How Circular Bio-Economy Can Be Adopted within the Agro-Industry in Denmark by Cascading and Coupling Biomass Residues

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates how to facilitate a green transition by use of biomass residues from the ago-industry in Denmark, exemplified through materials flow analysis (MFA) within the slaughterhouse industry. The proposed system suggests how circular bio-economy can be addresses at the local level, by deploying internal circulation (IC) and anaerobic digestion (AD) biogas reactors digesting wastewater and biomass residues from the slaughterhouse industry, as well as the local community. Thus, by cascading and coupling activities, including supply of organic household waste and manure from the local community and agriculture, this paper shows how various environmental benefits can be achieved, as for example production of biogas substituting fossil fuel usage, reduction of waste generation and lower air emissions. The proposed system relies solely on local renewable resources being produced and re-used within a narrow geographic area, as opposed to the existing system, limiting energy distribution losses and long transportation distances of biomass residues, as well as the extraction of and further processing of raw materials, etc. The new system emphasize local bound solutions, meets and supports local stakeholder interests and development opportunities.

1. INTRODUCTION

It is projected that biomass resources in the future will play a vital role in achieving climate change mitigation, as well as reaching the global community's targets for greenhouse gas (GHG) reductions put forward in the Paris Agreement from 2015 [1;2]. Energy from biomass resources are currently utilized for energy purposes in various sectors, as for example within the transport sector as an energy carrier based on e.g. biogas, biodiesel, or ethanol, and within the energy industry sector, by e.g. thermal gasification and combustion of biomass as e.g. wood chips, wood pellets, cereal and rice straw. In many household's woodburning stoves or fires are also utilized for heating and/or cooking purposes [3;4;5]. The European Union (EU) has strongly emphasized the concept of bio-economy and member state countries, as well as other countries around the World, have adapted this way of thinking in their national biomass policies [6]. The definition of bio-economy is, according to the European Commission [7], the "*production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bio-energy"*.

Some scholars however point to the lack of sustainability and circularity, or circular economy [8], being embedded in the bio-economy concept [9;10], and point to the risk of simply following a business-as-usual approach when applying this concept. Others, on the other hand, argue that bio-economy concept in its nature adopt a circular approach. The European Commission [11] defines circular economy (CE) as *"minimizing the generation of waste and maintaining the value of products, materials and resources for as long as possible"*. As a consequence of this critique, and the ongoing discussions about the true value of bio-economy, bio-related policies initiated by the EU has in recent years been linked closer to the concept of circular economy [6]. Besides this, the European Union has newly launched a merging of the two concepts, and now targeting a circular bio-economic approach in their policies. Thus, the European Commission recognizes that bio-economy must have sustainability and circularity as its core focus [12].

Hence, the circular bio-economy concept is relatively new and the role of this approach in a future green transition is not yet fully defined nor exemplified at the local and regional level [1]. In this paper, we will contribute to the lack of knowledge of how to adopt and apply this concept in a local context emphasizing Danish agro-industry to facilitate a pathway for green transition. Examples of how to utilize biomass residues from the agro-industry, otherwise being wasted for the most part, will be addressed. We will highlight how such waste streams could be valorized and utilized, by means of cascading and

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coupled production methods, which currently is underrepresented in the circular bio-economy literature [1]. Further, we will show how biological processes in such production methods of agro-industries are important to achieve a green transition.

2. METHODOLOGY

2.1. Cascading & MFA-analysis

Cascading: The concept of 'cascading' related to industrial practices was first developed by [13] emphasizing resource conservation, and developed further by [14] to achieve e.g. resource sustainability with applications for product design. The concept of 'cascading', in this paper, is utilized to develop more sustainable production processes within the agro-industry by relinking biomass residues to higher cascade levels or to other substance cycles after cascading. Cascading revolves around a repetitive use of waste products, in which the waste first is sought used for high value products, and then gradually for less valuable products and finally for energy production like e.g. combustion or digestion. The utilization of biomass residues can therefore be regarded as a pyramid where the value of the specific fraction increases for each step up in the pyramid and decreases for each step down. Various literatures suggest, that in order to achieve enhanced resource consumption the concept of cascading can be beneficially. Highlighted by [15] is for example, that large savings of primary resources can be obtained, and that the time a certain resource can be used is extended considerable by cascading.

According to [14] cascading provides a platform for a sequential re-utilization of the same unit of a certain resource for multiple high-grade materials of which the latter step can be energy production. It is further stressed by [15] and [16], that maximizing the cascading effects, secondary resources should be used in the application with the highest possible quality for which they are intrinsically suitable. Many different types of materials can be more efficiently utilized when applying the cascading method, e.g. wood residues from industry or forests, building materials, recyclable bio-waste, and different types of plastic [17;18;19;20].

Materials Flow Analysis: In order to point to opportunities for establishing and enhancing a circular bio-economy contribution from the Danish agro-industry, we will identify the materials flow (input/output) within a Danish agro-industry applying a material flow analysis (MFA). Such analysis is based on stocks and flows of substances or materials within a system that, according to [21], is clearly defined. The basis for an MFA-analysis is hence mass conservation and the emphasis on balancing materials inputs and outputs within the targeted industrial sectors [22]. In this study, emphasis is on inputs of agricultural raw materials, excipients, electricity and fuel for heating and processing purposes. Outputs are the finished goods being produced by the company, as well as solid waste, wastewater and emissions to air. The emphasis of our MFA-analysis within the agro-industry is depicted in Figure 1 below.

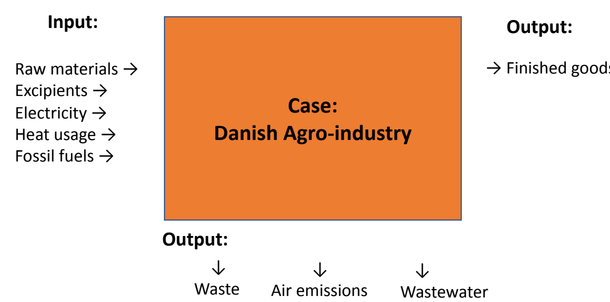

Fig. 1. Input and output streams of materials and energy within Danish agro-industry, will determine the possible cascading and coupling activities to apply. Data collected by means of an MFA-analysis within the case industry.

2.2. Data retrieval

Company visits and interviews with staff members within the case agro-industry, being a slaughterhouse industry, were conducted during the winter of 2020. The emphasis of this was to gather data for the MFA-analysis and to investigate the production site facility. Besides information from the case company, the method of triangulation has been applied through the Green Accounts and CSR reports from the company, as well as through more generic information sources obtained through peer review journal articles, branch organization reports on ago-industrial manufacturing. The interview methods applied were based on the semi-structured qualitative interview form in which the informants, besides detailing data for the MFA analysis, also provided space for describing and addressing personal experiences and other relevant issues related to the company and its operation practices [23].

Besides this, studies of potential quantities of manure from local farmers in Ringsted has been assessed by means of online data-bases of livestock animals in Denmark - the 'CHR register' - just as information about the potentials for supplying source separated organic household waste (SOHW) has been obtained from the municipal waste company Affald Plus in the city of Ringsted. Technical data on energy technology, efficiency and energy conversion rates etc., has been obtained from the technical data report [24]. Biogas energy potentials from animal manure, source separated organic household waste (SOHW) and wastewater etc. has also been obtained from the above, as well as from various background literature provided by Danish research institutions and governmental organization, as for example [25] and [26].

3. FINDINGS AND ANALYSIS

3.1. Results of MFA-analysis

Departing from the results of the MFA-analysis depicted in Figure 2 below, we will propose a new cascaded and coupled materials and energy system within the case agro-industry, described and presented further in the paragraph below. But first, we present the existing system deployed within the slaughterhouse case industry.

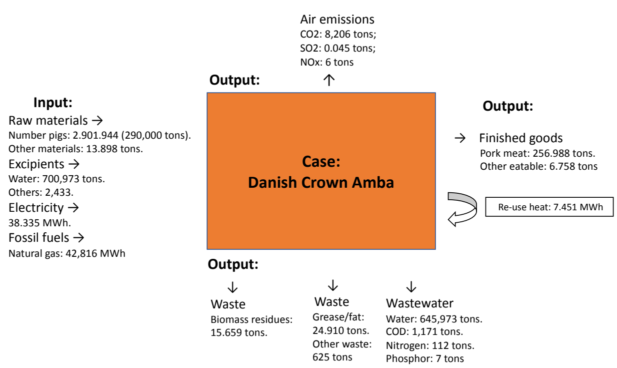

Fig. 2. MFA in a Danish slaughterhouse agro-industry (Danish Crown Amba).

3.2. Existing system and drawbacks

Raw materials, finished goods, energy and wastes: See Figure 2. Besides slaughter-pigs, accounting for 290.000 tons, the raw materials consist of smaller amounts of refined meat from other Danish Crow companies, which together lead to a total output of 256.988 tons meat, and a smaller fraction being edible blood. Besides water usage of 700,973 tons annually, the use of excipients consists of chlorine, ammonia, liquid carbon dioxide, dry ice, chemicals for wastewater treatment. 645.973 tons of wastewater is hence treated by filters on-site removing larger organic particles - but with no energy extraction - before discharged to the public wastewater treatment plant. The energy supply is based on electricity (38.335 MWh) from the grid with a variable fossil/renewable energy mix, as well as on natural gas (42.816 MWh) utilized for heating-up water and for process heating purposes. Heat recovery amount to 7.882 MWh annually and mainly happens from cooling processes, compressed air compressors and from the oven for pig hair removal, where the energy hence returned to be utilized for water heating purposes.

Biomass residues are non-edible wastes such as intestinal like stomach and guts, as well as fat/grease including bones and tendons from cut offs. In the existing system the fat/grease/bones/tendons are send to DAKA for use as animal feed and to produce biodiesel (24.910 tons), just as the non-edible biomass residues, accounting for 15.659 tons, is transported by truck to Hashøj Centralized Biogas plant in another part of Zealand to be used for renewable energy production, together with animal manure etc. Besides organic waste the company also generates different fractions of waste materials used in waste incineration and wastes removed to landfills.

Drawback of existing system: As seen from the above outline of the existing system at Danish Crown, it is evident, that the resource efficiency is low, and that the cascaded and coupled systems (DAKA and Hashøj) and cascaded systems (Re-use heat), already applied, can be developed further. Especially with emphasis on more regional/local solutions providing benefits for nearby citizens, industry and farmers. Existing cascading and coupling activities have character of cost reduction, and ‘do more with less’ adopting the LEAN-tool [27], and not the creation of value adding by circular activities within the local community. Resources like wastewater are e.g. not being utilized for energy production, and the external use of biomass residues require relatively much transportation. No focus on converting fossil fuel usage to renewable energy is likewise identified, albeit re-usage of a minor part of the ‘fossil-fuel’ waste heat has been applied. Due to the lack of a more holistic approach to materials and energy consumption within the case industry, valuable cascading and coupling activities - with green transition pathway having a much higher impact - are not achieved. In our proposal of a new cascaded and coupled materials and energy system within the case industry, we will apply a more circular and resource efficient system based on renewable materials and energy adopted within a local context.

3.3. Proposed system by cascaded and coupled materials and energy

Biogas energy 1: See Figure 3. Energy production from biomass residues, here wastewater, is suggested to be digested in an Internal Circulation, IC Reactor tank, which is a third-generation anaerobic reactor, capable of digesting fully mixed wastewater with a relatively low dry matter content in large quantities to secure the efficiency [28]. This plant will replace the existing wastewater treatment at the agro-industry. The biogas yield from 645,973 tons of wastewater, which consist of effluent organic materials from the processing of slaughter-pigs, corresponds to 16,100 MWh of energy. The energy produced can be utilized within the slaughterhouse as fuel in the furnace for process heat and for space heating. The renewable energy production will hence substitute the existing use of fossil fuels, being natural gas, in combination with the biogas production from the AD Reactor, see below.

Biogas energy 2: Emphasis is here to establish a municipal situated biogas plant in Ringsted, in which fruitful couplings to the agro -, and waste sectors could be applied. The AD Reactor will produce co-generation (combined heat and power, CHP) by means of heat and electricity and utilizes a variety of biomass residues from within and outside the company, including the local community. Thus, biomass residues from the slaughterhouse, amounting to 35,660 tons, can be feed to the reactor tank, together with biomass residues from the nearby community, like animal manure (here estimated to 94,240 tons) from local dairy cow and pig stables, as well as source separated organic household waste (SOHW) from local residences (here estimated to 27,100 tons) collected by the municipal waste company 'Affald Plus'.

In total, 157,000 tons of different types of biomass residues can be fed to the reactor tank, providing a heat generation corresponding to 22,810 MWh, where the majority (19,265 MWh) can be utilized for energy purposes within the slaughterhouse for process heating purposes, and a minor part (3,545 MWh) led to the district heating network in the community as external energy usage. Alternatively, the majority of the heat could be distributed as district heating (DH) to the local community, and other types of local renewable energy sources could be applied at the industry, e.g. combustion of wood chips, cereal straw. Electricity generation account for 24,160 MWh and will distributed on the local electricity grid for external usage. As seen in Figure 3 below, air emissions related to the previous production of energy (process heat) based on fossil fuels are reduced significantly, especially CO2 emissions, by adopting to renewable energy.

Biodiesel: Quantities of highly greasy/fatty biomass waste are currently distributed for external usage to a Danish company named 'DAKA' who, by means of transesterification to crude oil followed by a refining process [29], and produce second generation biodiesel corresponding to 12,633 MWh. Biodiesel is regarded as a promising alternative resource for diesel engines, especially from such non-edible grease/fat feedstock [30]. Thus, this existing cascading of biomass residues is thus favorable and should be sustained.

Re-use heat and savings on cooling: Additional heat re-usage can be applied within the slaughterhouse agro-industry, which currently corresponds to 7,451 MWh of energy, which will reduce the drawing of virgin resources to produce this, and minimize heat wastes in general. It is estimated that 48 TWh of recoverable heat within the manufacturing industry are lost on a yearly basis, which stress the importance of re-capturing this, often low temperature heat, and hence identify relevant purposes for its usage. Low temperature waste heat can be utilized for e.g. cleaning purposes, but also for process heat purposes when reconsidering retention time and temperature levels in the production process. High temperature levels can also be obtained by applying e.g. vacuum in which boiling activities can be applied already at 70-75 degrees C. [31]. The '>' symbol in Figure 3 thus indicate that the 're-use heat' potentials are higher than what is currently applied within the ago-industry, but not estimated further in this paper. Energy savings within cooling activities - not applied within the case agro-industry - can for instance be freezing of pig bodies by higher temperatures, separation of freezing storage room in different temperature zones according to the needs, better insulation of the piping system and improved monitoring and control systems in general. Within the slaughterhouse agro-industry cooling is normally provided by thermal operated absorption chillers, and/or by mechanical operated compressors using electricity [31].

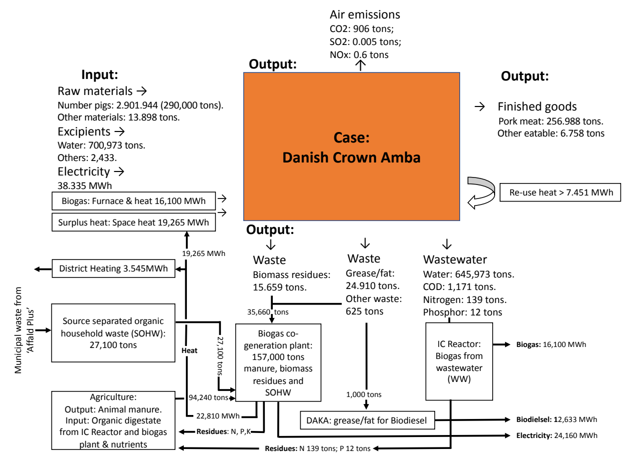

Fig. 3. Cascaded and coupled means of production in case slaughterhouse.

Digestate & nutrients: Besides energy production and substitution of fossil fuels the proposed system also provides N, P and K from the digestate of the IC and AD Reactors, which can substitute the use of artificial fertilizer with high carbon footprints and thus return nutrients to farmland. The total amount of N, P and K is calculated to 139 tons N and 12 tons P respectively. Besides this, valuable minerals are provided to the farm soil when returning the digestate to farmland [32;33]. The importance of restoring nutrients circularity within local agro-industries is emphasized by [34], who calls for stronger focus on such valuable resources in the future to safeguard food security, to preserve natural resources and to reduce environmental stresses. This role of agro-industries in this re-storing is hence especially important today, as the previous coupling within agriculture between quantities of nutrients generated and an adequate area of farmland for distribution of these nutrients has disappeared in many places.

3.4. Results of cascading and coupling

The results of the cascading and coupling, proposed in the new system, lead to value-continuity, where the final end-product is nutrients to farmland. Due to not only a few cascading's activities outside the community (current situation), but to various both cascading *and* couplings activities within the local community (proposed system), the environmental benefits of the proposed system are enhanced and the resource efficiency improved extensively.

4. DISCUSSION

The proposed system applying cascading and coupling, by means of biological processes through IC and AD reactors, provides an integrated solution which comply with most of the biomass residues generated by the slaughterhouse case industry; biomass waste, wastewater, grease/fat, etc. It also addresses solutions for energy production and consumption based on renewable energy having a high displacement factor as far as fossil fuels, as biogas both displaced fossil fuels for energy usage but also methane emissions related to the decomposition of biomass residues not being utilized and thus discharged. Besides an extensive renewable energy production valuable nutrient are re-cycled, which substitutes the use of new such resources, as well as the utilization of fossil fuels in the extraction of and raw materials processing process. For example, only 25 % of the P resources distributed on farmland today relies on re-cycled P [35], implying the importance of developing new types of concepts for re-use and re-cycling of such resources, some being finite like phosphor [36]. The proposed system contributes to such new concept-thinking.

As opposed to the current system adopted by the case agro-industry, relying on only a few cascading and coupling activities, applied within a large geographical area - as well as the use of resources requiring extraction and further raw materials processing - the proposed system apply solutions within the near-by community. It relies on local renewable resources being produced and re-used within a narrow geographic area limiting energy distribution losses and long transportation distances of biomass residues, as well as the extraction of and further processing of raw materials, etc. The system emphasize local bound solutions, meets and supports local stakeholder interests and development opportunities.

The proposed system developed in this paper revolves around a slaughterhouse case agro-industry and provides many benefits for the company, municipality and society, and illustrates how biomass residues from this type of agro-industry can be an important element in a green transition pathway. Other types of relevant agro-industries, than the once highlighted here, could be e.g. dairy, - sugar, beet and greenhouse companies, as well as some plastic and medical manufactures. The analysis reviles that local communities must emphasize such companies, and through dialogue and cooperation initiate and facilitate such cascading and coupling activities in their community.

5. CONCLUSION

This paper exemplifies how circular bio-economy concept can be addressed at the community level to achieve a green transition pathway - potentially involving various local stakeholders within the energy, -industry -, waste and agricultural sectors, when applying cascading and coupling activities, which have been poorly addressed in the past literature [1]. To succeed in this, future policies addressing circular bio-economy must however include some of the above issues in the design of new support mechanism. Increased focus on cascading opportunities for company externalities, here emphasizing biomass residues, must be emphasized more strongly and thought into the regulatory framework. Combined with for example higher taxes on re-usable biomass residues this could be achieved in the future.

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