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**Enhancing identified circular economic benefits related to the deployment of the Solrød biogas plant**

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**Abstract**

This paper investigates how experiences from the deployment of the Solrød biogas plant in Denmark - a large scale centralized biogas plant - can assist future biogas technologies in achieving circular economic benefits. Departing from a theoretical understanding of a circular economy provided by the Ellen MacArthur Foundation, the paper analyzes three areas: 1) biogas production, 2) nitrogen, phosphorous & green house gas (GHG) emissions, and 3) re-cycle/cascade materials. It consequently elaborates on the environmental benefits obtained, in terms of CO<sub>2</sub> emission from biogas production substituted for fossil fuels, improved water quality and hence reduced GHG emissions due to lower nitrogen effluents, and re-cycling of nutrients on farmland thereby recovering finite resources and improving crop yield. Economic spin-off effects are presented, including new jobs created in the local community. Learning from Solrød Biogas, this paper further proposes to include the following activities when planning for future biogas plants: waste-stream identification and coupling in the local community, measuring the value of digestate as a fertilizer, short distance to farmers delivering manure, and plant design adapted to the local energy market.

Finally, the paper suggests how to qualify the circular economic concept based on the findings from the Solrød biogas plant. It is here concluded, that emphasis should be on cascading energy from biogas production by means of combined heat and power (CHP), district heating or process heat to industry. Besides this, cascades in the manufacturing chain must also be intensified, allowing a more efficient materials and energy utilization and re-cycling in this part of the production chain. This will consequently reduce the total quantity of waste being generated by manufacturing industries, and thus benefit re-cycling strategies that only capture and seek to re-use a limited fraction of the waste being generated from industry.

**Keywords:** Circular Economy, Cascading, biogas, Solrød biogas plant, Denmark

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**1. Introduction***1.1 European policies on Circular Economy*

Since the European Union launched its flagship ‘Roadmap to a Resource Efficient Europe’ [1] under the “European 2020 Strategy for smart, sustainable and inclusive growth” [2], development of a circular economy has been an important priority within the EU. Recently, the European Commission published the report “Towards a circular economy: A zero waste program for Europe” with three main focuses: 1) ‘Design out waste’ by establish partnerships, by the Eco-design Directive and strategies for biomass cascading, and by the EU Research and Innovation Programme, 2) Support investments in green public procurement, by encouraging EU member states to integrate a circular economy into funding of activities under the European Structural and Investment Fund. 3) Redefining European waste policy and targets, by proposing adapting to the Circular Economy Package, providing targets for waste

streams under the Waste and Landfill Directives, among others. [3].

Ultimo 2015, and after a revision, the Commission proposes a revised Circular Economy Package, which would entail that member countries before 2030 shall recycle 65% of municipal waste, 75% packaging waste, and reduce landfill to 10% of all waste, and in general promote re-use and stimulate industrial symbiosis [4]. Primo 2016 Circular Economy initiatives concerning the utilisation and distribution of fertilizer within the EU have been proposed, focusing on production of organic based fertilizer within the EU - based on secondary materials - as opposed to artificial fertilizer based on imported resources, to promote re-use of finite and imported resources such as phosphorous, and to re-use minerals and nitrogen. The regulation emphasizes the opening of EU inner markets for export of organic based fertilizer among member countries, with a target of increasing the sustainability of European agriculture, as far as plant nutrient utilization, and to convert resources and waste streams to products with added value [5]. Thus,

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European regulations now explicitly propose to address the importance of organic based fertilizer, as a way forward in promoting a circular economy. But what is a circular economy?

A circular economy is an approach in which materials and energy flows are designed and shaped with the purpose of facilitating re-use and re-cycling. The concept of circular economy is applied to re-think the existing production and consumption patterns. Its purpose is to develop sustainable environmental and commercial circles and cascades within industrial and agricultural resource utilization. The inspiration for this is primarily derived from Industrial Ecology theory [6], in which the concepts of natural ecosystems are applied to industrial activities. In such natural systems, nothing is wasted and resources go through ecosystems from plants, to animals and eventually predators, who then die and decompose into nutrients that are provided to plants, animals and micro-organisms. [7-11]. Circular economy thinking is thus a termination of the concept of linear-economic thinking, where goods are utilized in a classical use-dispose matter. The linear economy puts pressure on natural ecosystems through an overconsumption of non-renewable resources and creates large quantities of waste, which should be avoided [12]. The Ellen MacArthur Foundation provides the following definition of a circular economy:

*“A circular economy is an industrial system that is restorative or regenerative by intension and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models”* [12].

Numerous research studies on how to adapt to a more circular waste and energy utilization, by means of a circular economy approach, have been conducted. Li & Ma (2015) [13], for example, analyzed how to obtain a more sustainable paper industry in China that is less energy consuming and waste generating. Other studies were done on how small scale bio-char technology can provide environmental, economic and societal benefits for South European farmers [14]. Genovese et al. (2015) [6] researched how a more sustainable supply chain management system can be developed by adapting the circular economic approach.

The purpose of this paper is to investigate circular economic benefits associated with the implementation of a new biogas plant, the Solrød biogas plant in Denmark, established some 30 km south of Copenhagen. We will identify the nature and ideas behind this project and analyze how the multiple impacts obtained by the implementation of this biogas plant can benefit future renewable energy projects of this kind, and whether lessons learned from Solrød Biogas can contribute to elements strengthening the concept of a circular economy, as well.

### 1.2 Features of biogas

Biogas consists of approximately 2/3 methane (CH<sub>4</sub>), 1/3 carbon dioxide (CO<sub>2</sub>), small amounts of hydrogen sulphide (H<sub>2</sub>S) as well as hydrogen (H<sub>2</sub>). These gasses are generated through a decomposition of animal manure and organic waste from industry and households in anaerobic (i.e., oxygen-free) reactor tanks - or digesters - that are heated and slowly stirred. The organic materials (feedstock) can remain in the reactor for about 2-3 weeks, after which the methane (biogas) can be utilized for electricity and heat production.

The biological decomposition takes place in the reactor tank by microorganisms producing methane gas. Biogas is also produced naturally from the decomposition of organic materials in nature, e.g., in bogs, in which swamp gas is developed. Thus, all organic materials can in principle decompose and produce biogas [15-17].

Biogas is thus a side-product from the respiration of microorganisms' decomposition of different types of organic materials. The type of organic materials being decomposed determines the amount of methane that is produced. Fatty or greasy organic materials lead to a high gas production, whereas materials primarily containing carbohydrates like glucose and other simple sugars, as well as high-molecular like cellulose and hemicelluloses, lead to a lower gas yield. The combustible part of the biogas consists of methane and hydrogen. It is an odorless and colorless gas with a boiling point of -162 °C, and it burns with a blue flame. The gas has a density of 0.75 kg/m<sup>3</sup> at standard pressure and temperature, and an upper calorific value of 39.8 MJ/m<sup>3</sup>, corresponding to a potential energy production of up to 11 kWh per m<sup>3</sup> of biogas [16-18].

In the production of biogas, it is common to utilize manure (a mix of slurry and solid animal waste) from livestock, sludge from waste water treatment, residues from agriculture and industrial biomass waste from the food and agro-industry. The primary feedstock for producing biogas in a Danish context is animal manure, but industrial organic waste, and energy crops, such as clover grass and beets, can also be added to increase the gas yield. In some European countries, e.g., the UK and Poland, biogas is mainly produced on landfill sites, where biogas develops naturally when the organic parts of the waste fractions are decomposed. Here, the biogas is extracted directly from within the landfill site by gas pipes for energy production, mainly for electricity production [16]. In other parts of the world, biogas is mainly produced from organic wastes from households without animal manure. The feedstock consists of primarily carbon and the digestion process transforms most of this carbon - depending on the reactor conditions - into biogas, whereas the nutrients are left in the digestate providing a valuable soil fertilizer [15-17].

### 1.3 Outline of Solrød biogas plant

The Bay of Køge is a nutrient rich ecosystem and produces a lot of cast seaweed being deposited along its shore. Thus, large parts of the beach are covered by seaweed resulting in odors which causes great nuisance to visitors and local residents. This, among others reasons, motivated the Municipality of Solrød and the homeowner associations along the beach decided to establish a beach cleaning association. Since 2008, this association has worked to develop an efficient solution to the problem by removing seaweed from the beach. Cleaning the beach led to the problem of finding a place to dispose of the large quantities of seaweed being collected. The Solrød Municipality had agreed upon a Climate Action Plan and a Heat Plan paving the way for increased renewable energy implementation. Hence, the idea of the Solrød biogas plant was initiated to facilitate the collection and utilization of cast seaweed, organic residues and livestock manure from local farmers to produce renewable energy [19].

The Solrød biogas plant converts biomass feedstock into renewable energy in the form of biogas. The plant can receive up to 200,000 tonnes of different biomass feedstock annually (see Figure 1). When the biogas has been extracted from the biomass, and the gas stored, the digested feedstock

(digestate) is used as a high quality fertilizer. Raw materials are residues from two pharmaceutical companies, CP Kelco and Chr. Hansen, livestock manure from local farmers, as well as cast seaweed from the nearby beaches. The composition and quantities vary depending on availability and costs, so alternative feedstocks are tested regularly. As the digestate is used for soil fertilizer by local farmers, Solrød Biogas can only receive organic materials complying with the rules about heavy metal content, as provided in the Statutory Order on Sludge [20]. Solrød Biogas is based on proven and reliable Danish biogas technology from the Bigadan company [21]. The biomass feedstocks are digested under anaerobic conditions at a temperature of around 52 °C. [19].

Solrød biogas plant produces sustainable energy from organic materials through a controlled process where the digestate can be used as fertilizer in agriculture. Below, we have outlined the different steps of the biogas process:

1) Transportation of feedstock: Residues from CP Kelco, Chr. Hansen, cast seaweed from the Bay of Køge, and livestock manure from local swine and cattle farmers are transported to the plant in closed containers, receiving approximately 28 loads per day.

2) Receiving unit: Biomass from agriculture is stored in manure tanks that can hold five days of supply. CP Kelco has storage capacity that equals 2-3 days of production at its pectin company. Seaweed is collected from the spring through autumn and is stored as silage, which makes the seaweed available for biogas production all year round.

3) Production of biogas: Liquid biomass, as manure, is pumped to the digester tanks. Here, it is mixed with solid biomass entering the digester by a conveyor belt and automatic loader. The biomass is heated before entering the digester, and the temperature kept constant by recirculation through heat exchangers to facilitate optimal microbial activity.

4) Storage and energy usage: The generated biogas ( $\text{CH}_4$ ) is collected and hydrogen sulphide ( $\text{H}_2\text{S}$ ) is removed in a gas cleaning system, after which it is stored in a gas container. From here the gas is supplied to, among others, the Solrød district heating company where it is used for generation of combined heat and power (CHP).

5) Digestate: The digested biomass is pumped to storage tanks with a capacity of five days of production. When farm trucks transport manure to the plant they also collect the digestate, which then is returned to farmers and used as soil fertilizer [19].

## 2. Materials and methods

This paper focuses on how the benefits of future renewable energy technology, here biogas, can be enhanced by lessons learned from the Solrød Biogas case. These issues

will be addressed by illuminating the potential benefits of such projects, taking a theoretical approach provided by the concept of a circular economy. Challenges for the future include how to reduce the utilization of the natural environment as sink for waste disposal through a self-sustaining system in which waste and organic residues enter new production cycles and are re-used. The main objective of this paper is to answer the following research questions:

*“Which major circular economic benefits can be identified as a consequence of the implementation of Solrød biogas plant? How can future renewable energy projects benefit from this case? How can the concept of a circular economy eventually be strengthened?”*

### 2.1 Theoretical considerations

#### 2.1.1 Circular Economy & Cascading

The concept of **Circular Economy** is depicted in Figure 2 below, which illustrate how biological materials pass through and cycle within the economic system, each with their own characteristics. Some non-biological materials, which are not cascaded to other types of materials, but the value of embedded energy is maintained [22].

Ellen MacArthur distinguishes between ‘durable components’, which are technical systems that consist of materials such as plastics and metals designed for re-use, but will at some point reach their end-of-life and become waste. Consumable components also exists, which are biological materials that can be returned to nature after being re-used in multiple cascading steps. These biological materials can become a part of the technical system (as for example bio-plastic composites mixed with traditional plastic), which builds on re-use, re-cycling and restoration. This technological ‘sphere’ differs from the biological ‘sphere’, as the waste materials cannot return to the biological system, and thus only undergo a life-extension approach [22].

Ellen MacArthur presented four elements depicting the concept of a circular economy, described below [22]:

1. *Power of the inner circle:* Substances or goods should be re-cycled with minimal energy inputs, materials and labor. Tighter inner circles will lower the pressure on utilization of virgin materials and energy crops by ‘*Extraction of biochemical feedstocks*’ for biogas production. The use of already generated waste or residues can therefore beneficially tighten the circles and lower the pressure on extraction and processing of this type of feedstock.

2. *Power of circling longer:* Substances or goods must be re-cycled as much as possible before depletion or reaching their end-use point. This can be achieved by utilizing nutrients more efficiently in several cycles, hence avoiding leakages of nutrients to water environments and by

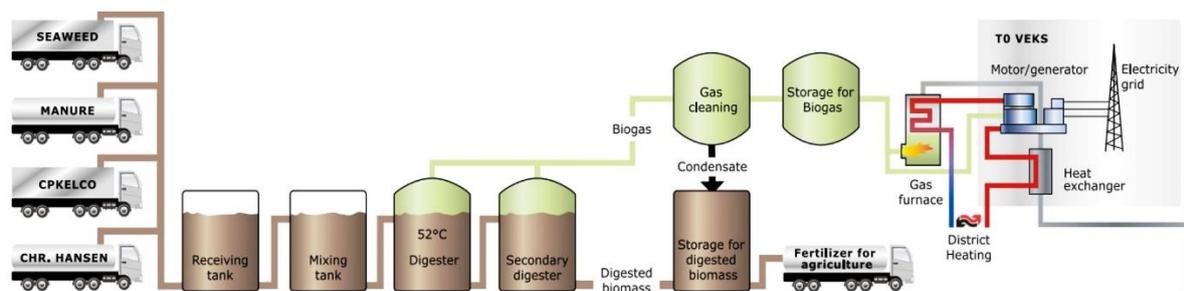
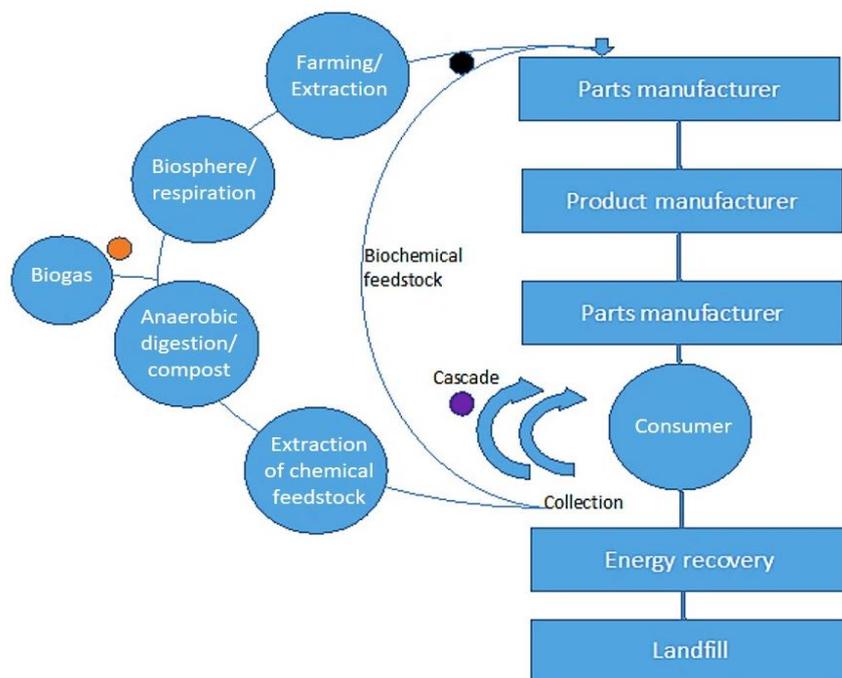


Figure 1 Process overview of the Solrød biogas plant [19].



**Figure 2** Elements in a Circular Economy (CE) with black, orange, purple circles indicating focus areas for identifying CE benefits related to Solrød biogas plant. The figure is inspired by the MacArthur Foundation [22].

improving the quality of and accessibility of the nutrients for farm crops by digesting the manure.

3. *Power of cascaded uses:* Substances or goods should be cascaded to other types of material usage, types of services or design components. Residues from food industries are currently utilized as animal feed, or simply discharged. They could, for example, alternatively be utilized for biogas production and create higher value, as renewable energy, higher value fertilizer, and conservation of nutrients.

4. *Power of pure cycles:* Substances or goods should contain non-toxic components and be easy to separate for re-use. Feedstock for a biogas plant should not contain heavy metals, which hamper the spreading of the digestate as fertilizer on soil. Both 'Landfill' deposit and 'Energy Recovery' methods such as incineration, should thus be avoided, as it only provides an end point for further re-use.

The concept of *cascading* is closely related to a circular economy, as activities involving cascading seek to utilize the above mentioned substances or materials, in which the highest value will be achieved first, where after secondary and tertiary waste materials and side streams are sought utilized in product or services with lower value [12, 22-23]. Cascading principles are mostly applied within sectors and industries focusing on water, wood residues and energy production and utilization [24-27]. Sirkin & ten Houten (1994) [28] explicitly elaborated on cascade technology converting agricultural residues to various beneficial components like fodder, energy, nutrients in biogas plants.

## 2.2 Research approach

The research approach in this paper is a Materials Flow Analysis (MFA) [10] uncovering the materials and energy streams associated with the Solrød biogas plant. MFA is thus an analytical method to quantify flows and stocks of materials and substances (including energy) in a well-

defined system or baseline. When applying the MFA approach, it is possible to study the biophysical aspects and consequences of human interference within different production systems. MFA is an integrated part of Industrial Ecology theory, as well as an Urban Metabolism approach, in which industrial systems should strive to mimic natural systems. Typical applications of MFA include the study of materials, energy and product flows across different industrial sectors or within ecosystems [10].

In our case we apply the MFA on a single industrial/agricultural installation, namely the Solrød biogas plant, to identify flows and origins of feedstock into the digester, as well as flows of nutrients and the related benefits associated with the production of digestate, renewable energy and limited leakage of pollutants into the water environments. [10]. The data input for the above analysis is based on documented studies (reports, journal articles) connected to environmental benefits and job creation related to the implementation of Solrød plant. Furthermore, data was collected from empirical inputs derived from a tour at the plant, as well as interviews with relevant stakeholders involved in the development of the plant and in the daily M&O of the technology.

We will now proceed by identifying the circular economic benefits achieved at Solrød biogas plant, as outlined in Figure 2 above. Focus will be on the following elements when identifying the benefits, as indicated in Figure 2 by with orange, black and purple circles: 1) *Biogas production*, 2) *Nitrogen, Phosphorous & GHG* and 3) *Recycled/Cascaded materials*. This will facilitate an identification of environmental and energy related benefits associated with the Solrød biogas plant. Additionally, we will elaborate on the economic benefits, including job related spin-offs. Finally, we provide some suggestions on how to add or strengthen the circular economic elements in the figure to enhance the benefits of future biogas technologies.

### 3. Results

The Solrød biogas plant provides multiple benefits for the environment and society, such as renewable energy that provides energy security by utilization of indigenous resources for the production of a flexible gas. It reduces problems for local citizens who reside by the Bay of Køge related to odor and for tourists visiting the area, as well as limits the pollution of the bay with organic matter from decomposition of cast seaweed. Moreover, the plant enhances the nutrient value of the digestate utilized by farmers, and reduces the emissions of methane from the biomass feedstock since it is now being digested in the biogas plant. The avoided use of fossil fuels and the reduced emissions of methane from agriculture provide extensive green house gas (GHG) emission reductions from the deployment of Solrød biogas plant. Below we will elaborate further on these benefits:

#### 3.1 Energy & Environment

##### 3.1.1 Biogas production (orange circle in Figure 2)

The Solrød biogas plant currently receives 188,300 tons of feedstock annually, separated as shown in Table 1 below:

**Table 1** Feedstock utilization at the Solrød biogas plant

Manure from local cattle and pig farmers	= 41,500 tons
Pectin residues from CP Kelko	= 79,400 tons
Fermentation waste from Chr. Hansen	= 60,000 tons
Cast seaweed from the Bay of Køge	= 7,400 tons
<b>Total</b>	<b>= 188,300 tons</b>

This biomass feedstock equals a production of 9.3 million m<sup>3</sup> raw biogas annually corresponding to 6 million m<sup>3</sup> of methane (natural gas quality). The biogas is converted to power and heat in the Solrød CHP plant, supplying energy to the local community and citizens in Køge Municipality in the form of 24,500 MWh of electricity and 28,600 MWh of heat. The avoided use of fossil fuel in Solrød Municipality hence leads to CO<sub>2</sub> emission reductions of 26,000 tons annually [19], and are incorporated into the municipality's Sustainable Energy Action Plan (SEAP) under the European Unions' Covenant of Mayors [29]. Consequently, GHG reductions are not only obtained by substituting renewable energy for fossil fuels, but also from avoided decay of biomass and by better utilization of manure as fertilizer, as discussed below.

##### 3.1.2 Nitrogen, Phosphorous & GHG (black circle in Figure 2)

Not only has odor been reduced, but also the water in the Bay of Køge has benefitted from collection of the cast seaweed, as leakage of nutrients into the bay are considerably reduced. From the 7,400 tons of cast seaweed previous covering the beach, the bay no longer receives annual leakage of 62 tons of nitrogen and 9 tons of phosphorous [30]. This not only improves the water quality of Køge Bay - this reduction of nutrients to the Bay of Køge corresponds to 100% and 72%, respectively, of the targets in the Water Framework Directive [31] - but also reduces GHG emissions from avoided decay of seaweed on the beach. This corresponds to a reduction of 11,900 tons of CO<sub>2</sub> equivalents annually [19]. A photo of the Solrød biogas plant is shown below in Figure 3.



**Figure 3** Solrød biogas plant [19].

Better utilization of the digestate as fertilizer also causes lower emissions of GHG's to the atmosphere. Enhanced plant access to nitrogen in the digestate reduces emissions of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) when distributing digested manure on farm soil, eventually reducing GHG emissions by 3,100 tons per year (CO<sub>2</sub> equivalents). Access to nitrogen also increases crop yield. Thus, the Solrød biogas plant reduces GHG emissions by 40,500 tons of CO<sub>2</sub> equivalents annually, calculated as reduced emissions of CH<sub>4</sub> and N<sub>2</sub>O from the distribution of manure and decay of cast seaweed, as well as avoided emissions of CO<sub>2</sub> from fossil fuel utilization. The use of diesel for feedstock transportation and electricity at the biogas - which account for 555 tons CO<sub>2</sub>/year - are included in this figure [19].

##### 3.1.3 Re-cycled/Cascaded materials (purple circle in Figure 2)

Organic materials from farmers and companies in Solrød Municipality and nearby areas are re-covered, and reduce the need for 'Extraction of biochemical feedstock' (see Figure 2), as the organic feedstock are re-cycled back into products and services (fertilizer and energy). Thus, from the total amount of digested biomass (digestate) the following nutrients and recalcitrant carbon is provided by Solrød biogas plant:

**Table 2** Nutrient and recalcitrant carbon output from Solrød biogas plant [19].

Total Nitrogen (N)	= 848 tons
NH <sub>4</sub> -N	= 614 tons
Phosphorous (P)	= 102 tons
Potassium (K)	= 234 tons
Carbon to soil	= 8,440 tons

To access the quality of the digestate, Solrød Biogas initiated both batch and full scale tests of the digestate, applying different quantities of industrial waste and cast seaweed. The purpose of these analyses was to investigate if and to what extent the seaweed hampers gas yield, and eventually to qualify the digestate as a valuable fertilizer for farmers. The analysis showed that seaweed provided little gas, did not hamper gas development in even large quantities, and that the content of nitrogen in the digestate increased with increased amounts of seaweed added to the feedstock [19, 30, 32]. Table 2 shows that 614 tons of ammonium (NH<sub>4</sub>-N) is directly accessible to the plants out of 848 tons of total N, that phosphorous and potassium are re-cycled in

the digestate, and that large amounts of carbon are applied to the soil as a potential sink.

An important contribution of the biogas plant is therefore the re-circulation of nutrients and increased value of the digestate as fertilizer [30]. The crop access to nitrogen increases with 10-25% in digested manure increasing crop yield, and odors problems are reduced by up to 30% when distributing digested manure on farmland. The risk of spreading pathogenic organisms is avoided through a hygienization process, taking place in the reactor tank [18]. By re-cycling nutrients in the feedstock on farmland, we avoid extraction and mining of virgin resources, of which some are scarce, e.g., phosphorous, and minerals. These nutrients are thus returned to farmland. Therefore, we also avoid the steps '*Energy recovery*' (waste incineration) and '*Landfill*' (deposit), illustrated in Figure 2, after which the biomass resources cannot be further re-used or re-stored.

Thus, both nutrients (providing crops for further processing by local companies and agro-industry), and the renewable energy produced at the biogas plant (leading to energy services distributed within the community), will eventually be utilized by the same industries that provide biomass feedstock to the biogas plant, and thus they enter a circular economy.

### 3.2 Economic benefits

Job opportunities at the biogas plant are connected to transport of feedstock and the maintenance & operation (M&O) of the technology. Thus, five job positions have been provided connected to M&O at the plant, and 10 in connection with transport of feedstocks. Economic benefits are estimated to be between 22-32 million Danish Kroner (DKK) annually, which equals 2.9-4.3 million Euros. These benefits are primarily derived from lower costs connected to energy production (no purchase of fossil fuels), higher crop yield and reduced expenses for artificial fertilizer [33, 19]. The total plant investment accounts for 85 million DKK or 11.33 million Euros. The annual profit is 23 million DKK, or 2.67 million Euros, with a payback period of 10 years [19].

## 4. Discussion

In the following, we proceed by answering the research questions previously posed in this paper, by separating them into three parts, as follows:

### 4.1 Multiple environmental benefits

(1) *Which major circular economic benefits can be identified as a consequence of the implementation of the Solrød biogas plant?*

The case of Solrød biogas plant illustrates the profound environmental and economic benefits that can be achieved if novel transition technologies are designed in the same manner as Solrød Biogas, where co-digestion of manure and different waste residues from the local community are used and the digestate returned to farmland as a fertilizer. Thus, consideration of the local environment in its specific context and the conditions that prevail were addressed in the case of Solrød and integrated into the design and operation of the biogas plant [19]. By adapting a circular approach, multiple benefits occur, and the solutions to environmental problems and formulated targets become cost effective. This is because the means of obtaining them solves more than one problem at a time as discussed below. The collection of cast seaweed, for example, not only limits odor from biomass decay on the

beach, but also reduces the nutrient load to the Bay of Køge with negative environmental consequences such as eutrophication, and thus complies with the EU Water Framework Directive [31] targeting more cost-effective operation [30, 32]. Alternatively, the cast seaweed would undergo other means of waste management such as plowing into the beach, or waste deposition elsewhere [34] requiring longer transportation, another end-point for further re-use and consequent loss of nutrients and minerals. The yearly cost of such waste management is estimated to 42,8 million DKK (5.7 million Euros), whereas the solution currently applied is 1/10 of this cost [32]. Hence, the seaweed instead becomes a digestate that is valuable as a soil fertilizer, where minerals such as nitrogen and phosphorous are recycled and benefit agricultural crops as valuable nutrients. This results in lower pressure on extraction of virgin materials and the production of artificial fertilizer with a high carbon footprint.

The biomass feedstocks derived from industry, i.e., cast seaweed and manure, now enter a cycle in which they are not only used for fertilizer (the manure), and cast seaweed for waste disposal (to landfill), industrial waste for one-time re-use (animal fodder), but are actually re-cycled and re-used for soil nutrients and renewable energy production. They are utilized for other types of valuable products. Thus, if not utilizing these waste materials for biogas production, other types of agricultural residues or even by energy crops would be needed, thus avoid the step '*Extraction from a biochemical feedstock*' (Figure 2).

The energy extracted from the biomass feedstock is used for production of heat and power (CHP), from which a total efficiency of up to 88 % can be achieved [35-36], and distributed to citizens in Solrød and Køge Municipality. This means that the biogas is used efficiently for power production, and waste heat utilized. It is then cascaded into the district heating network for household heating and hot water. Thus, CHP production and cascading of energy, by means of district heating, leads to extensive CO<sub>2</sub> emission reduction compared to separate production of heat and power [27, 37].

### 4.2 Learning from the Solrød biogas plant

(2) *...and how can future renewable energy projects benefit from this case?*

Looking at all the possible benefits obtained from Solrød Biogas, the initial planning process influenced this outcome. In the initial phase Solrød Biogas, distinguished itself in its planning process from other biogas plants in Denmark using the following approach:

i) Waste-stream identification and coupling in the local community:

The main feedstock in Solrød Biogas was from the beginning planned to be industrial residues and only 25 % by volume is manure from local farmers. The initial idea for implementing a biogas plant in Solrød was the large quantities of residues from CP Kelco, which were utilized as cheap and low value animal fodder in Jutland with consequently long transportation. With the homeowner association's interest in removing the cast seaweed, this idea was thus realized, but not before extensive laboratory data were generated regarding gas yield and fertilizer value [30, 32]. Thus, Chr. Hansen was included as a supplier of feedstock when it was clear that their wastes provide more nitrogen than seaweed, and it was needed as part of the feedstock to provide a high quality fertilizer.

ii) Measuring the value of digestate as fertilizer:

The relatively low gas yield and sand content of cast seaweed has challenged the operation of the biogas plant. Sand is now removed by a cyclone [34]. However, the fertilizer value of the seaweed is relatively high when mixed with the other feedstocks [36]. To increase the content of nitrogen in the digestate, since it was relatively low in the pectin residue provided in the highest biomass input of Chr. Hansen, other feedstocks were identified in the local community with high levels of nitrogen (milk-acid residue) appropriate as fertilizer, and at that time utilized as animal fodder [34].

iii) Short distance to farmers delivering manure:

Manure only accounts for 25% of the feedstock, which is unusual in a Danish context. It would normally be opposite, but Solrød Biogas works with the closest farmers in the community to avoid long transportation distances and thus expenses. Currently 6 million DKK, or 0.8 million Euros, are utilized for transporting feedstock and digestate to and from the biogas plant [34]. It is not unusual that up to 30% of the running costs of the centralized biogas plant are used for transportation of manure between farms and the biogas plant [18]. Thus, at Solrød Biogas, expenses for transportation from farmers are minimized and residues from local companies are utilized instead, providing lower transport frequency, higher gas yield and fertilizer quality.

iv) Plant design according to local energy market:

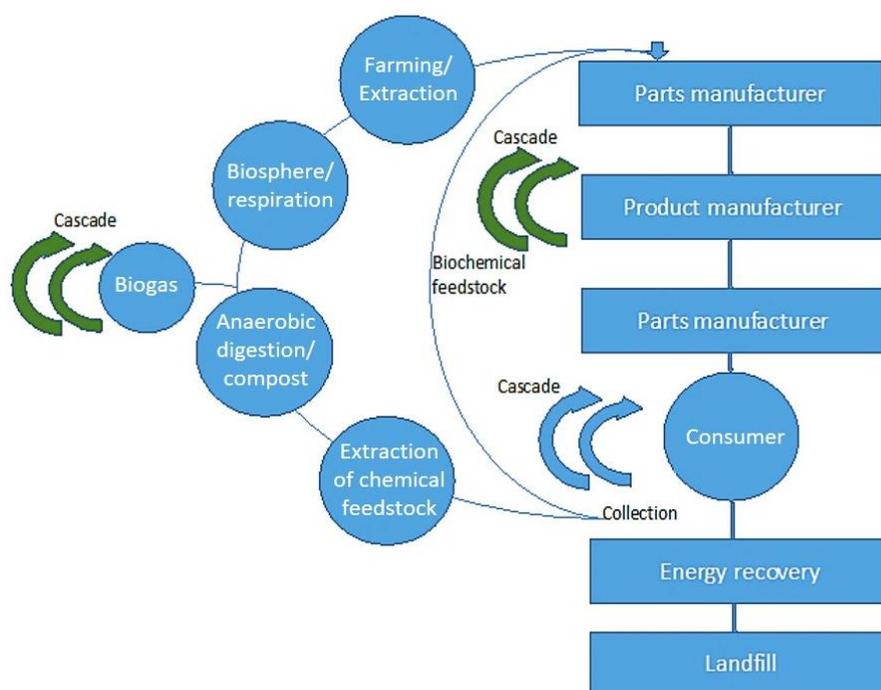
As opposed to newer biogas plants in Denmark, Solrød biogas is dimensioned to supply heat to a local/regional heat market, and not to upgrade raw biogas for distribution in the natural gas network. Thus, the socio-economic benefits have been focused on the production of CHP adjusted to the local energy needs. The market for heat was identified, improving the societal benefits of energy production [38-39]. When surplus heat is generated, primarily during summer periods, excess heat is transmitted to the Køge district heating network, covering a larger area within the VEKS-district heating system [36].

Future biogas plants should adopt some of the planning elements exemplified by Solrød Biogas to facilitate multiple environmental benefits from applying this technology. High socio-economic benefits could be obtained from energy production and utilization, provide farmers with nitrogen-rich digestate from community-based industries, and from limiting the use of low gas manure transported long distances. This approach has been used at the Odsherred Biogas Plant, which is now being developed. Gas yield tests are being done on new types of feedstocks, and local companies, e.g., Lundbeck pharmaceutical, were identified as suppliers of appropriate feedstocks that will increase both gas yield and the fertilizer value [40]. Another plant being developed, Kalundborg Biogas Plant, is planned to operate on farm manure as feedstock and with gas-rich and high nitrogen industrial residues from the near-by community. The energy will be solely utilized locally with no up-grading of the gas [40].

#### 4.3 New circular economic elements

(3)... *How can the concept of a circular economy eventually be strengthened?"*

We suggest that the biogas produced - the 'biogas' step - be utilized for CHP and further cascaded for district heating [37], and where possible, strengthen the concept of a circular economy, which is illustrated in Figure 4 below. This off course requires the availability of a heat market and district heating networks, but excess heat (steam) could also be cascaded and utilized within a larger industry requiring steam at lower temperatures and pressures, and possibly even in tropical developing countries [11, 33]. Another way of strengthen the concept of a circular economy, and learning from the Solrød case, is to look at possible cascades within the 'manufacturing' steps of a circular economy. As suggested by the MacArthur Foundation (2013b) [22] and illustrated in Figure 4 below, the cascading activities happen after the specific goods are manufactured and consumed.



**Figure 4** Identification of areas for strengthening the concept of a circular economy, shown as green arrows in the figure above. The figure is inspired by the MacArthur Foundation [22].

We, however, suggest that focus should be on cascades within the manufacturing industries that were not addressed by Ellen MacArthur, to reach the full potential of materials for further re-use [37]. Within the iron and steel manufacturing industries, it is common to look at re-use options, whereas the food manufacturing industry lacks such activities. Other sectors, e.g., the textile industry, are also challenges, where most of the raw cotton is wasted in the production of clothes, leaving only a minor fraction to be re-used later [40-41].

In the case of CP Kelco, we can actually identify a 'manufacturing' cascade, before the pectin residues are utilized for energy purposes at Solrød Biogas. In Latin America, citrus fruit is pressed to produce juice (50%), and small amounts of ethereal oil (2.5%), then dried (40%) and shipped to Denmark. The remaining fruit (7.5%) is utilized for manufacturing raw pectin (1%) and the residues (6.5%) are used for biogas production at Solrød biogas, which account for 90.000 tons annually, and around 73% of the total gas production [40].

## 5. Conclusions

This paper identifies various environmental benefits from the implementation of Solrød biogas plant situated in Denmark, for reduction in CO<sub>2</sub> emissions from renewable energy use, GHG emission reductions from enhanced management and utilization of biomass that previously resulted in losses of phosphorous and nitrogen to water environments, and from optimization in the recycling of nitrogen on farmland for enhanced crop yield.

Learning from the Solrød case, we suggest that the planning of new biogas plants consider the following issues: waste-stream identification and coupling in the local community, measuring the value of the digestate as a fertilizer, shortest distance to farmers delivering manure, and plant design tailored to the local energy market [38].

The paper further suggests that cascades should be established within the 'biogas' step such as CHP and district heating, or alternatively as industrial process. Focus on cascading within the manufacturing industries, along the 'manufacturing' chain, is also important to avoid waste generation [37]. Today, re-use of the final product alone is often the focus of many cascading initiatives, but unfortunately it only captures a small part of the total waste materials. In textiles, for example, 80% of materials losses happen within the manufacturing process, but cascading or recycling strategies are only applied to the 20% that ends up as final products [41]. We, therefore, need to cascade all along the manufacturing chain. With these elements, it is possible to strengthening the concept of a circular economy.

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