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The implications of economic instruments on biogas value chains

– a case study comparison between Norway and Denmark

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Abstract

This paper studies biogas value chains and the effect from various economic support instruments on these value chains. This is done by comparing two European countries that are quite similar in size, income levels and environmental ambitions, but which are using very different instruments to support biogas development. Norway provides investment support combined with support for inputs, while Danish support is focused on the biogas output side.

The aim of the comparison is to clarify if the policies in use have affected the design of biogas value chains such that they are determined by national support and are not viable under alternative support structures. Based on the findings possible modifications of national support and other biogas regulation policy are suggested. The comparative study assesses the costs and income of an exemplary Norwegian and a Danish value chain. The cases are evaluated by assessing the economic consequences of implementing the Danish instruments for a Norwegian value chain, and vice versa. We find that structural and regulatory conditions have a large impact on the configuration of the value chains. The Danish value chain in Norwegian settings results in a large deficit (-12.7€/tonne), while it was profitable in Denmark (+4.9€/tonne). The same is observed for the Norwegian value chain, but to a lesser extent.

The policy implication of end-use support in Denmark is large-scale plants, maximising the output through co-digestion of manure and high yield substrates, while avoiding losses. Investment support in Norway has increased biogas production from organic waste with less emphasis on efficient gas usage, while input support regarding manure has led to an increase in the usage of manure as substrate.

Keywords

Biogas; Environmental policy; Regulation; Value chain

1 Introduction

Biogas production from organic resources is seen as a measure to reduce greenhouse gas (GHG) emissions in several sectors. A large variety of policies have been proposed and implemented to increase and improve biogas production. In this paper, we aim to clarify how these policies can affect biogas value chains, specifically by evaluating the effect of regulatory measures. This is done by comparing two countries, Denmark and Norway, with similar income level, size and policy objectives, but different structural conditions for biogas and using different types of economic instruments. Denmark currently provides an end-use support through a feed-in tariff for electrical power and gas

delivered to the grid, while Norway provides investments support for plants and support to farmers sending manure to biogas production. The similarity of the two countries largely removes the effect of different cost levels, wages and possible scale effects from country size, allowing the direct comparison of effects from different biogas policies. Considering a situation where the regulatory conditions present in Denmark were transferred to Norway and vice versa, we want to answer if the present biogas value chain designs in Norway and Denmark are economically viable or not. If not, this is likely to explain why there is presently a large difference between value chain designs in Denmark and Norway.

Biogas is produced through an anaerobic digestion process using substrates such as manure, sewage sludge and organic waste from households or industry. Two products are produced: biogas and digestate. Biogas can be used to generate heat and electricity, or upgraded to a higher methane content and used as a fuel in transport or fed into the natural gas grid as biomethane. Digestate can be used as a fertiliser or separated into a wet and a dry fraction, where the wet fraction is sent to waste water treatment and the dry fraction is used for soil improvement. Some countries have restrictions on the use of digestate as fertiliser on agricultural lands, depending on which substrates are used.

There is a large diversity of biogas value chains in Europe. In Germany, Denmark and the Netherlands the substrate for biogas is mainly from agriculture (IEA Bioenergy 2014), while in UK, Italy, Spain and France a large share of the biogas production originates from landfills (EurObserv'ER 2014). In Norway, Sweden and Finland biogas is mostly produced from sewage sludge, or organic waste from household and industry (Huttunen, Kivimaa, et al. 2014; Olsson and Falde 2014). In many countries, biogas production is driven by the targets for renewable energy, and feed-in tariffs for electricity and gas production to the grid are used as incentives for production (e.g. Germany, Austria and Denmark). In Norway, Sweden and Finland, however, biogas is increasingly used as a fuel for transport ((EurObserv'ER 2014)(Lantz et al. 2007) (Jacobsen et al. 2013) (Brudermann et al. 2015)).

Few studies specifically focus on biogas in a context of policy regulation. (Raven and Gregersen 2007) made a comparative assessment between biogas development in the Netherlands and Denmark. They underline the importance of formal rules and conclude that subsidy grants and investment grants played a role in both countries. The long-term character of the economic support mechanisms in Denmark has been an important factor and proved to be successful compared to the ad hoc support in the Netherlands. Policy support was usually linked to broader regime developments (e.g. energy strategy, manure handling problems, climate change). Also the possible effect of incumbent traditional energy suppliers hindering the development of new renewable energy producers as biogas has been studied (Fevolden and Klitkou 2017).

(Wirth et al. 2013) examined how the effects of formal institutions depend on informal institutional structures through a comparative assessment of biogas technology in Austrian regions. They found that the professional culture in which the farmers are embedded modulates the effects of feed-in tariffs and investment subsidies. This explain large differences in diffusions and technology in the regions, which cannot be explained by geographical conditions or prevailing economic structures in agriculture alone.

(Lantz et al. 2007) analysed the regulatory landscape for biogas in Sweden and distinguished between production and utilisation of biogas, identifying both barriers and incentives. They concluded that the existing policy in Sweden was not enough to exploit the full potential for biogas production, which depend on a large variety of incentives and barriers within several sectors. (Larsson et al. 2016) performed an analysis of the development of upgraded biogas in the Swedish transport sector in relation to policy instruments and the availability of a natural gas grid. They concluded that investment support schemes and exemptions from energy and carbon dioxide taxes have been key instruments in initiating the establishment of new biogas production facilities and infrastructure. The transport use is also in focus in Norway, but not in Denmark and the following analysis will explain this. (Carrosio 2013) studied policies and organisational models for biogas plants managed by farmers in Italy. His conclusion was that the intentions of the policies are thwarted because of the institutional creation of a dominant unsustainable organisation model, and he recommended thus a diversification in the use of biogas and reorganisation of the policy induced incentives. This problem of a policy induced single organisation model may be relevant also in our study and we evaluate the robustness of the value chain organisation by exposing it to a different regulatory system.

All of the studies above underline the importance of economic instruments and policies in general to facilitate the development of sustainable biogas value chains. None of the studies compare national value chains exposed to two radically different support strategies one with support to input in biogas production and one with biogas output support. In this study, we intend to cover this gap by quantitatively investigating how economic instruments can affect the feasibility of country specific biogas value chains under radically different support regimes. The paper is organised with an introductory section, followed by section 2 giving the detailed context of Danish and Norwegian biogas sector conditions and regulation. Then section 3 provides the method for the economic comparison and some structural data for the value chains. In section 4, the results are given followed by a broader discussion of these results and biogas development perspectives in Denmark and Norway including regulatory options. Finally, section 6 provides the conclusions.

2 Regulatory and structural context for biogas value chains in Norway and Denmark

The effect of economic instruments cannot be assessed without considering other aspects that will affect the value chain such as structural conditions, political goals and the regulatory system in general, as well as markets for substrates, biogas and digestate. As exemplified in (Hiranandani 2010) these conditions affect the significance of a given policy and therefore these conditions are compared and their importance for Denmark and Norway discussed in the following sections.

2.1 Structural conditions for biogas production in the two countries

		NO	DK
Agriculture	Average livestock unit, small farms ¹	23	86
	Average livestock units, large farms ¹	61	681
Waste	Share of households with source separation of organic waste(Hanssen et al. 2013) ²	67 %	30%
	Logistics: Population density, inhabitants (inhabitants/km ²) Worldatlas (2017)	13	125
Energy	Share of renewables in gross final consumption of energy (2016) ³	69.4 %	32.2 %
	Electricity prices for household consumers, including all taxes and levies, 2016 (EURO/kWh) ⁴	0.157	0.309
	Gas consumption as share of gross energy consumption, 2016 ⁴	4%	14%
	Biogas as share of final gas consumption ⁴	5.2%	5.0%
Transport	Share of renewable fuels for transport (2016) ⁵	17.0%	6.8%
	Share of gas consumption (natural gas and biogas) used for transport ⁴	25.7%	0.2%
	Share of gas in transport fuel consumption (2016) ^{6,7}	3%	0.06%
	Fuel prices diesel net (EURO/liter)DKV Euro Service (2017)	1.148	1.014

Table 1 Factors affecting biogas production in the two countries

¹ (European Commission 2017)

² Own calculations based on respectively (Norwegian Ministry of Climate and Environment 2014) and (Danish Ministry of Environment 2016; Statistics Denmark 2017)

³ (Eurostat 2018), Share of renewable energy in gross final energy consumption

⁴ (Eurostat 2018), data are without own consumption for oil and gas extraction, as these data would be distorted by the high gas- and oil production in Norway

⁵ (Eurostat - statistics explained 2018), share of renewable energy sources in transport

⁶ Danish Energy statistics 2016, tables (<https://ens.dk/service/statistik-data-noegletal-og-kort/maanedlig-og-aarlig-energistatistik>)

⁷ Own calculations based on (Statistics Norway 2017b)

Norway and Denmark are countries closely located, with similar climatic conditions. There are, however, large differences in topography, total surface area and general framework conditions of biogas production. To understand these differences, we map the demographic and structural conditions for the relevant sectors in Table 1.

Both Norway and Denmark are countries with ambitions of sustaining a productive agricultural sector; however, there is a substantial difference in farm structure. The Norwegian agricultural strategy is based on an ambition to increase the degree of self-sufficiency and maintain employment in rural areas. Denmark is a large exporter of a livestock based agricultural production that bears the mark of a highly efficient sector that competes in international markets, taking advantage of the topography that enables a high degree of economy of scale. This affects the access to manure as substrate for biogas production. Large distances and smaller concentrations of manure in Norway is likely to result in higher transportation costs.

The share of households with source separation of OW is higher in Norway compared with Denmark, despite lower population density. For Denmark, this can be explained by a large capacity of waste incineration plants that produces heat- and power. This capacity has historically lowered the Danish interest in source separation. The large share of source separated OW in Norway indicates better access to OW resources for existing biogas plants. This access, together with the willingness to pay for high yield substrates in Denmark has led to export of pre-treated OW from Norway to Danish biogas plants. Hjort-Gregersen et al (Martinsen 2012) estimated that about 470,000 tonnes of OW were exported per year to Denmark and Sweden.

Norway has (together with Iceland) the largest share of renewable energy in Europe, low electricity costs and heating primarily based on electricity. Denmark has a lower share of renewables and high energy prices, when taxes are included (Eurostat 2016).

Due to a highly developed natural gas grid in Denmark, it has been natural to use biogas in local heat and power production, similar to several other countries (Hjort-Gregersen et al. 2011). Today with the rapid expansion of wind- and solar power, local heat- and power plants (CHP's) are less profitable, and heat is increasingly produced independently based on biomass. Norway a leading producer and exporter of natural gas, but the domestic use is low and the gas infrastructure is limited.

The shares of renewable fuels in the transport sector has until 2015 been relatively similar in the two countries, but in 2016 the share increased substantially in Norway. The diesel price in Norway is higher. In both countries, the interest in biogas as a renewable transport fuel is increasing.

2.2 Policy goals in the two countries

Table 2 summarises the policy goals relevant for biogas production and use at EU level and for Norway and Denmark. Norway is not part of the EU, but the country is collaborating closely through the European Economic Area (EEA-agreement) and has committed to the EU target of reducing at least 40% of GHG emissions by 2030.

	EU	Norway	Denmark
Agriculture	CO ₂ -reduction goals in agriculture	30% of manure to biogas production within 2020 ⁸	50% manure in biogas by 2020 ⁹
Waste	70% material recycling or reuse for waste from households within 2030 ¹⁰	75% of waste to recycling within 2010, further escalation to 80% ¹¹ Increased biogas production ¹²	50% of waste to recycling within 2022 ¹³
Energy	The EU's Renewable energy		A goal for an "ambitious

⁸ White paper on agriculture (Danish Ministry of Environment 2013)

⁹ Green Growth agreement (Danish Government 2012)

¹⁰ Circular economy package (Danish Ministry of Climate 2013)

¹¹ Norwegian waste strategy (European Parliament 2009a)

¹² Norwegian cross sectional biogas strategy (European Parliament 2009b)

¹³ Facts on the resource strategy (European Commission 2014)

	directive sets a binding target of 20% final energy consumption from renewable sources by 2020. EU target of a 80-95% CO ₂ -reduction by 2050 ¹²		expansion” of the biogas production, e.g. 17PJ biogas by 2020 Danish goal that heat and power production should be renewable by 2035, and the total energy consumption should be based on renewables by 2050 ¹⁴
Transport	- At least 10% of the energy used in the transport sector should be renewable within 2020 - CO ₂ -reduction goals in transport ¹⁵	- Regional goals: e.g. Oslo: public transport non-fossil within 2020 - Biogas strategy (states that biogas should be used for transport)	Municipal goals, e.g. Randers Municipality have a goal of 30% of municipal biogas should be used for biogas ¹⁶

Table 2 Policy goals relevant for biogas value chains in EU, Norway and Denmark

Norway has a goal of increasing the biogas production which is stated in the National Biogas Strategy (Norwegian Ministry of Climate and Environment 2014). Denmark does not have a separate strategy for biogas, although a biogas task force was created to aid an increase in production along with new regulation (Danish Government 2012). Denmark has high goals for renewable energy production and for becoming independent of fossil fuels by 2050.

Norway is highly independent of fossil fuels and focuses on waste resources, with a goal of over 75% recycling. In Denmark, there is a long tradition for waste incineration with a large capacity. New initiatives have started to increase the recycling level in Denmark aided by EU recycling-targets and the resource strategy in 2013.

A white paper from 2009 states that 30% of the manure in Norway should go to biogas production within 2020 (The Norwegian Department of Agriculture and food 2009) as a measure to reduce GHG in the agricultural sector. Simultaneously a 50%-goal was set in Denmark (Danish Government 2009a). This goal has not been ratified later.

There is no clear text concerning actual goals for biogas or renewable fuels in the transport sector for any of the two countries.

In summary, the Norwegian goals are mostly targeted towards management of manure and waste resources, indicating that policy makers focus on GHG-reduction and waste recycling. The objectives in Denmark are more directed towards renewable energy and secondarily the agricultural sector, which may originate from a focus on GHG-reduction *and* security of energy supply. This can be explained by the high degree of security of energy supply in Norway and that Denmark could become dependent on foreign energy supply in near future.

2.3 Biogas production in Norway

2.3.1 Development of biogas production

In Norway biogas production emerged primarily as a waste treatment option for sewage sludge and OW. Due to a large share of renewable and clean hydropower in the electricity grid and low prices on electricity, there has been few drivers for producing electricity from waste resources in Norway.

Historically the use of biogas has been inefficient. In 2007 about 19% of the biogas was flared, 53% was used for heat purposes, while only 2% of the gas was used for transport purposes (Raadal et al. 2008). In 2010 about 63% of the energy generated from biogas plants was used for heating of own

¹⁴ Energy Agreement 2012 (Danish Government, 2012) and The Danish governmental climate plan (Danish Ministry of Climate, 2013)

¹⁵ Renewable energy directive (RED) (Danish Government 2012) and Transport fuel directive (Energinet.dk 2017)

¹⁶ Regional Bioeconomy profile, central Denmark (European Commission, 2014)

premises and only about two thirds of the capacity of the biogas plants was exploited (Nedland and Ohr 2010). The share of biogas used for transport has increased to more than 30% of the consumed biogas in 2015 (Statistics Norway 2016a). The total consumption was 308 GWh (1.1PJ), 48 GWh was used for district heating and electricity production, 105 GWh (0.4PJ) for transport, 30 GWh for industrial purposes and 126 GWh (0.5PJ) by other consumer groups. Biogas constitute about 3% of the total national biofuel use (Statistics Norway 2016b) and has currently a marginal significance in the total energy use in Norway. According to the national waste statistics, about 48% of the solid organic waste went to biogas production in 2015 (Statistics Norway 2017a). A significant share of the available sewage sludge resources are currently being used for biogas production, and the future potential for biogas production was identified to be the organic waste and manure resources (Norwegian climate and pollution agency 2013a). The production capacity of biogas is expected to be up to 600 GWh (2.2PJ) in 2016 (Måge 2015). The deviation between the estimated capacity and the national statistics on consumption indicates that there are still large amounts of gas being flared and that the total capacity of the plants is not being exploited.

About 58% of the gas is produced from sewage sludge in wastewater treatment facilities, while only 1% is produced at farms with small-scale plants. The rest is produced based on OW and co-digestion plants (Lånke et al. 2016), (Norwegian climate and pollution agency 2013b).

Digestate is dewatered and composted in many plants, and the dry digestate is used as a soil improvement product. The experience related to use of liquid digestate on an industrial scale as a fertiliser is limited to a few, recently built plants.

2.3.2 The regulatory system

The regulatory system in Norway relevant for biogas production is shown in Table 3. Investors of industrial scale biogas plants can apply for investment support through the Enova programme. Applications are evaluated based on criteria related to cost efficiency and energy efficiency. Farm scale plants can apply for investment support through Innovation Norway.

		Regulatory framework	Economic incentives
Input	Access to substrates	=>Public procurement on municipal organic waste. =>For certain substrates hygienisation is required.	Support per tonne manure to biogas (to the farmer)
Plant	Anaerobic digestion plant	Cost of service regulation for municipal organic waste affects income.	=>Investment support (30%). =>Plants that co-digest substrates can apply for funding to become national pilot.
Output	Biogas to Heat/CHP		
	Biogas for upgrade		
	Biogas for transport	Public procurement for public transport (buses) and waste collection vehicles	Exempt from road fee and CO ₂ tax compared to other transport fuels
	Digestate in agriculture	=>Restriction on spreading areas for waste water residues => Logistics: Cleaning of vehicles to avoid infections	

Table 3 The regulatory system in Norway relevant for the study objects

Norway has an economic incentive system with support to farmers per tonne of manure supplied to a biogas plant. The support is calculated based on the dry matter content of the manure delivered to the farm and is regulated according to (FOR-2014-12-19-1815 2015).

Municipally owned biogas plants must follow a cost of service regulation (“the self-cost principle”), as described in the national waste regulation (FOR-2004-06-01-930 2004). This means

that the income from treatment of municipal waste (gate fee) must cover the cost of treating the waste, and cannot pay for, or be financed by, other substrates treated in the plant. The rationale behind this is that the waste fee the inhabitants pay to the municipality to cover the treatment of their waste should reflect the actual price of the service.

Public procurement criterions affect the value chains both with respect to income from treatment of waste and sales of biomethane. Municipalities that do have source separation of OW in the households that do not have their own treatment facilities, perform public procurement of the waste treatment service. The treatment plants are selected based on a request for tenders. Privately owned biogas plants and municipal plants from other areas can compete based on pre-defined criterions, such as price and environmental impact. The income from the treatment of waste make up a large portion of the income for Norwegian plants (66-78%) and there are large variations in the price per tonne waste treated (between 67 and 107 Euro/tonne treated) (Lyng et al. 2018). Biomethane is normally used in public transport and waste collection trucks, purchased through public procurement tenders.

Biogas used for transport has an advantage compared to fossil fuels because renewable fuels are exempted from road fee and CO₂-tax. The most common market competitors are vehicles running on diesel. Because the fees for the fossil alternatives are per litre, and because the efficiency in gas and diesel motors is different, the economic advantage for biogas as a fuel cannot be compared directly. In Table 4, the fees for diesel are shown per litre and per kWh before and after transmission losses in the diesel motor.

	Road fee	CO ₂ tax	Total
Euro/Per litre Ministry of finance (2016)	0.4	0.1	0.5
Euro/kWh (before transmission losses) ¹⁷	4.1	1.3	5.5
Euro/kWh (transmission losses included) ¹⁸	1.7	0.5	2.2

Table 4 Avoided fees for biogas used as transport fuel compared to diesel in Norway in 2016

There is no economic support targeting the use of digestate or biogas for heat and electricity production. Other regulations affecting biogas plants includes the regulation of the need for sterilisation (FOR-2016-09-14-1064 2016) and the fertiliser ordinance, which regulates use of digestate as fertiliser (FOR-2016-09-14-1064 2016).

2.4 Biogas production in Denmark

2.4.1 Development of biogas production

The Danish biogas production emerged because of the oil crisis in the 1970's leading Danish farmers to look for an alternative energy supply. Later biogas was introduced as a mean to distribute nitrogen and phosphorous resources to avoid environmental problems and reduce odour (Lybaek et al. 2013).

Approximately 85% of the biogas produced in Denmark is based on manure as a substrate (Danish Energy Agency 2017a). Most of this production includes an added co-substrate to increase the yield, mainly OW products (≈18%) and energy crops (≈2%). The most common energy crops are corn and sugar beet. The interest for energy crops are low due to a Danish regulatory limit on the usage of energy crops and to a large demand from Germany, which has resulted in increased prices (Jacobsen 2014). Biogas producers therefore search for usable waste inputs. The lack of industrial OW has been a barrier for biogas production in Denmark (Raven and Gregersen 2007) (Lybaek et al. 2013). A few biogas producers have solved this problem by importing OW from for example Norway, which has proven profitable due to the differences in regulation between the two countries.

¹⁷ Lower heating value for diesel 43,1 MJ/kg, 0,85 kg/litre

¹⁸ Efficiency diesel motor 40%

In contrast to in Norway, most of the digestate is used as fertiliser and spread on the fields in agricultural production. Only some of the digestate, mainly from wastewater treatment plants, is dewatered and composted. Consequently, producers with the choice of co-substrates will not risk inputs with even small levels of pollution. This limitation is due to Danish regulation and organisations within the agricultural sectors with requirements on which substrates may be used to produce digestate spread on agricultural soil that produces cow feed. There is a development towards using other agricultural waste products such as straw, deep litter and some experiments with grass and algae.

The usage of municipal OW is experiencing a growing interest, since more municipalities have started to implement sorting and the dairy sector have started to consider municipal OW as “uncritical” – (under specific conditions). Currently municipal OW constitute less than 1% of the total biomass input and approximately 2% of the co-substrates in the manure based biogas production (Danish Energy Agency 2017b). The amount of sewage sludge and organic waste sent to anaerobic digestion constitute a small share of the total mass compared to other waste treatment methods.

Until 2012, biogas was primarily used for heat and power production as the economic support targeted this application. In 2012 the support increased and changed so that also biogas upgraded for the natural gas grid could receive support (Danish Government 2012). Consequently, biogas production has increased from approximately 1100GWh (4PJ) in 2012 to above 2200GWh (8PJ) in 2016 and is expected to be somewhere between 3600-5800GWh (13-21PJ) by 2020 (Harder 2016). Biogas production is foreseen to play a marginal role in the total energy consumption, of approximately 750PJ by 2017 (Danish Energy Agency 2017c).

Currently most new biogas plants are upgrading biogas for the grid, and also older plants have installed upgrading facilities (Harder 2016). When the biogas is upgraded to biomethane the biogas can be sold as natural gas quality together with a green certificate and be used in industry or heat-and power production. While gas for transport has been almost non-existent in Denmark, the transport industry recently started to show interest for gas.

2.4.2 The regulatory system

The main driver for biogas development in Denmark is the output-based support see Table 5. The secondary focus is on using agricultural residues such as manure from the large livestock production, which can contribute to reductions in GHG emissions, reduced smell and reduced nutrients emissions in the ground water¹⁹. The economic incentives on this part are, however, weak and contradict the renewable energy focus at least regarding the usage of manure.

¹⁹ Examples of this can be found in (Lukehurst et al. 2010), however, it should be noticed that this is not always the case

Table 5 Regulatory system in Denmark relevant to the study objects

		Regulatory framework	Economic incentives
Input	Access to substrates	=> Supported biogas should be based on manure, other waste or waste water =>(25%) 12% maximum of energy crops (Energistyrelsen 2015), (Agency n.d.)	
Plant	Anaerobic digestion plant	=>Planning regulation =>Requirements to sterilisation of waste water slurry	Occasionally investment support ²⁰
Output	Biogas to Heat/CHP	Monopoly regulation on district heat	<i>CHP</i> =>Feed-in tariff on electricity produced on biogas =>Tax exemption on fuel for heat <i>Industry</i> => lower support <i>Heat-only</i> => tax exemption and lowest support ¹⁸
	Biogas for upgrade	=>Gas quality requirements, wobbe-index =>Pressure demand from grid =>Biogas certificates ²¹	=>Feed-in premium on upgraded biogas ¹⁸ =>Same taxation as for natural gas (high taxes), when taken from the grid =>with a biogas certificate can CO ₂ -quotas be avoided
	Biogas for transport	=>5.75% blending demand on biofuels =>0.9% blending demand on advanced biofuels (Danish Government 2009b), (Danish Government 2016) =>Many biogas plants can be certified to as producing advanced biofuels => this is not yet connected to the biogas-certificate and can thus – not yet – add any value through upgrading for the net	=>Feed-in tariff for direct use in transport, same level as industry ¹⁸
	Digestate in agriculture	=>Restriction on spreading areas for waste water residues(The Norwegian Department of Agriculture and food 2009)and organic household waste =>Ecological digestate compared to conventional (not allowed with complete mix of manure from Ecological and conventional farms)(Danish Government 2009a) =>Excess phosphorus can be reshuffled Restrictions on digestate based on org. waste	=>A little more nitrate is allowed =>improved fertilizer value

A maximum of 25% energy crops in weight input can be added to the biogas production and still be defined as sustainable. After August 2018 this was reduced to 12% (Energistyrelsen 2015). This has not been a challenge for the biogas producers, since energy crops accounts for less than 1% of the total biomass in biogas production and approximately 2% of the input in manure based biogas.

In most cases, the digestate is returned to the livestock farmers and used as fertiliser for the fields. In consideration of the water environment, farmers are often restricted on the amount of fertilisers and thereby manure that they can add to the soil, through the statute on manure usage (Danish Government 2017). In Denmark, these restrictions apply both for nitrates and in some areas

²⁰ See for example (Danish Government, 2012)

²¹ See the homepage of the Danish TSO for electricity and gas (Energinet.dk, 2017)

phosphorus. The digestate has approximately the same fertilising effect as manure; however, the nutrient mix might be different and plants can potentially absorb the nutrients better. Still, the digestate is regulated as manure, which increases the fertilizer value.

Within the regulation on fertiliser for agricultural soils are also restrictions regarding spreading pollution on the soils. When OW products are mixed into the biogas production, restrictions apply on whether this input could be considered as pure agricultural waste (regulated following the statute on manure-usage) or as waste. If it is the last type, it is only allowed to spread a small share before the total mix will be regulated following the statute on sludge (Miljøministeriet 2006). Forces are working on moving the categorisation of organic household waste away from potential polluted waste towards a cleaner product.

The biogas support was initially a feed-in tariff on electricity produced on biogas. As most of the biogas-based power-producing units are regulated by the combined heat and power demand, most of the biogas is also indirectly supported by a tax exemption on the fuel used for heat production²². Fossil fuels and electricity used for heat production are taxed, while there are no taxes on fuels used for electricity production. The feed-in tariff on electricity is not dependent on scale as in other countries (Delzeit and Kellner 2013; Walla and Schneeberger 2008); instead the plant size is determined by heat demand in the given area, which may not result in the optimal size (Skovsgaard and Jacobsen 2017).

The Danish Government (Danish Government 2012) has decided to increase the support and expand it to other applications of the biogas. Upgraded biogas receive a feed-in premium corresponding to the support for biogas used in heat and power production, while biogas used directly for industry, transport or heat production receive a lower support, see Table 6.

2016	Direct use			Upgraded
	CHP	Heat	Industry & transport	
Unit	Euro/MWh	Euro/GJ	Euro/GJ	Euro/GJ
Feed-in tariff	108.6			
Feed-in premium	59.2		5.23	10.86
NG price dependent	45.0	4.50	4.50	4.50
Temporary	10.7	1.07	1.07	1.07
Total	164.3	5.58	10.80	16.43
Tax, when the gas is used for heating	-	0	0,0	9.6
Tax, when the gas is used for transport	-	-	11.2	12.9

Table 6 Feed in support for biogas in Denmark

The purpose is to increase the support temporarily by two additional fees, a declining temporary support and a fee that is negatively correlated with the natural gas price the year before. If the natural gas price increase, the support will decrease as the need is decreased, and vice versa.

If upgraded gas is used in the grid, it receives a higher support and the tax is only marginally higher than in the case of direct use. It is thus likely that most biogas plants decide to upgrade the gas for the grid.

3 Method for comparing economic impact on value chains

In this comparative assessment, we study the effects that the regulatory system has on the private economy of biogas value chains under the two support regimes. This is done by defining a typical value chain in each of the countries and comparing their total cost and income. The effects of

²² If the power producer also is supplied with other fuels such as natural gas, will the plant receive a feed-in premium for the electricity based on biogas

the policy instruments are then evaluated by assessing the economy for the defined Norwegian value chain under Danish regulation and vice versa. The scales of biogas plants vary significantly across countries and studies in literature from very small household scale as seen e.g. in (Shahzad and Hanif 2014) and (Grant and Lawrence 2014) to very large scale in (Skovsgaard and Jacobsen 2017). Generally, the scales in tonnes of treated substrates at each plant are larger in Denmark than in Norway. In the case study, we have chosen to analyse a plant that is large in the Norwegian context, and small in the Danish context to ensure comparability. We have chosen to include two types of substrates in the case study: organic waste (OW) (source separated food waste from households and solid organic waste from industry and service sector) and substrates from agriculture (manure and deep litter) because they were identified as the substrate types with the largest potential. Both countries have expressed ambitions to increase the amount of manure to biogas production, and the interest for recycling of organic waste is increasing due to the circular economy package and the European bio-economy strategy. Sewage sludge was not included as a substrate as the use of sewage sludge for anaerobic digestion is decreasing in Denmark (Danish Energy Agency 2017b) and identified as the substrate with lowest potential in Norway (Norwegian climate and pollution agency 2013a).

The Norwegian case under Norwegian conditions (**NO**): A co-digestion plant treating OW and manure from cattle and pig, capacity is 110.000 tonnes of input and the plant is based on an actual plant situated in Vestfold County, which is currently the only large-scale plant in Norway receiving considerable amounts of manure from surrounding farms and municipal OW. The biomethane is used as fuel for transport. The actors included in the assessment are livestock farmers and OW treatment plant (biogas plant including an upgrading facility), see Figure 1. The farmers receiving the biofertiliser and the transporter using the biogas is outside the system boundary. Farmers are paid to receive digestate.

Figure 1 Actors in the Norwegian biogas value chain

The Danish case under Danish conditions (**DK**): A plant producing biogas from manure and deep litter from farms in Northern Jutland. The plant is a model plant with the capacity of 150.000 tonnes of input and geographically situated in Northern Jutland. This area is dominated by agricultural production, and has a vast supply of manure and potential co-substrates. Experience from using a plant optimization model described in (Jensen et al. 2017) show, that a substrate mix of 70% manure and 30% deep-litter is an optimal solution for a plant situated in this area, given a set of assumptions presented in (Skovsgaard, Lise; Jensen 2018). The actors included in the assessment are livestock farmers, biogas plant and energy converter (CHP plant), see Figure 2. The farmers receiving the digestate and the farmers supplying deep litter are outside the system boundaries. The digestate is assumed to represent an income.

Figure 2 Actors in the Danish biogas value chain

	NO	NO->DK	DK	DK->NO
Capacity (tonnes)	110,000	110,000	150,000	150,000
Input (substrates)	45% organic waste, 55% manure	45% pre-treated organic waste, 55% manure	70% manure 30% co-substrate (deep litter)	70% manure 30% co-substrate (deep litter)
Biogas produced	7,113,750 Nm3 (43GWh)	4,200,000 Nm3 (26 GWh)	5,977,500 Nm3 (36GWh)	5,977,500 Nm3 (36GWh)
Output (Use of biogas)	Upgrade (for transport)	Upgrade (for natural gas grid)	Combined heat and power (CHP)	Heat plant
Investments	Pre-treatment food waste, digester, upgrading (water scrubber)	Digester, upgrading (water scrubber)	Digester, CHP plant	Digester, heat converter

Table 7 Definition of biogas value chains in Norway and Denmark

When studying the Norwegian case under Danish conditions (**NO** → **DK**) (see Table 7), two major adjustments were done to make the case realistic: (1) We assume the same share of OW, however, the biogas plant does not invest in a pre-treatment facility. While treatment of OW is an income for Norwegian biogas plants, it is more likely that a Danish biogas plant must pay to get access to the substrate. We assume that the waste has been pre-treated before it arrives to the plant, resulting in a dry-matter content of 20%, compared to 33% in the **NO**-case, resulting in the typical dry matter content in an ordinary Danish biogas production (Jørgensen 2013). The large share of municipal OW is unusual and requires a higher level of control of the digestate to allow it to be spread on agricultural soils. (2) It is assumed that the biomethane is fed into a natural gas grid rather than directly used for transport. Further, the market prices for biomethane, costs and income related to digestate is changed, and the investment support is removed, see Table 8. The transport costs are reduced because of larger farms and thus shorter transport distances.

		NO	NO -> DK	DK	DK -> NO
Input	CAPEX	Pre-treatment organic waste	Payment for organic waste	Pre-treatment deep litter and input price	Pre-treatment deep litter and input price
	OPEX	Gate fee on waste			Support for manure as input
	Income	Support for manure as input			
Conversion	CAPEX	Plant and after treatment (reactor size larger due to addition of water in pre-treatment process). Investment support 30% of Capex.	Plant and after treatment	Plant and after treatment	Plant and after treatment. Investment support 30% of Capex.
	OPEX				
Output	CAPEX	Upgrading facility (and pressure regulation)	Upgrading facility and pressure regulation	CHP-plant	Heat converter
	OPEX	Payment to farmers receiving digestate			Payment to farmers receiving digestate
	Income	Sold biogas	Feed-in premium for biomethane, market price biomethane and sold digestate	Feed-in tariff electricity, heat price and sold digestate	Electricity and heat prices
Transport	Total	Norwegian transport cost	Danish transport cost	Danish transport cost	Norwegian transport cost

Table 8 Costs and income in each of the scenarios

The Danish case under Norwegian conditions (**DK** → **NO**) result in the following adjustments as shown in Table 8: As production of electricity is assumed not to be profitable in Norway, the plant produces heat from biogas and invests in a heat generator instead of a CHP plant. The transport costs are increased due to smaller farm sizes and larger transport distances. The market prices for heat are adjusted to Norwegian conditions and feed-in tariffs are removed, while investment support is introduced.

A large share of the income is related to direct- or indirect support. How this support is shared between the actors of the value chain is out of scope for this paper. Other studies have been done on profit sharing, see e.g. (Skovsgaard and Jensen, 2018). Profit sharing is left out by assessing the total profit of all the actors of the value chain, which are directly affected by the regulation in the respective countries. As the purpose of this study is to compare the effect of regulation, we have decided to use the same cost data in the two countries and assume the same cost level. This is a simplification, as costs are likely to be slightly higher in Norway; according to the OECD price level index, the general price level is about 5% higher in Norway (OECD 2016). The possible implications of this for the Norwegian case will be further discussed in the result chapter. The results cannot be used to conclude on the profitability of the different scenarios or a direct comparison of the annual results. They are, however, suitable to discuss the effect of different regulations and to compare the differences in type of income.

4 Results

4.1 Comparative analyses of biogas value chains in Norway and Denmark

As the development of biogas value chains is affected by a large range of other factors than the economic instruments, the structural conditions and policy objectives described in Section 2.2 must be considered when assessing the effect of policy instruments. The key differences in biogas production in the two countries are summarised in Figure 3. Biogas production is significantly larger in Denmark

than in Norway: 500 GWh (1.8PJ) per year in Norway (Lånke et al. 2016), Norwegian climate and pollution agency, 2013) and 1764 GWh (6.4PJ) in Denmark (Danish Energy Agency 2017c).

Figure 3 Production, feedstocks and utilisation of biogas in Norway and Denmark

The main difference in input is the use of OW from household and industry in Norway and of manure and other residues from agriculture in Denmark. While Norwegian plants in the past have had a history of flaring and internal use of heat from biogas in the production, there is now a development towards using the gas as a transport fuel. In Denmark, biogas is mainly used to produce heat and electricity. There are no official statistics on the use of digestate in the two countries. The large share of substrates from agriculture in Denmark implies, however, that the use of digestate in agriculture is widespread because these plants are closely integrated with the farms. In Norway, the use of liquid digestate as a fertiliser on an industrial scale is limited to a few plants, and it is more common to use dry digestate as a soil improvement product.

The economic assessment of the Norwegian value chain under Norwegian conditions and the Danish value chain under Danish conditions are presented in Figure 4 and 5. The figures indicate the importance of the various cost and income factors. The profit in the Norwegian value chain is approximately $50 - 28 \approx 22$ Euro/tonnes input while the profit in the Danish value chain is approximately $21 - 16 \approx 5$ Euro/tonnes input. This is a large difference, which to a high degree can be explained by the assumptions made in the case study.

Figure 4 Distribution of cost and income in the Norwegian biogas value chain in Euro per tonne treated

Figure 5 Distribution of costs and income in the Danish biogas value chain Euro per tonne treated

The high profit for the Norwegian value chain is influenced by the assumption of the same cost level in the two countries, which adds to profit as revenue is based on Norwegian prices and costs are based on Danish prices as described in section 2.2. The income from treatment of OW is for most plants regulated by the cost of service regulation, described in section 2.3.2. Because the treatment cost of OW is regulated to reflect the actual cost of the service, profits would be lower as income from gate fees in reality would be adjusted. The profit for the Norwegian case is thus not realistic and cannot be used to conclude on whether the Norwegian biogas value chain is profitable or not. Results should therefore only be used to compare types of costs, and the effect from the regulatory systems on the value chains.

The total costs in Norway are higher due to inclusion of OW that requires pre-treatment and increased Capex and Opex. All cost factors are presented in Euro per tonne input, and for the Norwegian biogas value chain the largest cost factors are the capital and operational costs for the

digester (3.9 €/t and 9.7 €/t) and capital costs and operational costs for pre-treatment of waste (4.6 €/t and 1.4 €/t) and transport costs (4.3 €/t).

In the Danish, value chain, the largest cost factors are related to operation (6.6 €/t) and capital costs (4.0 €/t) of the anaerobic digestion facilities together with operational (1.3 €/t) and capital costs (1.9 €/t) of the CHP plant.

Estimated costs for transport is approximately 100% higher in Norway (4.3 €/t) than in Denmark (2.1 €/t), but even though transport of manure and digestate represent significant cost factors in both countries, they do not seem to have a determining effect on the final results in the two defined cases.

The main difference in profitability of biogas value chains in Denmark and Norway is the organization of the economic incentives. In Norway, more than 60% of the total revenues originate at the input side as income from waste- and manure treatment. Capital expenditures on the anaerobic digestion facilities are reduced by an investment support of 30%.

The economic support to Danish biogas value chains is founded in energy supply from the biogas production (electricity and heat production), where more than 90% of the revenues originates from sales of energy with feed-in tariffs or a premium. In our case, the support accounts for 60-75% of the total income. Another income, which is not supported, is the sales of surplus digestate. In Denmark, the agriculture has a long tradition in using digestate, and it is considered as an improved fertiliser compared to manure. In contrast, the use of liquid digestate represents a cost for the farmers in Norway, due to the need to invest in infrastructure. Consequently, the biogas plant must pay the farmer to accept the digestate.

4.2 Economic results from changing the support instruments and regulatory setup

The implications of the annual economic results when constructing the Norwegian value chain in Denmark and vice versa is shown in Table 9 (per tonne treated) and Table 10 (per GWh biogas produced, before transmission losses). The costs and income are categorised into their occurrence in the value chain: input, conversion, output and transport.

		NO	NO->DK	DK	DK->NO
	Input	110,000 tonnes		150,000 tonnes	
Input (substrates)	CAPEX	1.44	0.0	0.0	0
	OPEX	5.0	9.0	1.0	1.0
	Revenue, manure	3.0	0	0	3.9
	Revenue, waste	31.7	0	0	0.0
Conversion	CAPEX	3.9	4.2	4.0	2.8
	OPEX	9.7	8.1	6.6	6.6
Output (biogas and digestate)	CAPEX	0.8	0.6	1.9	1.1
	OPEX	2.9	0.2	1.3	6.0
	Revenue, digestate	0	1.8	2.0	0
	Revenue, gas	15.4	20.2	19.7	5.9
Transport	Costs	4.3	1.1	2.1	5.1
Total in Euro/tonnes input		22.1	-1.2	4.9	-12.7

Table 9 Results in Euro per tonne treated

	NO	NO->DK	DK	DK->NO
Production (GWh)	43	32	36	36

Input (substrates)	CAPEX	3667	0	11	11
	OPEX	12802	31223	4110	4110
	Revenue, manure	7756	0	0	16154
	Revenue, waste	80798	0	0	0
Conversion	CAPEX	10024	14436	16412	11488
	OPEX	24734	27877	27078	27078
Output (biogas and digestate)	CAPEX	2104	2104	7815	4445
	OPEX	7386	572	5557	24850
	Revenue, digestate	0	6107	8411	0
	Revenue, gas	39200	69717	81302	24566
Transport	Costs	10831	3924	8475	21208
Total in Euro/GWh produced		56207	-4312	20256	-52471

Table 10 Results in Euro per GWh produced (before transmission losses)

The waste sector plays a large role in Norwegian biogas production, and the income from treatment of waste represents the main income for biogas plants. In Denmark, the treatment of OW appears to be less important and is motivated by the wish to increase the biogas yield. There is no support for the use of OW and it is seen as a challenge when it comes to quality of the digestate. There is, however, a movement towards a more sustainable treatment of the OW resources.

The Norwegian value chain in a Danish setting (NO->DK) misses the investment support, save Capex and Opex from pre-treatment facilities for OW, and faces a 75% reduction in transport costs. As the support per tonne manure disappears and the biogas plant is assumed to pay for the waste rather than receiving a payment for waste treatment, the total income is largely reduced. In Denmark, the share of renewable energy is the main goal and this is reflected in the economic instruments through a feed-in tariff. The support for production of biomethane to the natural gas grid is considerable. Upgraded gas in Denmark is more likely to be injected into the natural gas grid than to be used for transport with the current Danish regulation. In Norway, the use of biogas as a fuel for transport has increased substantially. In Denmark, the share of biogas used for transport is low and there are no specific policy goals for this.

The overall economic result for the NO->DK value chain is slightly negative. The loss is reduced by a high level of support for biomethane, and that OW provides a reasonable yield. The DK plant in a Norwegian setting (DK->NO) is not profitable primarily due to the loss of revenue on the output side from the feed-in tariff for renewable electricity. In Norway, there are no particular policy goals or incentives to use biogas in the energy sector, due to the high share of renewable hydropower. The choice for the plant in Norway is assumed to be production of heat only and not electricity. The agricultural sector has been less important in Norwegian biogas production; however, a new support system aims at including farms to reduce GHG emissions from manure handling through a small subsidy to the manure treatment. In Norway, this subsidy is not sufficient to outweigh the loss of output subsidy. The investment support represents reduced Capex, but not enough to compensate lost revenue from feed-in and the income from digestate is turned into a cost due to a lack of digestate demand in Norway. Earlier analysis show that biogas production is a socioeconomic costly way to reduce GHG emissions in Danish agriculture (Dubgaard and Jacobsen 2013), however compared to Germany it is relatively cheaper (Jacobsen 2014).

The results per GWh produced (before transmission losses) in Table 10 show the significance of the support on the output side in Denmark. The income from the produced gas is lower for the two cases in Norway (NO and DK->NO), however the income from treatment of waste in the NO-case is in the same range as the income from the sales of biogas in the DK-case. The use of OW as an input increases the biogas yield, but at the same time, costs are increased due to the need for pre-treatment and additional Capex and Opex for the digester.

5 Discussions of quantitative results and policy choices in Denmark and Norway

Two countries with fundamentally different support systems for biogas are compared in this study. The economic instruments used have a strong effect on the value chain designs. One clear consequence of output support is that it incentivises the use of high-yield inputs and contributes to avoiding biogas losses. Input support on the other hand; result in less focus on the biogas yield, more flaring and own use in the production. What is most efficient depend on the overall goals for biogas production and waste treatment. Biogas production can contribute to reducing GHG emissions in agriculture through degassing of manure and thereby avoiding methane- and nitrous emissions leaving only the CO₂-emissions from combustion of biogas. Furthermore, biogas production can potentially reduce the leakage of nutrients with digestate as a fertiliser instead of manure and mineral fertiliser. While the agricultural sector is dominating the biogas value chains in Denmark, the inclusion of the agricultural sector is under development in Norway. The quantitative results showed that the Norwegian value chain in Denmark was not profitable (-4312€/GWh) because the biogas output revenue could not fully replace the input revenue from OW and manure it would receive in Norway. This means it cannot serve its OW treatment role as in Norway

Both countries have stated a policy goal of increasing the amount of manure used in biogas production, however, only Norway is targeting this specifically through a support to farmers per tonne of manure delivered. In Norway, there has been an increase in the use of manure in biogas production, but the potential remains high. In Denmark, the combination of biogas support and the sustainability criteria has led to high use of manure as a substrate. The output support is scale independent and with access to large amounts of manure within relatively short distances, investments in large-scale biogas plants has been the result. Introducing support on input in addition to output could contribute to increasing the amount of manure used for biogas production even more. This may also contribute to an increase of manure treatment in areas with lower farm density and a decrease in socioeconomic costs of GHG-emission reductions, as pure degasification of manure can be less costly from a socioeconomic perspective according to (Dubgaard and Jacobsen 2013).

In Norway, the emphasis is on increasing the biogas production, motivated by ambitions of a more sustainable management of waste resources. This has led to increased biogas production and increased amount of OW being source separated. (Raven and Gregersen 2007) concluded that one of the most important factors causing reduction in establishment of new biogas plants in Denmark in the late 90's was limited access to organic waste. (Clercq et al. 2017) identified lack of source separation as a common obstacle for increased anaerobic digestion of organic waste in several countries, and suggest that this should be addressed by policymakers.

More municipalities have started to sort organic household waste in Denmark. The economic instruments for biogas in Denmark are solely targeting the output hence the use of OW is only supported indirectly because it can increase the yield when co-digesting with manure. Therefore prices for OW as a biogas substrate are high in Denmark.

In Norway, income from treatment of waste is essential for the centralised biogas plants. The quantitative case illustrates this by a revenue share of more than 60%, where OW input has a cost in the Danish case. This shows that there are large differences in the conditions for waste handling, which determines whether the treatment of waste represent a cost or an income.

None of the countries seems to have specific policy goals for using digestate from biogas production as a fertiliser in agriculture; however, in Denmark it is implicitly a part of regulation, since farmers are obliged to find usage of the manure arising from their production. In Norway, the market for digestate as a fertiliser is still under development, while Danish farmers are experienced in using digestate from agricultural waste as fertiliser. Huttunen et al (Huttunen, Manninen, et al. 2014) identified end use of the digestate as one of the most critical points for biogas production in Finland. In Norway, the digestate represent a cost for centralised biogas plants, as there is no willingness to pay for the digestate. Because there are no incentives targeting recycling of nutrients, it is hard to predict whether the demand for digestate as a fertiliser will increase and represent an income rather than a cost in the future. Experience in using digestate in agriculture is likely to increase due to the support to

manure for biogas, because most farmers that supply manure to a biogas plant would expect to receive the digestate in return.

Biogas use can replace fossil fuels, both in the energy systems and in the transport sector. In Denmark, the regulatory system is focused on increasing the share of renewable energy and thereby reduce CO₂ emissions *within* the energy system. The economic support for biogas output incentivises the use of high yield substrates together with manure and an efficient use of biogas, while flaring and internal use of biogas is minimised.

Table 9 and table 10 illustrate that the Danish value chain is entirely dependent on the revenue from biogas output (90%) while biogas only represent a small income under Norwegian regulations. In the Danish regulation, there is a degree of flexibility in the regulation, as the output support is given both for upgraded biogas and for several applications of direct biogas usage. This allows each producer to design the value chain in order to fit upgrading for the grid or electricity generation.

The input based regulation (investment support) in Norway has led to an increase in biogas production. The system contains few incentives on the output side, which is likely to have contributed to a high amount of flaring and use of the heat biogas internally at the plant. The lack of incentives on the output side became particularly clear when a Danish value chain was tested under Norwegian conditions, resulting in the worst result, despite low investment- and operational costs (DK prices). Without the output support, it would not be profitable to build a CHP plant or a heat generator. Due to the high share of hydropower and low demand for gas, the CHP solution is irrelevant in Norway, while in Denmark the existence of district heating systems has been important for the development of the biogas industry (Raven and Gregersen 2007).

The use of biogas as a fuel for transport has increased in Norway, aided by an indirect support through an exemption from road fee and CO₂-tax compared to fossil alternatives. The increase in use of biogas as a fuel for transport will most probably lead to less flaring and better use of the production capacity in the plants. Tax exemption has also been crucial in Sweden (Larsson et al. 2016), which is one of the European countries with the largest number of upgrading plants (EurObserv'ER 2014).

Both Norway and Denmark have no specific goals for biogas in transport, all though they share the EU targets of 10% renewable fuels in the transport sector by 2020 and CO₂-reduction goals in transport. (Poeschl et al. 2010) identified upgrading of biogas for utilisation in the transport sector as the most promising option for use of biogas in the future in Germany, which is currently the largest producer of biogas in Europe. Except for the tax exemption in Norway, there are no instruments specifically targeting use of biogas in transport in the two countries.

6 Conclusions

We find that *several value chain designs for biogas can be profitable*, and we find viable value chains both in Norway and in Denmark. We do however also find that the *viability of a value chain is highly dependent on structural conditions and the regulation applied* directly on the biogas plants as well as the adjacent sectors.

When comparing the biogas value chains in the two countries, we see that agriculture dominates as the supplier of inputs in Denmark, which enables large-scale plants because of the abundant availability of agricultural waste products. In Norway, biogas production has been a part of the waste sector, where biogas and digestate have been secondary products.

The comparative case study demonstrates that the profitability of the value chain deteriorates remarkably, if Danish regulations were to be implemented on a Norwegian value chain, and vice versa. This is explained by the Norwegian value chain relying on *high incomes from the input operation* in the form of a waste treatment fee, while the Danish regulation remunerates a high biogas yield through *support on the output side*.

The difference in support both affects the value chain design and usage of biogas. Incentives for biogas output have been few in Norway, resulting in a large amount of flaring and self-use. In Denmark, this is kept to a minimum.

Overall, the national targets and regulation in both countries are directed towards *GHG-reduction*, though the emission sources are not equally targeted, as the *GHG-reduction* in Denmark is concentrated on *CO₂-displacement in the energy system*, and less focused on emission reduction in the

agricultural sector. Norway already has renewable electricity supply by hydropower and therefore biogas output for electricity and heat is not supported. On the other hand, the transport sector is highly fossil fuel dependent in Norway, which directs the effort to use biogas in this sector.

Though goals and structural conditions are not completely the same for the two countries, they can learn from each other and there are several **policy implications** based on this comparative assessment. If the main objective is domestic *GHG-reduction* in Denmark, the options for emission reduction on the input side should be equally supported as the fossil fuel reduction in the energy system as this may imply cheaper reductions.

In Denmark, most new biogas plants are upgrading for the natural gas grid, while receiving high support. It could be considered to *shift* some of this *support to the manure treatment*, and *thereby increase the incentives for GHG-reduction* and at the same time *distribute the support more evenly in the value chain*.

The Norwegian support for the transport use of biogas is less than the average support in Denmark, but the input support, gate fee and investment support compensate for this. The development in Norway shows that biogas can and will be used in transport with the right incentives. It could, however, be considered to supplement the tax-exemption with a corresponding feed-in premium for upgraded biogas, as *direct or indirect support towards the use of biogas can decrease flaring and lead to a more efficient use of the capacity at the plants*.

We cannot conclude that one support system is superior to the other, as they are designed to fit different structural conditions and needs, however, it may be possible to increase regulatory efficiency if the countries take inspiration from each other.

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