GOVERNANCE OF ENVIRONMENTAL SUSTAINABILITY

of manure-based centralised biogas production in Denmark

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Governance of environmental sustainability of manure-based centralised biogas production in Denmark

Teodorita Al Seadi (Biosantech, Esbjerg, Denmark)
Inge Stupak (Department of Geosciences and Natural Resource Management, Faculty of Science, University of Copenhagen, Denmark)
C. Tattersall Smith (Department of Geography & Planning, University of Toronto, Ontario, Canada)

Edited by: Jerry D. Murphy (MaREI Centre, University College Cork, Ireland)

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Executive summary

Manure-based centralised co-digestion is a Danish biogas production concept that developed in the late 1980s. Manure and slurries are supplied from several farms to a centrally located biogas plant, for co-digestion with up to 25% digestible wastes. From its early stages of development, centralised co-digestion of manure was recognised by the Danish society as a multifunctional, environmentally sustainable concept, able to deliver a number of benefits for the agriculture, environment, and energy sectors, and society as a whole. In 2016, the annual production of biogas surpassed 9 PJ, with 75-85% of the produced biogas originating from manure-based plants. The goal is to increase annual production to 16 PJ by 2020.

The development of the Danish biogas sector has gone through different phases. The first phase was characterized by entrepreneurship, a high level of flexibility and a low level of governance. The second phase was characterised by build-up and innovation through governmental financial incentives, and support for research, education and information sharing. Farmers were motivated by new restrictions to reduce nitrogen pollution from farming, which biogas production could help to solve without major costs. During this phase, a common understanding developed that manure-based centralised biogas production is a multifunctional, environmentally sustainable concept, that is able to deliver a number of intertwined benefits for the agriculture, environment, and energy sectors, and for society as a whole. During the third phase, government commitment to biogas development ceased, and the sector was subject to market conditions, resulting in stagnation. The fourth phase began with the energy agreement from 2012, which reintroduced political commitment to the development of the biogas sector, and a goal that 50% of the manure produced in Denmark should be used for biogas production by 2030.

It is expected that the next phase will involve improved integration with the energy system as a whole, with a narrative of biogas developments as part of the circular bioeconomy. The biogas sector is seen as a solution to several environmental challenges that occur in connection with intensive agriculture. Financial incentives can thus be seen as part of sustainability governance. These incentives have been in place in periods of time during the development of this sector and absent in other periods. A new energy agreement is expected very soon. This will dictate the fourth phase and will either lead to the sector becoming more vibrant or to a loss in momentum, depending on the outcome of negotiations.

In Denmark, at the moment, biogas is seen to have two new important functions: supporting intermittent renewable electricity (from wind and solar energy); and playing a central role in the circular bioeconomy. The most significant sustainability concern associated with biogas has been undesirable indirect land use changes and competition with fodder and food production. This led to restrictions on the use of energy crops as feedstock, and a political decision to phase out their use in Danish biogas production. Biogas sustainability is first of all about following best practice to ensure safety and sustainability improvements, throughout the closed loop supply chain. This involves the use of good practice in: crop production; handling and management of the feedstock; appropriate digestion to avoid sanitary problems of the digestate; reduction of fugitive emissions and leakages from the plant; and safe and sound application of the digestate as a biofertiliser in the field. A mix of laws, statutory orders, voluntary monitoring systems and good practice guidelines govern these issues.

1. Introduction

Manure-based centralised co-digestion is an original Danish concept of biogas production, developed in the late 1980s. A key component of the concept is the supply of manure and slurries from several farms to a centrally located biogas plant, to be co-digested with up to 25% digestible wastes. From its early stages of development, centralised co-digestion of manure was recognised by the Danish society as a multifunctional, environmentally sustainable concept, able to deliver a number of intertwined benefits for the agriculture, environment, and energy sectors, and for society as a whole. This recognition is considered to be one of the key factors for the successful development of biogas in Denmark (Hjort-Gregersen, 1999; Raven & Hjort-Gregersen, 2007; Lybæk et al, 2010).

The production and utilisation of biogas from anaerobic digestion (AD) in Denmark takes place in a very complex, cross-sectorial arena, where it is governed by a mix of frameworks developed by each of the sectors, or for biogas specifically (Al Seadi et al, 2001). The policy initiatives and strategies as well as the governing methodologies and frameworks for biogas are continuously challenged and reshaped through the interaction of the actors in the biogas arena and contributing sectors, such as farming, food, households, energy, and municipalities. The interaction of these actors leads to policy interventions and governance frameworks that aim to promote the potential sustainability benefits and address potential sustainability challenges of the manure-based centralised biogas concept. The aim of this report is to examine the relationship between these policies and governance frameworks and the general level of trust in the sustainability of the manure-based centralised biogas concept. We look at these two questions in a historical perspective up until the present, to suggest what is needed in the future. The manure-based centralised biogas production system is quantitatively the most important source of biogas in Denmark, and it has a large future potential, due to vast amounts of manure feedstock that are still available.

As an input to the analyses, we first describe the developments in biogas production in Denmark over time, and its role in the Danish energy system (Section 2), as well as the manure-based centralised biogas concept (Section 3). To examine if policies have been effective in supporting biogas deployment in different phases of development, we compared biogas production patterns with the occurrence of renewable energy and greening policies, strategies and agreements and financial incentives over time (Section 4). Based on this analysis, we identified some key elements for success, and where the measures put in place perhaps missed some opportunities (Section 5). To further discuss how the policies and governance might be linked to trust in sustainability of biogas, we reviewed the most important sustainability benefits and concerns (Section 6) and the associated governance in Denmark to promote or address these (Section 7), with a focus on manure-based centralised biogas production. As a part of this review, we described the policy setting of the governance frameworks, focussing on two dimensions - flexibility and prescriptiveness (Mansoor et al., 2018). Flexibility indicates if policies are voluntary or mandatory, or take some intermediate form, while the prescriptiveness refers to the process of predefining ways to achieve the policy goals, and the extent to which thresholds have been set.

2. The development in biogas production in Denmark

The production of biogas in Denmark took off in the 1970s and increased significantly in the late 1980s (Fig. 1). Production reached about 3 PJ in the year 2000. This production took place in 20 manure-based centralised plants, more than 35 farm-scale plants (Raven & Hjort-Gregersen, 2007), in waste water treatment facilities, and as methane recovery from landfills. In 2007, production reached almost 4 PJ, which came from: 22 centralised and 66 farm-scale manure-based plants (60% of the energy produced from biogas); 45 municipal waste water treatment plants (22%); methane production from landfills (14%); and from industrial waste water treatment plants (4%) (Brancheforeningen for biogas, 2009).

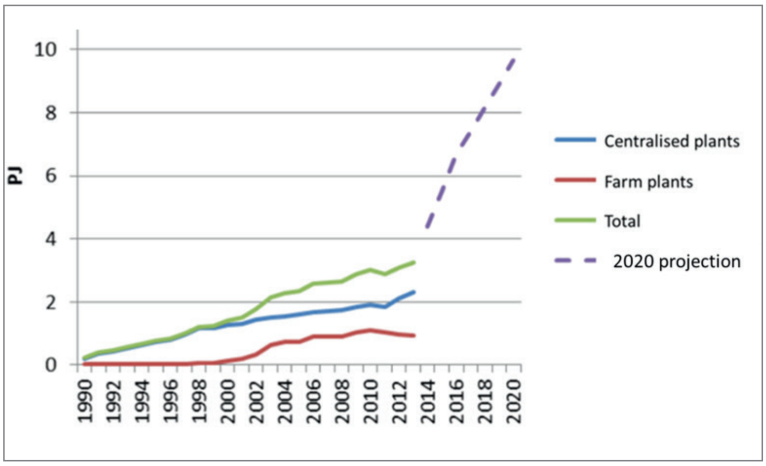

Figure 2. Development in the production of biogas from centralised and individual manure-based plants, 1990-2012, and projection up to 2020 (Adapted after Sander-Nielsen, 2016a & b, cf. Al Seadi, 2017).

Since 2000, manure-based biogas production has continued to increase, especially for centralised plants, which are normally the largest plants, (scale of 100-600 TJ yr^{-1}, Annex 1). As of 2016, the total annual production of biogas has passed 9 PJ, corresponding to 1.4% of the primary energy production in Denmark and to about 10% of the natural gas consumption (Energistyrelsen, 2017). Some 75-85% of the produced biogas originates from manure-based plants (Fig. 1 & Annex 1), with more than two-thirds being produced in centralised facilities and a little less than one-third in farm-scale plants (Fig. 2). At the same time, biogas production from landfills has decreased to a stable level of about 0.1 PJ (23 mostly smaller plants producing less than 20 TJ yr^{-1}, Annex 1), due to the ban on landfilling of organic wastes. The amount of biogas produced from waste water treatment plants has remained almost constant at a level of about 1 PJ (mainly medium sized plants of 20-100 TJ yr^{-1}, Annex 1).

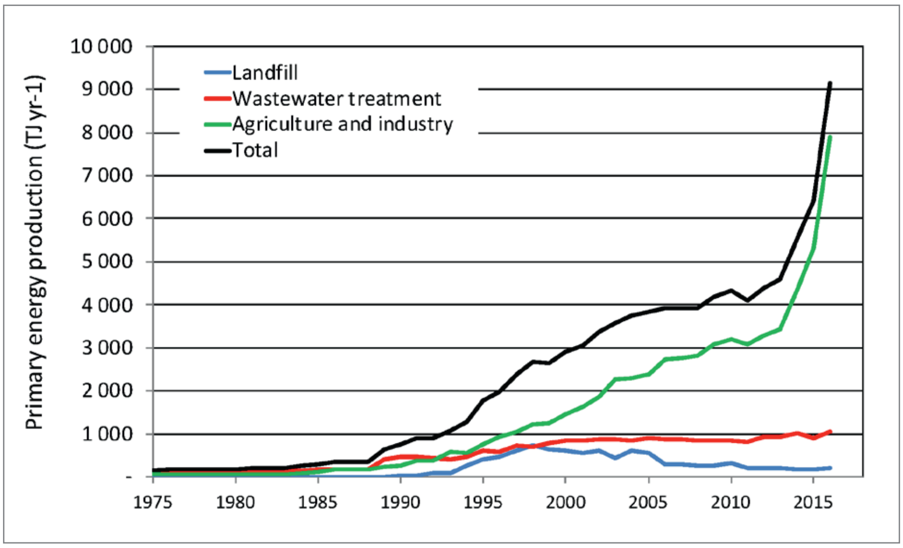

Figure 1. Development in primary biogas production in Denmark from 1975-2016 (based on data from Energistyrelsen (2017)).

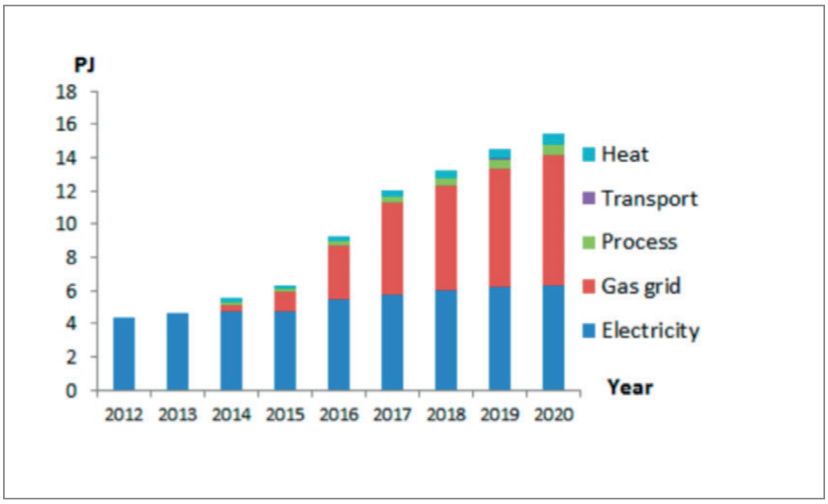

Figure 3. Historical and expected future biogas production and its use in Denmark 2012-2020 (Energistyrelsen, 2018a & b).

The majority of the produced biogas is used in electricity production (Fig. 3). In 2015, electricity including heat losses constituted 66% of the energy production from biogas, while heat and injection to the gas grid by upgrading was 16% and 17%, respectively. The rest, less than 1%, is burned off by flaring (Energistyrelsen, 2017). It is expected that in the future, an increasing share will be upgraded for injection to the natural gas grid (Fig. 3). The first Danish biogas upgrading plant was established in Fredericia, in 2011. As there are economic incentives, there is also great interest in the upgrading and grid injection of biomethane. Today, biomethane represents about 11% of the gas in the natural gas grid (Kousgaard & Pedersen, 2017) with an increasing share every year. Some 75% of new biogas production is expected to be upgraded and grid injected, while 20% will be used for combined heat and power (CHP) at the AD plant, or sold, and 5% for production process (on site process, or sold) (Fig. 3). The target for total biogas production by 2020 is up to 16 PJ yr^{-1} (Fig. 3), see also section 4.4. Biogas is thus becoming a significant contributor to the renewable energy mix in Denmark (Fig. 4).

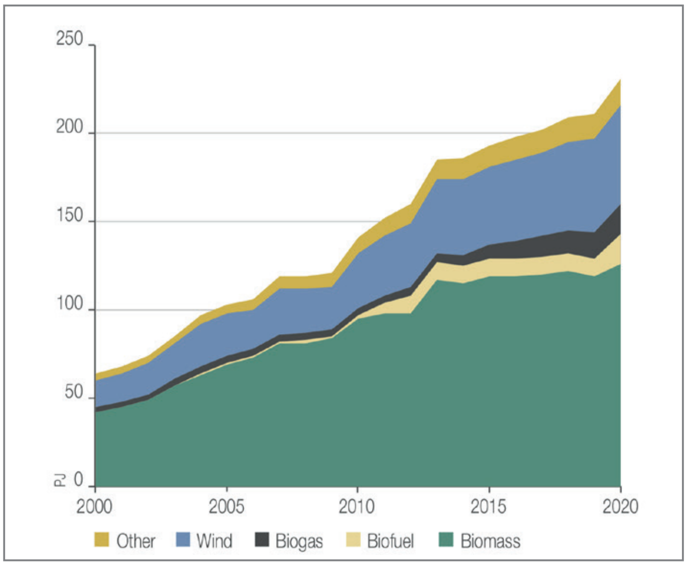

Figure 4. Development in renewable gross energy consumption in Denmark, historical and expected 2000-2020 as foreseen in the Government's Energy Strategy until 2050, with a 2020 target for biogas of about 15 PJ (The Danish Government, 2011). Biomass refers almost entirely to the solid biomass, such as wood, straw and biowaste, used for CHP generation and district heating.

3. The concept of centralised manure co-digestion

The development of biogas systems in Denmark is generally recognised as a success (Hjort-Gregersen, 1999; Raven & Hjort-Gregersen, 2007; Lybæk & Kjær, 2010). The pioneering years, followed by almost 40 years of RD&D have situated Denmark as a front runner in the area of biogas production, in particular due its original concept of centralised manure co-digestion. The concept is based on the cooperation between communities of farmers, who supply their manure to a centrally located biogas plant and receive back digestate to be used as a high quality plant biofertiliser.

The concept of centralised manure co-digestion has been in operation in Denmark since 1987-88 (Hjort-Gregersen, 1999; Raven & Hjort-Gregersen, 2007; Lybæk et al, 2010). It is based on production of biogas by co-digesting animal manure and slurries (mainly pig and cattle) with other digestible biomass feedstock (also known as alternative biomass), mainly organic wastes. The alternative biomass has the role of increasing the biogas yield of the manure digestion. It typically includes abattoir waste, digestible wastes from food- and agro-industries, by-products and residual vegetable biomass from the agricultural sector, food waste and source separated organic waste from municipalities, households and catering. The co-digestion plants are centrally located (hence the name), in areas with intensive animal production, and thus high manure density. Such central locations aim to minimise the costs of biomass transport between manure and slurry suppliers and the biogas plant.

The manure and slurries are collected from the pre-storage tanks of the farms, in specially designed vacuum container trucks, and transported to the biogas plant, where it is mixed with alternative biomass (Holm-Nielsen & Al Seadi, 1997). The mix is homogenised and pumped into the reactor tank (digester). The biogas plant collects and supports the costs of the transport of fresh animal manure from the farms to the biogas plant, and of the transport of digested biomass (digestate) from the biogas plant to the storage facilities on the farms, located close to those fields where digestate is to be applied as fertiliser. The transport of the alternative biomass to the biogas plant is usually the responsibility of the individual suppliers (Holm-Nielsen & Al Seadi, 1997). Fig. 5 shows the main mass streams of the centralised manure co-digestion concept.

The anaerobic digestion (AD) process takes place inside the digester, in the absence of oxygen, at mesophilic (30-40°C) or thermophilic (50-55°C) process temperatures, depending on the substrates to be digested and on other process parameters (Holm-Nielsen & Al Seadi, 1997). The retention time of the biomass inside the digester depends on the process temperature, and

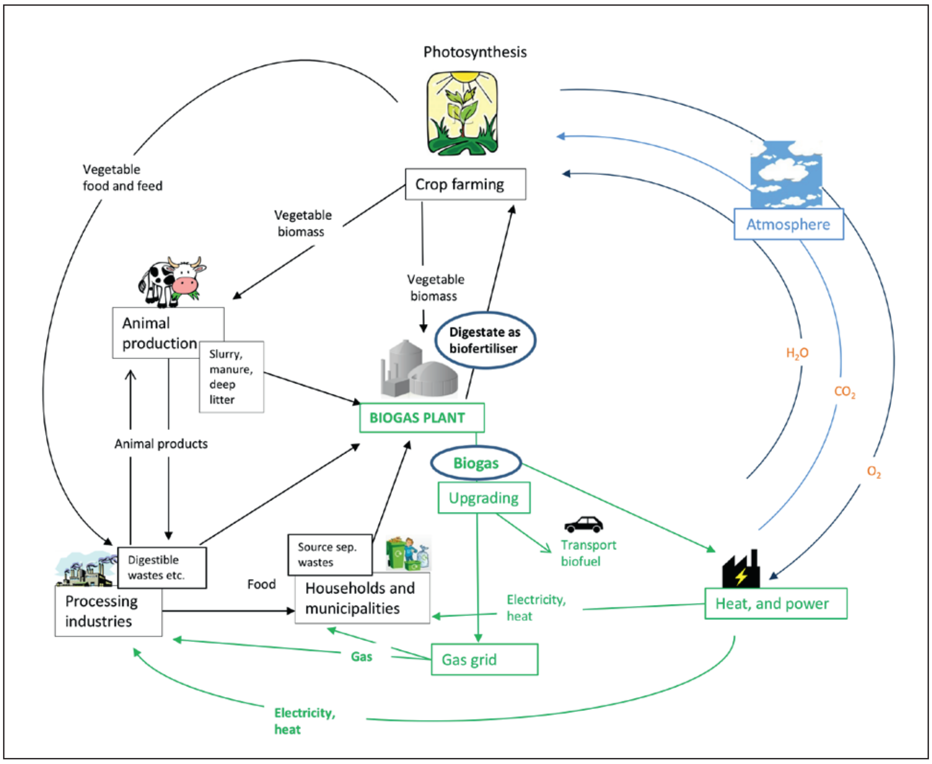

Figure 5. The closed loop and main streams of the concept of centralised manure co-digestion in Denmark.

it ranges between 18 and 25 days. The AD process is continuous, which means that a constant amount of biomass is concomitantly pumped in and out of the digester, through automatically set pumping sequences. The digestate pumped out of the reactor is transferred to a membrane-covered gas tight storage tank, where biogas production continues at ambient-temperature (post-digestion). Up to 15–25% of the total gas production may originate from the post-digestion process.

Biogas produced in centralised co-digestion plants in Denmark usually has a methane content of around 65% by volume. The newly established plants and an increasing number of older biogas plants have established biogas upgrading units, or are planning to do so, in order to purify the biogas by removing CO_2 and other impurities (Al Seadi, 2017). This enhances the methane content to 97-99% (biomethane), depending on the applied upgrading technology (Energistyrelsen, 2014). Biomethane is then injected to the natural gas grid, or it is compressed (CNG: compressed natural gas) and used as vehicle fuel. Raw (un-upgraded) biogas is also used for CHP, and for process heating.

At the biogas plant, the biomass feedstock undergoes a process of controlled sanitation, by running the AD process at a certain combination of retention time and temperature, or by a separate pasteurisation step. The aim is to get an effective pathogen and weed seed inactivation in the digestate, so its application as fertiliser will be safer, compared to applying raw manure and slurry directly in the fields; this should break the contamination potential of application of digestate to agricultural land (Bendixen, 1999).

Before being transported to the farmers' digestate storage tanks, the digestate is analysed for dry matter and nutrient content (NPK). This makes possible complete and precise integration of digestate in the fertilisation plan of each farm. The storage tanks are located out in the fields, where the digestate is to be applied as fertiliser. Compared with raw slurry, most of the nutrients in digestate are in mineral form, thus more easily accessible to plant roots. This increases the efficiency of the nutrient uptake and reduces the risk of surface run-off and of pollution of ground water through infiltration of nutrients. The digestate application is carefully planned, including amount, timing and the most suitable equipment for uniform and rapid incorporation of digestate into the soil (Al Seadi & Lukehurst 2012). Digestate can be applied as fertiliser immediately after leaving the AD plant, or it can be further processed through various technologies and processes, aiming to extract and concentrate the nutrients contained in it (Drosg et al, 2015; Al Seadi & Lukehurst, 2012). Some centralised co-digestion plants are thus equipped with digestate processing installations, for volume reduction and higher nutrient recovery.

The farmers supplying manure and slurry to the AD plant take back only that amount of digestate which they are allowed to use for their crops. The digestate in excess of this is sold by the biogas plant to crop farmers in the area, who need nutrients. In all situations, the digestate is fully integrated in the fertilisation plan of the farm, displacing significant amounts of mineral fertilisers that are more expensive and fossil fuel intensive. Delivery of digestate directly to the fields and the sale of the excess amounts to other crop farmers contribute to a significant redistribution of nutrients in the agricultural area in the vicinity of the plant.

Apart from offering a renewable biofuel for energy and transport, with all the sustainability benefits derived from it, the concept solves the farmers' problems with excess manure. It reduces the environmental pressure from intensive animal farming through redistribution of nutrients from manure and reduces nutrient leaching to ground water. The use of digestate eliminates bad odours and flies, which occur at the application of raw slurry, thus improving air quality and quality of life in rural areas. The concept contributes to reduction of greenhouse gas (GHG) emissions from storage, transport and application of digestate compared to manure. Economic benefits for farmers are obtained from the reduced need to purchase and apply chemical fertilisers, pesticides and herbicides, the reduced costs of manure transport and storage, and higher crops yields due to higher nutrient efficiency of the digestate. The biogas plant pays for transport of biomass and establishes shared digestate storage, close to the agricultural fields where the digestate will be applied. The multiple benefits in the fields of energy, climate, agriculture, and waste management and transport were already recognised in the 1990s, and today, centralised manure co-digestion is seen as a typical example of the circular bioeconomy (Sander-Nielsen, 2016a&b).

4. Phases of development

This section examines the linkages between biogas production patterns and dedicated national energy strategies and agreements over time, especially those that specifically address the biogas sector. An overview is given in Fig. 6, while the next sub-sections provide more detailed observations.

4.1. Phase I: Pioneering

The idea of establishing centralised biogas plants, where a larger number of farmers could supply and treat their liquid manure emerged in the early 1980s, because of the oil crisis in the 1970s (Raven & Hjort-Gregersen, 2007). Several Danish villages decided to establish centralised biogas plants, with the aim of demonstrating energy self-sustainability, providing jobs and use of local resources available in the area, mainly manure and waste. Thus, for the first plants, during the 1970s and the early 1980s, the main driver for biogas development was the production of biogas as renewable and secure energy. The first centralised plant was designed only for manure digesting, but later, it became evident that addition and co-digestion of industrial organic waste increased the methane yield (Energistyrelsen, 1995; Hjort-Gregersen, 1999). The plants established in the next phase were therefore manure and waste co-digestion plants.

4.2. Phase II: Build-up and innovation

The development during this phase was closely linked to an increased focus on agriculture's nitrogen pollution from fields and manure storage in the 1980s. This led to the first freshwater action plan in 1987, more than one decade before the adoption of the Water Framework Directive by the European Union in 2000, which required that farmers must have 6-9 months storage capacity for the produced animal slurries. The aim was to secure that slurries and liquid animal wastes would be applied as fertilisers only during the growing period of crops, for a quick nutrient uptake, and reduced risk of water pollution from nutrients. Furthermore, the amount of manure allowed to be applied per hectare was restricted through the so-called "harmony rules", aiming at securing a balance between the amount of land controlled by the farm and its livestock production (Raven & Hjort-Gregersen, 2007). These were costly measures for the farmers. When the *Biogas Action Programme* was launched in 1988, it helped to create an incentive for biogas production, as farmers saw an opportunity to deliver slurry to a biogas plant, because the plant could make the investments in the necessary slurry storage capacities.

The Biogas Action Program aimed at investigating the economic viability of centralised biogas plants, and considered the multiple benefits to the agricultural, energy, and environmental sectors. The program accelerated the technological development and enlargement of biogas plants in Denmark (Raven & Hjort-Gregersen, 2007; Al Seadi et al., 2007). It provided investment grants for new biogas plants and focussed on the construction and monitoring of these plants, as well as information activities, development work, and funding of special research tasks. The programme proved a good way to get the biogas sector started. An important feature was the biogas monitoring programme in which gained experiences were collected, analysed and communicated to the farmers, plant managers, plant owners, companies, authorities and the political system. This also contributed significantly to creating a favourable condition for establishing new centralised biogas plants, and exploiting the opportunities through an effective innovation process with internal momentum. By the mid-1990s, the niche of centralised biogas plants was technologically ready for wider take-off, but this development was obstructed in the beginning of the 2000s, when new uncertainties and non-technical barriers occurred (Lybæk et al., 2010; Al Seadi, 2017).

4.3. Phase III: Market liberalization and biogas stagnation

A period of stagnation in Danish biogas development started in late 1990s and it largely lasted until 2009 when the *Green Growth* (Regeringen, 2009) strategy was launched. This was followed in 2012 by a new politically broad energy agreement (Fig. 6). The stagnation was mainly caused by a shift in policy focus, away from the environment and climate focus that had prevailed in the years following the publication of Brundtland report (United Nations, 1987) in 1987. This report and the work of the World Commission on Environment and Development (WCDE) established the foundation for *The Rio Declaration* in 1992, the *Agenda 21* and the establishment of the *UN Commission for Sustainable Development*. With the entrance of a new Danish government in 2001, focus shifted towards liberalization of the energy markets, economic growth and energy security (Nygård, 2013). The Ministry of Environmental & Energy was abolished in 2002, with its responsibilities being transferred to the Ministry of Economic Affairs and Business (2002-2005), and later, to the Ministry of Transport and Energy (2005–2007), until the Ministry of Climate & Energy was established in 2007. Entering the free market conditions in 2002 brought about a lot of uncertainty about financial frameworks and prospects for biogas, and how its profitability would be affected by changes in subsidy schemes and energy policies. The *Biogas Action Programme* ended during this period, which also contributed to uncertainty and a slowdown of all biogas investments in Denmark. This interruption in development programmes resulted in an overall loss of momentum, and subsequent loss of expertise and competences. As a contributing factor, the biogas sector was increasingly facing a limited availability of organic waste as a co-substrate for manure digestion (Raven & Hjort-Gregersen, 2007).

4.4. Phase IV: Dedicated policies and large scale production

Around 2009, the economic prospects for biogas improved again, due to new ambitious governmental energy policies and strategies to boost the actual biogas development. In 2007, the Ministry of Climate and Energy was established, and in 2009, the Government's *Green Growth* strategy was published. This stipulates, *inter alia*, that 50% of livestock manure is to be processed for green energy by 2020. *Green Growth* furthermore formed the basis for a political agreement, which was concluded in June 2009. This agreement includes the same 50% goal for the use of manure for energy.

The *Green Growth* initiative requires significant acceleration of biogas deployment, and in the same year as it was published, a new research programme for biogas was launched, which is still running as of June 2018. Together with the *Green Growth* initiative, it has given a renewed focus to the biogas industry, even if there has been a shift in focus compared to the Biogas Action Program from 1988 (Lybæk et al., 2010). A key element in the new strategy is the increased integration between agricultural and energy policies. Environmental concerns related to nitrogen leaching when raw manure and slurries are spread on the fields is still a main driver for biogas production in Denmark, but linkage to energy policies has become stronger, with high quantitative targets for the amount of energy to be produced from biogas plants (Lybæk et al., 2010).

The insufficient availability of industrial organic wastes, which have traditionally been used as methane-booster co-substrates, has been a real barrier for biogas deployment, especially during the last decade. The need to find new co-substrates to increase the efficiency of manure co-digestion, and the development of manure mono-digesting plants have also resulted in a new, close linkage to agricultural policies (Lybæk et al., 2010). For environmental sustainability reasons, Danish politicians have decided that biogas in Denmark should not be developed based on energy crops. Therefore, increasing limitations for the share of energy crops to be used in biogas production have been introduced. Instead, there is now growing interest in using other available waste biomass a a co-substrate. These include animal bedding, especially deep litter, straw, beetroot silage, grass cuttings, micro and macro algae and household waste. The *Green Growth* strategy also connects biogas technology to industrial policies, as the technology - now more than ever – is perceived as a new business opportunity for Danish farmers (Lybæk et al., 2010).

In 2011, the Government's Energy Strategy 2050 was launched, which has as its goal to make Denmark a fossil-free economy by 2050 (The Danish Government, 2011). The independence from coal, oil and natural gas should be achieved through a shift to predominately wind and biomass. The sub-target for 2020 is a 33% decrease in consumption of fossil fuels.

In March 2012, the new Danish Government furthermore reached a politically broad agreement for the future energy policy in the period 2012–2020. The agreement includes several elements and calls for a significant enhancement of the share of renewables in Danish energy supply. The main aim is still to make Denmark fossil fuel free by 2050, and biogas is a key area for development. The Danish Energy Agency, in its projection from 2012, predicted an almost four-fold increase from 4.4 PJ in 2012 to 16.8 PJ by 2020. A Biogas Task Force was established to analyse and give recommendations for further biogas deployment, in close cooperation with all stakeholders. The Task Force concluded in 2013 that only a doubling to around 10 PJ is achievable by 2020. The Biogas Task Force also highlighted that the increase in biogas production could be higher if a number of biogas plant projects, which are for the moment assessed as uncertain, will be implemented.

This highlights that increases in the biogas industry still have various challenges and barriers to overcome. About 37 million tonnes of animal slurries and manure are produced yearly in Denmark, but only around 10% are used for biogas production in centralised manure co-digestion plants (Landbrugsavisen, 2018). During the coming years, this number is expected to reach 25-30%. However, if the political objective of using 50% of the manure, corresponding to an energy production of around 16 PJ, should be achieved by 2020, further incentivising measures or innovative solutions will be needed (Zemo and Termansen, 218).

4.5. Phase V: Integration with future energy systems

There is currently a shift of paradigm regarding the main role of biogas for the Danish society, towards primarily seeing biogas as a renewable energy and transportation fuel supplier for climate change mitigation purposes. It is expected that biogas will play a key role in a future integrated renewable energy system, as a buffer (and facilitator) for a wind-dominated electricity production system (Persson et al., 2014). Biomethane will be a supplemental fuel in a private transport system dominated by electric cars and will play a stronger role in commercial vehicles and buses.

If this vision is to be realized, there are still challenges to be overcome. The costs of producing biogas are typically 130 – 142 DKK GJ^{-1} (17.5 – 19 € GJ^{-1}) and 154 – 166 DKK GJ^{-1} (20.5 to 22 € GJ^{-1}) if it is in an upgraded form (Al Seadi, 2017). Despite the current subsidies, the future financial viability of biogas plants is still uncertain, because subsidies are being phased out until 2020. Natural gas prices are another uncertainty as it affects the amount of variable subsidy received. It is expected that the price of natural gas will increase slightly in the coming years (Bundgaard et al, 2014; Koema.com, 2017). Price uncertainty is also an issue for biogas facilities in areas not connected to the natural gas grid. It is thus still a complex process to sell biogas for a competitive bankable price. Furthermore, biogas is subject to complex legislation and regulation, which makes the planning and approval process of new plants difficult (Energistyrelsen, 2014).

There is a need to improve the legislative and financial support incentives to better achieve present and future biogas deployment objectives. This includes simplification of project approval procedures, but also granting of subsidies for biogas production and infrastructure, and for use of biogas in industrial processes. Strategies should furthermore be developed for better integration of biogas in the national energy supply, for example by promotion of upgrading and sales through the natural gas grid. It should be considered if biogas can replace coal in energy plants, following the industry's decisions to close the last three coal-fired CHP units in Denmark by 2023. Along the same lines, small power plants up to 20 MW should have the possibility to convert from natural gas to biomass by freely choosing their fuel source, and producers and consumers of district heat should have the freedom to make contracts. Also, it should increasingly be encouraged to develop and use biogas for transport, for example, by implementing a mandatory share of 10% biofuels in transportation by 2020 (Al Seadi, 2017). The number of filling stations serving CNG increased to 16 in 2017, and there are 123 city buses, 115 heavy duty vehicles and 223 light vehicles using CNG as fuel. Up to now there is no LNG used for transport in Denmark. Finally, it is anticipated in the future, that it will become commercially viable to store wind power through power to methane systems (Persson et al., 2014). This involves storing electricity as hydrogen (via electrolysis) and using this hydrogen to upgrade biogas to methane, which practically doubles the methane output of the biogas system ($4H_2 + CO_2 = CH_4 + 2H_2O$). This methanation step can be realised either catalytically or biologically (Sander-Nielsen, 2016a&b; Wall et al., 2017).

The insufficient availability of industrial organic wastes, used to boost the methane yield of the manure and slurries, is a major barrier, and research is underway, which aims to identify and test some new co-substrates.

Finally, it is important to consider what made biogas a success story in the first place. It is important to continue consideration of the direct local sale opportunities, and establishment of local biogas infrastructures (Al Seadi, 2017). Training, education and information dissemination should be provided for plant managers and operators, farmers and the public at large. The national biogas association should continue to modernize itself, for example, through creation of local platforms for project generation. All such processes should receive enhanced commitment and involvement by policy and decision makers. The key elements of development will still be innovation, integration and detection of potential synergistic systems. It should also be restated the extent to which biogas systems protect the environment, reduce greenhouse gas emissions from agriculture, mitigate climate change, provide sustainable waste management and create economic activity in agriculture and the agro-industry sectors.

4.6. Phase VI: Biogas as part of the circular economy

For most of the biogas production in Denmark, livestock manure and slurries are digested and converted to biogas in anaerobic digestion facilities, together with digestible residual fractions from industry, households and the service sector. This results in a cooperation between rural areas and the city, which helps to recycle nutrients, including nitrogen, phosphorus, and potassium (Sander-Nielsen, 2016a&b). Such cooperation also helps to recycle a significant part of the carbon in manure and waste, which helps maintain the humus content of soils and their long-term suitability for agriculture. Biogas plants therefore help to maintain the carbon cycles, without enlarging them, through the earlier mentioned dual benefits: reduction of methane emissions from animal farming, and reduction of greenhouse gas emissions, when the biogas replaces fossil fuels. The biogas production systems should furthermore be designed to comply with the waste hierarchy, which means that the waste is recycled to the product of highest value or environmental or social benefit. These cyclic properties suggest that biogas has a significant role to play, as the circular bioeconomy develops, and that it might be an important part of biogas deployment strategy to develop the narrative and communicate this strategy to farmers, the public and business and political decision makers. Biogas is thus anticipated to become the central player in the development of the circular economy in Denmark, as is mentioned in the preparative documents of the new Danish Energy Agreement, to be adopted by the end of 2018, which will design the development path for biogas in Denmark up to 2030.

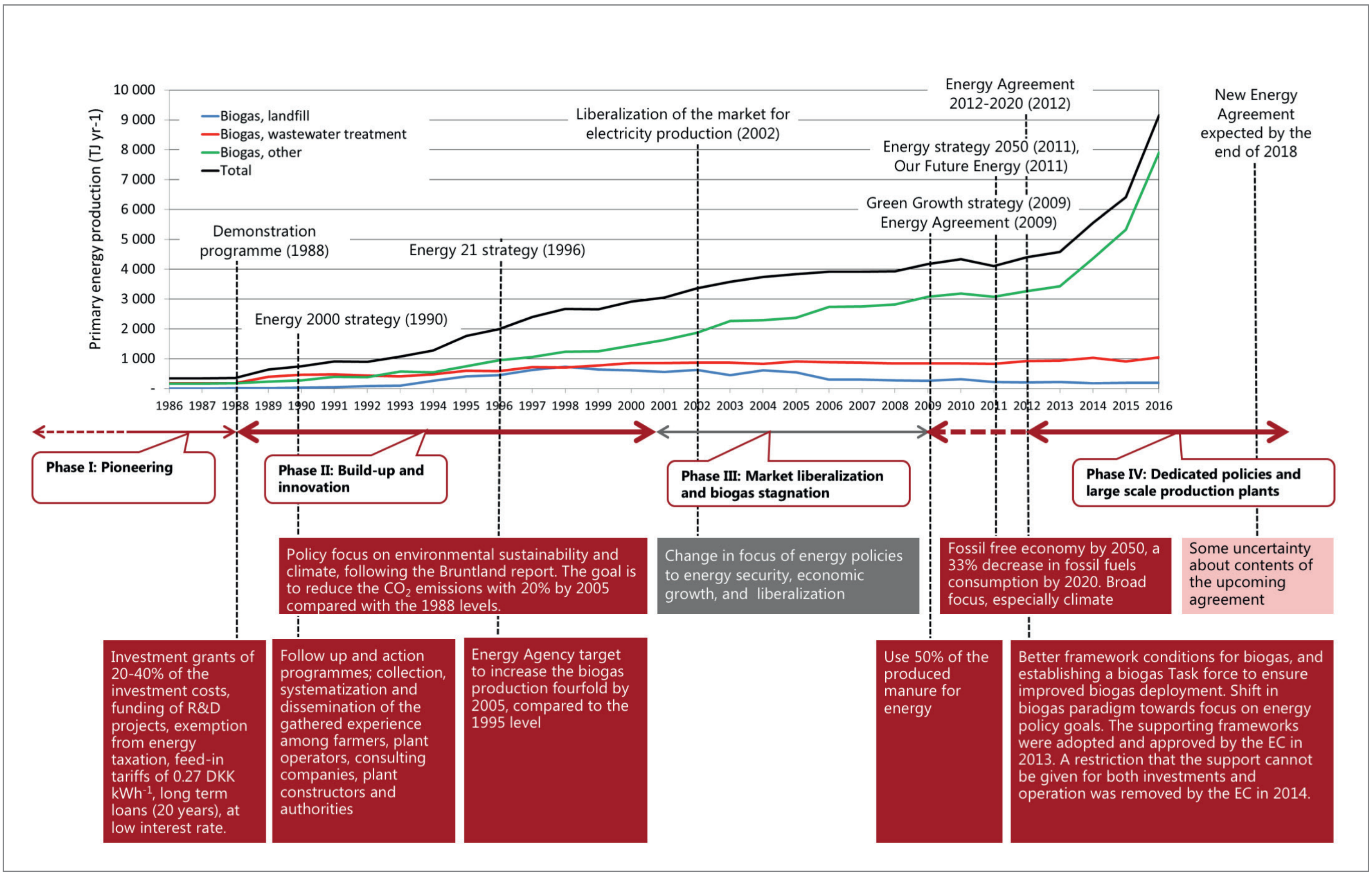

Figure 6. Comparison of biogas production levels with selected relevant energy, agricultural and environmental policy strategies and agreements during the period 1986-2016. A new energy agreement is expected in 2018

5. Key elements of success

While section 4 sought to link the biogas production patterns with dedicated energy strategies and agreements over time, this section seeks to link the production patterns and phases of development to various other, or related, elements that have been identified as critical to the success of manure-based centralised biogas. The implementation of sustainable technologies is often a very long-term and fragile process, which requires time before sufficient momentum emerges. Experiences from the Danish biogas sector show that apart from consolidated policies, a well-defined learning-based approach has helped to provide adequate support for various actors to build solid network platforms, which include farmers and farmer's organisations, industries, researchers, end-users and policy makers (Raven & Hjort-Gregersen, 2007). Experiences and lessons learned are gathered and disseminated to all levels among stakeholders and are used to create know-how and to the further improvement of the concept and the technology.

Authors like Raven & Hjort-Gregersen, (2007) indicate that along with consolidated policies, the key element of success is not primarily the technical and economic performance of the concept, but factors such as:

- Availability of AD feedstock;
- The perception of the system as a sustainable technology;
- The organisation, ownership, and social context;
- Favourable pre-conditions;
- Viable financial business plans;
- The supporting policies and regulatory frameworks.

Alignment between all these factors, and the technical and economic resources and consolidated policies provided the basis for building up the needed momentum for successful biogas deployment (Raven & Hjort-Gregersen, 2007).

5.1. Availability of AD feedstock

The availability of large, unused biogas feedstock potentials, especially within the agricultural sector (such as livestock manure and crop residues), is one of the most critical factors for the development of a biogas sector. The amounts of animal manure and slurries that are produced annually in Denmark are in the order of about 36 million tonnes yr^{-1} (Bundgaard et al, 2014). Animal slurries constitute around 75% of the biomass feedstock for the centralised manure co-digestion plants; 80% of the 21 PJ biogas target to be produced by 2030 should originate from animal manure. As food and fodder processing industries are concentrated in the high manure density areas, co-digestion of the produced organic wastes is not only appropriate and safe, but also convenient and economically advantageous.

5.2. Continuity in financing

A key factor to the early success was the continuity of the action programme and financial support over a long period of time (Raven & Hjort-Gregersen, 2007). When the development of manure-based centralised biogas plants started, their establishment was co-financed through government grants with up to 40% of the total investment costs. The share of the government grants was even higher for the earliest plants. As the operational stability and the economic results of the plants improved, the grants gradually decreased up to 2002. After 2002, grants were absent for almost a decade, and the biogas sector was faced with free market conditions. After the government's *Green Growth* initiative in 2009 (Danish Government, 2009), the possibility of receiving government grants was reintroduced for projects with elements of novelty and innovative technologies.

The construction of a biogas plant can also be co-financed by indexed mortgage loans (Hjort-Gregersen, 1999), which in many cases are guaranteed by municipalities. Some plants raise bank loans or loans guaranteed by county councils. A number of the early plants were partly financed by traditional mortgage loans, but this type of loan is no longer used. Recently, the energy companies have become important actors in the biogas arena. They have built and own many of the newly established centralised co-digestion plants and bring their own financing into the biogas sector.

5.3. Organisation, ownership and social context

For the first generation of plants, the most frequent organisational form is the cooperative company, where the farmers supplying manure to the plant are also the owners. The cooperative was generally preferred among farmers in Denmark and a well-known structure in Danish society (Raven & Hjort-Gregersen, 2007). There is a long-term tradition for Danish farmers of cooperating in small communities (Pedersen, 1977; Raven & Hjort-Gregersen, 2007). The lack of special cooperative legislation made Danish farmers quite free to frame their cooperative statute and rules completely for the benefit of the members. The cooperation between farmers in setting up biogas plants, and in some cases for supplying manure to the biogas plant, was thus a logical step in the development of centralised biogas plants (Raven & Hjort-Gregersen, 2007). Organisation and ownership of the centralised co-digestion plants differs from plant to plant, according to the local conditions and interests. Some biogas plants are, for example, owned jointly by farmers and heat consumers, by municipalities, by private foundations or by limited companies.

It is suggested that new forms of ownership and collaboration is a needed element to overcome the current barriers to increasing biogas deployment (Lybæk et al., 2014). Lybæk et al. (2014) suggest that stakeholders from the energy sector and municipalities should play a more active role in biogas development, and that farmers must seek new corporate design concepts rather than traditional centralized and farm biogas plants. They suggest that municipalities could, for example, facilitate access to new sources of raw materials, and enhance energy planning by targeting biogas in their municipal heat planning. Energy companies could benefit from new market opportunities, such as the supply of biogas for transportation purposes, and farmers may beneficially seek new types of corporate designs rather than traditional centralized and farm biogas plants. Zemo and Termansen (2018) take these ideas one step further by asking farmers about their willingness to participate in a theoretical 'partnership-based biogas investment'. They defined the partnership-based biogas investment as an association of two or more farmers that collectively own a biogas plant, by pooling their resources together to invest in biogas production with a plant size between a farm scale plant (average capacity 25,000 tonnes yr^{-1}) and a large-scale biogas plant (capacity to treat 50,000–500,000 tonnes yr^{-1}). The study showed that the majority of the surveyed farmers would be interested in partnership-based biogas investment, including farmers who never considered investing in biogas before and farmers that already participate in conventional centralised biogas plants.

5.4. Bottom-up strategy

The long-term provisioning of financial support allowed the dedicated actors to gain experience and build up competencies, but this development was also supported by ministries' or governmental departments' (such as agriculture, energy and environment) application of a bottom-up strategy. The bottom-up strategy facilitated interaction and mutual learning. Sharing experiences, lessons-learned and know-how between various biogas stakeholders and interest groups was encouraged. This resulted in the formation of a broad social network, which acted as a platform for biogas development and project generation. The bottom-up approach emphasised some of the important benefits of the centralised concept, such as reduced need for mineral fertilisers, importance of reduced transport distances, reduced costs, and practicalities such as shared digestate storage facilities out in the fields. The perception of centralised manure co-digestion as a multifunctional, environmentally sustainable technology emerged especially under the *Biogas Action Programme*, which was launched in 1988 (Raven & Hjort-Gregersen, 2007). These broadly recognized sustainability aspects of biogas further stimulated the relevant governmental departments, farmers organisations, researchers and biogas stakeholders to collaborate on continuous improvement of all aspects of the centralised concept, both technical (such as process optimisation) and non-technical (such as removal of barriers). It is suggested that a bottom-up strategy is also important to future deployment of biogas (Lybæk et al., 2014).

5.5. Supporting 'push' policies and other favourable policies

Several supporting policies have helped indirectly to push development of a biogas sector in Denmark. The role of freshwater action plans created an incentive for farmers to become engaged; policies for waste handling and manure management also played a role (Hjort-Gregersen, 1999). The EU Directive on hazardous waste disposal (91/689/EEC) from 1991, and the Ministry of Environment and Energy's action plan for waste and recirculation (1993-97) from 1992 set a target for recycling of as much as 50% of organic waste. During the 1990s, taxes on landfill and incineration were significantly increased several times. In 1997, the Danish Government introduced a total ban on landfilling organic or combustible wastes (Al Seadi et al, 2001). At the same time a tax exemption was introduced for waste recycling. In support of finding other uses, a statutory order from the Ministry of Environment and Energy on application of waste products for agricultural purposes (BEK no. 823 of September 16, 1996) was adopted to control and regulate the safe application of waste products for agricultural purposes (Al Seadi et al., 2001). These increasingly stricter environmental and waste management policies pushed the municipalities to divert organic waste streams from landfilling and incineration towards biogas treatment and recycling (Al Seadi et al, 2001).

A legislative push also came from regulations on manure handling and application that became increasingly stricter. The statutory order from the Ministry of the Environment on professional livestock, livestock manure and silage (BEK no. 906 of 14 October 1996) included a mandatory requirement that the slurry storage capacity should be 6-9 months, restricting the period of slurry application on the fields to the growing season for crops, for maximum nutrient uptake and minimum pollution (Al Seadi et al, 2001). The same order includes restrictions on the amount of manure that can be applied per hectare, the so-called *harmony rules* (Al Seadi et al, 2001). In 2017, the *harmony rules* were replaced by new regulation principles concerning application of manure and digestate as fertiliser. The regulation aims to increase sustainability through pollution avoidance and resources management, prescribing an average of 170 kg nitrogen ha^{-1} yr^{-1} as well as restrictions on phosphorus applications of 30 kg ha^{-1} yr^{-1}, with even lower limits for cattle breeding farms (BEK no. 1380 of 30 November 2017). Phosphorus is an important resource for life, but the natural phosphorus resources on our planet are limited and could be depleted within the next 30-100 years. Excessive application of phosphorus as fertiliser not only misuse a precious resource but poses serious pollution risks for surface and ground water environment. (Miljø- og Fødevareministeriet, 2017).

Other favourable policies promoted decentralised CHP, and district heating systems. House heating is necessary 6 to 8 months of the year in Denmark, which creates a considerable need for heat.

6. Biogas sustainability challenges

The overall sustainability benefits of biogas are, as mentioned, well recognised, but there are also potential sustainability risks if good practices are not applied. The most important concern probably used to be undesirable indirect land use changes (ILUC) and competition with fodder and food production. This resulted from demand for crop biomass feedstock to increase digester methane production efficiency. Other than this, the overall sustainability benefits of manure-based centralised biogas production are well recognised and biogas sustainability is mostly about following best practices to ensure safety and sustainability improvements at the margins. This would include good practice in the management and measurement of fugitive emissions from the biogas facility as described by Liebetrau et al. (2017). Also, agricultural practices, transport, plant establishment and operation should thus optimise practices for the benefits to climate, soil, water, air, and biodiversity, and potential impacts on landscape aesthetics should be considered (Energistyrelsen, 2014).

The question about sustainability of feedstock production and origin is thus a critical one, and it must be produced through environmentally sustainable and climate-friendly processes. The benefits of animal manure and slurries as a sustainable substrate for biogas production remain undisputed and these are the main feedstock types in the centralised biogas concept. However, the diversity of potential co-digestion feedstock materials is high, and sustainability of these is more debated. Substrates for co-digestion can be grouped into waste, residues, and energy crops. Deep animal bedding and other organic waste material is an important feedstock for biogas plants. They are generally considered to be sustainable if feedstock quality is controlled and there is no other use for higher value products in the waste hierarchy (Al Seadi & Lukehurst, 2012). Sewage sludge was previously used as a co-digestion substrate, but this has stopped due to substrate quality problems associated with the content of heavy metals and organic pollutants.

Non-waste feedstock including residues, such as straw, and by-products from industry are considered to be somewhat less sustainable, due to other competing end-uses. Experience from countries like Germany indicate that dedicated energy crops are the least sustainable feedstock, due to potential ILUC and competition with fodder and food production (Britz & Delzeit, 2013). Significant ILUC impacts have not been confirmed in Denmark.

ILUC, competition with food and fodder, substrate qualities and good practices must be considered and managed along the whole AD cycle (Fig. 7), from biomass production in the field, transport of the biogas feedstock, quality control of feedstock at the plant, the AD process itself at the plant, further handling, storage and utilisation of the produced biogas and recycling of digestate as fertiliser back to the soil. For the purpose of analysing sustainability governance, the main sustainability issues and associated governance have been separated into seven groups (Table 1). The first addresses the overall sustainability benefits of the centralised manure co-digestion concept, and the other groups are organised according to where issues occur in the cyclic supply chain. This is outlined in Fig. 7 which is based upon the concepts described in Fig. 5. The overall sustainability benefits, SB, have been described in the previous sections and are summarised in section 6.1, while other issues, S1-S6, are described in more detail in sections 6.2-6.7. The corresponding governance measures, GB and G1-G6, are addressed in Section 7.

Table 1. Overview of the main sustainability issues in biogas production in the centralised manure co-digestion concept as used in Denmark.

No	Governance issues at different links in the closed loop supply chain of the centralised manure co-digestion concept
SB/GB	All sustainability benefits of manure-based biogas production
S1/G1	Sustainability of plant-based feedstock produced in the fields
S2/G2	Sustainable management of animal manure and slurry feedstock
S3/G3	Sustainable management of organic waste feedstock
S4/G4	Sustainable plant operation
S5/G5	Biogas and biomethane as renewable biofuels that reduce GHG emissions
S6/G6	Sustainable recycling of digestate as biofertiliser.

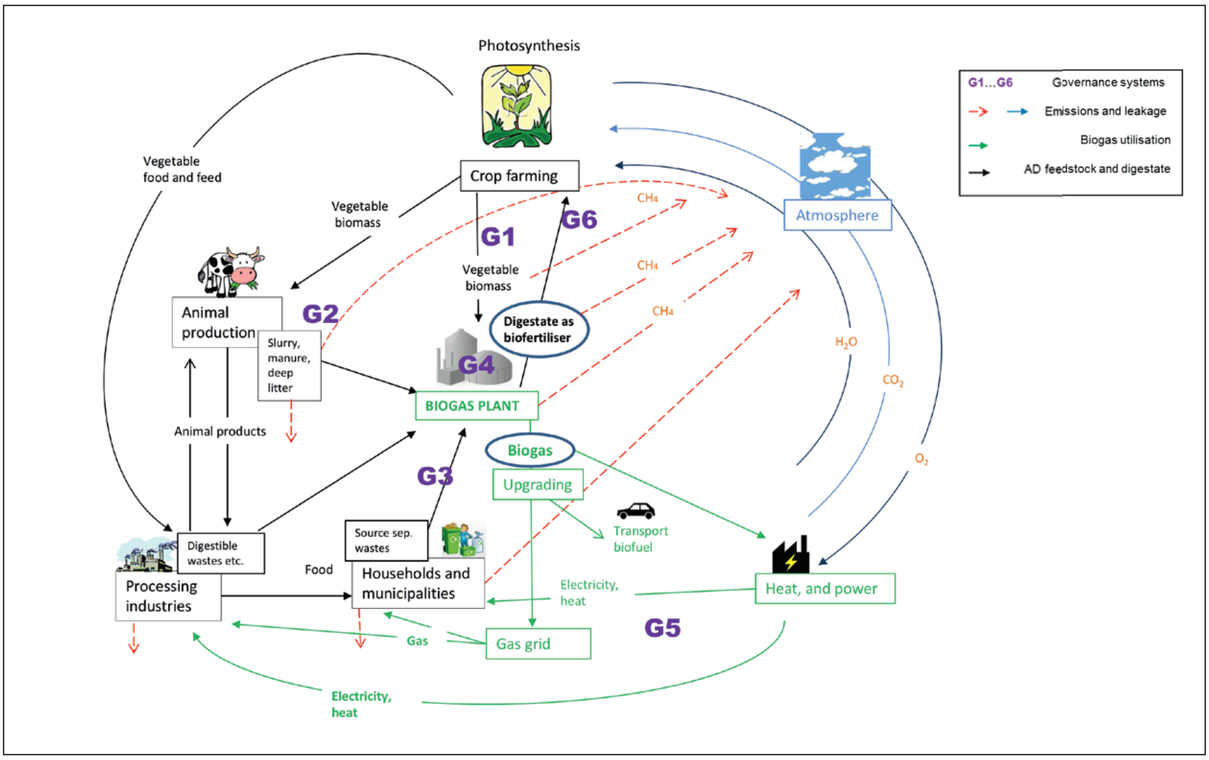

Figure 7. Grouping of main sustainability issues and associated governance (S1-S6/G1-G6), according to where they occur in the closed loop supply chain of the centralised manure co-digestion concept. See Table 1 for an overview of the sustainability issues, and sections 6.2 to 6.7 for further description of each of these issues.

6.1. All sustainability benefits of manure-based centralised biogas concept (SB)

Manure-based centralised biogas is a concept that has been designed to solve significant environmental problems due to animal husbandry, while also providing important energy and climate benefits (Al Seadi et al, 2007). For assessment of the sustainability benefits, the main element defining the reference situation is application of the raw slurries to the farm field (Energistyrelsen, 2014). This means that the sustainability of animal husbandry for food production is not questioned, as such. Compared to spreading of raw slurry, the sustainability benefits of manure-based biogas production can be summarised using the following key issues:

- Production of biofuel for transport and renewable energy production;
- Increased national security of energy supply, due to reduced dependence on imported fossil fuels;
- Reduced emissions of greenhouse gases (CH_4, CO_2, NO_x) from agriculture, transport and energy sectors;
- Improved nutrient and manure management, including redistribution of nutrients on larger areas, higher nutrient uptake efficiency, and less nutrient leakage to ground and surface waters;
- Improved veterinary safety through sanitation, and pathogen and weed seed inactivation;
- Reduced nuisances from odours and flies, and better air quality in rural areas;
- Economic savings for the farmers, from higher crop yields and less purchase of agrochemicals;
- Sustainable treatment and recycling of organic wastes;
- Assistance to local, rural economies, through creation of new local jobs;
- Suitable AD technology for organic farming, in need of plant nutrients;
- Export of technology, know-how and knowledge.

6.2. Sustainability of plant-based feedstock produced in the fields (S1)

Dedicated energy crops, such as maize or wheat, may greatly increase the yields of biogas from centralised manure co-digestion plants. Due to need for fertilisation, pesticides, and crop care, typically associated with increased use of fossil fuel, crops produced intentionally for biogas production are considered a more expensive solution for society that does not effectively contribute to reduction of GHG emissions (Britz & Delzeit, 2013) as compared to the use of crop residues, vegetable by-products, wastes, and grass cuttings. Whether they are produced domestically or sourced from abroad, use of dedicated crops for energy production may not be sustainable, due to increased risk of ILUC (Britz & Delzeit, 2013), competition with food production, increased transport and associated fossil fuel use, and other potential sustainability challenges, such as sourcing from land with a high biodiversity value or high carbon stock (Jorgensen and Anderson, 2012). Using dedicated energy crops in biogas production as co-substrate for manure in a Danish context is therefore not considered desirable as a means to fulfilling the political target of using 50% of all manure for biogas production by 2020. Exceptions to this are applied to perennial ryegrass and clovers from land that has not been tilled for 5 years (see section 7.2).

6.3. Management of animal manure and slurries (S2)

Manure and slurries represent the main feedstock in manure-based centralised biogas production in Denmark, which is considered to be a valuable source of nutrients for agriculture, especially when digested in a biogas plant. Animal manure and slurries have a significant pollution potential, when not managed properly (stored, handled and applied according to good agricultural practices, and in line with existing regulations and requirements). Along with animal deep bedding, these are considered sustainable feedstock substrates for biogas production, as their use as feedstock for AD can result in significant reductions of GHG emissions, especially ammonia, NO_x and methane. Their use as AD feedstock does not compete with other uses and it offers potentials for better nutrient management in agriculture, and less pollution of air and water environments (Al Seadi & Lukehurst, 2012). Nevertheless, the sustainability of using manure to produce biogas is still questioned by some NGOs, who claim that manure must not be seen as a waste from the animal production, which is per se free from environmental and climate impacts (Jorgensen and Anderson, 2012). It is argued that animal production is a great consumer of resources, including of land for the production of fodder, with valuable protein that could also be used directly for human consumption. NGOs fear that incentives for use of manure for biogas will contribute to increasing an already large and unsustainable level of animal production industry in Denmark. Research results indicate that the carnivore diet (eating meat) is a major source of GHG emissions, and significant reduction in meat consumption, or conversion to vegetarianism would be extremely beneficial to the climate (Smyth & Murphy, 2011).

6.4. Organic waste management (S3)

Organic waste materials are important feedstock types for biogas production from manure co-digestion. The treatment of organic waste during biogas production is commonly considered to be a cheap and sustainable alternative to other treatment options. However, source separation of municipal and household waste is required, if the waste is to be used as feedstock for AD. Such wastes must have a suitable quality with respect to their content of physical, chemical, and organic/biologic contaminants, due to the subsequent application of the digestate to the soil as biofertiliser (Al Seadi & Lukehurst, 2012). Focus on feedstock quality means that feedstock types such as sewage sludge, which was commonly used as co-substrate and a methane booster in the early years of manure co-digestion, is no longer acceptable due its content of heavy metals and organic contaminants (Al Seadi & Lukehurst, 2012).

6.5. Plant operation sustainability (S4)

Plant operation sustainability mainly relates to three issues: (1) the stabilisation of the digested substrate, to avoid fast release of methane; (2) hygiene and sanitation with respect to animal and human health, in relation to safe application of digestate as fertiliser to crops; and (3) avoiding unintended emissions of bad odours and of GHGs. The first two issues can be dealt with through proper process control at the plant, by running an AD process, which is suitable for the types of substrates to be co-digested, and with an adequate retention time of biomass at suitable process temperature (Baggesen, 2007; Al Seadi & Lukehurst, 2012).

Regarding the third issue, the AD process aims to extract as much of the methane potential as possible, from the substrate, thereby also reducing the potential unintended GHG emissions from this production. For example, it is important to cover storage facilities for feedstock materials as well as for digestate. The savings in fugitive methane emissions from open slurry tanks, which are displaced in covered gas tight anaerobic digestion facilities, typically leads to a carbon negative biogas (Liebetrau et al., 2017). Handling of biomass must also take place so that no odour emissions to the atmosphere take place.

Another focus area is control of methane emissions at the biogas plant. Voluntary measurements of methane emissions in selected biogas plants suggested on average slippage of 4.2% of total methane production

(Energistyrelsen, 2016). The emissions originated from big and small leakage sources, and plant owners were informed of the extent and presence of identified leakages. Subsequent repair of identified leakages reduced the average methane emissions from 4.2 to 0.8% of total methane production (Kvist, 2016). The reduction of methane emissions reduced the GHG emissions of the biogas production from 40 to 31 kg CO_2 equivalent per tonne of digested biomass (Nørregaard et al., 2015). There is no direct regulation on this issue, but the methane emissions from biogas plants are in strong focus nowadays. In 2016, a mandatory requirement of gas tight digester tanks and pipe lines was introduced in the standards for environmental approval of a biogas plant (BEK no. 519 of 27 May 2016). For more detailed elaboration on this matter, IEA Bioenergy have recently published guidance on measurement and management of methane slippage at biogas facilities (Liebetrau et al., 2017).

6.6. Biogas and biomethane as renewable biofuels that reduce GHG emissions (S5)

Biogas and biomethane should, as renewable biofuels, reduce CO_2 emissions. Biomethane can potentially be a major contributor to reaching the Danish national climate and greenhouse gas emission reduction goals associated with the Paris Agreement (Energistyrelsen, 2016). Biomethane is a dispatchable energy vector, which can be stored in existing natural gas facilities, thus acting as a buffer for and facilitator of other intermittent renewable energies such as wind and solar (Persson et al., 2014). Biomethane is ideally suited to decarbonise the transport sector through use of upgraded biogas (Compressed Natural Gas, CNG, or Compressed BioGas, CBG) for city buses and trucks. This use is becoming more prevalent in Denmark as biogas proves to be cheaper than imported diesel (Damgaard, 2017). Another driver of this development is the wish to have better air quality by reducing the level of air pollution in urban areas with dense traffic in Denmark (Al Seadi, 2017). Diesel is also becoming unpopular in a number of cities, which are proposing future bans on diesel use (Paris, Mexico, Athens) or immediate bans on certain roads for older diesel vehicles (Hamburg) on the basis of air quality. Biomethane is one of the easiest decarbonised fuel substitutes for heavy commercial vehicles and intercity long-distance buses.

6.7. Recycling digestate as a biofertiliser (S6)

Sustainable recycling of digestate as a biofertiliser must ensure the quality of the digestate as fertiliser, and avoid contents that are harmful to the environment, soil, crops, and to human and animal health. Utilisation of nutrients in digestate is more efficient than their mineral form, as it makes them easily accessible to plant roots. The mineral form increases the risk of infiltration and leakage to surface and ground water (Lukehurst et al., 2010).

In a biogas reactor almost all easily degradable organic compounds are degraded and converted into biogas (methane), including the volatile organic compounds that smell very badly. The intensity and the persistence of odours from digestate application as fertiliser are lower, compared with raw slurry. Digestate has a strong ammonia smell, which persists only a few hours after application. Smell reduction by fertilisation with digestate instead of raw slurry is a very important attribute as it improves the air quality in rural areas, and increases the public acceptance of animal farming. Application of digestate in line with good agricultural practice, on growing crops, in cold and humid weather, with immediate incorporation in the topsoil, will minimise the odour nuisance and the risk of GHG emissions significantly.

As most animal farms produce more manure and slurries than they are allowed to apply on their fields, the excess amounts are sold to the crop famers in the vicinity. This means that a significant redistribution of nutrients in the respective agricultural area takes place, lowering the environmental pressure from intensive animal farming.

During AD, between 20–95% of the feedstock organic matter is decomposed and converted to biogas, depending on feedstock composition and the digestion process applied. It is the easily degradable carbon compounds in the feedstock that are decomposed by AD, while the remaining carbon is recycled back to soil with the digestate, along with the macro and micro nutrients. This helps build up the humus content of the soil and its long-term suitability for agriculture. It is not known if it is of importance that the amount of recycled carbon is lower for digestate compared to manure.

7. Governance of biogas sustainability in Denmark

Manure-based centralised biogas production systems were designed to solve several environmental challenges, while also contributing to renewable energy and reduction of GHG emissions. Financial incentives must thus be considered part of the sustainability governance framework for biogas. For other sustainability issues,

Table 2. Overview of the most important legislation, regulations and other governance that addresses the different environmental sustainability aspects of biogas production (GB, G1–G6, see Fig. 7 and Table 1).

No	Relevant legislation and other governance
GB	EU: • Renewable Energy Directive (2009/28/EC). DK: • Energy Strategy 2050 – from coal, oil and gas to green energy, http://dfcgreenfellows.net/Documents/EnergyStrategy2050_Summary.pdf • Renewable Energy Law (LBK no. 119 of 09/02/2018) • Natural Gas Supply Law (LBK no. 1157 of 06/09/2016) • Statutory order on price premiums for upgraded biogas delivered to the natural gas grid and cleaned gas delivered to the town gas grid (BEK no. 299 of 25/03/2015) • Statutory order on price premiums for power produced from certain solar panels and other renewable technologies than wind mills (BEK no. 1730 of 26/12/2017) • Various laws on biogas taxes, tax exemption and refund.
G1	EU: • Waste Framework Directive (2008/98/EC) • Nitrates Directive (91/676/EEC) DK: • Government's "Denmark without waste – recycle more, incinerate less"– strategy (2013), http://mst.dk/affald-jord/affald/affaldshaandtering-strategi-aktiviteter/danmark-uden-affald-strategi-plan/ • Resource management plan 2013–2018, guidance from the Environmental Agency, no. 4 (2014), http://mst.dk/affald-jord/affald/affaldshaandtering-strategi-aktiviteter/danmark-uden-affald-strategi-plan/ • Energy Agreement from March 2012, https://ens.dk/ansvarsomraader/energi-klimapolitik/politiske-aftaler-paa-energiomraadet/energiaftalen-22-marts-2012 • Statutory order of sustainable production of biogas (BEK no. 301 of 25/03/2015) • Statutory order on Waste (BEK no. 1309 of 18/12/2012) • Minister's note on use of maize and other energy crops for production of biogas, https://ens.dk/ansvarsomraader/bioenergi/energiafgroeder-til-biogas • Environmental Protection Law (LBK no. 966 of 23/06/2017)
G2	DK: • Statutory order on Livestock Manure (BEK no. 865 of 23/06/2017).
G3	EU: • Animal By-product Regulation (Regulation EC No. 1069/2009). DK: • Government strategy, "Denmark without waste – recycle more, incinerate less" (2013), http://mst.dk/affald-jord/affald/affaldshaandtering-strategi-aktiviteter/danmark-uden-affald-strategi-plan/
G4	EU: • Animal By-products Regulation (EC No. 1069/2009). DK: • Own hygiene and sanitary control protocols implemented on each biogas plant to fulfil the requirements of the EC No. 1069/2009.
G5	DK: • Heat Procurement Law (LBK no. 523 of 22/05/2017). • Statutory orders BEK no. 299 of 25/03/2015; BEK no. 1730 of 26/12/2017 (See GB): The Energy Agreement from March 2012, https://ens.dk/ansvarsomraader/energi-klimapolitik/politiske-aftaler-paa-energiomraadet/energiaftalen-22-marts-2012
G6	EU: • Cross Compliance rules under the Common Agricultural Policy (CAP): Statutory Management Requirements (SMRs), and Good Agricultural and Environmental Conditions (GAECs) (legal basis: Council Regulation 1306/2013, Commission Implementing Regulation 809/2014, Commission Delegated Regulation 640/2014) • The Habitats Directive (92/43/EEC) DK: • Fertilization and Plant Cover Law (LBK no. 433 of 03/05/2017) • Statutory order on Livestock Manure (BEK no. 865 of 23/06/2017). • Statutory order on Utilisation of Waste Products for Agricultural Purposes (BEK no. 843 of 23/06/2017). • Quality management guidelines of digestate quality management through control of feedstock quality, stabilisation, sanitation, product declaration. • Guidelines for good agricultural practices for optimal application of digestate as fertiliser and minimization of ammonia volatilization. • Several laws on nature protection: http://mst.dk/natur-vand/natur/natura-2000/lovgivning/

biogas production in Denmark is governed through a mix of policies, legislation, regulations and rules, combined with implementation of know-how and good practices (Al Seadi et al, 2001). An overview of the mix of relevant governance measures, GB and G1-G6, is given in Table 2 for each sustainability issue, SB and S1-S6. Each group of measures are described in more detail in sections 7.1-7.7.

7.1. Financial incentives to promote the overall concept and its benefits (GB)

In Denmark, utilisation of biogas and biomethane is mainly governed by the Heat Procurement Law (LBK no. 523 of 22 May 2017). Since 2012, the Energy Agreement bought about new policies for renewable energy and improved economic frameworks for biogas production. The agreement was made in the context of new visions, in which biogas should be used to a greater extent in the future, for applications other than CHP generation. Today, the biogas sector benefits from a significantly improved financial support mechanism, adopted by the Danish Government, and subsequently approved by the EC in 2013. Furthermore, in 2014, an EC restriction was removed, which concerned the possibility of the same plant receiving financial support for both investment and operation. This consolidated the confidence in the future of biogas technologies, and consequently boosted the deployment of biogas in Denmark.

The main elements of the Danish financial support scheme for biogas are highlighted below:

- €56 MWh^{-1} for biogas used in a CHP unit or injected into the gas grid (€15.3 GJ^{-1}), and
- €37 MWh^{-1} for direct usage for transport or industrial purposes (€10 GJ^{-1}).

These tariffs include natural gas price compensation of a maximum of €12 MWh^{-1} (€3.46 GJ^{-1}) and temporary support of €0.5 MWh^{-1} (€0.14 GJ^{-1}), phased out in 2016.

It is also possible to apply for investment grants for plants digesting only manure. The support for upgraded biogas supplied to the natural gas network in the calendar year is payable to both upgraded biogas supplied to the natural gas grid and to purified biogas entering a town gas grid. This support is provided since 1 December 2013. In the Energy Agreement from 2012 (Fig. 6), new support incentives for biogas to transport, process and other applications were also agreed upon.

The subsidies for heat and power, upgrading and industrial production and transport are:

- €15 GJ^{-1} in basic subsidy for CHP heating (direct and indirect subsidies) (80 DKK GJ^{-1}, improved to 115 DKK GJ^{-1} in 2012);
- €10.6 GJ^{-1} in basic subsidy for upgrading and distribution via the natural gas grid (80 DKK GJ^{-1}), and;
- €5.2 GJ^{-1} in basis subsidy for industrial processes and transport (39 DKK GJ^{-1}).

Additionally, temporary subsidies are given for all applications for the period 2016-2020.

- €3.5 GJ^{-1} for all applications – scaled down with increasing price of natural gas. If the natural gas price the year before is higher than a base price of €7.1 GJ^{-1} the subsidy is reduced accordingly.
- €1.34 GJ^{-1} for all applications – scaled down linearly every year from 2016 to 2020, when the subsidy expires.

Municipalities are furthermore obliged to give biogas first priority for use in collective heat supply, if it is the socio-economically cheapest fuel and does not give higher heating prices. There are also improved economic conditions with incentives so that biogas can be used outside the cogeneration sector.

There is political willingness to continue the favourable economic framework conditions for biogas, also after 2020. During the summer and fall 2018, a new Energy Agreement is under preparation, including, *inter alia*, the economic biogas prospects up to 2030, with the aim of ensuring the continuation of the present development of the biogas sector and its crucial future functions for society: to back up the intermittent renewable electricity from wind and photovoltaic, and to be the central player in the development of the circular economy in Denmark.

7.2. Sustainability of plant-based feedstock produced in the fields (G1)

National Danish agreements and legislation (Energy Agreement from March 2012, statutory order on sustainable production of biogas, BEK no. 301 of 25

March 2015, and statutory order on price premiums for power produced from renewable energy, BEK no. 1730 of 26 December 2017) stipulate that use of energy crops as feedstock for biogas should decrease significantly as these are not considered to effectively contribute to reducing GHG emissions. Also, their use for biogas production does not contribute directly to fulfilling the target of co-digesting 50% of all manure by 2020. For this reason, there is a limitation on the use of energy crops to a maximum of 12% of the feedstock mass up to 2020, with expected further reduction after this date (Energistyrelsen, 2012; Jacobsen et al., 2014; Jorgensen et al., 2012).

The legislation has some further specifications and exemptions. For example, it is permitted to use clover grass from organic farms and grass and clover grass from areas that have not been ploughed for the last 5 years. Power plants and other users of biogas for energy can only get financial support for using the biogas if the feedstock percentage of energy crops is below the prescribed limit. If biogas is used directly for transportation, support can only be received if no food crops are used as feedstock (maize, grain, beets, etc.). This approach to ILUC and competition with food and fodder does not provide full assurance in each specific case, but it most likely limits the undesired impacts to a minimum level. At the same time, it is very simple, transparent and administratively cheap for both economic actors and the authorities.

7.3. Management of animal manure and slurries (G2)

With the adoption of the new statutory order for Livestock Manure in 2017, previous requirements for compliance with the *harmony rules* (Miljøstyrelsen, 2006) and area requirements for livestock production were cancelled. The new order gives permission for animal production without requirement for ownership of corresponding land areas. As a consequence, an increased need for sale and redistribution of nutrients from manure and slurry from the animal farms to the crop farms is expected to occur. This redistribution is desirable in order to avoid impacts on water, environment and biodiversity. Co-digestion of manure and slurry in biogas plants facilitates the redistribution of manure and nutrients in the agricultural areas as well as sale of digestate to crop farms in need of nutrients and organic matter. The driver for using biogas for redistribution is still financial support through various national ordinances, see section 7.1.

7.4. Organic waste management (G3)

The ordinances for organic waste management sets threshold values for heavy metals and for organic pollutants in waste materials applied on soils (Al Seadi & Lukehurst, 2012). The waste management strategy "Denmark without waste" from 2013 pushes towards recycling and reuse of 50% of household waste by 2023, with 60% of the organic waste from the service sector being reused and recycled by 2018. At the same time, the strategy aims to redirect the organic fraction of the household waste away from incineration, and towards biogas production. Co-digestion of animal by products in biogas plants is controlled by the Animal by-product regulation (European Parliament and Council, 2009).

7.5. Plant operation sustainability (G4)

Voluntary monitoring and control of methane emissions and leakage from the biogas plant contribute to both environmental sustainability and economic sustainability of the biogas plant. Good practice and know-how, combined with regulations concerning process control show how a biogas plant is well operated, by running an AD process that is suitable for the types of substrates to be co-digested.

7.6. Biogas and biomethane as renewable biofuels that reduce GHG emissions (G5)

No governance includes thresholds on minimum greenhouse gas emission reductions, except indirectly through control of the energy crop input to AD feedstock (see also section 7.2). Apart from this, it is likely that such reductions are considered obvious, with motivation to achieve these through financial support schemes. National laws provide new economic frameworks for biogas production and utilisation, including gas upgrading for grid injection. In 2017, about 11% of the gas in the Danish natural gas grid was biomethane (Kousgaard & Pedersen, 2017). Danish Energy Agency (Energistyrelsen) expects that 2,200 GWh (7.92PJ) of biomethane will be fed to the gas grid by 2020, which is an increase of about 70% compared with 2017. There are also financial incentives for the use of upgraded biomethane as transport fuel, as well as for the utilisation of biogas as fuel for industrial processes, electricity production or heating, see also section 7.1.

7.7. Recycling digestate as a biofertiliser (G6)

Application of digestate from centralised manure co-digestion as fertiliser in agriculture is governed by the same rules which regulate the management and application of animal manure. The regulations require digestate to be stored in covered facilities with a capacity to store the digestate for 6 to 9 months. The covering of storage facilities for slurry and digestate is a measure to minimise the risk of GHG emissions and ammonia. Application as biofertiliser also requires that the digestate is a high quality product (Al Seadi & Lukehurst, 2012), and BEK no. 843 of 23 June 2017 requires quality management of digestate through feedstock quality (Al Seadi & Lukehurst 2012; Baggesen, 2007), stabilization, sanitation, and product declaration.

Compared to raw slurry, digestate can be more precisely integrated in the fertilisation plan of the farm, along with chemical fertilisers, as it is homogenous and with a declared content of NPK and dry matter. The mandatory statutory order on Livestock Manure, governing also digestate application as fertiliser, was strengthened in August 2017. The new regulation includes a limit for N application and, as an element of novelty, also sets a limit for P application, thus aiming to prevent accumulation of P in ground waters. The new regulation of phosphorus includes both organic and commercial fertilizers and requires a specific phosphorus account within the overall fertilizer accounts (Miljø- og Fødevareministeriet, 2017; Miljøstyrelsen, 2017). Regulations ensure that the digestate is only applied during the period of the growing season, when the crops are in vegetative growth, when water and nutrient uptake is high, and the risk of off-site pollution is low. “Good agricultural practices” are used with respect to the application methods, machinery uses, type of crops and required weather situation, in order to prevent pollution and enhance sustainability.

Regulations of digestate application thus aim to ensure that no harmful substances are added to farm soils, and that off-site nutrient losses to surface and groundwater are minimised, together with losses of air-borne emissions and odours to the atmosphere.

8. Conclusion

The pioneering phase of biogas development in Denmark was largely characterised by the absence of governance restrictions and by few incentives and supporting policies, which seems to have given innovative pioneers the freedom to develop and test various solutions and identify the most successful ones. However, from its early stages of development, the concept of biogas production from centralised manure co-digestion has been recognised as a system with multiple environmental, economic and social benefits for several sectors, including the environment, agriculture, energy, manure and waste management, local economies, and later on climate, and transport. The financing of the early plants seems to have relied on plant owners that were probably motivated by altruistic idealism, as was the case in the early phases of wind power development (Nielson, 2018).

The build-up phase was characterised by new financial incentives and governmental support for development of the system, as was also the case in the development of the wind power sector. A similar phase has been identified for the biogas sector development in Germany, for the period 2002-2012 (Schaubach et al., 2018). The build-up phase in Denmark was also relatively free from restrictions, with regard to ownership and plant governance structures. This probably left pioneers and entrepreneurs with decision-making power, ownership of the development process, and flexibility in finding the best local solutions. It is worth noting that an adaptive feature has been identified as a key parameter for the development in this phase. This feature consisted of a monitoring system and a communication platform for collection and sharing of experiences and know-how. This system seems to have disappeared during the years associated with stagnation due to liberalisation of the energy market in Denmark. Considering that we are probably facing a phase with an accelerated development of biogas, now with new elements such as large scale production, upgrading and use for transport, it is worth considering if a new and effective monitoring system and communication platform / media should be established. There are indications that such systems may play a key role for building up trust in a technology and legitimate governance for sustainability. It could be considered if a new monitoring system should also monitor sustainability parameters under discussion for the circular bioeconomy, and high level sustainability criteria, such as the UN Sustainable Development Goals (SDGs), even if it is still crucial that these are translated in a way that can be understood and make sense at the local and practical level.

The market liberalization and biogas stagnation phases seem to be an example of lost opportunities, due to an abrupt and too early cessation of adequate financial support. In the case of the German biogas sector development, an initial phase was instead followed by a phase with consolidation, stricter regulations, and optional market integration, before a new phase started in 2015, with gradual removal of feed-in tariffs and full market exposure through auctions (Schaubach et al., 2018). At present, it seems there are similar risks of losing opportunities. Even if rapid development seems to be taking place, there are still uncertainties with regard to policy frameworks and financing, which restrain developers and investors from taking full advantages of the vast feedstock that is available and enable actors to solve challenges with solid feedstock supplies for co-digestion, upscaling, upgrading, use for transport, and improved integration with the energy system as a whole. According to former Minister of Energy (1979-1982), Poul Nielson (Nielson, 2018), the development of biogas plants remained at a pre-industrial level for a long period of time, because key industry actors declined invitations to engage and share their knowledge, and because agriculture and other feedstock producers were not confronted with a mandated obligation of feedstock delivery. According to Nielson (2018), the same political ideology rules today as in the stagnation phase. Ambitious targets are set for renewables, but focus is still on economy and market-based solutions. The current development can still be seen as a result of political commitments in the build-up phase, and a visionary industry that increasingly reacts to global and public calls for sustainable development. The question is if such private forces can keep up the development over time, without dedicated public inputs. It has been pointed out that there is hesitation due to political uncertainties, in spite of ambitious general goals and the positive signals.

The only major sustainability push-back for the biogas sector in Denmark has been the use of energy crops for co-digestion. This issue was quickly solved in Denmark, with simple feedstock requirements. Unlike Denmark, the significantly larger German biogas sector was, until recently, almost entirely based on non-waste feedstock (dedicated energy crops), causing significant land use to change inside and outside of Germany. The biogas business has bought profit to the German agricultural sector, but according to Britz, and Delzeit (2013) it had negative effects on global agricultural markets, with increased food prices and higher domestic electricity prices, due to subsidies for biogas production. Since 1 August 2014, when the amendment of the Renewable Energy Sources Act was introduced, more holistic considerations, aiming to shaping bioenergy in a sustainable system were taken. The amendment brought focus on other effects, beyond a narrowly defined bioenergy policy. It was used to assess competition and synergies in addition to resolving conflicting aims, for example how food security can be implemented in the case of interwoven bioeconomic added value chains (Bioöknomierat.de, 2015).

Other than this, there has so far been no major push back on the biogas sector, due to sustainability issues. However, it is still a question if substrates for co-digestion will become the limiting factor for the development. In the long-term, it is also possible that manure production may decrease, if current trends towards more plant-based diets take off at a larger scale. The risks and challenges of the biogas sector are thus more related to other issues than sustainability.

Large parts of the sustainability requirements relevant to biogas in Denmark are embedded in legislative requirements that are frequently rooted in EU legislative frameworks, such as regulation of impacts on water quality and safety and specification of substrate quality. Furthermore, substantial governance elements rely on voluntary measures. This includes the reduction of methane emissions and leakage at the biogas plant and good agricultural practices for application of the digestate as biofertiliser. The reduction of emissions had economic benefits as a driver, but probably awareness of climate change and the risk of critics have also played a role as a driver to seek compliance. Compliance with the use of good agricultural practices is audited by the state authorities, as part documentation for fulfilling requirements to receive subsidies from the general agricultural subsidy schemes.

The amount of sustainability legislation and voluntary guidelines, and the degree of prescriptiveness seem to have increased over the years, probably as a natural consequence of increasing knowledge and awareness, and joint efforts made to find the most economic and environmentally and socially sound solutions. Many challenges are related to implementation of good practices, but others relate to location, logistics and planning. As centralised plants with manure co-digestion installations become larger in size and number, it is increasingly important to deal with issues around high biomass transport volumes that must come from larger and larger distances. On average, the current transport distances are 20-25 km around the plant. The risks of odour nuisances from the plant and the heavy transport activity to and from the AD unit has implications for air pollution and noise for the rural residents, while it also increases the production cost of the biogas. It is a crucial issue to solve such local issues, as well as ensuring a high level of political support.

It seems that there is a political willingness to continue having favourable economic framework conditions for biogas after 2020. At the end of 2018, a new Energy Agreement will be adopted, which will design the development path for biogas until 2030. Biogas is foreseen to have two new important functions for the Danish society: facilitating intermittent wind and solar energy supplies; and playing a central role as part of the circular bioeconomy.

How the Danish manure-based biogas plants will be owned, financed, incentivised and governed in the future, in the overall national energy sector, will depend on the level of societal acceptability and legitimacy granted by local and national level actors. These actors include farmers, industries and businesses, governmental institutions, associations, NGOs and the public at large (Jørgensen et al., 2017). If the sector should develop as intended, it seems important that each of these actors can collaborate with a great level of trust between them, and that each of them plays an active role where they are best placed to do so.

Annex 1


Hvims
Hjørring
Sindal
Rønnovsholm
Vrejlev
BB-Biogas
Grøngas Vrå
GFE Krogenskær
Biokraft
Ålborg V.
Tovsgård
Vaarst
Vegger
Limfjorden
Rybjerg
Madsen
Lemvig
Ausumgaard
Foulum
BPB Group
Randers
Maabjerg
Grønhøj
ØL
Thorsø
Bånlev
Hedegaard
Frijsenborg
Viftrup
Sinding-Ørre
Herning
Studsgård
Marselisborg
Vestjysk
Månsson
Horsens
Sdr. Vium
Blåhøj
Horsens
Blaabjerg
Filskov
Kroghsminde
Grindsted
Vejle
Novozymes
Snertinge
Mølleåværket
Lynetten
Damhusåen
Korskro
Lykkeslund
Avedøre
Holsted
Fredericia
Nordfyn
Solrød
Esbjerg V.
Zastrow
Ejby Mølle
Ribe
Linkogas
Fangel
Hashøj
Holbæk
Faxe
Midtfyn
Sønderjysk
Lynggård
Taagholm
Nordic Sugar
Nordic Sugar
Nysted
Type of plants
Waste water plants
Industrial plants
Landfill gas
Centralised plants
Single farm plants
Production (TJ/year)
0 - 20
21 - 100
101 - 600
In construction
In operation since 2015
0
25
50
100
Km
Energistyrelsen

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IEA Bioenergy

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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.

The following countries are members of Task 37, in the 2018 Work Programme:

Australia	Bernadette McCABE
Austria	Bernhard DROSG
	Günther BOCHMANN
Brazil	Paulo SCHMIDT
	Marcelo ALVES DE SOUSA
	Rodrigo REGIS DE ALMEIDA GALVÃO
Denmark	Teodorita AL-SEADI
Estonia	Elis VOLLMER
Finland	Saija RASI
France	Olivier THÉOBALD
	Guillaume BASTIDE
Germany	Jan LIEBETRAU
Ireland	Jerry D MURPHY (Task Leader)
Korea	Soon Chul PARK
Netherlands	Mathieu DUMONT
Norway	Tormod BRISEID
Sweden	Anton FAGERSTRÖM
Switzerland	Urs BAIER
United Kingdom	Clare LUKEHURST
	Charles BANKS

WRITTEN BY:
Teodorita Al Seadi (Biosantech, Esbjerg, Denmark)
Inge Stupak (Department of Geosciences and Natural Resource Management, Faculty of Science, University of Copenhagen, Denmark)
C. Tattersall Smith (Department of Geography & Planning, University of Toronto, Ontario, Canada)

EDITED BY:
Jerry D. Murphy (MaREI Centre, University College Cork, Ireland)

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Contact us:
www.ieabioenergy.com/contact-us/