THE ROLE OF ANAEROBIC DIGESTION AND BIOGAS IN THE CIRCULAR ECONOMY

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The role of Anaerobic Digestion and Biogas in the Circular Economy

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1. Executive summary

This technical report has been written to highlight the diversity of benefits from anaerobic digestion and biogas systems. Biogas from anaerobic digestion is not merely a concept of production of renewable energy; it cannot be compared to a wind turbine or a photovoltaic array. Nor can anaerobic digestion be bracketed as just a means of waste treatment or as a tool to reduce greenhouse gases in agriculture and in energy. It cannot be pigeonholed as a means of producing biofertilizer through mineralisation of the nutrients in slurry to optimise availability, or as a means of protecting water quality in streams and aquifers. It is all these and more. The multifunctionality of this concept is its clearest strength. Sustainable biogas systems include processes for treatment of waste, for protection of environment, for conversion of low-value material to higher-value material, for the production of electricity, heat and of advanced gaseous biofuel. Biogas and anaerobic digestion systems are dispatchable and as such can facilitate intermittent renewable electricity.

The target group for the report is represented by biogas stakeholders in general, and by decision makers and the biogas business actors. The reader should have a conceptual understanding of biogas, anaerobic digestion, the energy and fuel system and the circular economy. The reader should be interested in how the pieces fit together and how the multifunctionality interlinks all these aspects. The scope of the report has thus been to create a narrative, on the topic of how anaerobic digestion and biogas fit into the concept of the circular economy.

The biogas plant and its basic functions are described, as are the concept of biorefineries and how they interlink to biogas production. The multiple functions of biogas in the circular economy are discussed under the following headings:

i) Biogas as an energy carrier;
ii) Reduction of GHG emissions;
iii) Energy security;
iv) Biogas as raw material – further use of carbon dioxide and methane;
v) Biogas from AD as a scavenger for organic waste streams;
vi) Biogas treatment for better water quality;
vii) Awareness tool on circular thinking;
viii) Biogas in agriculture;
ix) Balancing income for rural areas; and
x) Challenges in using waste as raw-material.

To show how closely related anaerobic digestion and biogas are to the concept of circular economy, the intimate relation is exemplified through four case-studies:

i) Vera Park, Sweden;
ii) BioKymppi, Finland;
iii) Sønderjysk Biogas Bevtoft, Denmark; and
iv) The Magic Factory, Norway.

These examples are just a few of the many more currently active and in the planning stage. They show how simple it can be to take a significant step towards circular economy concepts with the aid of biogas and anaerobic digestion.

We are still in the advent of the circular economy. Products from bio-based resources will grow in both absolute and relative terms in the coming years. In the future bioeconomy, wastes will be transformed to high-value products and chemical building blocks, fuels, power and heating; biogas facilities will play a vital role in this development, and in the implementation of the novel production paths that arise in the transition to a bio-economy. The future of the biogas facility is a factory where value is created from previously wasted materials; this ensures sustainability of the environment and potential for financial gain for the local community. The flexibility of the anaerobic digestion system and its ability to digest a multitude of organic feedstocks, while producing a significant range of products ensures the role of anaerobic digestion and biogas in the circular economy.

2. Introduction

The biogas plant is the hub in the future circular economy. Streams of excess materials, previously regarded as waste, from industrial processes, agriculture and other human activity can be channeled through biogas digesters and converted to useful energy carriers, nutrient-rich organic fertilizer and novel materials.

2.1 From linear to circular economy

The *linear economy* may be summarized as follows:

- take (the resources you need);
- make (profit and goods);
- dispose (of everything not needed, also the product at the end of its lifecycle).

As the world population grows and new industrial and developed areas expand, both in absolute and relative terms, the linear economy will move towards constraint of supply of materials, including food. This may lead to economic hardship, human suffering and conflict (Sariatli, 2017).

A *circular economy* (figure 1) is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value, at all times. The concept distinguishes between technical and biological cycles (Ellen McArthur foundation, 2015).

Bio-based economies can be defined as: "*technological developments that lead to a significant replacement of fossil fuels by biomass in the production of pharmaceuticals, chemicals, materials, transportation fuels, electricity and heat*" (Sariatli, 2017). The very closely related concept of "bio-economy" usually focuses on the utilization of biomass in primary production processes in forestry, fisheries and agriculture and increased valorization of raw materials used. The term bio-economy will be used to encompass both definitions (bio-based economy and bio-economy) in this text.

The higher the recycling and re-usage of waste in an industrial foundation, the more it comes in-line with the concept of the circular economy while being less harmful to its surroundings and more profitable (Sariatli, 2017). Wastes, materials and energy consumption need to be minimized in the circular economy. In pre-industrial times, natural and circular economy systems were applied while the linear economy was introduced during industrial times. It is incumbent on us to return to the circular economy. The quality and value of the unit or subject of circular flows is the key in the circular economy.

2.2 The biogas plant – the hub in the bio-economy

The anaerobic digestion process is a fermentation process, which takes place in a closed airtight digester where organic raw materials such as manure, food waste, sewage sludge and organic industrial waste are converted into biogas and digestate as products. The produced biogas is a mixture of 50 – 70% methane and 30 – 50% carbon dioxide and smaller amounts of water vapor, hydrogen sulphide and other minor components and trace elements. The wet digestate results from anaerobic digestion of the substrates, which are pumped out of the digester tank, after the extraction of biogas. The digestate consists of slow degradable, stable organic components such as lignin, nitrogen and phosphorous in various forms, inorganic salts containing phosphate, ammonium, potassium, and other minerals.

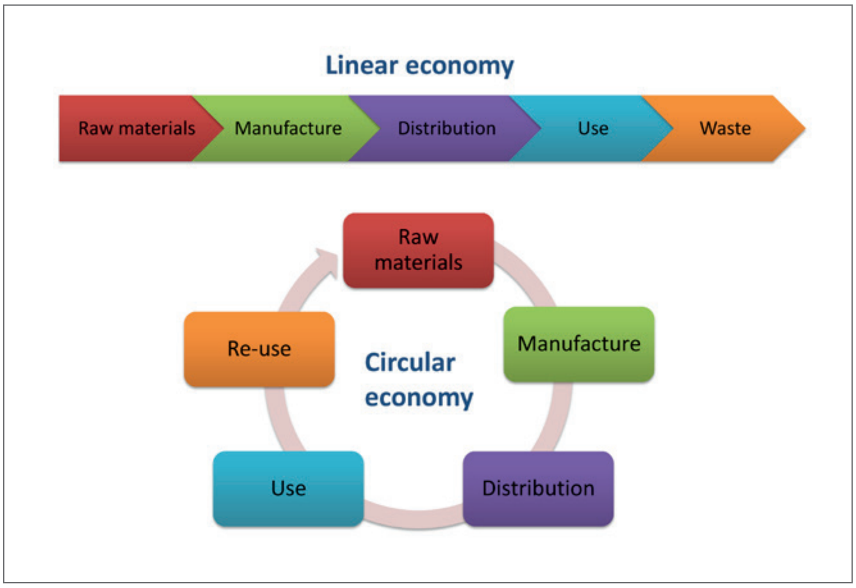

Figure 1. Differences between the linear and the circular economy.

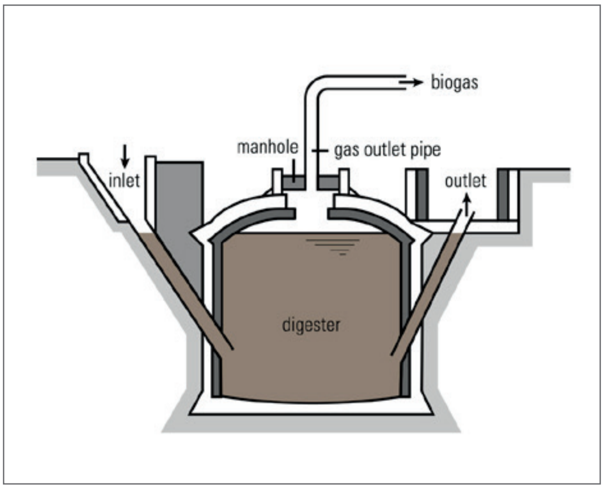

Figure 2. A representation of a basic form of digester primarily used for manure treatment. (McCabe et al., 2018; modified from Bond and Templeton, 2011)

Very simple biogas digesters have been used in China, India and many other Asian countries for many years. A recent report IEA Bioenergy report (McCabe et al, 2018) discusses local applications of anaerobic digestion (AD) in more detail. These type of digesters, produce heat for cooking and flames for lighting as well as digestate for fertilizer. An example is shown in figure 2.

Industrial applications of biogas production started well over 50 years ago as a means of stabilizing sewage sludge at waste water treatment plants. The biogas industry expanded in the 1970's and 1980's as increased production of different organic materials (such as manure and industrial wastewater from sugar refinery and pulp mills) became more widely used. Starting in the mid 1990's extraction of landfill gas (low quality biogas) came to the fore, along with the construction of farm-based biogas plants and anaerobic digestion of solid wastes from food industry and food waste. From the turn of the new millennium increased interest in, and an acceleration of, construction of farm-based biogas plants took place and an industrial sector was established. Figure 3 shows an example of a modern innovative industrial biogas plant as an integrated element of pulp and paper and fish farming industries.

There is a strong linkage between the bio-based economy, the circular economy and the biogas plant as depicted in figure 4. Two views are prominent:

- Biogas production is the last step in a cascading biomass system, where a renewable energy carrier (biogas) is simultaneously produced with sanitized bio-fertilizer (digestate).
- Alternatively, and often in conjunction with the former, anaerobic digestion is viewed as a process step where value is created from waste. Hence, a problem of disposing waste is transformed through upcycling (Martin and Parsapour, 2012) to a high-value product stream, via the biogas production facility.

Linked to this latter view is the concept of anaerobic digester based *biorefineries*.

Figure 3. Biokraft biogas plant in Trønderlag in Norway is positioned at the harbor and close to Skogn pulp and paper plant. The plant uses residual products from the pulp and paper industry and the fish farm industry as substrates and has the capacity to produce about 25 million m^3 liquid methane for vehicle fuel per year.

2.3 Biorefineries based around the biogas plant

Biorefineries can be designed in many ways and can utilize a variety of raw materials to produce a variety of products for different markets. Biorefineries include for example: paper and pulp mills; sugar factories and ethanol plants; as well as biogas plants. In the future, as biomass will be the source for even a wider array of products such as materials, chemicals, fuels and new food and feed products to an increasing population, the biorefinery concept needs to develop and penetrate an ever-increasing part of the manufacturing industry. For biomass to meet the needs of food and energy, the biorefineries must be resource-efficient. The products must therefore be reused or used as a resource in new processes in a circular manner (Willqvist et al, 2014).

De Jong et al (2012) presents a blueprint of the wide array of products that can be produced in a biorefinery; they describe various possibilities for raw material platforms and building block chemicals that form the basis of a very large proportion of the chemicals and materials used today. The biogas plant has a special place in this blueprint as one of the major facilities for converting biomass to high-value or bulk products in the circular economy. Solutions involving biogas can be part of a dynamic innovation culture where novel materials may be produced, which have a substantially higher value per mass or energy content than biogas and digestate. These materials may include specialty chemicals, single-cell proteins or enzymes.

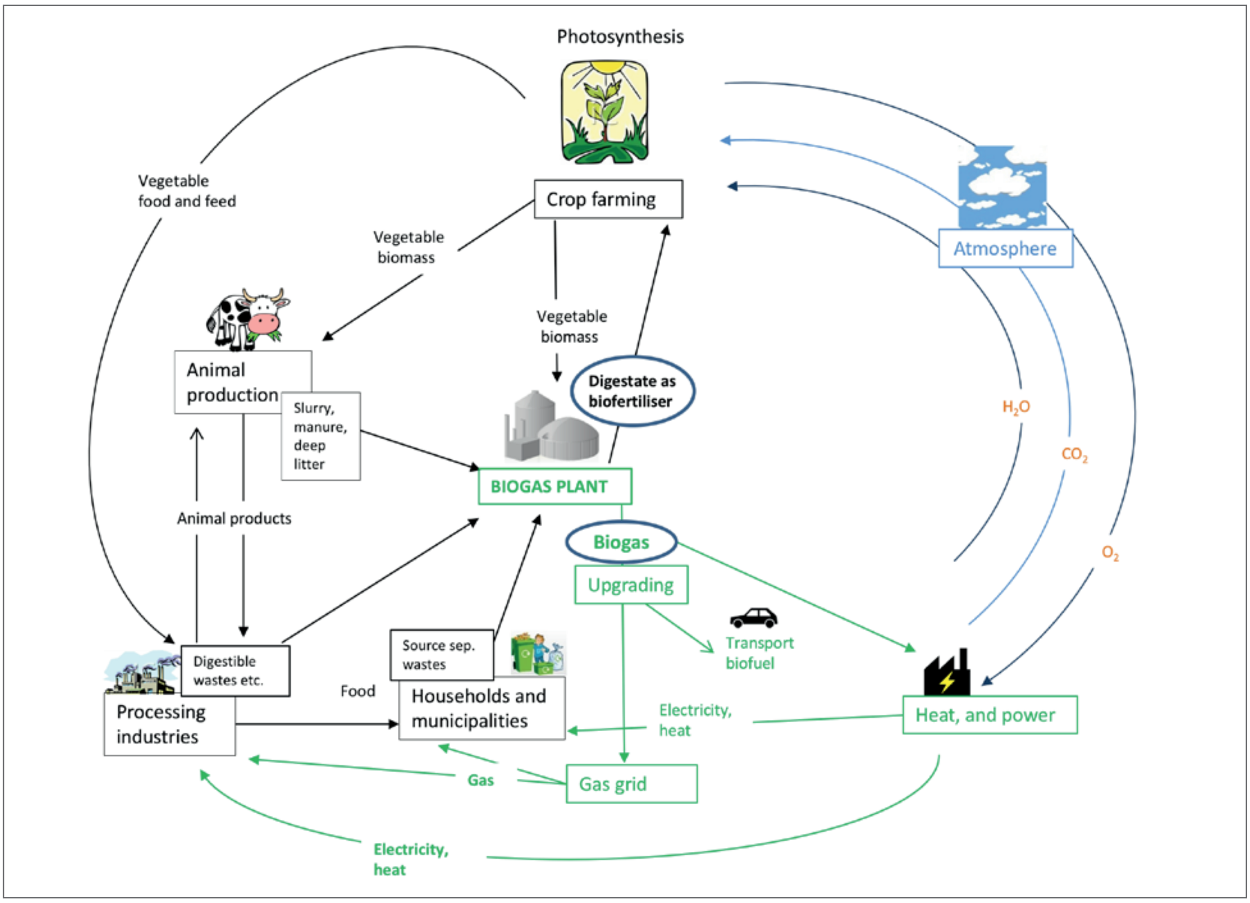

Figure 4. An example of how a modern co-digestion biogas plant fits into the circular economy (Source: Al Seadi et al, 2018)

3. The multiple functions of biogas in circular economy and its challenges

3.1 Biogas as an energy carrier

(adapted from: Fagerström, 2016)

3.1.1 Biogas – a part of the modern society's energy supply system

The use of biogas, made from organic waste streams, does not add to the carbon dioxide load in the atmosphere; carbon dioxide produced during combustion of biogas is offset by either the carbon dioxide consumed by the biomass, which is digested or by avoided fugitive methane emissions from open slurry storage. Biogas is thus a "green" sustainable energy vector and has a significant role in shifting to a sustainable decarbonised society. Biogas has many uses in the sustainable society that can be utilized in a broader perspective than today. Industries, as well as households, can use biogas for heating and hot water supply. Biogas can be used to supply warm air for drying, for example, in laundries, carpentries, industrial coating facilities and other places where there is a need for fast and efficient drying. The exhausts from upgraded biogas combustion are clean and do not generate odours or particles. In the food industry, the need for clean fuel is important. Increased use of cleaned upgraded biomethane could be available for further applications in, for example, catering and industrial kitchens, bakeries, and in the food industry where instantaneous, continuous heat and fast regulation are demanded. Natural gas is the choice of thermal energy for evaporation processes in breweries, distilleries and creameries; this is easily replaced by renewable gas leading to decarbonisation of these industries. Due to the clean exhaust gases of gas combustion, gas is already used to a considerable extent, for example in, roasting of coffee beans, biscuits or chips. At present, fossil Liquefied Petroleum Gas (LPG) is often used for the latter examples, but green LPG or biomethane could be used in lieu. When renewable gas or green gas is used instead of fossil alternatives, industrial applications become significantly more environmentally friendly, decarbonised and sustainable. IEA Bioenergy recently produced a report on *green gas* (Wall et al., 2018).

3.1.2 Biogas used for heat and electricity production

The most common use of biogas is in a non-upgraded form for production of electricity and heat production. The default use of biogas is for CHP (Central Heat and Power) production, which is in fact production of renewable electricity and heat, also known as cogeneration. The heat from the CHP engine can also be used to drive an absorption chiller to give a source of cooling, resulting in a combined cooling, heat and power (CCHP), also known as trigeneration.

The CHP technology is based on the bock heat and electricity plants (BHPP), where electricity is produced by a combustion engine. The electricity is used locally, or it can be supplied to the grid. The thermal energy (renewable heat) is a by-product produced by the engine, and it is normally used locally (such as in district heating). There are various kinds of power generation units, such as four-stroke engines, micro turbines or Stirling engines; their electrical efficiency ranges between 25-45%, depending on the type of co-generation set (Persson et al, 2014; Kaparaju and Rintala, 2013). The CHP generation unit can be placed at the biogas facility, or the biogas can be transferred through a piping system, usually at low-pressure, to a CHP plant or a district heating unit in the area. The utilization of the renewable heat is very important, as it brings about significant additional economic and environmental benefits, on top of the utilization of biogas for renewable electricity production (Hengeveld et al. 2016).

3.1.3 Upgraded biogas (biomethane) used as vehicle fuel

Raw biogas can be upgraded in a process which removes hydrogen sulphide, water, particles and CO_2 present in the gas. The process creates a gas consisting mainly of methane and thus increases its energy content. Clean upgraded biogas is used as fuel for cars, buses and trucks of various sizes. In several countries, there is a well-developed infrastructure for vehicle gas, and it is possible to fuel natural gas vehicles (NGVs) in the most densely populated areas of such countries. Today, vehicle gas is used mostly for buses, trucks and passenger cars. The interest of using Compressed

Natural Gas (CNG) and Liquified Natural Gas (LNG), or the corresponding biogas-based alternatives CBG and LBG, in heavy transport has increased and this could bring new opportunities for biogas. Upgraded biogas is completely interchangeable with its fossil equivalent. The real challenge for the transport sector lies in abandoning fossil fuels and decarbonising energy. In the conversion, this means that all renewable fuels, including biogas, electricity, fuel cells, and many others, have a role to play. In practice, NGVs are one of several realistic renewable alternatives, for heavy transport and long-distance travel.

3.1.4 Upgraded biogas (biomethane) injection into the gas grid

Biomethane from renewable sources is also fed into the national transmission network for natural gas in several countries. Through this network, renewable gas or "*green gas*" reaches customers in households and industry as well as vehicle fuel stations (Wall et al, 2018). As the number of biogas to grid systems has increased, the level of renewable gas in the transmission networks has also increased. The composition of the gas in the grid is not homogeneous. Depending on where the gas is taken from the grid, the molecules have various levels of fossil and renewable origin. It is however possible to purchase 100% renewable gas anywhere on the gas network by ensuring that as much renewable gas is fed into the grid as sold to the customer through a mass balance system. This market is normally managed by a green gas certification system.

3.2 Reduction of GHG emissions

Biogas can be produced in many ways and from many different substrates, with different targets in gas quality. The production facilities may be of varying design and specification and the operation of the process may differ between producers. Hence, the contribution of biogas production to GHG emission reduction may also vary significantly (Liebetrau, et al, 2017).

One of the main reasons for a transition from fossil energy and fuel to renewable energy and fuel is the reduction in greenhouse gas (GHG) emissions. Displacing fossil fuels is, independent of the biogas produced, always a win; but it is important that the production of biofuels and bioenergy contributes to a significant reduction of GHG emissions. Liebetrau and co-authors (2017) employed a methodology and used data from the European Commission (EC) Joint Research Centre (JRC) to assess the impact of fugitive emissions on the sustainability of biogas. In this process they assumed a target for sustainability of 30% of the GHG emissions of the Fossil Fuel Comparator (FFC) for electricity. They found for example that mono-digestion of energy crops will struggle to meet these reduction targets, however manure-based systems readily meet these targets due to the savings in fugitive emissions from displaced open slurry tanks. Co-digestion of slurry and energy crops can be effected at mix ratios that allow sustainability.

Biogas from AD is a multifunctional technology, offering solutions for, *inter alia*, treatment and management of digestible wastes of crop and animal origin, as well as animal manures and slurries. In many areas around the world, organic substances, considered as waste, are still deposited in landfill sites where they decompose, releasing methane (CH_4) with a global warming potential (GWP) 21 times that of CO_2. When these streams of organic waste are redirected from landfill to a biogas facility, a significant reduction in methane emissions from landfills occurs (Bogner et al, 2008). Use of animal manure and slurries as feedstock for AD, reduces the emissions of CH_4 from manure and slurry storage and application. In theory this can lead to carbon negative energy and fuels as the CO_2 emitted in combusting biogas has a lower global warming potential that the methane emitted to the atmosphere in a do-nothing scenario without a biogas system (Murphy et al., 2004). Along with this, the possibility of better nutrient management in digestate, combined with good agricultural practices (Holm-Nielsen et al, 1997), contributes to reduction of ammonia and NO_x emissions from the storage and application of manure as fertiliser (Energistyrelsen, 2016).

3.2.1 Improved nutrient up-take efficiency in agriculture

Intensive agriculture is one of the major greenhouse gas sources worldwide; these emissions are associated with enteric fermentation, management of manures and production of synthetic fossil fuel based fertilizers. Anaerobic digestion systems remove the easily degradable carbon compounds in feedstocks such as slurries and manures and converts them to biogas (Clements, et al, 2012). When the remaining digestate is applied as biofertiliser, the slow to degrade carbon is recycled back to soils, contributing to build up of the humus content of the soil and its long-term suitability for agriculture. Digestate improves the soil organic carbon of agricultural land. At the same time, macro- and micro- nutrients contained in digestate are predominately in mineral form. This makes them more easily accessible to the plant roots, compared with nutrients in raw manure and slurry, which are mainly organic compounds, and must be mineralized in order to be up-taken by the plants. As such digestate has a higher nutrient uptake efficiency, compared with raw manure and slurries. (Al Seadi et al, 2018).

AD plants, able to handle substantial amounts of crop feedstock, are very beneficial for organic farming, in particular those in need of nutrients. Use of organic digestate as fertilizer has the potential to ensure the future development of organic agriculture. Additionally, organic matter in digestate can build up the humus content in the soil; this is a benefit unique to organic fertilizers, which is particularly crucial for arid and semi-arid lands with low carbon content. The destruction of weed seeds in the AD process is another significant benefit to organic farmers.

3.3 Energy security

Fossil energy is still in abundant use around the world. This energy comes in the form of coal, oil and natural gas from a relatively limited geographical region and is used worldwide. Many countries are thus dependent on a few countries for energy supply. A transition to a bio-based/renewable energy production system would better balance the energy supply situation around the world; more countries and regions would be able to become energy self-sustainable. Depending on their boundaries, these energy systems can be of varied scale. When producing energy such as biogas, it is more likely for a municipality to become more energy independent and industries can benefit from creating more of their energy themselves. Centralized energy production can be more sensitive to the risk of interruption of energy distribution in case of storms or other nature events. Distributed energy production could balance energy production, when grids are vulnerable, such as with significant weather events. Both gas grids and available biomass can act as energy storage and balance other renewable intermittent energy sources such as wind and solar (Persson et al, 2014).

3.4 Biogas as raw material – further use of carbon dioxide and methane

Biogas consists mainly of methane and carbon dioxide. Generally, methane is used as an energy source with the carbon dioxide element of the biogas released to the atmosphere. Bioenergy, carbon capture and sequestration (BECCS) is seen as essential to keep the world's temperature below 1.5°C (EASAC, 2018). This is very applicable to biogas. When biogas is used as a natural gas substitute in gas to grid systems the CO_2 needs to be separated from the CH_4 in the biogas. Sequestration of this CO_2 is an expensive process, but in the short term (and the long term) the CO_2 may be reused.

In future energy systems, including circular economy concepts, both components (CO_2 and CH_4) may be used as raw materials for production of food and feed as well as various kinds of materials. Carbon dioxide capture can be either from off gas from a co-gen set producing CHP or from the CO_2 separated from CH_4 in biogas upgrading. Depending on the purity of the CO_2, it can be cleaned and used to increase the carbon dioxide concentration in greenhouses for increased plant and food production, it can be used as a carrier in cooling systems or as a raw material for chemical production. Very clean carbon dioxide might also be used in the food industry, for production of mineral water, and in breweries to add gaseous bubbles to beer. The production of micro-algae in closed loop systems also needs substantial amounts of carbon dioxide. Indeed, micro-algae may be used as a means of capturing CO_2 from biogas and upgrading the biogas to biomethane (Xia et al, 2015).

By adding hydrogen to a biogas plant the biogas may be upgraded to almost 100% methane; the hydrogen reacts with the CO_2 in the biogas converting it to more CH_4 ($4H_2 + CO_2 = CH_4 + 2H_2O$). This may be carried out either *in situ*, whereby the hydrogen is directly injected into the digester where the AD process is carried out, or *ex situ*, where the produced biogas is reacted with the hydrogen in an additional reactor. This microbiological process is called biomethanation, whereby the microorganisms (hydrotrophic methanogens) reduce the carbon dioxide to methane (Guneratnam et al, 2017). Employing this process in an ex-situ process may produce biogas with a sufficiently high content of methane as to reach vehicle fuel quality in the future. If the hydrogen used in this process is sourced from electricity, via electrolysis, the concept is referred to as *power to gas. Carbon capture* is achieved as CO_2 is combined with hydrogen to create renewable methane; this may be termed gaseous fuel from non-biological origin. There are also thermochemical versions of this concept. The power to gas system has many attributes, including balancing of the electricity grid (McDonagh et al, 2018).

Instead of combusting the methane as an energy source, the methane might be used as an organic chemical component in the same way as natural gas in the chemical industry. Methane is a possible source to produce single cell bioproteins. This is already possible in large scale and will probably be a part of the future circular economy.

When biogas is used as raw material for further production of food, feed and materials, the biogas process acts as a carbon dioxide sink, not only as a carbon dioxide neutral energy source.

3.5 Biogas from AD as a scavenger for organic waste streams

Organic waste streams occur in many places in society. In the food supply chain, food waste is generated in households as well as in supermarkets, restaurants and food production facilities. In a sustainable society where resources are used efficiently, what previously was considered to be waste is instead included in a production circle where organic material and nutrients such as nitrogen and phosphorus are returned to the soil to replace chemical fossil fuel sourced fertilizer. When digesting municipal and industrial food waste such as waste from super markets and restaurants or slaughterhouse waste, biogas is produced, and valuable nutrients accumulate in the digestate where they are easily used as fertilizer.

3.5.1 Biogas from food waste

The Food and Agricultural Organisation (FAO) within the United Nations (UN) published a report in 2011 on global food waste, indicating that roughly a third of food produced for human consumption is lost or wasted globally, amounting to 1.3 billion tons per year (discussed in: Al Seadi et al., 2013). This corresponds to a huge resource of feedstock for biomethane systems. Some countries already have targets for energy recovery from food waste. The Swedish government, for example, has a target that at least half of all generated food waste from households, shops and restaurants be separated and treated to recover nutrients and that 40% is treated to recover energy by 2018 (Naturvårdsverket, 2014). In 2016, through implementation of mainly food collecting systems and treatment by mostly anaerobic digestion, 40% of food waste was treated to recover nutrients and 32% treated to recover both nutrients and energy (Avfall Sverige, 2018). One ton of digested food waste produces 1200 kWh biogas energy, which is enough fuel to drive 1900 km with a gas fueled car. The food waste from 3000 households can fuel a gas bus for a year (Andersson, 2016).

3.6 Biogas treatment for better water quality

When organic streams are treated in biogas plants and the produced digestate is used as fertilizer, eutrophication of local streams, lakes and fjords due to leakage from organic waste disposal can be avoided or reduced. Treatment of organic waste in biogas plants instead of disposal at landfills will reduce local water contamination and emission of methane from the landfills. Biogas treatment of manure in areas with high stocking rate reduces eutrophication of local rivers and lakes, which is problematic in many countries. The mineralization of the nutrients in the digested manures and the potential to separate digestate into nitrogen rich liquors and phosphorous rich solids facilitates optimal management, application and usage of the manure based nutrients.

The fish farming industry can be made more sustainable by incorporation of an anaerobic digester into the system. Fish farms generate substantial amounts of sludge, faeces and feed surplus, which up to now has generally been disposed at the bottom of the fjords or found its way to local streams and lakes; these materials may be digested to produce biogas.

Specially designed biogas digesters are also used as water purification plants for heavily organic polluted water with low particle content, for example effluents from pulp and paper industry.

3.7 Awareness tool on circular thinking

Circular economy is a broad concept, which can be hard to comprehend. The biogas plant is a concept which could also be used for education purposes to give children concrete examples of a circular economy concept. Showrooms in farms have been used to show "where the food comes from" to school groups. These same concepts could be used more widely to explain how separate collection of food waste in homes can be used to produce green energy or fertilizer production.

3.8 Biogas in agriculture

3.8.1 Centralised manure co-digestion is circular economy in practice (Adapted after Sander Nielsen, 2016)

Centralized manure co-digestion is an example of a present-day circular economy concept. Already in the 1990s, it was considered a multifunctional technology, providing intertwined benefits in the fields of energy and transport, agriculture and waste management and for the overall environment/climate sectors (Al Seadi et al., 2018). The economies are in the form of:

- i) production of biofuel and of renewable energy;
- ii) reduced emissions of greenhouse gasses (CH_4, CO_2, NO_x);
- iii) improved manure management and nutrient uptake efficiency;
- iv) veterinary safety through sanitation;
- v) reduced nuisances from odors and flies;
- vi) financial savings for farmers;
- vii) sustainable treatment and recycling of organic wastes;
- viii) less pollution of air and water environment;
- ix) improved local/rural economies.

Organic residual fractions from industry, households and the service sector are treated in biogas plants together with livestock manure and slurries. The result is a countryside / city co-operation, a utilization of energy potential in the form of biogas, recirculation and recycling of nutrients, including phosphorus, potassium and nitrogen. At the same time, a significant part of the carbon in manure and waste is recycled, which maintains the humus content of the soils and their long-term suitability for agriculture. Biogas plants produce a dual climate effect, through reduction of methane emissions from animal farming (through removal of open storage of slurry and optimal digestate management), and by producing a decarbonised biofuel. Co-digestion improves the value of manure as fertiliser. The concept is based on the cooperation between communities of farmers, who supply their manure to a centrally located biogas plant, receiving back digestate, to be used as a high quality plant biofertiliser. Centralised manure co-digestion is exemplified in figure 4.

3.8.2 Using digestate as fertiliser

The application of digestate as crop fertiliser must be done during the growth season of the specific crop, to maximise the nutrient uptake by the plants and to prevent nutrient leaching and run off. Utilisation as fertiliser requires a specific quality, apart from the declared nutrient content. The quality refers to sanitation and pathogen reduction, as well as to the prescribed limits of chemical (heavy metals, organic compounds) and of physical plastic and other physical contaminants. For more information about utilisation see also IEA Bioenergy Task 37 reports (Lukehurst et al, 2010; Al Seadi and Lukehurst, 2012).

As a minimum measurement, the digestate is analysed for dry matter content and for nutrient content (NPK). The digestate is transported back to the farms to the storage tanks located in the fields, where digestate is to be applied as fertiliser. Compared with raw slurry, the nutrients in digestate are easily accessible to plant roots, increasing the nutrient up-take and reducing the risk of surface and ground water pollution, when it is applied through good agricultural practice. Use of digestate eliminates malodours and flies from application of raw slurry, improving air and quality of life in rural areas. The slurry suppliers can take back only that amount of digestate, which they can use on their agricultural land. Surplus digestate can be sold to crop farms, who need nutrients. In both situations, digestate can be fully integrated in the fertilisation plan of the farm, displacing significant amounts of expensive and fossil mineral fertilisers. Delivery of digestate directly to the fields and the sale of excess digestate to crop farmers contribute to a significant redistribution of nutrients in the respective agricultural area, solving the farmer's problem of excess manure, and lowering the environmental pressure from intensive animal farming. To achieve the environmental and economic benefits from the application of digestate as fertilizer, some basic principles of good agricultural practice must be fulfilled (Holm Nielsen et al, 1997; Lukehurst et al, 2010). As a principal rule, digestate should only be applied during the crop growing season. The risk of ammonia volatilization is reduced by using the right equipment (dragging hoses, soil injectors) and by taking the weather into consideration. The optimum conditions are when it is raining or there is very high humidity and no wind. Dry, sunny and windy weather reduces the N-efficiency considerably. When digestate is applied to grass crops, direct injection into the top soil gives the highest N-efficiency. Digestate storage tanks should be placed in the shade, sheltered from wind. It is important to ensure a crusting surface on the liquid, in the storage tank. The digestate should always be pumped from the bottom of the tank, to avoid unnecessary stirring. Stirring is done only prior to application. It is possibility to acidify the digestate on application, decreasing the pH-value and thereby limiting the volatility of ammonia (Holm Nielsen et al, 1997).

3.8.3 AD of animal slurries improves air quality

Animal slurry contains more than 300 different smell compounds. Each of them contributes to creating odour nuisance when slurry is stored or applied as fertiliser. Inside the AD reactor, many of these compounds are degraded, so AD contributes to reduction of odour nuisance from slurry. The smell reduction is proportional to the retention time inside the reactor; longer retention times lead to greater reductions in malodour (Birkmose, 2012). The intensity and the persistence of odours from digestate application as fertiliser are lower, compared with raw slurry. Digestate smells like ammonia, but the smell persists only a few hours after application as fertiliser. Smell reduction by AD of animal manures and slurries is very important for the acceptance of biogas technologies and of animal farming as it improves the air quality in rural areas (Al Seadi et al, 2018).

3.9 Balancing income for rural areas

The biogas plant itself is not labor intensive but it can create new business opportunities in rural areas which otherwise suffer from depopulation. Through collaboration with different farms, the biogas plant can create different job opportunities along the process chain, such as raw material cultivation and collection. By increasing local energy production, income stays in the local area instead of going to global energy markets. The challenges are high investment costs and, in some countries, low energy prices. Moreover, the different and varying incentives creates uneven markets in and between different counties. This emphasizes the fact that biogas plants create two different end products (energy and fertilizers) and both should be utilized as efficiently as possible to facilitate business opportunities.

3.10 Challenges in using waste as raw-material

Waste contains many usable substances and materials, which can be utilized and transformed into something reusable. However, some waste also may contain unwanted substances or material such as pathogens, antibiotics, pharmaceutical residues, micro plastics or heavy metals. Some of these entities do not pose a problem when the waste is converted into something inert and is not consumed by animals or humans. If it is converted to food and feed, however, or to something degradable, in contact with humans or animals, the story changes. If wastes are to be converted to food or feed or products, it needs to be certain that the novel product is unharmful. Moreover, in a circular economy, where the same material is recirculated many times, the possibility of accumulation or enrichment of unwanted substances in the loop needs to be considered and addressed. The usage of waste as raw material for feed or food is currently highly regulated and is subjected to numerous laws in most countries. These regulations may need to be updated to keep pace with the development of the circular economy so as not to hinder its wider implementation in society.

4. Case stories

4.1 Vera Park, Sweden

Vera Park, in Helsingborg, Sweden, claims to be the only fully functional completely circular solution for waste management in the world. Everything that enters is taken care of, processed and upgraded to new products, which are sold for profit. Vera Park is not just a physical place; it is just as much a way of thinking and acting in a circular economy. The concept means that NSR (the local public waste company) has opened its facilities around the region for different players. Vera Park serves as an industrial park (and test bed for research projects) for waste and recycling. Today, Vera Park has sixteen companies including NSR. The process around Vera Park is led by the Sustainable Business Hub, which is a cluster of sustainable and environmental technology with approximately 100 members, including all companies at Vera Park. What was previously a municipal waste facility, today is a highly profitable industrial centre where private companies with their own employees run profitable commercial activities with "waste" as their raw material. All organic material that enters the facility is converted into biogas, which is upgraded to vehicle gas and liquid biogas (LBG). The digestate fraction, which possesses good fertilizer properties is pumped in pipelines to farmers in the area. Within the industrial park, several other companies carry out biogas production. In addition to this, Vera Park also has its own research, which is conducted together with Lund University. Because of this, the facility expects to introduce their own products, which will improve the yield in biogas production during 2018. Non-organic fractions are also taken care of in Vera Park. Glass, plastics and paper are upgraded, and new products marketed by a separate company. Hazardous waste is handled, and metals are recycled by two other companies. Combustible fractions are utilized by the energy company Öresundskraft in their CHP-plant where research on energy-storage is carried out. Woody materials are converted by NSR to fibreboards in a unique process without use of formaldehyde. In addition to the regular activities, Vera Park also arranges courses in circular economy within waste management together with Lund University. These courses deal with how to work efficiently and profitably with residual products as a resource and commodity, instead of managing it as a costly waste. Soon, Vera Park, will introduce their Certificate of Circularity (CoC) a certificate that proves that a product really is fully circular; from production through distribution, use, disposal and handling in the recycling system. Vera Park is also involved in international co-operation in Georgia, Kenya, Chile and Estonia, to distribute know-how on waste management and fully circular biogas production.

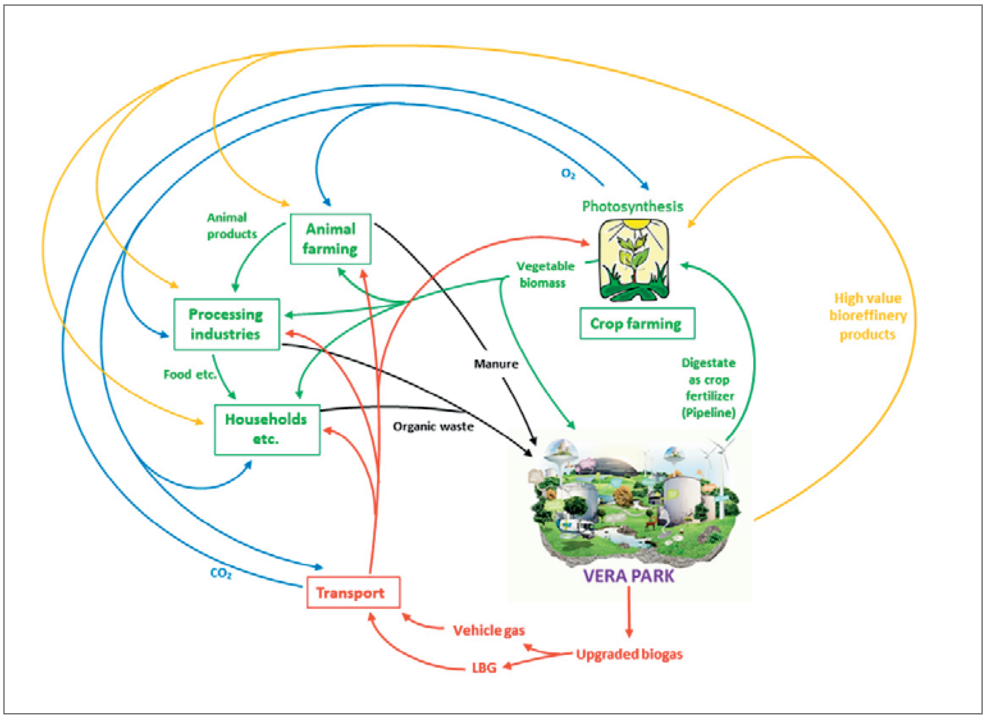

Figure 5. Vera Park circular flow diagram. The blue lines depict the flow of gasses in the atmosphere. The black lines show waste-flows. The green lines represent the flow of biomass (including treated digestate).
The red lines depict the flow, and usage of, gaseous fuels. The yellow lines represent the flow of all high-value products from the biorefinery.

4.2 BioKymppi, Finland

Biogas plant BioKymppi (www.bio10.fi) in eastern Finland collaborates with several local farms and other companies, both with raw material collection for biogas plants, as well as end product use. The plant is a mesophilic wet digestion process with two production lines, one for sewage sludge and one for organic materials suitable for organic fertiliser production. Used raw materials include separately collected household bio-waste, packed bio-waste, side streams from the food industry, sewage, waste fat (from cooking), fish and manure. The total treatment capacity ranges from 15 000 to 19 000 t/a. The gas from the biogas plant is used, together with landfill gas collected nearby, for heat and power production. The plant has a CHP plant at the site but some of the gas is distributed via a gas pipeline to a nearby heat production plant where the gas is used for district heating for local communities. The biogas plant collaborates with an energy company from Oulu, who sells green electricity to the national grid. The green electricity is traded via the Eko-Energy certificate from the Finnish Association for Nature Conservation. The annual heat production is about 8000 MWh with electricity production of 2000 MWh. The digestate is separated and liquid fertiliser is used for organic farming. Solid fertiliser is used for organic farming and household gardens. The digested sewage sludge is also used for farming. In total between 1000 to 1500 ha of land uses the digestate from this plant. BioKymppi plant has been actively involved with several research projects to improve the efficiency of the plant and the products. For example, in a project Bio-Raee BioKympi is developing with other project partners safe and efficiently recycled fertilizers. The goal is to ensure that the tested fertilizers are environmentally friendly and economically feasible compared to conventional fertilizers.

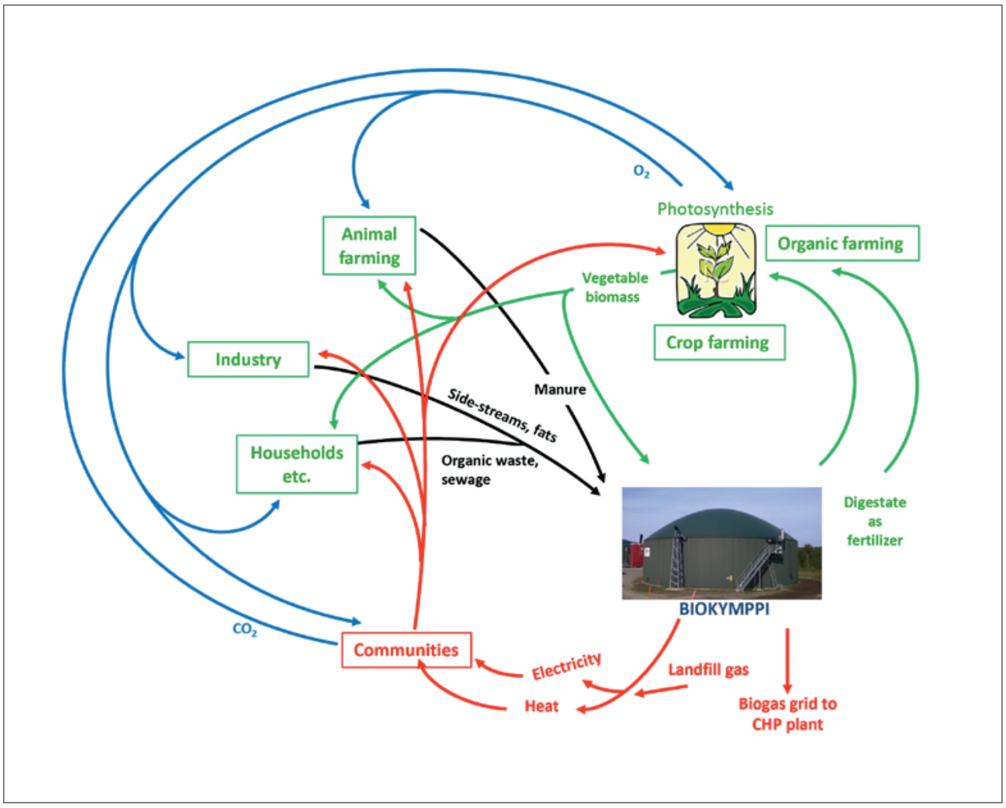

Figure 6. BioKymppi circular flow diagram. See caption figure 5 for explanation.

4.3 Sønderjysk Biogas Bevtoft, Denmark

The high tech anaerobic digestion plant in Bevtoft started operation in April 2016. With its treatment capacity of more than 600,000 tons biomass per year (some 450,000 tons of animal slurries from local farms and 150,000 tons straw and of other digestible waste materials) the biogas plant is an important contributor to meeting the policy objectives of processing half of the Danish livestock slurries by anaerobic digestion. The biogas plant is owned and operated in a 50-50 joint-venture between E.ON and the farmers owned Sønderjysk Biogas Invest A/S. The produced biogas containing 54 % methane is upgraded to 99% biomethane, in an upgrading plant with a capacity of 6000 Nm^3 biogas /h, leading to a biomethane production of 21 million m^3/year. This represents the equivalent of the annual energy consumption of 15,000 households, 571 city buses or 10,000 cars, and provides a reduction of 51,000 tons CO_2 emissions per year. The biomethane is injected directly into the natural gas grid. There are no additional costs or energy consumption associated with treating the tail gas, and harmful emissions to the environment are avoided. The produced digestate is returned to farmers in the area, to be recycled back to the soil, as fertilizer. Application of digested slurry as fertilizer reduces significantly the nuisance from odors and flies in rural areas. Digestate application is associated with higher nutrient efficiency and less nitrate leaching, compared with application of raw slurry as fertilizer. The biogas plant created 10 new jobs at the plant and contributes to creating and maintaining 20 – 30 derived jobs in the local area. The biogas plant is located on a 16-hectare area located approx. 2 km north of Bevtoft. The location was chosen in co-operation with Haderslev Municipality, with great emphasis on fitting the installation into the surrounding landscape, with suitable distance to neighbors and good access conditions.

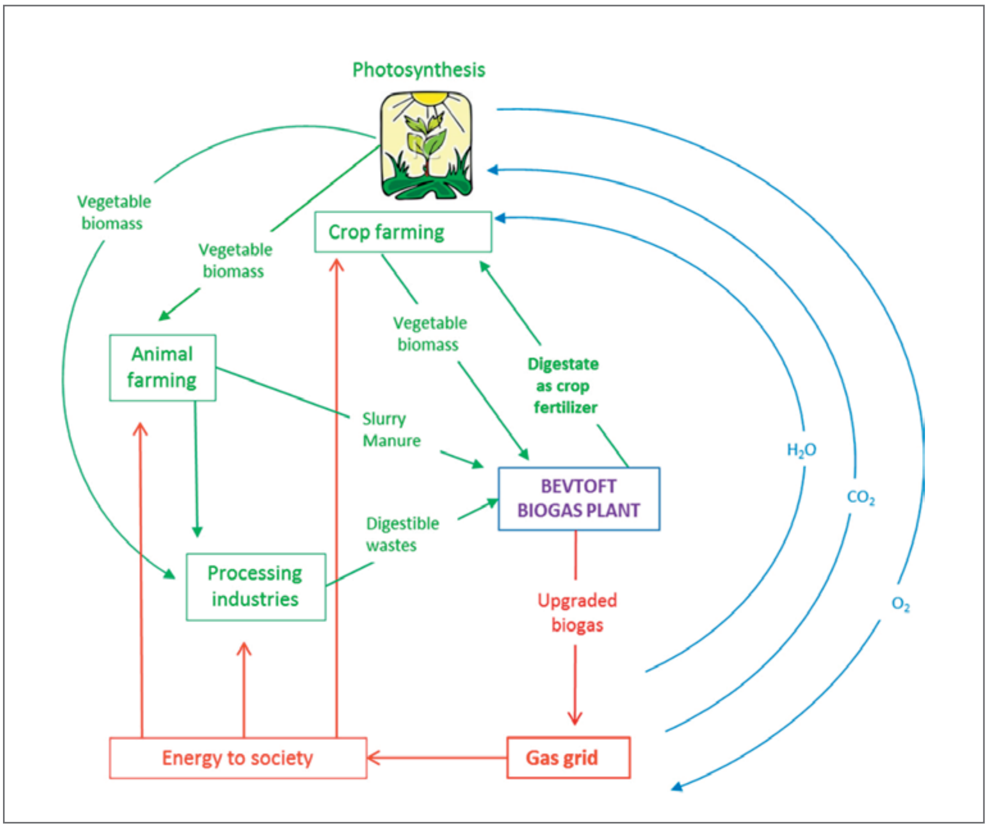

Figure 7. Bevtoft circular flow diagram. See caption figure 5 for explanation.

4.4 Magic Factory, Norway

The Magic Factory - close to Tønsberg in the south-east part of Norway recycles food waste and manure into biogas, green CO_2 and valuable biofertilizer for the production of new food. The food waste comes from households and the manure comes from farms in Vestfold county. Currently some 110,000 tonnes of food waste and manure are recycled annually at the plant. The produced biogas is upgraded and fed into a gas grid and is primarily used as vehicle fuel replacing about 5 million litres of diesel.

The close collaboration with agriculture has contributed to the plant receiving status as a National Pilot Plant. Agriculture in Vestfold county (2157 km^2 and about 250 000 inhabitants) reached the government's goal of 30% of all manure being digested to produce biogas before 2020, by 2016. The Magic Factory's goal is to become an international pioneer for green carbon capture. Carbon capture takes place through renewable and green CO_2 from the factory being used inside industrially-adapted greenhouses for food production, together with bio-fertiliser from the factory. A Magic Pilot Greenhouse is under construction, with a plan for rolling out industrial greenhouses for local food production. Work is also under way on a knowledge and visitor centre next to The Magic Factory.

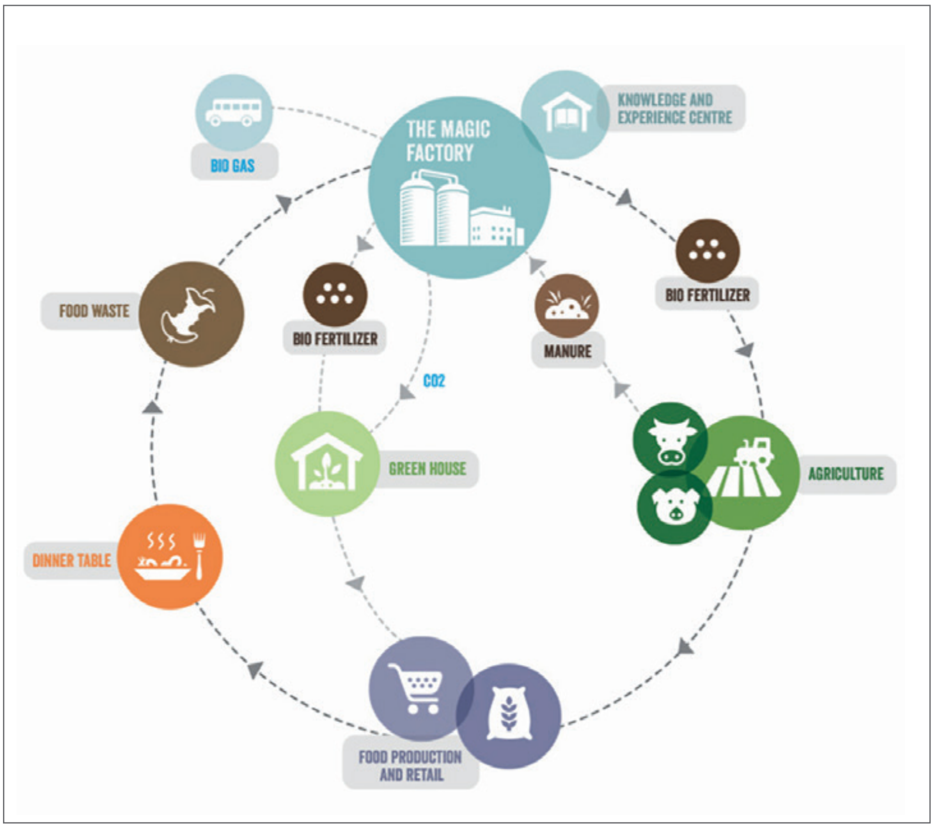

Figure 8. The circularity of the biogas plant – "The Magic Factory"

5. Final remarks

We are still in the advent of the circular economy. Products from bio-based resources will grow in both absolute and relative terms in the coming years. In the future bio-economy, wastes will be transformed to high-value products and chemical building blocks, fuels, power and heating; biogas facilities will play a vital role in this development, and in the implementation of the novel production paths that arise in the transition to a bio-economy. The future of the biogas facility is a factory where value is created from previously wasted materials; this ensures sustainability of the environment and potential for financial gain for the local community. The flexibility of the anaerobic digestion system and its ability to digest a multitude of organic feedstocks, while producing a significant range of products ensures the role of anaerobic digestion and biogas in the circular economy.

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Task 37 – Energy from Biogas

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of the work of IEA Bioenergy Task 37: Energy from Biogas.

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