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Study of cast seaweed harvesting technologies used in the bay of Køge and their implications for effective biogas production: Applying a circular bio-economy approach

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ABSTRACT

This paper focuses on the technical methods used to maximize the collection of cast seaweed from the Bay of Køge within Solrød Municipality in Denmark. The study assesses the efficiency of various seaweed harvesting technologies, as well as the pre-treatment of the seaweed (i.e. removal of sand) at the Solrød Biogas plant. As the digestate is utilized as fertilizer (N, P, K) on surrounding agricultural farmland, it is also crucial to minimize the presence of heavy metals in the digestate resulting from the use of seaweed as feedstock. The paper discusses the various ways in which sand-laden seaweed used as feedstock can contribute to energy production. It highlights the circularity and advantages of collecting cast seaweed and how this can produce nitrogen-rich fertilizer, thereby reducing CO_2 emissions. The theoretical framework employed in this study is based on the Circular Bio-Economy school of thought, which supports the cascading and reuse of biomass resources to boost and prolong their value and usefulness. Interviews with pertinent parties involved in the collection of cast seaweed and the operation of the biogas technology within Solrød Municipality serve as the basis for the research data. Moreover, data from Solrød evaluation reports and reviews of seaweed digestion data are utilized, as well as pertinent scientific literature. Among other outcomes, it is concluded that the seaweed harvesting technology now in use is useful in marine environments near to the shoreline, but less effective for collecting seaweed from further up the beach. However, it will be necessary to develop the technology, or utilize complementary harvesting technologies, in the future to improve collection efficiency and reduce the amount of sand collected with the seaweed. Problematic factors include the likelihood of sand accumulating in the biogas reactor tank, as well as damage to the cyclone stirrer and the macerator. To support the Circular Bio-Economy in terms of the collection and use of cast seaweed within Solrød Municipality, new technological methods should hence be promoted.

1. Introduction

1.1. Environmental situation & seaweed around the bay of Køge

Nitrogen and phosphorus pollution in the Baltic Sea has led to the eutrophication of the marine environment, which is affecting biodiversity in the region (Finnish Environmental Institute, 2014). As a result, there has been an increase in the growth of seaweed on the beaches of its coast due to the water's increased nutrient content (Murray et al., 2019). Cast seaweed causes odour issues, which reduces the environmental status of beach areas (Coastal Biogas, 2020a).

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This problem is particularly noticeable in Solrød Municipality, situated in the Bay of Køge, where seaside recreation has been hampered by the accumulation of cast seaweed. As a result, there have been joint efforts made within the municipality to remove the cast seaweed from the beach and utilize it at the neighbouring Solrød Biogas Plant to produce renewable energy by co-digesting the cast seaweed with animal manure, household waste and industrial biomass waste.

The full length of Køge Bay includes 38.6 km of beach, from which it is estimated that around 30,825 tn of cast seaweed might potentially be harvested on an annual basis (Coastal Biogas, 2020a; Lybæk and Kjær, 2017; Angelidaki et al., 2017). Just 3.7 km of the Køge Bay coastline falls under the Solrød Municipality; this portion has an estimated maximum annual cast seaweed harvest capacity of 7400 tn, or 2000 tn/km of beach (Lybæk and Kjær, 2017). Køge Bay has a catchment area of 49,492 ha of farmland, from which 1658 tn of excess nitrogen (N) are lost into the bay each year (20% of the total N losses), while 444 tn of N are absorbed annually by green vegetation, including seaweed. Because of its N content, the cast seaweed is useful for fertilizing the soil (Coastal Biogas, 2020a).

The quantity of heavy metals found in the biomass normally determines whether the cast seaweed can be utilized at Solrød Municipality's biogas facility. The Solrød Biogas Plant can only use seaweed for energy production if the cadmium (Cd) level is less than 0.8 mg/kg dry matter (DM) (Coastal Biogas, 2020a). After the seaweed has been co-digested at the biogas plant, alongside industrial biomass waste from nearby companies, livestock manure (from cows and pigs) and sorted organic household waste, it is redistributed and hence subsequently recirculated on the farmland as a useful digestate (fertilizer).

The seaweed is, however, occasionally returned to the aquatic environment during the winter months (Lybæk and Kjær, 2017; Angelidaki et al., 2017) if the cadmium concentration exceeds the environmental threshold. During the winter, when biological materials are absent because they have been transformed into gas and ammonium (NH_4^+), the concentration of cadmium rises. Cast seaweed is mostly collected along the shores of Solrød Municipality from April to September or October at the latest, depending on the weather (Coastal Biogas, 2020a).

Besides the issue of the high level of cadmium in the seaweed, making the digestate unusable as fertilizer during the winter, the cast seaweed contains sand because the latter adheres to the seaweed from the beach. This sand prevents the cast seaweed from being utilized appropriately for energy production and from being recycled effectively as a valuable agricultural fertilizer (digestate). In this study, we hence investigate the operation of the seaweed collection systems and the usability of the specific seaweed harvesting technology utilized on the beach in Solrød Municipality. The problems that sand causes for the biogas operation are also highlighted, along with the pre-treatment methods adopted at the biogas facility before the seaweed is fed into the biogas reactor tanks. The collection of seaweed at inappropriate periods and improper management of the sand collected along with it will hamper the circular use of the biomass resources and hence the potential CO_2 emissions reductions achieved by the operation of the Solrød Biogas Plant. In this work the following research question is posed: How efficient is the collection of cast seaweed and the pre-treatment of sand, and what are the environmental consequences?.

1.2. Previous investigations

Several studies, such as those by Tedesco and Daniels (2018) and Dias et al. (2023), investigate the potential for obtaining high-value materials from the biorefining of seaweed, as well as the use of seaweed for energy production. The researchers concluded that seaweed is significantly under-utilized in this field and that it is suitable for the generation of bioenergy, if biorefinery technology is used for the final-stage valorization of bio-resources. Other studies investigate the use of seaweed as a valuable feedstock for producing biodiesel (El-Shenody et al., 2023; Binwheel et al., 2023), and verify that its relatively high lipid productivity makes this biomass resource suitable for such a task (El-Sheekh et al., 2021).

The ability to efficiently digest seaweed into large yields of biogas and biofertilizer has been investigated by Akila et al., (2019) and Deng et al. (2020). The former claim that seaweed biofertilizers might serve as an effective catalyst for sustainability in agriculture and maintaining the soil's health, while the latter analyses how gas yield potentials increase when adding biochar to the digestion process. Another study investigates the use of seaweed-derived biogas as a soil fertilizer when the heavy metals are removed. It was shown that while the anaerobic digestion process decreased the amount of heavy metals in the seaweed feedstock, it also had a negative impact on the yield (production) of bio-methane in the reactor tank (Nkemka and Murto, 2010). Several other studies highlight the ability to generate biogas from the co-digestion of seaweed and animal manure, and all concluded that the gas output is larger when co-digesting the two feedstocks than when digesting seaweed on its own (see, e.g., Akila et al., (2019); Tabassum et al. (2016); Tsapekos et al. (2021)).

1.3. Focus of this study

In contrast to earlier research, as exemplified above, this paper investigates the collection and use of *cast* seaweed, rather than seaweed collected directly from the maritime environment for energy generation. We provide an assessment of the various methods that are used for collecting cast seaweed from the shores of Solrød Municipality, as well as how the seaweed is fed into the biogas reactor. Various seaweed harvesting technologies have been used and their efficiency is assessed regarding their ability to collect seaweed with low sand content both from the shoreline and further up the beach. The difficulties associated with high sand content are described, and an assessment made of how cast seaweed is pre-treated (rinsed to remove sand) at the biogas facility before being used for energy production. The benefits and drawbacks of the technology are discussed and the need for new technologies to sustain the high circularity of the Solrød Biogas plant is highlighted.

Solrød Biogas Plant is the only contemporary biogas plant that uses cast seaweed as feedstock, and little knowledge exists about the techniques used to collect cast seaweed. Using Solrød Municipality and the biogas facility as an example, this work contributes valuable knowledge of how cast seaweed is collected, makes a request for the development of new technology in this regard, and highlights the difficulties that sand-laden seaweed presents for efficient energy production and the circular use of bio-materials.

2. Material and methods

2.1. Theoretical approach

The notion of the bio-economy (BE) is heavily emphasized by the European Union (EU) and its member states, as well as by other nations worldwide that have adopted the concept in their national biomass utilization policies (Fund et al., 2018). According to the European Commission (2012), the BE is defined as 'the production of renewable biological resources and the conversion of these resources and waste streams into value-added goods, such as food, feed, bio-based products, and bio-energy'. The existing circular economy (CE), which is defined as 'minimizing the generation of waste and maintaining the value of products, materials, and resources for as long as possible', has been criticized for not being circular and sustainable, and for merely applying a business-as-usual approach (Pfau et al., 2014; Hetemäki, et al., 2017). As a result, the EU has combined the two concepts above to create the 'circular bio-economy' (CBE) concept, under which the European Commission proposes that the BE adopts a more circular focus in order to be successful (European Commission, 2018).

On the European level the CBE initially emphasized the '4Fs': food, feed, forests, and fibre (European Commission, 2012) and many northern European countries, with their large forest areas, have placed forestry at the centre of their CBE activities. On a global scale, countries such as Costa Rica, Malaysia, South Africa, Thailand, Columbia and Uruguay, which all highly valorize their biodiversity, have focused on developing bio-products with new properties (Patermann and Aguilar, 2021). More recently, an emphasis on health and biomedicine has also been included as a focus of the CBE, as detailed by Teitelbau et al. (2020) in their study which provided a global overview of CBE activities. The use of wood-based construction materials as substitutes for, for instance, steel and concrete, as being investigated in Canada, has also been highlighted more recently as a CBE focus area (Teitelbau et al., 2020). Finally, the use of cellulosic fibres (i.e. wood-based) in the textiles industry is an example of another area that has received attention recently, as a substitute for synthetic or cotton-based textiles (Hetemäki, et al., 2017).

The theoretical framework applied in this work takes as its point of departure the CBE way of thinking – encouraged by EU policy (European Commission, 2018), as noted above – wherein biological materials are cascaded and recirculated to improve and prolong their value and usability. Within the CBE way of thinking, resource cascading is a crucial component for optimizing resource consumption, with the intention of prolonging the total time of use and maintaining the quality of the resource. Cascading entails the use of outputs from one process as inputs in a subsequent process at a higher, lower or maintained level in the cascade chain (Sirkin, 1990).

In the cascade chain, three possibilities must be taken into consideration: that the resource can be (i) upgraded or upcycled to a higher level in the same cascade chain or in a new cycle, (ii) cascaded to the next level (lower) in the chain, or (iii) maintained at the same level of quality (Sirkin and ten Houten, 1994). The major focus of this study is hence on upgrading/upcycling to new cycles or higher levels in the cascade chain. This upgrade is associated with both the effective collection and efficient use of seaweed for biogas production and fertilizer usage. We hence consider option (i) in the cascade chain to be superior to the others, as we strive to avoid the downcycling of biological materials, in this case, cast seaweed.

2.2. CBE benefits of the Solrød biogas plant

Roskilde University, the energy companies Bigadan and VEKS, the companies CP Kelco and Chr. Hansen, and the agricultural industry – of which the latter three supply biomass residues to the Solrød biogas facility – jointly worked together to establish the Solrød Biogas Plant. The facility is situated approximately 40 km south of Copenhagen, the capital of Denmark, and faces the Baltic Sea to the east. The operation of the facility has significantly improved the water quality of the bay and further reduced Solrød Municipality's greenhouse gas emissions due to the utilization of biomass residues in energy production. These residues include seaweed collected from Solrød Beach and the Bay of Køge.

The facility is the first of its kind to utilize *cast* seaweed to produce green energy. The biomass, comprising industrial residues, sorted household waste, animal manure and seaweed, was first fed to the reactor tanks in the late summer of 2015. In October of the same year, gas production commenced at a rate of around 300 m^3 of biogas/h. A total of 90% of the cast seaweed washed up on the shores of Solrød Municipality annually has so far been gathered due to the seaweed collection efforts of the municipality and its citizens (Coastal Biogas, 2020b).

Today (2023), the Solrød Biogas Plant's total annual capacity of 226,000 tn of feedstock is consistently being met, and the future entails even more digestion of source-separated household waste from the Municipality of Copenhagen in new reactor tanks that will soon be fully operational (not described in this paper). While the former energy supply of Solrød Municipality was primarily based on fossil fuels, two gas engines with a combined capacity of 3.5 MWe, now convert the biogas into electricity and heat (co-generation). The latter is provided as district heating to around 6000 local residents and has decreased CO_2 emissions for the area by 32,800 tn/y, as shown in Fig. 1 (Solrød Biogas Plant, 2023).

Recently, an upgraded facility, with a biogas capacity of 17 million m^3, has been put into operation. This facility produces 13.3 million m^3 of pure bio-methane (CH_4), which is immediately fed into the national gas system and utilized by industry and residents for electricity and heating purposes. This has reduced CO_2 emissions by 26,500 tn per year. In addition, the chilling of the digestate using a heat exchanger results in an additional reduction in CO_2 of 4900 tn per year. The reduction in the use of chemical fertilizers in agriculture has also resulted in a decrease of 7500 tn of CO_2 annually, while the elimination of the decomposition of undigested

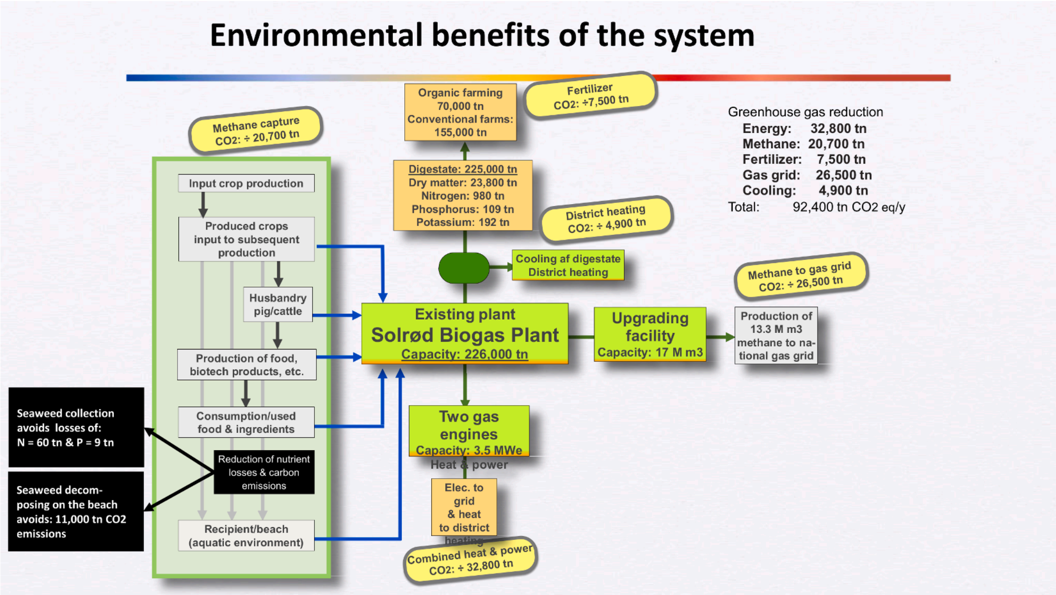

Fig. 1. CBE benefits of the Solrød Biogas Plant (greenhouse gas emissions in CO_2 e/y) (figure by authors).

manure in fields has led to a reduction of another 20,700 tn of CO_2 annually (through avoided methane emissions) (Coastal Biogas, 2020b; Solrød Biogas Plant, 2023).

The circularity of the Solrød Biogas Plant, as illustrated above, is further qualified – or improved – by the collection of cast seaweed from the beach (see text in black box of Fig. 1). This utilization of the seaweed hampers the dissemination of nitrogen and phosphorous in the bay, corresponding to avoided leaks of 60 tn/y and 9 tn/y, respectively. The already polluted Bay of Køge hence avoids receiving further nutrient escapes that could cause the blooming of algae and overgrowth of seaweed. Furthermore, since the seaweed is collected and no longer decomposes on the beach, emissions of 11,000 tn of CO_2 e/y (see text in black box Fig. 1) are avoided annually. This seaweed is then redistributed on agricultural soil as fertilizer, together with the other substrates that are converted to digestate at the biogas plant. This limits the need for artificial fertilizer and consequently reduces CO_2 emissions by a further 7500 tn/y.

Despite the limited amount of seaweed being collected and digested at the biogas plant, it has a significant impact on the total CO_2 emission reductions achieved by the facility (See Fig. 1 above). It is therefore important to investigate which seaweed collection technology is the best to pursue, and hence current experiences regarding the handling of sand-laden seaweed, which is the focus of this paper.

2.3. Data collection and literature review

The information used in this study was primarily gathered as part of the EU Interreg project COASTAL Biogas, which ran from 2014 to 2020 and focused on anaerobic digestion, environmental services – or eco-system services – and nutrient removal from the Baltic Sea. Several deliverables were produced, of which this work mainly relies on deliverable 3.2, titled 'A report on operating biogas facilities utilizing anaerobic digestion of cast seaweed' (2020), as well as deliverable 3.3, titled 'Report on potential of cast seaweed and policy frameworks in South Baltic Sea' (2020). In addition, various reports, such as Solrød Municipality's progress and assessment reports on biogas production, are studied, as well as investigations into the benefits of using cast seaweed as energy feedstock and digestate.

Alongside these, a short literature review has been presented in the introduction to shed light on research into the use of seaweed for energy production in biogas or biorefinery facilities. The literature review retrieved the scientific literature using search engines, for example, Google Scholar, using key phrases (Bates, 2006) such as 'co-digestion of seaweed and animal manure', 'renewable energy production from seaweed', 'nutrient value of digestate from seaweed' and so forth. The literature review exemplifies the research within the field, and as such does not aim to provide a full list of the published work within this research area.

Empirical data collection was achieved through interviews with pertinent parties, such as municipal planners and the personnel involved the collection of cast seaweed and operation of the biogas plant and pre-treatment technology. The empirical data collection method mainly relied upon the qualitative research approach, in which fixed questions are posed but there is space for a more open dialogue, as described by Kvale and Brinkmann (2015). Alongside this, field observations (Burgess, 2002) on the beach and at the Solrød Biogas Plant were used to explore and understand the processes connected with the collection and handling of sand-laden seaweed. Photographic documentation is additionally provided and used to illustrate the different technological methods. We will now proceed to present the findings of this work in the section that follows.

3. Results and discussion

3.1. Cast seaweed harvesting technology utilized

Along the Solrød Municipality's coastline, several technologies have been used to collect cast seaweed and separate it from sand. Fig. 2 below shows several methods, with the first (a) being an excavator with a very big shovel on the front that can remove cast seaweed from both the beach and the shoreline. A beach cleaning machine (b) has also been used, which mostly operates on the beach. Seaweed is collected in a tank, and the sand and seaweed are separated by a shaking line (Solrød Municipality, 2016). The tank must be emptied frequently because it has a limited capacity, equal to just 6 m^3 of cast seaweed/h.

Seaweed has also been harvested straight from the shore and the shoreline using a loader tractor (c). When dragged up and down in the water, the shovel on the loader tractor can also be used to wash the seaweed (Solrød Municipality, 2016). Another harvesting technology that has been used is a large metal rake attached to a tractor (d), which works best on the beach. In addition to the harvesting technologies mentioned above, various other technical appliances, including amphibian and pontoon harvesters, have been trialled. These appliances were not, however, found to be suitable due to problems with collection capacity, as well as difficulties in loading the collected seaweed into dump trucks for transport to the biogas plant (Solrød Municipality, 2016).

The cast seaweed is occasionally put back into the ocean to rinse off any excess sand, and if the currents are not strong enough to carry it away, the seaweed will float back to the shore again. Dump trucks with capacities of 12 tn–15 tn transfer the seaweed to the Solrød Biogas Plant, if it is determined that its composition is suitable for energy usage. The harvesting methods outlined above, which require pre-treatment before the seaweed can be used as feedstock at the biogas plant, result in an average sand content of 60%–90% (% of DM).

Cast seaweed has also been sieved to reduce the amount of sand in the biogas feedstock. This is achieved with the use of a very large movable drum sieve, which is shown in Fig. 3(a). The sand and seaweed are thus separated on the beach using the drum sieve,

Fig. 2. (a) An excavator with a large front shovel and a dump truck; (b) a beach cleaning machine; (c) a loader tractor; and (d) a tractor with a large metal rake connected to it (Coastal Biogas, 2020b).

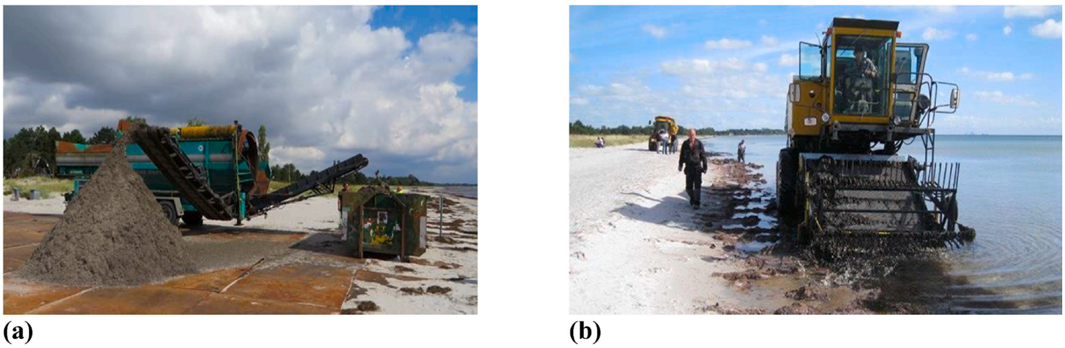

Fig. 3. (a) Container and drum sieve separating sand from seaweed; (b) the Halmstad prototype harvester trialled by Solrød Municipality (Coastal Biogas, 2020b).

and the separated materials then deposited on iron plates or into containers, depending on which was more appropriate. To prevent the enormous drum sieve and container from harming the beach or becoming trapped in the sand, iron plates were placed on top of the sand before positioning the sieve. The drum sieve's estimated capacity is around 20–25 tn/h (Solrød Municipality, 2016). However, this approach to sand reduction has the drawback of requiring the regular transportation of the iron plates, drum sieve and container to the required location on the beach, which is an expensive and time-consuming procedure (Coastal Biogas, 2020b).

Fig. 3(b) shows a prototype harvester from Sweden, the Halmstad harvester, which has been trialled by Solrød Municipality. Unlike previously used methods, the Halmstad harvester can collect as much as 30 m^3 of cast seaweed every hour and gathers considerably less sand. When collected from the shoreline, as seen in Fig. 3(b), as much as (all figures in % of DM) 49% seaweed was obtained, together with 33% sand and 18% ash. Further up the beach, away from the water, 48% seaweed, 40% sand and 12% ash were collected. The average proportions, when actually testing these results by hand collection from the shoreline, were found to be 64%, 18% and 18% (Coastal Biogas, 2020b), illustrating the Halmstad harvester's high efficiency. So, compared to the other techniques discussed, the Halmstad harvester offers a superior technology; however, it is not the best option for the entire area (shoreline and beach). Regular use of the Halmstad harvester along the shoreline might, however, hinder the movement of cast seaweed further up on the beach, where more sand would be collected during harvesting.

If the Halmstad harvester cannot be modified and further developed, several complementary harvester technologies may be required to sustain the CBE outputs of the Solrød Biogas Plant. The higher content of N in the fresh and wet cast seaweed collected on the shoreline, with 8 kg N/tn DM, in contract to the 2–4 kg N/tn DM found in dry seaweed collected on the beach, is another advantage of using the Halmstad harvester, and other shoreline harvesters, viewed through the lens of the CBE. When fresh and wet shoreline cast seaweed containing high levels of N is recirculated from the biogas plant to nearby farmland, it has a higher value as fertilizer.

Furthermore, using fresh and wet cast seaweed from the shoreline, rather than drier seaweed from the beach, increases the biogas yield from 54 m^3 biogas/tn DM to 120 m^3 biogas/tn DM (Coastal Biogas, 2020). Shoreline cast seaweed should hence be the focus for the more effective exploitation of biomass resources, once more taking the approach of the CBE.

3.2. Pre-treatment at Solrød biogas plant

Additional sand separation occurs at the biogas facility. Several appliances, such as the 'drum washer', with its varying hole sizes for separating sand and seaweed, were examined for their potential effectiveness prior to the implementation of the current separation method. The 'float/down system', in which sand drops to the bottom and the seaweed floats, could also be used to separate the two elements (Solrød Municipality, 2016). Fig. 4(a) shows the technology that was ultimately selected, in which the digestate (seaweed) is poured into a 'cyclone' upon arrival at the Solrød Biogas Plant. Sand gathers at the bottom of the conical tank, and the seaweed is separated from it using a powerful stirrer.

Using a macerator, the washed seaweed is then cut into smaller pieces and mixed with theother feedstock. Bio-methane is then produced in the biogas reactor tanks (digesters) from this substrate, which is piped directly into the tanks from the cyclone (Coastal Biogas, 2020b). As a result of this method, the macerator and stirrer of the cyclone are constantly at risk of wear and tear, and new techniques should be used to boost the plant's continuous energy output and lower the expenses associated with replacing technical equipment.

Other investigations support the idea that it is crucial to restrict the quantity of sand that enters the biogas reactor (see Lybæk and Kjær, 2019). Sand presents several operational issues for the biogas process, as demonstrated by the experience of Danish biogas plants that collect sand-laden manure from cattle farms utilizing sand bedding. Sand will progressively fill the bottom of the digester as it enters the biogas reactor, reducing capacity over time. If large volumes of sand-laden feedstock are used, a biogas reactor's volume could be replaced by sand in just six months, drastically reducing the efficiency of the process.

Several Danish biogas facilities that receive sand-laden manure typically remove the sand by physically or mechanically emptying the reactor tanks, using tools such as a skid steer loader, as described in Lybæk and Kjær (2019). This should be avoided if at all feasible, as this procedure is time-consuming, costly and necessitates a halt in production at the biogas plant. After pre-treatment in the cyclone at the Solrød Biogas Plant, the concentration of sand in the feedstock is between 10% and 20% (of DM), increasing its usability and, thus, the system's CBE outputs.

(a) **(b)**

Fig. 4. (a) Pre-treatment at Solrød Biogas Plant, separating seaweed and sand, and (b) N rich digestate distributed as fertilizer on nearby farms (Coastal Biogas, 2020b).

3.3. Enrichment of digestate

As mentioned earlier, the Solrød Biogas Plant treats around 226,000 tn of residual feedstock each year, including seaweed, and yields 209,000 tn of digestate that is – as shown in Fig. 4(b) – distributed on agricultural farmland. The amount of cast seaweed in the total feedstock is negligible, but it does contribute to the nutritional content of the digestate. The digestate's typical nutritional content is as follows (in kg/tn): nitrogen (N): 4.66; ammonium (NH_4^+): 3.27; phosphorus (P): 0.63 and potassium (K): 1.10 (Coastal Biogas, 2020b). Compared to undigested N, ammoniacal nitrogen (mineralized) is better absorbed by plants and crops, causing less nutrient run-off, and promoting crop development.

As the feedstock is digested, its DM content decreases, because substances such as sugars, proteins, lipids, and other components are transformed into biogas, which annually produces around 209,000 tn of fertilizer. The result is a more liquid digestate that can be applied directly to the soil using drag hoses (see Fig. 4(b)), preventing the evaporation of nitrogen and methane. When applying the CBE perspective, elements such as the upcycling of the digestate's quality and its environmental effects should be more clearly emphasized in contemporary farming methods.

3.4. CBE outputs

The cast seaweed collection and energy production at Solrød Biogas Plant are highly relevant to CBE-thinking, as materials are substituted (natural digestate instead of artificial fertilizer; renewable biomass energy instead of fossil fuels). The energy is furthermore being upcycled for higher-quality usage (into pure bio-methane (CH_4) as opposed to simply biogas), and ultimately uses the non-upgraded fractions of the biogas more efficiently (for power and heat by co-generation as opposed to power only), as well as waste heat (using a heat exchanger to extract waste heat from the cooling processes).

Furthermore, when using cast seaweed from the shoreline in preference to other seaweed, the gas yield and the digestate's N content are improved. All of this considerably improves the value and usefulness of the materials and energy by extending their useful lifetime before they exit the circular system. The use of seaweed that contains high levels of sand and cadmium could thus compromise the existing high circularity – and hence the CBE outputs – of the Solrød Biogas Plant. It is therefore of the utmost importance to find solutions to continue the recirculation of seaweed, as it provides numerous environmental benefits when handled appropriately.

4. Conclusions

In this work the following research question is posed and answered below: How efficient is the collection of cast seaweed and the pre-treatment of sand, and what are the environmental consequences?.

The Halmstad harvesting technology used on the Solrød Municipality's coastline, has been shown to be useful on the shoreline of the marine environment but less useful when gathering seaweed from further up the beach. It was found that priority should be given to seaweed collected on the shoreline since this produces more biogas and a greater N concentration in the digestate. However, to improve the effectiveness of cast seaweed harvesting, new technologies must be developed, or methods for several technologies to work in tandem are needed. Currently, the amount of sand brought to the Solrød Biogas Plant with the seaweed continues to cause operational issues, and it is crucial to prevent too much sand from entering the biogas reactor tanks since it seriously impairs the biogas process and the circularity of the whole plant system. Seaweed is now pre-treated at the Solrød Biogas Plant in a cyclone with a powerful stirrer that washes out the sand, which collects at the bottom of the tank. After being chopped by a macerator, the seaweed is combined with the other feedstocks and piped to the reactor tank.

Nevertheless, there are issues with wear to the macerator and the stirrer in the cyclone, and new techniques should be used to boost the biogas plant's continuous energy output and, as a result, lower the cost of replacing technical equipment. Using large amounts of cast seaweed as feedstock can thus potentially compromise the high circularity and upcycling of materials and energy at the Solrød Biogas Plant – that is, its CBE outputs – including its significant CO_2 emission reductions. Nonetheless, this study illustrates that technical solutions *can* be developed, which is encouraging in the context of the continued use of cast seaweed, and advocates for the development of new, more effective technologies.

Author contribution

Tyge Kjær: Conceptualization, visualization, validation. Rikke Lybæk: Methodology, investigation & analysis, original draft presentation, review and editing. All authors have read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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