations, free sulfide is accumulated in the sediments and bottom waters. Hydrogen sulfide has toxic effects on aquatic organisms in concentration higher than 14 $\mu mol/dm^3$, when hydrogen sulfide concentrations in Baltic waters vary from several to several hundred $\mu mol/dm^3$ [24]. Sediments have an ability to sink heavy metals. High concentrations of: copper, zinc or leads in sediments are mostly caused by discharges during industrial period. This ability of sediments to accumulate heavy metals is a threat for benthic habitats that are exposed for high concentrations of toxic substances [25]. Collection of algae in coastal areas would decrease the sedimentation and enhance the water purification processes, like ability of binding sulfides. It could also reduce heavy metal content in the Baltic Sea, by removing contaminated algae.

CULTURAL

Recreation – swimming, sports, fishing, tourism

Large amounts of marine biomass lead to high levels of nutrients in water bodies. The consequence of this is accelerated grow of algae and cyanobacteria blooms, which lead to two serious consequences. The first is a cyanobacteria bloom, which causes toxins to appear in the reservoir, thus making it impossible to use the water tank for recreation. The second is the decreasing level of oxygen in water for aquatic organisms and their subsequent death. These two causes will discourage tourists from visiting the region. Seaweed harvesting, will mitigate eutrophication and thus encourage tourists to visit the region and enjoy its attractions.

Aesthetics – water, beaches, scenery

Clear water and beaches create unique scenery that makes people often visit coastal places. Algae and seaweed floating on the water surface discourage tourists from enjoying the sights in such places. In addition, the decomposing matter itself emits an unpleasant odor and is an electrode that deters potential visitors. The collection of dumped marine biomass contributes to maintaining a pleasant coastal atmosphere for tourists, reducing nutrient inputs to the water and coastal erosion.

Education and science – data for environmental studies and museums

Algae are a source of research owing to their yet undiscovered properties. Some species are becoming extinct while others are yet to be discovered. Eutrophication in environmental terms is still an unresolved and unfavorable problem. It is therefore necessary to educate the public about the threats posed by algae, but also about the benefits they can bring.

Cultural heritage – historic finds, wrecks, villages

Algae have been present in the culture of coastal settlements since the beginning of time. They were used for healing, cooking, and making items such as nets. Sunken ships are full of seaweeds and bacteria. They provide new information about the organisms living in the deep sea and the conditions that exist there.

Despite its biological charms, the marine biome constitutes a certain stream of inspiration in art. It is described both in scientific publications and in popular adventure or fantasy books. In these genres, it is usually presented as a source of energy that will be used in the future. In movies, marine biomass is presented as a threat to humanity. In music, you can find the sound of algae moving through the water, or in advanced musical works, the story of their life. If one were to combine all these works into one, it would create a drama with a moral. The COASTAL biogas project is a substitute for what can be achieved through joint collaboration.

Legacy – for future generations

Management of marine biomass is still a problem for many countries. Along with raising people's awareness of environmental issues, it is also necessary to introduce new legal provisions on an ongoing basis so that the potential of seaweed is released and it is no longer just waste.

Table 19 Environmental impact assessment of the collection of seaweed in 3 scenarios

Aspect	Size of impact (A)			Frequency (B)			Local environment (C)			Local society (D)			|AxBxCxD|			Significance (|AxBxCxD| > 6)		
Collection																		
Emission:	1	2	2	2	2	2	2	1	1	1	1	1	4	2	2	x	x	x
Sewage:	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	x	x	x
Waste:	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	x	x	x
Soil pollution:	1	2	2	2	2	2	1	1	1	1	1	1	1	4	4	x	x	x
Raw resources consumption:	1	2	2	2	2	2	1	1	1	1	1	1	2	4	4	x	x	x
Other (noise, radiation, etc.):	3	2	2	2	2	2	2	3	3	2	2	2	8	24	24	Unfavorable appearance and odors of the seaweed at the beach is a problem for local society and visitors.	Noise related with machinery usage (backhoes, tractors etc.) might be disturbing for flora, fauna and people at the beach. Collecting the algae by wheel loaders could have a negative impact on landscape appearance.	

where:
Column 1 in aspects is scenario 1
Column 2 in aspect is scenario 2
Column 3 in aspect is scenario 3

A Size of impact: 3 – significant, 2- moderate 1- marginal
B- Frequency: 3- Continuous, 2- Periodic, 1- Never
C- Local environment: 3 – High, 2- Moderate, 1 - Low
D- Local Society: 3 – High, 2- Moderate, 1 – Low

The aspects is considered as significant if greater than 6.
X – aspect not significant

Table 20 Environmental impact assessment of the pre-treatment of seaweed in 3 scenarios

Aspect	Size of impact (A)			Frequency (B)			Local environment (C)			Local society (D)			|AxBxCxD|			Significance (|AxBxCxD| > 6)		
Pre-treatment																		
Emission:	1	2	2	1	2	2	1	1	1	1	1	1	1	4	4	X	X	X
Sewage:	1	2	2	1	2	2	1	2	2	1	1	1	1	8	8	X	Effluent produced during cleaning process in a float/sink separator.	
Waste:	1	2	2	1	2	2	1	2	2	1	1	1	1	8	8	X	Sand residue separated from biomass.	
Soil pollution:	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	X	X	X
Raw resources consumption:	1	3	3	1	3	3	1	1	1	1	1	1	1	9	9	X	Resources such as: chemical reagents (acid, bases) are needed to increase biodegradability of seaweed or source of energy for high- temperature processes.	
Other (noise, radiation, etc.):	1	2	2	1	2	2	1	1	1	1	2	2	1	8	8	X	Odors may appear during chopping, mixing and heating the biomass and potentially can be problematic for local society.	

where:
Column 1 in aspects is scenario 1
Column 2 in aspect is scenario 2
Column 3 in aspect is scenario 3

A Size of impact: 3 – significant, 2- moderate 1- marginal
B- Frequency: 3- Continuous, 2- Periodic, 1- Never
C- Local environment: 3 – High, 2- Moderate, 1 - Low
D- Local Society: 3 – High, 2- Moderate, 1 – Low

The aspects is considered as significant if greater than 6.
X – aspect not significant

Table 21 Environmental impact assessment of the processing of seaweed in 3 scenarios

Aspect	Size of impact (A)			Frequency (B)			Local environment (C)			Local society (D)			|AxBxCxD|			Significance (|AxBxCxD| > 6)		
Processing																		
Emission:	1	1	3	1	1	2	1	1	2	1	1	1	1	1	12	X	X	Gas emission during the gas formation process.
Sewage:	1	2	2	1	2	2	1	1	1	1	1	1	1	4	4	X	X	X
Waste:	1	2	2	1	2	2	1	1	1	1	1	1	1	4	4	X	X	X
Soil pollution:	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	X	X	X
Raw resources consumption:	1	2	3	1	2	3	1	1	1	1	1	1	1	2	9	X	X	All the resources that are necessary for gas formation process from biomass.
Other (noise, radiation, etc.):	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	X	X	X

where:
Column 1 in aspects is scenario 1
Column 2 in aspect is scenario 2
Column 3 in aspect is scenario 3

A Size of impact: 3 – significant, 2- moderate 1- marginal
B- Frequency: 3- Continuous, 2- Periodic, 1- Never
C- Local environment: 3 – High, 2- Moderate, 1 - Low
D- Local Society: 3 – High, 2- Moderate, 1 – Low

The aspects is considered as significant if greater than 6.
X – aspect not significant

Table 22 Environmental impact assessment of the utilisation of seaweed processing in 3 scenarios

<table>
<tr><th>Aspect</th><th colspan="3">Size of impact (A)</th><th colspan="3">Frequency (B)</th><th colspan="3">Local environment (C)</th><th colspan="3">Local society (D)</th><th colspan="3">|AxBxCxD|</th><th colspan="3">Significance</th></tr>
<tr><td colspan="19">Products utilisation</td></tr>
<tr><td>Emission:</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>8</td><td>8</td><td>X</td><td colspan="2">Uncleaned biogas emissions contain</td></tr>
<tr><td>Sewage:</td><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>2</td><td>1</td><td>1</td><td>2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>4</td><td>12</td><td>X</td><td>X</td><td>Liquid waste produced after gas formation process.</td></tr>
<tr><td>Waste:</td><td>1</td><td>3</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>12</td><td>4</td><td>X</td><td>Digestate may contain heavy metals or their compounds that may need to be removed.</td><td>X</td></tr>
<tr><td>Soil pollution:</td><td>1</td><td>3</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>12</td><td>4</td><td>X</td><td>Biomass produced from co-digestion of the cast seaweed and used as a bio-fertiliser may contain low levels of heavy metals.</td><td>X</td></tr>
<tr><td>Raw resources consumption:</td><td>1</td><td>1</td><td>2</td><td>1</td><td>2</td><td>2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>2</td><td>4</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Other (noise, radiation, etc.):</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>X</td><td>X</td><td>X</td></tr>
</table>

where:

Column 1 in aspects is scenario 1

Column 2 in aspect is scenario 2

Column 3 in aspect is scenario 3

A Size of impact: 3 – significant, 2- moderate 1- marginal
B- Frequency: 3- Continuous, 2- Periodic, 1- Never
C- Local environment: 3 – High, 2- Moderate, 1 - Low
D- Local Society: 3 – High, 2- Moderate, 1 – Low

The aspects is considered as significant if greater than 6.
X – aspect not significant

6. Concluding remarks

The amounts of cast marine biomass vary significantly in Baltic countries. Still there is a need to remove it from beaches to ensure safety, health and aesthetic values of the region. The potential of using cast seaweed is dependent of the residence time, litter amount and sand content. Feasibility analysis reveled that the one of the most important steps in utilisation of case seaweed for nutrients recovery and biogas production is the collection process. Beach cleaning operations can be performed using different machines, which give different results in terms of garbage collection and sand content in the biomass, which is the major concern in the process. Moreover, heavy machines can alter the coastline. Therefore, their use must be carefully planned.

Pre-treatment of collected biomass requires first of all sand removal and further fragmentation which can be followed by thermal, chemical or mixed treatment to increase bioavailability of biomass. If the biomass is collected fresh, from shallow water no specific additional equipment is needed in the biogas plant. If the sand is present it can be separated in a cone shaped stirred tank.

In general, the amounts of maritime biomass enable its use directly after collection and no additional storage space is required. In case of heavy winds and enhanced biomass input to the beaches, the amount of seaweed should not be more than to cover one or two days of storage and in most cases have enough storage space at site.

The maritime biomass can be used as a co-substrate and it is known from the experiments conducted within Work Package 4 of the COASTAL Biogas project that is does not affect the process negatively ensuring optimal addition and acceptable heavy metals level.

Resulting digestate can be further processed for the production of rich in carbon, nitrogen and other valuable substances, due to the diversity of substrates utilised as a feedstock for an anaerobic digestion.

Taking into account factors affecting the feasibility of using cast seaweed for the recovery of nutrients using anaerobic digestion, maritime biomass can be a valuable source of carbon and nitrogen, which can be relatively easy in handling if appropriate method of collection and pretreatment is applied.

As a conclusion in Figure 52 of aspects affecting the development of AD technology for seaweed digestion are presented and strengths, weaknesses, threats and opportunities for the use of cast seaweed are specified below.

Strengths of nutrients recycling by anaerobic digestion of cast seaweed

environmental	ecosystem services increase renewable energy production sustainable use of natural resources eutrophication reduction GHG emission reduction
technical	already existing infrastructure ease of biomass handling
economic	energetic independence low cost resources low cost of production of valuable gas and fertiliser low competitiveness
social	improvement of coastal areas new job positions

Weaknesses of nutrients recycling by anaerobic digestion of cast seaweed

environmental	collecting machines intrude the beaches cast seaweed can be considered as a habitat transportation of biomass from the beach causes GHG emission
technical	biomass can be contaminated with sand and garbage prediction of cast seaweed amounts is difficult amount of biomass vary due to the season
legal and economic	complex procedures to obtain permissions legal restrictions unclear responsibility for the Baltic Sea environment heavy metal contents could be too high to use the digestate as fertiliser
social	risk of noise from the collecting machines objection to habitats destruction

Opportunities of nutrients recycling by anaerobic digestion of cast seaweed

environmental	progressive eutrophication provides more biomass to use climate changes force the development of the solutions for its mitigation
technical	integrate new technologies across Baltic Sea protection improve collaboration and information exchange knowledge dissemination
Economic	new support mechanisms creation of strategic partnership for Baltic Sea protection promotion of sustainability and circular bioeconomy Support for wide transnational collaboration in research
social	increasing social awareness social engagement

Threats of nutrients recycling by anaerobic digestion of cast seaweed

environmental	heavy metals concentration increase progressive beaches destruction
technical	enhanced infrastructure use due to sand content
economic	changes in transnational policies uncertainty of market acceptance under defined transnational responsibility rising cost for transportation of biomass charges for biomass use
social	unexpected social objection uncertainty of social acceptance in local communities

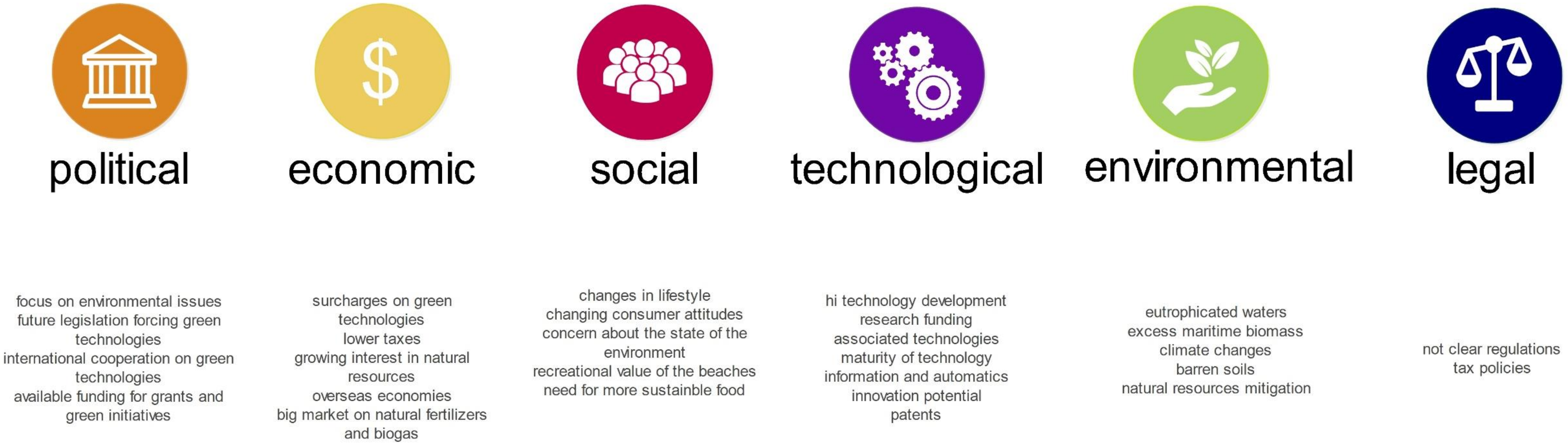

Figure 52 Analysis of aspects affecting the development of AD technology for seaweed digestion

7. Literature

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