ESRI

Working Paper No. 630

July 2019

Promoting biogas and biomethane production: Lessons from cross country studies

Tong Zhu*[a,b], John Curtis[a,b] and Matthew Clancy[c]

Abstract: While a rich body of literature has looked at greenhouse gas emissions in biogas production systems and the potential impacts of biogas production on food supply, broader issues relating to the economic, environmental and social pillars of sustainability need to be carefully considered. Drawing upon experiences from European countries, we identify key outcomes associated with large-scale implementation of biogas and biomethane production. Topics of particular interest include policy instruments, farm intensification, and supply chain risks. We conclude by recommending policy directions for countries such as Ireland that are at earlier developmental stages for biogas and biomethane deployment.

*Corresponding Author: tong.zhu@esri.ie

Keywords: renewable energy, biogas, biomethane, anaerobic digestion, greenhouse gas emissions, agricultural sector

Acknowledgements: This work was funded by the Economic and Social Research Institute's (ESRI) Energy Policy Research Centre (EPRC) of which the Sustainable Energy Authority of Ireland (SEAI) is a funding contributor.

a The Economic and Social Research Institute, Dublin
b Trinity College, Dublin
c The Sustainable Energy Authority of Ireland, Dublin

Promoting biogas and biomethane production: Lessons from cross-country studies

Tong Zhu[a,b,*], John Curtis[a,b], Matthew Clancy[c]

[a] *Economic and Social Research Institute, Sir John Rogerson's Quay, Dublin, Ireland*

[b] *Trinity College Dublin, Dublin, Ireland*

[c] *The Sustainable Energy Authority of Ireland, Wilton Park House, Wilton Place, Dublin, Ireland*

Abstract

While a rich body of literature has looked at greenhouse gas emissions in biogas production systems and the potential impacts of biogas production on food supply, broader issues relating to the economic, environmental and social pillars of sustainability need to be carefully considered. Drawing upon experiences from European countries, we identify key outcomes associated with large-scale implementation of biogas and biomethane production. Topics of particular interest include policy instruments, farm intensification, and supply chain risks. We conclude by recommending policy directions for countries such as Ireland that are at earlier developmental stages for biogas and biomethane deployment.

Highlights

- We present the timeline of biogas and biomethane development with various drivers
- Emerging issues are identified regarding large-scale implementation
- Topics include policy instruments, farm intensification, supply chain risks
- Learnings are discussed for countries seeking to stimulate biogas development

Keywords: renewable energy, biogas, biomethane, anaerobic digestion, greenhouse gas emissions, agricultural sector

*Corresponding author. Tel: +353(01)8632000. Address: Whitaker Square, Sir John Rogerson's Quay, Grand Canal Dock, Dublin 2, Ireland.

Email addresses: Tong.Zhu@esri.ie (Tong Zhu), john.curtis@esri.ie (John Curtis), Matthew.Clancy@seai.ie (Matthew Clancy)

Word count: 7,650

List of Abbreviations

ABP	Animal By-products
AD	Anaerobic digestion
CAP	Common Agricultural Policy
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
EEG	Renewable Energy Sources Act (German: Erneuerbara-Energien-Gesetz)
EU	European Union
FiTs	Feed-in Tariffs
FiPs	Feed-in Premiums
GHG	Greenhouse gas
GWh	Gigawatt hours
kWh	Kilowatt hour
IEA	International Energy Agency
Mtoe	Million tonnes of oil equivalent
RED	Renewable Energy Directive
RED II	The recast of the Renewable Energy Directive
TWh	Terawatt Hours

1. Introduction

Biogas is a versatile fuel that can be produced from a wide range of organic substances. As a by-product generated during the process of anaerobic digestion (AD), biogas consists of approximately 60% methane (CH_4), 40% carbon dioxide (CO_2), and other trace substances [1].[1] Biogas can be combusted in boilers to produce heat, or used in combined heat and power (CHP) plant gas engines generating both heat and electricity. By removing CO_2 and other impurities, the upgraded biogas, namely biomethane, has similar chemical properties to fossil gas and thus can be fed directly into the existing gas grid, transported via tankers to large off-grid users, or dispensed as a vehicle fuel at fuelling stations.[2] Biogas generated from organic wastes, such as food scraps, industry by-products and animal manure, helps meet broader waste management, agricultural and environmental policy goals. These organic wastes are typically available to AD plants at low prices or a negative price in the case of food waste and other organic wastes diverted from landfill. Energy crops have also been used to produce biogas to increase renewable energy output and to reduce greenhouse gas (GHG) emissions in the energy sector.

As an alternative to fossil gas, biogas has received increasing attention in recent years, as reflected in accelerated growth in biogas production worldwide. In the decade to 2016 global production of biogas has grown almost three-fold reaching 61 billion m^3 (Table 1). Europe is the world leader in biogas production, accounting for more than half of global production, followed by Asia with a 30% share (Figure 1). The European Union (EU) legislative framework surrounding biogas has played an essential role in shaping the industry. A wide spectrum of legislation is involved regarding climate change, energy security, waste recycling, and Health and Safety. Primary, overarching legislative frameworks include: the revised Renewable Energy Directive (EU) 2018/2001, the Waste Framework Directive (2008/98/EC), and the Animal By-products (ABP) Regulations (1069/2009).

The development of biogas and biomethane across European countries is at very different stages, reflecting differences in national legislative frameworks, as well as agricultural structures and approaches to waste management. A review of experiences across countries provides insight into the challenges countries face in developing a biogas production sector, and provides lessons to countries at earlier stages of development. While a rich body of literature has looked at the GHG emissions associated with biogas production [e.g. 6] and the potential impacts of biogas production

[1] Anaerobic digestion (AD) is a sequence of biological processes where microorganisms break down biodegraded organic material in the absence of oxygen [2].

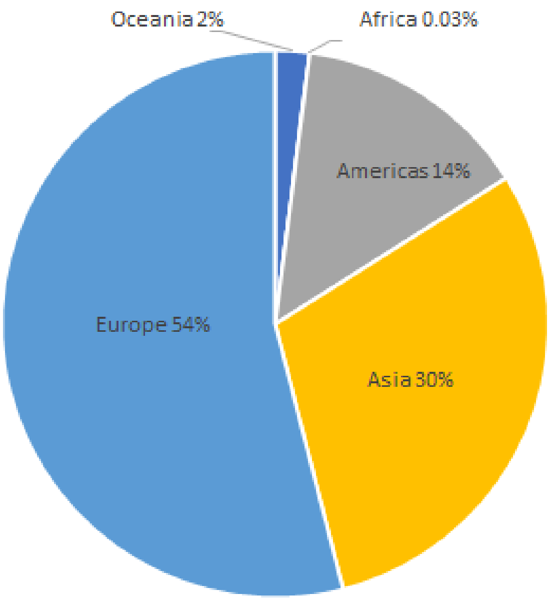
[2] For more technical details please see [3].

Table 1: Global biogas production

	Biogas (Billion m^3)	Biogas (Billion (EJ))
2000	13.2	0.28
2005	23.1	0.50
2010	38.7	0.84
2015	60.0	1.30
2016	60.8	1.31

Source: International Energy Agency (IEA) Key World Energy Statistics [4].

Figure 1: Biogas production in continents in 2016



Source: World Bioenergy Association [5]

on food supply [e.g. 7], broader issues relating to the economic, environmental and social pillars of sustainability need to be carefully considered. This research contributes to a growing literature that considers such issues [e.g. 8–11]. Drawing upon experiences from European countries, we identify key outcomes associated with large-scale implementation of biogas and biomethane production. Among the countries considered, Germany is leading in terms of AD deployment by a substantial margin, while the biogas industry in Ireland is relatively nascent in its development. Ireland is included because it is a country with a large animal herd and a high technical potential for energy crop cultivation [12–15]. The extensive outdoor farming system puts Ireland in an unique place in developing AD as it is a promising pathway to achieve GHG emissions reduction and sustainable farming simultaneously.

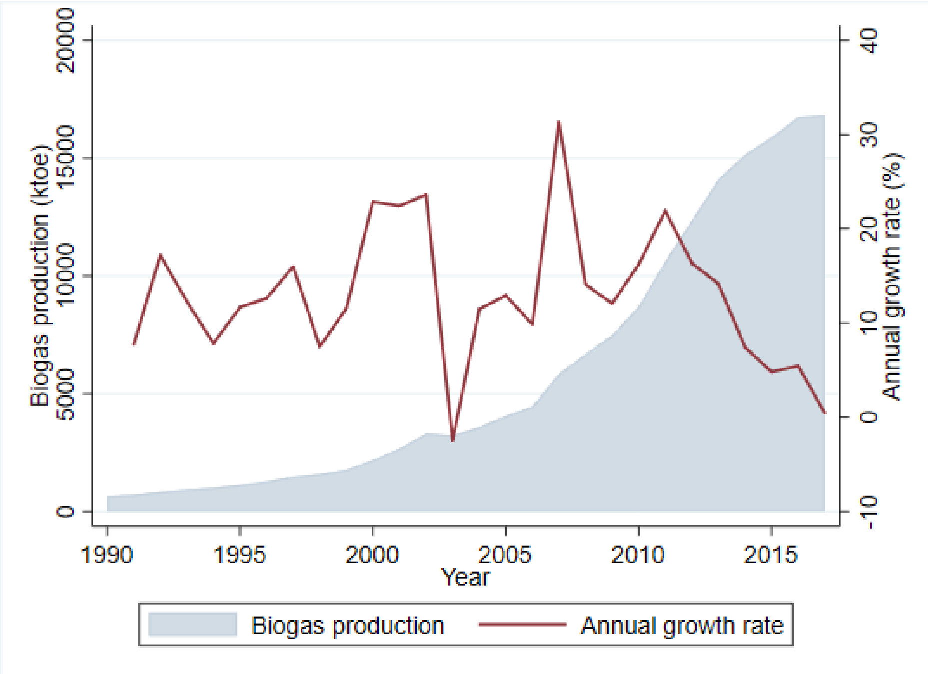
The focus of this research is to yield useful lessons for countries such as Ireland that are at earlier developmental stages for the biogas and biomethane industry. In order to do so we document a wide range of EU policies and legislative developments regarding biogas production and utilization. Cross-sectoral unintended consequences are then discussed, particularly regarding policy instruments, farm intensification and supply chain risks. A better understanding of international experiences is necessary to help improve the efficiency of policy incentives and also avoid undesired outcomes. We conclude by highlighting where policies can address some of the risks and by sharing the key learnings for countries seeking to expand biogas industry in order to reduce their GHG emissions.

The rest of the paper is organized as follows. Section 2 overviews the development of biogas and biomethane in Europe. Section 3 documents policies and support schemes that relate to biogas and biomethane deployment. Section 4 focuses on emerging issues associated with large-scale biogas deployment, including a discussion of policy lessons. Section 5 presents some conclusions.

2. Biogas and biomethane development in the EU

Biogas production in Europe has increased by more than 700% since 2000. Despite a recent slowdown in the growth of biogas, the EU 28 countries produced 16.8 Mtoe (million tonnes of oil equivalent) biogas in 2017, accounting for approximately 7.4% of total primary renewable energy production (Figure 2). Meanwhile, European biomethane has also been increasing significantly, with annual production rising from 700 Gigawatt Hours (GWh) in 2011 to above 17 Terawatt Hours (TWh) in 2016. The total number of biomethane installations reached nearly 500 by the first quarter of 2017, while in 2011 there were only 187 in Europe.

Figure 2: Evolution of biogas production in the EU 28 (1990-2017)



Source: Data collected from Eurostat.

The development of biogas and biomethane across European countries is at very different stages in terms of production scales, feedstocks consumed and consumption pathways. Table 2 presents biogas production and utilization in 12 Member States with the highest biogas production. These 12 countries account for approximately 95% of total production in EU 28. Germany produced 7,845 ktoe biogas in 2017, more than double the amount produced in the UK in second place. On the utilization side, about three-quarters (75.6%) of biogas produced in the EU 28 is used as a transformation input to be converted into other energy fuels. The rest of biogas produced is delivered to end-user sectors including agriculture and forestry, industry, transport, commercial and public services, and households.

The distribution of biomethane production is shown in Table 3. In the first quarter of 2017 biomethane was produced in 497 plants in 16 European countries. Germany (194), United Kingdom (85) and Sweden (63) lead biomethane plant deployment in Europe. Comparing country rankings in Table 2 and 3, Italy is third placed in terms of biogas production while its biomethane sector remains relatively less developed, ranking only tenth in Europe. On the other hand, Sweden is third placed in biomethane production – more than 60% of biogas produced in Sweden in 2017 was upgraded into biomethane and used to fuel vehicles (Table 2). In terms of feedstock, biomethane originates in different European countries from a wide range of diverse substrates, as illustrated in Table 3. Existing data shows that by the first quarter of 2017 the majority of biomethane plants in Europe utilize energy crops as their main substrate. [3]

Biogas and biomethane sector in Ireland is at the initial stage of development with just 38 biogas plants in 2018, one biogas upgrading plant with grid injection, although other projects are underway [16–18]. In 2017, primary production of biogas in Ireland was 54.6 ktoe, more than 80% of which was utilized as transformation input in electricity and heat generation.

Table 2: Biogas production and utilization (2017)

Country	Primary production	Transformation input in Electricity & heat generation	End-user consumption in Industry	End-user consumption in Transport	End-user consumption in Others
Germany	7845	5796	66.21	38.29	1362
UK	2733	2230	45.70	0	244.0
Italy	1898	1849	18.58	0.0239	22.71
France	899.5	593.6	128.2	0	142.4
Czechia	607.7	449.2	7.223	0	151.3
Denmark	389.0	167.4	39.34	0.333	56.19
Netherlands	320.8	138.0	16.70	0	90.82
Poland	280.6	196.6	14.56	0	68.59
Spain	261.4	201.0	39.98	0	13.23
Austria	246.1	197.1	36.70	0.273	11.95
Belgium	224.3	130.0	31.64	0	62.08
Sweden	177.8	13.23	2.771	111.1	32.65
EU 28	16826	12718	498.8	150.4	2365

Source: Eurostat. Unit: ktoe. Transformation input covers all inputs into the transformation plants destined to be converted into derived products. Transformation is only recorded when the energy products are physically or chemically modified to produce other energy products, electricity and/or heat. Other end-user sectors include Commercial & public services, Households, Agriculture & forestry.

[3]This may change in the future as the recast of the Renewable Energy Directive (RED II) sets sustainability criteria for biomass and biogas for heating, cooling and electricity generation for the period 2020-2030. This is discussed further in Section 3.2.

Table 3: Biomethane installation (2017 Q1)

Country	Biomethane Plants	Main feedstocks						
		AGR	MSW	ENC	FAB	LAN	SGW	NA
Germany	194	8	11	164	6		2	3
UK	85							85
Sweden	63	1		1			2	59
Switzerland	31	3	10		2		15	1
France	30	19	4		1		3	3
Netherlands	26	4	3		4	4	2	9
Denmark	22	20					1	1
Austria	15	1	7	3			4	
Finland	12	2	7				2	1
Italy	7	2	3			1	1	
Norway	4	1					1	2
Luxembourg	3	1	1	1				
Europe	497	62	47	169	14	7	34	164

Source: Authors' elaboration based on the European Biomethane Map 2018. Main substrates include AGR (Agricultural Residues, Manure, and Plant Residues), MSW (Bio- and Municipal Waste), ENC (Energy Crops), FAB (Industrial Organic Waste from Food and Beverage Industries), LAN (Landfill Wastes), SGW (Sewage Sludge, Gas and Waste), and NA (No Information).

3. Drivers of biogas and biomethane development

Over the expansion period of biogas and biomethane, EU legislation on environmental issues such as waste management [e.g. 19, 20], water quality [e.g. 21] and nutriment management [e.g. 22, 23] have improved the economics of AD as a waste management option. The legislation focused on increasing the quantity of renewable energy and reducing GHG emissions has helped this further, with some countries providing substantial fiscal support for renewable energy output. In this section we outline major EU legislation and policies that influence the development of biogas and biomethane industry. The schematic presented in Figure 3 highlights the dominant EU legislative instruments in chronological order.

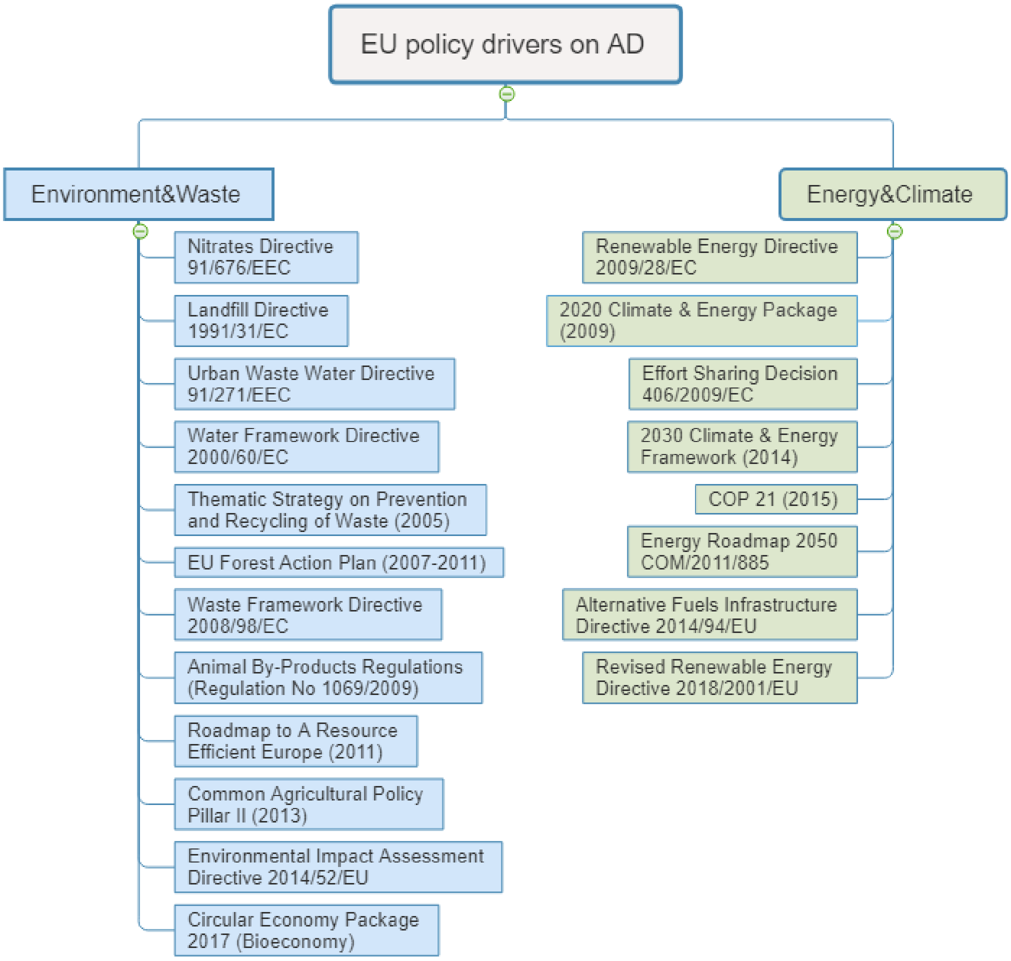
3.1. Environmental drivers

The Nitrates Directive gives an indirect impetus for AD uptake because farmers are encouraged to adopt manure treatment systems [25]. The digestate output from AD plants can serve as a more effective fertiliser than raw manure and slurry plus it is a less costly substitute for manufactured fertiliser. In comparison with mineral fertilisers and untreated slurry, digestate has a high fertiliser value because of its larger share of available nitrogen, phosphorus, potassium and micro-nutrients, although quality varies largely depending on feedstock, AD process and treatments [26]. Because of the nutrient concentrations, a farm that fertilises with digestate can often get the same fertilising effect with 10-20% smaller dose [27].

Representing about 40% of the total EU annual budget, the Common Agricultural Policy (CAP) provides subsidies and support to farmers, and sets out the rules for the common agricultural market. Bioenergy is the renewable energy most evidently connected with rural areas. During the funding period 2007-2013, the supply of bioenergy from agriculture and forestry and the use of bioenergy on farms and in rural areas were specifically encouraged by CAP through its rural development measures. Types of operations supported include: biogas production in AD plants using animal waste, perennial energy crops, processing of agricultural and forest biomass for renewable energy, and installations and infrastructure for renewable energy using biomass [28]. These operations are no longer emphasized in the current CAP period 2014-2020. Facilitating the supply and use of renewable sources of energy is covered under Priority 5: Resource-efficient, Climate-resilient Economy [29].

The Waste Framework Directive (2008/98/EC) enshrines a principle aiming to move waste away from landfill and towards treatment options, including AD, which are better for the envi-

Figure 3: EU legislation and policies related to biogas and biomethane production



Source: Authors' elaboration based on CRE [24].

ronment than disposal. The separate collection of biowaste with a view to its biological treatment is also encouraged by this Directive. The objective of landfill diversion is also a requirement of the Landfill Directive (1999/31/EC). ABP Regulation lays down health rules regarding ABP and derived products not intended for human consumption. Movement, processing and disposal of ABP such as manure, catering wastes and post-AD digestate are all subject to ABP Regulation. Other EU strategies that encourage the uptake of AD for the benefit of waste management include the EU Thematic Strategy on the Prevention and Recycling of Waste (2005), Roadmap to a Resource Efficient Europe (2011) and Circular Economy Package (2017). In particular, the Circular Economy Package (2017) sets new targets on biowaste collection by 2023, providing opportunities for agricultural residues to be used for AD. The multiple functions of AD in the circular economy are discussed in depth in IEA Bioenergy Task 37 [30].

3.2. Energy drivers

The Renewable Energy Directive (RED) establishes the overarching policy framework for the production and promotion of energy from renewable sources in the EU. RED II came into force in December 2018. An updated binding renewable energy target for the EU for 2030 is set at a 32% minimum of final energy consumption, with a clause for a possible upwards revision by 2023. Notably, RED II increased the sustainability criteria versus RED for biofuels used in transport and bioliquids, and solid and gaseous biomass fuels used for heat and power. A 70% GHG saving threshold is introduced for bioenergy pathways in electricity, heating and cooling sectors. This implies that, under current cultivation practices, energy crops can only make up to 30% of the feedstock with the rest to be animal manure [15, 31]. The potential of energy crops will be therefore limited by GHG saving criteria under current cultivation practices and there is likely to be a change of the crop mix towards sustainable species.

The EU Effort Sharing Decision establishes binding GHG emission reduction targets concerning mostly non-ETS sectors, such as transport, buildings, agriculture and waste. Biogas production plays a role in helping to achieve emissions reduction in all these sectors. The Climate and Energy Package (2020) is a set of binding legislation regarding emissions reduction, renewables and energy efficiency, to ensure the EU meets its climate and energy targets by the year 2020. The EU 2030 Climate and Energy includes targets and policy objectives for the period 2021-2030. The Alternative Fuels Infrastructure Directive sets out minimum requirements for the building of alternative fuels infrastructure, including refuelling points for compressed natural gas (CNG) that biomethane can benefit from. Furthermore, in order to comply with the climate commitment made at the COP21 in Paris, the EU will need to effect an energy transition in all sectors to achieve climate neutrality goals by 2050. The Energy Roadmap 2050 (COM/2011/885) explores the transition of the energy system, which accounts for more than 75% of the EU's GHG emissions, through four main routes to a more sustainable, competitive and secure energy system in 2050. In general, all these binding targets will have positive impacts on fostering large-scale take up of biogas and biomethane in the next decade.

While Member States are subject to binding targets under EU legislation, national governments can decide individually on which support policies to implement. This has led to a wide range of support schemes in the EU. To provide an aggregated overview of available options for countries that are interested in developing biogas industry, we summarize a range of support schemes in Table 4 including both financial and non-financial activities that favour biomethane/biogas development in selected European countries. These countries are leading the biomethane industry in Europe and include Germany, UK, Sweden, Switzerland, France, Netherlands, and Denmark. Ireland is also included for the purpose of reference. Legislative information summarized in the table is mainly sourced from IEA Bioenergy Task 37 [1], SEAI [14], IEA Bioenergy Task 37 [16], Strauch et al. [32], BIOGAS3 Consortium [33], Agency [34], RES LEGAL Europe [35]. Table 4 shows that the support schemes share some design features but vary from country to country. Importantly, these schemes have been evolving as the renewable market develops.

Most countries reviewed in Table 4 implement a form of Feed-in Tariffs (FiTs) and/or Feed-in Premiums (FiPs). Several studies consider FiTs to be the most frequent measure to support electricity generation from renewable energy sources [36, 37]. Under the fixed payment scheme of FiTs, generators receive a fixed amount per unit of electricity generated or biomethane injected regardless of the costs of generation or market prices. Table 4 shows that FiPs are less frequently used than FiTs. They are employed in Germany, France, Netherlands and Denmark. Under the FiPs a fixed amount is added to the market price and the overall price is hence less predictable than under the FiTs [38]. Germany used FiTs for biogas upgrading based on the 2012 Amendment of the Renewable Energy Sources Act (EEG 2012) [39]. A bonus of €0.01-0.03 per kilowatt hour (kWh) was paid for processing and feed-in of biomethane depending on the production scale. The scheme was abolished during the 2014 amendment (EEG 2014) [40]. In the UK, biomethane production is all gas-to-grid due principally to the Renewable Heat Incentive that operates in a similar manner to FiTs [41].

Alternatively, some countries use a quota or green certificate scheme instead of FiTs or FiPs. Producers of electricity from biogas in Sweden receive electricity certificates and sell them within the Norway-Sweden Green Certificate Scheme for renewable electricity. Buyers of the certificate

Table 4: Support schemes for biogas and biomethane development

Support schemes	Germany	UK	Sweden	Switzerland	France	Netherlands	Denmark	Ireland
Supply side								
Investment subsidies to producers/operators	√	√	√	√	√			
Investment loans under special conditions	√	√			√	√		
Feed-in tariffs for biomethane injection/electricity production	√	√		√	√	√	√	
Feed-in premiums for biomethane injection/electricity production	√				√	√	√	
Additional support for small-scale/farm-based facilities	√				√	√		
Additional support for using certain feedstock (e.g. manure, organic waste)	√		√	√	√	√	√	
Demand side								
Quota scheme in energy/transportation sector	√	√	√		√	√	√	√
Subsidies to consumers for heating/transportation		√	√				√	√
Tax exemption (e.g. energy tax, carbon tax)	√		√	√		√		√
Knowledge-oriented and other institutional support								
Support through information actions	√	√	√	√	√	√	√	√
Biogas production as part of rural development strategies	√		√					
Priority access to national electric grid/gas network	√			√				√

Source: [1, 14, 16, 32–35]. Incentives can be either provided to producers directly or to one of the key players down the supply chain, for example, to the gas supplier or the end user. Incentives at the supply side include providing capital grants or provision of loans at reduced interest rates. Demand side incentives may also include a similar capital grants for investment in CHP running on biomethane, or payments to the end user for each unit of biogas consumed or per unit of electricity/heat produced from biogas. From the perspective of support schemes, incentives can be either financial (e.g. investment support, Feed-in Tariffs (FiTs), Feed-in Premiums (FiPs), green certificates or quotas, and taxation exemption) or non-financial activities (e.g. knowledge-oriented supports, priority access for biomethane or electricity generated from biogas to public grids). In most cases different schemes coexist in a country.

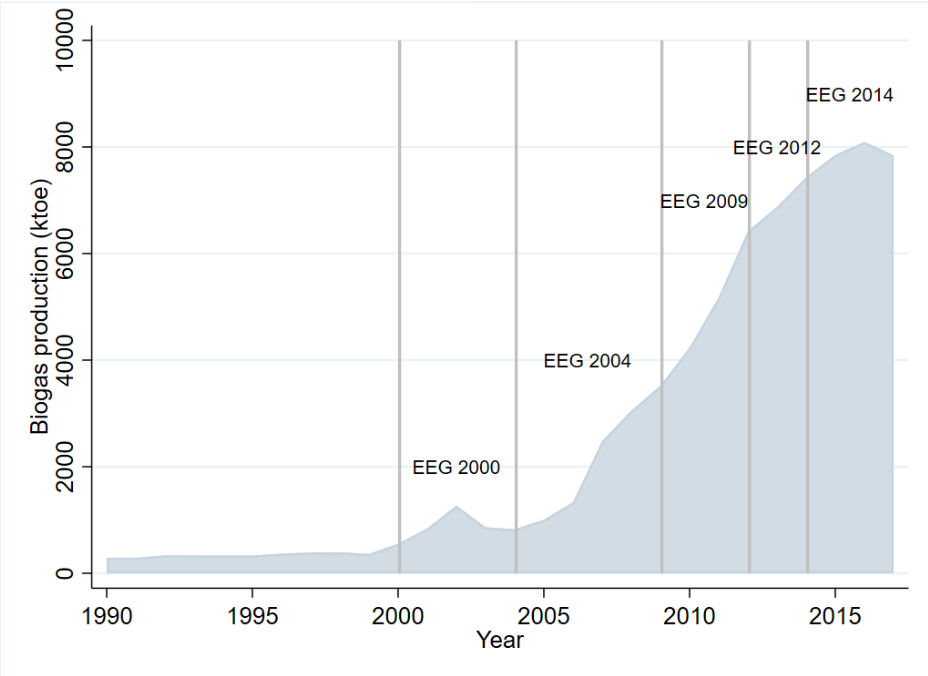
may include electricity suppliers, certain electricity consumers and energy-intensive companies who are obliged to acquire a certain number of certificates according to their electricity sales or consumption level [42]. It is common that countries have a combination of support measures. For example, the UK has both FiTs and a quota scheme, namely the Renewable Obligation Certificates. Under the scheme electricity suppliers must prove a certain percentage of electricity supplied to final consumers from renewable sources including biogas from AD. The quota scheme can also be applied to the transportation sector to promote the substitution of fossil fuel with biofuel. Biofuel quota schemes exist in Germany, UK, France, Netherlands and Denmark.

On the demand side, tax exemptions are often used to complement other types of incentive schemes. Seven out of eight countries in our review have employed tax-based incentives such as tax exemptions and tax credits to promote the utilization of biogas. Tax exemption as a fiscal adjustment is highly flexible, as it can target specific renewable technologies and impact market participants selectively [43]. In France, lowering the tax on biofuels made them competitive compared to high-taxed fossil fuels. In Ireland and Netherlands companies receive tax relief if they invest in renewable electricity projects and equipment [44]. Carbon taxation is sometimes also considered as an instrument to help to promote renewable energy. A carbon tax would help stimulate market penetration of biofuels significantly when it is applied to fossil fuels, and additionally if the tax revenue is used to finance the biofuel subsidy [45].

In recent years biogas support schemes in Europe have followed several notable trends. Supports for biogas and biomethane have declined over time [46, 47]. For example, FiTs for electricity generation from biogas was first introduced in 2000 when the Renewable Energy Sources Act (Erneuerbara-Energien-Gesetz, or EEG) came into force. Biogas development has expanded since then and experienced exponential growth until 2012-2014, after which there were recent EEG 2012 and EEG 2014 period as tariff reductions [48]. Competition between technologies has been introduced in support schemes. The EEG 2017 changed the funding for RES from a fixed tariff to a tender system, a support scheme widely used for wind power and photovoltaics [49]. Accordingly, plants have to participate successfully in tendering procedures to qualify for their funding in the scope of the EEG. This has resulted in cost reductions for many of the technologies supported [50].

Attribute subsidies are used by governments to guide specific future development of the sector. Bioenergy supports often vary according to facility scales and feedstock types. A significant feature of the EEG 2012 comparing to the EEG 2009 is the bonus payment for manure and biowaste digestion. Meanwhile, the EEG 2012 also limits the use of maize and corn up to 60%. Later in 2017, despite the shift to a tender system, biowaste-based biogas plants and small scale manure-based plants remain independent from the tender system and are covered by a tariff structure determined by EEG 2014. Similarly, small-scale farm-based AD plants receive an advanced tariff in France and Netherlands. In general, bioenergy supports across countries are becoming increasingly similar in terms of policy types, with FiTs playing a dominant role [51–53].

Figure 4: Evolution of biogas development in Germany



Source: Data collected from Eurostat. Information on policy instruments collected from IEA and IRENA [54] and IEA Bioenergy Task 37 [16]. EEG: Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG).

4. Emerging issues and new developments

In this section we discuss a wide range of issues relating to the large-scale implementation of biogas production. Each sub-section concludes with a discussion of social, environmental or economic implications for future biogas development in countries aiming to develop a biogas sector, often using Ireland as a case study.

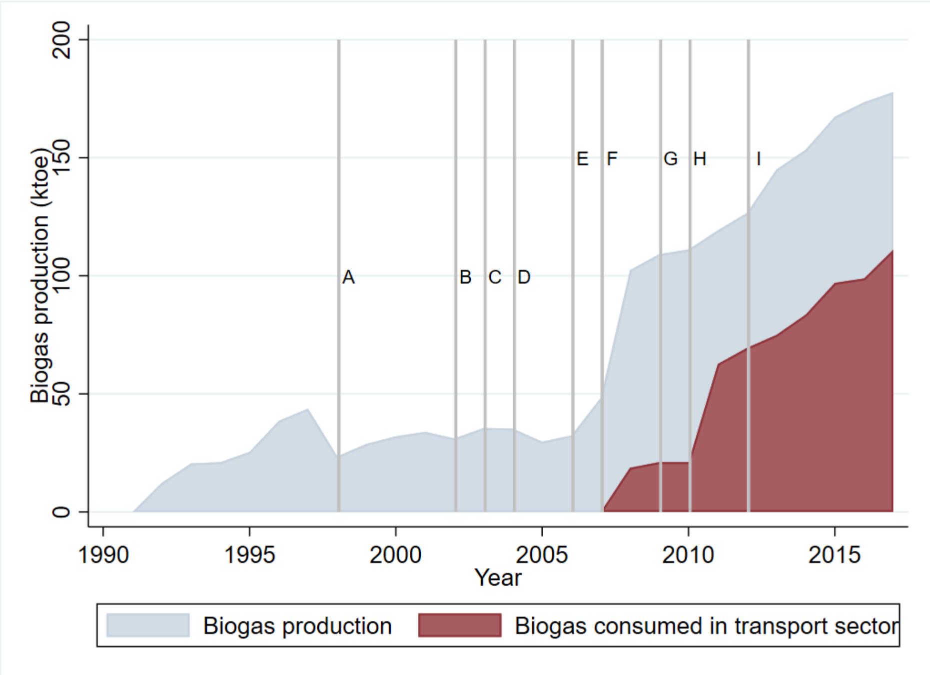
4.1. Specialisation

4.1.1. Policy supports for technologies & biogas end-uses

A package of support schemes can be designed in favour of one specific technology or end-user sector. Among the reviewed countries, the Swedish support system shows a clear emphasis for promoting green transportation. Using biogas for transportation purposes is considered to be associated with the greatest climate benefit [55]. On the supply side, the Swedish support system supports not only biogas production, but also end-use infrastructure (e.g. filling stations, vehicles). On the demand side, exemption from a variety of taxes (e.g. energy and carbon dioxide taxes, vehicle tax) has also driven growth in biogas for transportation. Larsson et al. [56] summarise 12 policy instruments related to biogas in the transport sector in Sweden and we mark them in Figure 5 which shows the evolution of biogas production in Sweden. The instruments implemented since 2006 appear to have delivered substantial positive impact on biogas production and utilization in Sweden but there is no single "silver bullet" measure, rather on-going supports continually evolving. At present, two-thirds of Swedish biogas production is upgraded and used for road transport with the volume of sales having increased five-fold since 2006 [57]. This has made Sweden a leader in biogas fuelled transport globally.

Denmark, on the other hand, has a long and well established technological practice for manure and organic waste digestion (Figure 6). The Biomass Agreement (1993) set targets for the first time specifically for biomass-based energy. The Green Growth Agreement launched in 2009 set the goal that 50% of the livestock manure in Denmark be used for green energy in 2020 and other supports include tax equalization between vegetable biomass and livestock manure, and modification of the Waste Incineration Directive [54]. An additional benefit using agricultural feedstocks in Denmark is the reduction in artificial fertiliser use, with manufactured fertiliser reduced by approximately 50% compared to 1985 levels without any nitrogen deficiencies [27]. Raven and Gregersen [58] cite three enablers for the development of biogas plants in Denmark: a bottom-up approach stimulated a broad interaction and learning process; a rich social network and long-term support; dedicated

Figure 5: Evolution of biogas development in Sweden

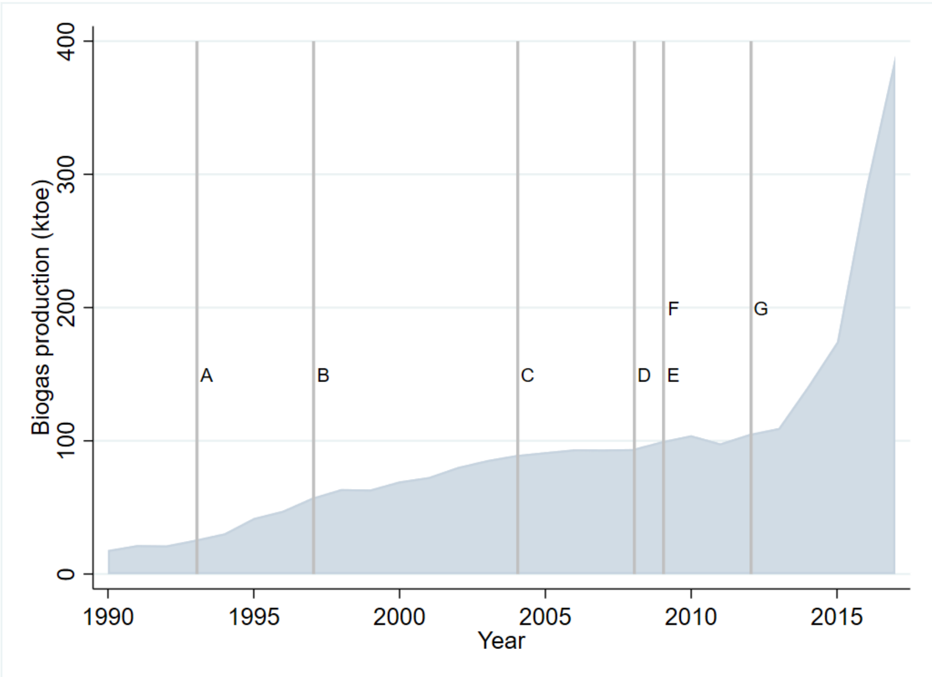


Source: Data collected from Eurostat. Information on policy instruments collected from Larsson et al. [56]. A: Local Investment Programme (LIP) to support all parts of the biogas chain (1998-2002); B: Reduction of fringe-benefit tax to support alternative vehicles (2002-); C: Climate investment programmes (KLIMP) similar to LIP (2003-2008); D: Full exemption for biogas used for heating and motor vehicles from energy and carbon dioxide tax (2004-); E: Carbon-differentiated vehicle tax (2006-), and Act on obligation to provide renewable fuel (2006-); F: Exemption from congestion fees in Stockholm (2007-2008), and Clean car bonus (2007-2009); G: Rural Development Programmes to support farm-scale biogas production (2009-2013); H: Exemption from vehicle tax during five years (2010-), and Investment support for projects regarding production, infrustructure and use of biogas (2010-); I: Special clean car bonus (2012).

policy supports, the existence of district heating systems, and farmer cooperation within small communities.

On-farm AD plants in Denmark also accept source-separated organic household wastes, under the condition that it is traceable and cleansed from impurities in a pre-processing facility before it enters the digester. Most of the centralized biogas plants located in rural areas now co-digest manure with food waste and other feedstocks. The inclusion of waste food feedstocks is supported by waste sector policies of high landfill and incineration taxes, plus the prohibition of landfilling of biodegradable municipal waste since 1997. The Danish government has a target to reuse 50% of household waste by 2022. Similar to the Swedish case, success has been achieved through constant evolution of legislative drivers and policy supports. What is also evident is that it is not a single sector issue but rather a collaborative engagement across sectors (i.e. waste, agriculture, energy, environment), which delivers multiple benefits not just GHG emissions reduction.

Figure 6: Evolution of biogas development in Denmark



Source: Data collected from Eurostat. Information on policy instruments collected from IEA and IRENA [54] and IEA Bioenergy Task 37 [16]. A: Biomass agreement (1993, revised in 1997, 2000) mandated the use of certain amounts of straw and wood chips for energy, with targets met in 2009; B: Landfill ban on biodegradable municipal waste (1997); C: Subsidies for Renewable Electricity Generation (2004); D: Energy Agreement (2008); E: Promotion of Renewable Energy Act, and Feed-in premium tariffs for renewable power (2009); F: Green Growth (2009) with the objective to treat 50% livestock manure in biogas plants by 2020; G: Energy Agreement (2012).

4.1.2. Learning: setting an overarching policy ambition

With an appropriate policy goal, a range of stakeholders can cooperatively work toward a shared ambition. Countries developing their biogas sector, such as Ireland, might also consider an enhanced support scheme targeting a specific type of feedstock, technology or end-user. Following the Swedish example is one option for Ireland, with potential economic and competitive benefits compared to other options [59, 60]. However, using biomethane for transport requires substantial investment in infrastructure and vehicles [61]. Such a policy move would also directly compete with existing policy supports for electric vehicles, which fits within the wider context of car manufacturers pivoting towards electric vehicles. Similar to other countries Ireland has already provided supports for using biomethane in transport and is developing a national CNG refuelling network intended primarily for commercial vehicles including trucks, buses and vans.[4] With such a network under development there is a strong economic and environmental case for earmarking biogas/biomethane production for transport use [59, 60] and enveloping biogas/biomethane plans within transport goals and policy.

Another option for an overarching policy ambition follows the Danish approach using anaerobic digestion as a means to manage wastes from the agricultural and food sectors. Following the Danish approach is also consistent with an ambition to use biogas for transport. There are several potential synergies from following the Danish example. From the perspective of biogas producers, it closely establishes biogas production within the agricultural sector, which is important to help build trust and networks along the supply chain. From the farmers' perspective, it is a prospective new income source, which is a significant benefit in Ireland where farm incomes are heavily reliant on direct income supports [62]. Furthermore, agriculture in Ireland is suspected of being the main cause of pollution in rivers [63] and anaerobic digestion affords a means to more effectively manage nutrient loadings. And not least, the agriculture sector is the largest source of GHG emissions within Ireland [63], accounting for one-third of total national emissions in 2017. Agriculture needs to share the burden of GHG emissions reductions and advocating biogas production as an agricultural policy goal has merit that transcends the sector itself.

[4] The network is co-financed by the EU's Connecting Europe Facility, see https://ec.europa.eu/inea/en/connecting-europe-facility.

4.2. *Intensive farming*

4.2.1. *Nutrient management and changing farming practices*

The Nitrates Directive gives an indirect impetus for AD uptake because farmers are encouraged to adopt manure treatment systems [25]. The digestate output from AD plants can serve as a more effective fertiliser than raw manure and slurry plus it is a less costly substitute for manufactured fertiliser. In comparison with mineral fertilisers and untreated slurry, digestate has a high fertiliser value because of its larger share of available nitrogen, phosphorus, potassium and micro-nutrients, although quality varies largely depending on feedstock, AD process and treatments [26]. Because of the nutrient concentrations, a farm that fertilises with digestate can often get the same fertilising effect with 10-20% smaller dose [27].

At present, anaerobic digestion does not change the legal definition of livestock manure and AD digestate is treated the same as other fertilisers. This implies digestate follows the application restrictions in the same way as artificial fertilisers and untreated manure. The European Biogas Association suggests that AD digestate should be treated differently as animal manure, as a large part of the "slow release" organic nitrogen is mineralized and converted into "quick release" mineral nitrogen, predominantly the nitrogen content of the ammonium ion [64]. If application requirements were eased for digestate spreading, farm systems could become more intensive, availing of less restrictive digestate application rates and expanding supply of slurry feedstock to biogas plants. Where herd size increases or more animals are housed indoors for manure collection there is a potential direct impact on GHG emissions. Stored manure (e.g., in tanks, lagoons etc.) decomposes anaerobically and can produce a significant quantity of methane, whereas when manure is deposited on pastures it tends to decompose under more aerobic conditions and less methane is produced. So any biogas supports may need to be designed to avoid such indirect impact on GHG emissions.

The net impact of biogas production on GHG emissions may be more nuanced than indicated by typical life cycle assessment. Countries will be interested in the net impact on aggregate national emissions not just the supply chains associated with biogas production. For example, if feedstock production entails a transition from extensive to intensive farming operations or land use changes, the baseline level of emissions may also change. If marginal or extensively farmed lands are intensively cultivated, for example with higher fertiliser use or grasslands ploughed, the net impact on aggregate national emissions may be less than envisaged. Policy supports for biogas need to be cognisant indirect impacts along the supply chain that reduce the aggregate net emissions reductions associated with biogas production.

4.2.2. *Learning: Interface across policy domains*

Biogas production and utilization involves a range of sectors. Cooperation in policy interactions across multiple domains plays an important role in biogas sector development. Supportive policies in one sector could become ineffective when combined with policies in other sectors. Hence, special attention should be devoted to the coherence between policies and instruments across different sectors, especially at local level [65]. The utilization of post-AD digestate offers the possibility to recycle nutrients from waste back to the food chain. Limited availability of land for digestate spreading may be a particular issue for large food waste digesters. The wider adoption of digestate for landspreading requires the development and adoption of digestate standards for various end-use purposes.

Many biodegradable feedstocks are classified as ABP and subject to ABP Regulations. For the purpose of preventing animal disease, rules are set in terms of building structure and design, size restriction of feedstock, heat treatment of feedstock/digestate, among others. These ABP requirements are designed for animal and human health protection but add a significant level of complexity and capital cost to the development of biogas plants. Biogas production, particularly anaerobic digestion, is reliant on the agri-food sector for feedstock but the regulatory framework surrounding use of ABP severely limits its operation and potential. It is arguable in the context of water quality challenges, as well climate policy ambitions, that the agri-food sector will become more reliant on the biogas sector for its future growth and sustainability. The regulatory framework surrounding ABP, while protecting animal and human health, must also be cognisant of the symbiotic relationship of the two sectors.

4.3. *Supply chain risks*

4.3.1. *Seasonality, trade, and storage*

Production of biogas requires feedstock inputs, and seasonality plays a role in feedstock supply. For example, a prolonged drought and heat wave in Ireland in summer 2018 resulted in low grass biomass production. This implies a potential supply chain risk and the biomass sector should be prepared for the possibility of more frequent summer droughts in the future. Selecting grass species with high soil holding capacity and the ability to maintain growth under drought and flood conditions is a potential solution [66]. However, while various grass feedstock types may be more resilient to weather stresses there is a corresponding difference in biogas yield per unit input [67]. Grass or maize silage supply also experiences seasonal fluctuations with lowest stocks in the late spring, early summer period and depending on the severity of winter weather, farmers' stocks can be completely exhausted. A viable biogas sector dependent on feedstock from the agricultural sector needs guaranteed feedstocks and not to be reliant on surpluses from the agricultural sector.

Biogas production from wastes may also experience seasonality. The composition of food waste in summer time is different than in winter. In general, food waste generation varies over time, often influenced by seasonality, special events and holidays [68]. The same can be said about yard trimmings and agriculture wastes. The landfill rate exhibits stable seasonality with a high level of compostable garden waste arising during spring and summer [69]. In autumn there is an influx of agriculture wastes [70]. Availability of stored animal manures is also subject to seasonal variation. During the summer when most livestock (excl. swine) are on pasture, and manure storage capacity is emptied in preparation for the following winter, slurry feedstock will also be in limited supply. These variations may cause substantial changes in feedstock composition, posing a challenge for planning and operation of a biogas plant.

If a large proportion of feedstock is sourced from abroad, a feedstock outage may happen due to trade related issues such as limitations to free trade or fluctuations in global markets. This may lead to serious implications for the security of a country's energy system if biogas accounts for a significant part of domestic energy consumption.

Finally, storage for animal slurries and post-AD digestate may represent a capacity constraint. The agriculture sector generally has sufficient slurry storage capacity for its needs and from which it can supply AD plants. That would continue to be the case unless digestate has to be stored separately from raw slurries. The biogas potential of digestate is low and therefore biogas plants will seek to avoid intake of previously used feedstock. And separately, if the regulatory environment for digestate includes specific landspreading conditions, especially if the digestate includes off-farms wastes, that may practically necessitate separate storage to enable compliance.

4.3.2. Learning: close integration with agriculture sector

Biogas production requires a constant and guaranteed feedstock supply, with minimal seasonal fluctuations. Biogas technologies that optimise gas production under different conditions are available but a broad and comprehensive collaboration between plant operators and feedstock suppliers is needed. Specialised supply chain management could also bring a beneficial effect in supplying qualified feedstock all year around. Long-term contractual supplies of agricultural and food waste feedstock would also address supply uncertainties. Nonetheless, feedstock supply shortages have the potential to curtail the growth in the biogas sector.

An alternative approach to address the seasonality of agricultural feedstock supply would be to match biogas production with seasonal feedstock supplies, possibly via small scale on-farm AD plants. If the produced biogas is intended for heating uses, the biogas production period would also match heating demand seasonality, and possibly be distributed locally. Apart from the other development challenges for biogas, the economics of operating essentially the same production plant on a seasonal versus continuous basis is likely to be quite difficult.

In Ireland a grass based biogas sector has been mooted [71–73] with cattle or sheep production likely to be displaced compared to other grass based enterprises, such as dairy. The displacement of cattle and sheep is because returns are substantially lower than other enterprises and farm families are heavily reliant on direct income supports [62]. Consequently, the response of the agriculture sector, and specifically beef farmers, to the demand from biogas plants for grass feedstock is critical for the development of the biogas sector. There is a cultural hesitation among farmers to switch their farms to non-traditional enterprises due to financial uncertainty, cultural barriers, as well as other reasons [74]. Farmers often see their enterprise as part of their identity, for example, as beef farmers. However, with suitable incentives and measures to ensure security of income, barriers to enterprise switching can be overcome. For example, there are long-standing policy incentives to increase forest cover but uptake among farmers has been substantially below target. With a strong financial case, as well as long-term guarantees, farmers may be willing to switch (or partial switch) enterprises [75, 76]. In Ireland this is already reflected in some areas with relatively high rates of afforestation on farms with poor or marginal land (e.g. county Leitrim) despite local opposition.

The cultivation of energy crops on marginal land which is unsuitable for food production is consistently proposed as a viable option [77, 78]. The term 'marginal land' is unclearly defined in the literature, often resulting in divergent interpretations in practice [79, 80]. An EU funded research project, SEEMLA, aims to clarify definitions and assessment methods for selecting marginal lands, while another EU funded project "MArginal Lands for Growing Industrial Crops" (MAGIC) is developing best practice for growing energy crops on marginal land.[5] A more basic question is whether energy crop production should be restricted to marginal land? By default, crop yields will be lower compared to more fertile land, meaning that the cost of the derived fuels will be higher

[5] See http://magic-h2020.eu/.

than is potentially feasible. With biogas production already requiring subsidy support to ensure cost competitiveness versus fossil fuels, limiting energy crop production to marginal lands further hamstrings the development of a biogas sector. With lower yields on marginal lands, a specific feedstock need will require greater land allocation. If marginal land is intensively cropped, are there potential unintended consequences, for example, nitrogen leaching and water pollution? If energy crops are concentrated on marginal lands there may also be a potential impact on feedstock transport distances. Biogas plants are ideally located close to feedstocks, of which energy crops may be just a part, but also plant location may also be influenced by proximity to biogas markets or grid injection facilities. Limiting energy crops to marginal land may impact on net emissions savings. In the case of Ireland the value of direct farm payments (i.e. income supports) exceeds 100% of its contribution cattle and sheep farmers' incomes [62], which means that on average they are unprofitable enterprises and subsidised by direct income supports. Consequently, there's an economic case for farmers to switch enterprise to energy crop production, which in this instance could be grass or maize production. Furthermore, with meat production having relatively high carbon intensity [81, 82], reducing national herd and flock sizes would reduce total GHG emissions both in absolute terms and agriculture's share.

The issue of sufficient storage capacity will only be clear when there is clarity on the regulatory environment surrounding the uses of AD digestates from different feedstocks. If existing storage capacity and its on-farm configuration is not adequate this would represent a significant barrier for the use of animal slurry in biogas production.

5. Conclusion

The objective of this research is twofold. First, to draw lessons from the European experience in biogas development that may be particularly useful to countries that have policy ambitions to increase biogas/biomethane production. An improved understanding of prior experiences with policy measures promoting biogas/biomethane deployment will contribute to the efficacy of future policy initiatives. Second, to broaden the policy and assessment discussions surrounding the merits of promoting biogas/biomethane production, including highlighting potential risks associated with such policies. There is a strong case to be made for continued growth in biogas/biomethane production, not least for the benefits associated with displacing fossil energy GHG emissions. But critical review of policy measures supporting biogas production have largely focused around just a few issues. These issues include the net GHG emissions associated with biogas production and the potential impact and sustainability of biogas production on food supply and prices. However, there are broader issues related to economic, environmental and social pillars of sustainability that merit more detailed consideration.

Beyond the mechanism of delivering financial support, devising an overarching ambition for the sector may be equally important. Without a clear vision, projects will be developer lead and there is no certainty that an integrated and cohesive sector will emerge. Denmark and Sweden represent good role models in this regard championing both the biogas sector as a means to manage agri-foods wastes and biogas for use in transport.

A critical risk for the biogas sector is securing adequate and consistent quality feedstock, as well as, outlets for post-processing by-products (e.g. digestate from anaerobic digestion). For the sector to expand project developers need to build trust with the farming sector. Long-term supply contracts are a means to reduce uncertainty, which will help farmers consider adapting their businesses to supply feedstock crops, as well as, animal manures and slurries. The development by government of an overarching vision for biogas/biomethane, as noted above, with the biogas and agriculture sectors working together can help foster a shared vision and mutual trust. The regulatory framework surrounding feedstock containing ABP, which is critical for protecting animal and human health, must reflect the symbiotic relationship between the two sectors. If biogas supply chain leads to a substantial change in agricultural practices, policy supports need to be cognisant indirect impacts that hamper the ability to reduce GHG emissions associated with biogas production.

Expansion of the biogas sector needs to be resilient to the impact of climate and weather variability on feedstock quantity and price. In years of high feedstock prices, possibly reflecting quantity shortages, biogas plants face a double risk. Interruptions to feedstock supply and or potentially uncompetitive feedstock prices will threaten their financial sustainability. It is difficult to physically hedge against such risks but close integration with the agricultural sector and controlled expansion is important. It will be particularly risky for biogas plants if their feedstock supplies are farm surpluses (i.e. surplus to the farmers' own needs) rather than an integral output of farming operations. Therefore, close business relationships with contracted supply chains will be important.

Finally, biogas production should be viewed as an opportunity for the agricultural sector, not a threat. Feedstock supply represents a potential new income source, while processing manures and slurries into AD digestate has the potential to provide a lower cost alternative to artificial fertilisers. Associated increases in land or fodder prices also benefit recipient farmers. Farm incomes are low and some types of farm enterprise are generally not profitable, specifically cattle and sheep production. Switching to more profitable enterprises and at the same time directly addressing two significant challenges facing the agricultural sector, namely curtailing GHG emissions and limiting nutrient emissions to water, is an opportunity to be embraced.

Acknowledgements

This work was funded by the Economic and Social Research Institute's (ESRI) Energy Policy Research Centre (EPRC) of which the Sustainable Energy Authority of Ireland (SEAI) is a funding contributor.

References

[1] IEA Bioenergy Task 37. Green Gas - Facilitating a future green gas grid through the production of renewable gas. International Energy Agency; 2018. ISBN 978-1-910154-38-0.

[2] Capodaglio, A.G., Callegari, A., Lopez, M.V.. European framework for the diffusion of biogas uses: emerging technologies, acceptance, incentive strategies, and institutional-regulatory support. Sustainability 2016;8(4):298.

[3] Fachverband & UNIDO. Biogas to biomethane. Fachverband, German Biogas Association; 2017. URL: https://www.biogas-to-biomethane.com/Download/BTB.pdf; accessed date 1 June 2019.

[4] IEA. Key world energy statistics 2018. International Energy Agency 2018;URL: https://webstore.iea.org/key-world-energy-statistics-2018; accessed date 1 June 2019.

[5] World Bioenergy Association. Global Bioenergy Statistics. Stockholm, Sweden 2018;URL: https://worldbioenergy.org/global-bioenergy-statistics; accessed date 1 June 2019.

[6] Hijazi, O., Munro, S., Zerhusen, B., Effenberger, M.. Review of life cycle assessment for biogas production in Europe. Renewable Sustainable Energy Rev 2016;54:1291–1300. URL: https://doi.org/10.1016/j.rser.2015.10.013; accessed date 1 June 2019.

[7] Harvey, M., Pilgrim, S.. The new competition for land: Food, energy, and climate change. Food Policy 2011;36:S40–S51. URL: https://doi.org/10.1016/j.foodpol.2010.11.009; accessed date 1 June 2019.

[8] Martinát, S., Navrátil, J., Dvořák, P., Van der Horst, D., Klusáček, P., Kunc, J., et al. Where AD plants wildly grow: The spatio-temporal diffusion of agricultural biogas production in the Czech Republic. Renew Energ 2016;95:85–97. URL: https://doi.org/10.1016/j.renene.2016.03.077; accessed date 1 June 2019.

[9] Dvořák, P., Martinát, S., Van der Horst, D., Frantál, B., Turečková, K.. Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with reference to EU benchmarks. Renewable Sustainable Energy Rev 2017;69:360–368. URL: https://doi.org/10.1016/j.rser.2016.11.158; accessed date 1 June 2019.

[10] Marinas, M.C., Dinu, M., Socol, A.G., Socol, C.. Renewable energy consumption and economic growth. Causality relationship in Central and Eastern European countries. PLoS One 2018;13(10):e0202951. URL: https://doi.org/10.1371/journal.pone.0202951; accessed date 1 June 2019.

[11] Aceleanu, M.I., Serban, A.C., Pociovălisteanu, D.M., Dimian, G.C.. Renewable energy: a way for a sustainable development in Romania. Energy Sources, Part B: Economics, Planning, and Policy 2017;12(11):958–963. URL: https://doi.org/10.1080/15567249.2017.1328621; accessed date 1 June 2019.

[12] Smyth, B.M., Murphy, J.D., O'Brien, C.M.. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews 2009;13(9):2349–2360.

[13] Singh, A., Smyth, B.M., Murphy, J.D.. A biofuel strategy for Ireland with an emphasis on production of biomethane and minimization of land-take. Renewable and sustainable energy reviews 2010;14(1):277–288.

[14] SEAI. Assessment of cost and benefits of biogas and biomethane in Ireland. Sustainable Energy Authority of Ireland 2017;URL: https://www.seai.ie/resources/publications/Assessment-of-Cost-and-Benefits-of-Biogas-and-Biomethane-in-Ireland.pdf; accessed date 1 June 2019.

[15] SEAI. Sustainability criteria options and impacts for Irish bioenergy resources. Sustainable Energy Authority of Ireland 2019;URL: https://www.seai.ie/resources/publications/Sustainability-Criteria-Options-and-Impacts-for-Irish-Bioenergy-Resources.pdf; accessed date 1 June 2019.

[16] IEA Bioenergy Task 37. Country Report Summaries 2018. International Energy Agency Bioenergy 2018;URL: http://task37.ieabioenergy.com/country-reports.html; accessed date 1 June 2019.

[17] AgriLand. Ireland's first grid injection biogas facility set to be commissioned in the new year. AgriLand 2018;URL: https://www.agriland.ie/farming-news/

irelands-first-grid-injection-biogas-facility-set-to-be-commissioned-in-the-new-year/; accessed date 1 June 2019.

[18] AgriLand. 'GRAZE Gas' project receives climate action funding. AgriLand 2018;URL: https://www.agriland.ie/farming-news/graze-gas-project-receives-climate-action-funding/; accessed date 1 June 2019.

[19] European Commission. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities 1999;URL: http://data.europa.eu/eli/dir/1999/31/oj.

[20] European Commission. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union 2008;URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098; accessed date 1 June 2019.

[21] European Commission. Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. Official Journal of the European Communities 1991;URL: http://data.europa.eu/eli/dir/1991/271/oj; accessed date 1 June 2019.

[22] European Commission. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of the European Communities 1991;URL: http://data.europa.eu/eli/dir/1991/676/oj; accessed date 1 June 2019.

[23] European Commission. Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers. Official Journal of the European Union 2003;URL: http://data.europa.eu/eli/reg/2003/2003/oj; accessed date 1 June 2019.

[24] CRE. Guidelines for anaerobic digestion in Ireland. Composting and Anaerobic Digestion Association of Ireland 2018;URL: http://www.cre.ie/web/wp-content/uploads/2018/03/Guidelines-for-Anaerobic-Digestion-in-Ireland_Final.pdf; accessed date 1 June 2019.

[25] Carrosio, G.. Energy production from biogas in the Italian countryside: policies and organizational models. Energ Policy 2013;63:3–9.

[26] European Commission. Resource Efficiency in Practice – Closing Mineral Cycles Final report. DG Environment, European Commission 2016;URL: http://ec.europa.eu/environment/water/water-nitrates/pdf/Closing_mineral_cycles_final%20report.pdf; accessed date 1 June 2019.

[27] Foged, H.L.. Livestock manure to energy status, technologies and innovation in Denmark. Agro Business Park A/S Niels Pedersens Allé 2, DK-8830 Tjele, Denmark 2012;URL: https://www.agropark.dk/admin/public/download.aspx?file=/Files/Files/ecom/products/Biogas-Go-Global/Livestock-Manure-to-Energy.pdf; accessed date 1 June 2019.

[28] European Commission. Council Regulation (EC) No 74/2009 of 19 January 2009 amending Regulation (EC) No 1698/2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). Official Journal of the European Communities 2009;URL: http://data.europa.eu/eli/reg/2005/1698/oj; accessed date 1 June 2019.

[29] European Commission. Regulation (EU) No 1305/2013 of the European Parlament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005. Official Journal of the European Communities 2013;URL: http://data.europa.eu/eli/reg/2013/1305/oj; accessed date 1 June 2019.

[30] IEA Bioenergy Task 37. The role of anaerobic digestion and biogas in the circular economy. IEA Bioenergy 2018;URL: https://www.ieabioenergy.com/publications/the-role-of-anaerobic-digestion-and-biogas-in-the-circular-economy/; accessed date 1 June 2019.

[31] Joint Research Centre. Solid and gaseous bioenergy pathways: input values and GHG emissions. Joint Research Centre, the European Commission 2017;URL: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC104759/ld1a27215enn.pdf; accessed date 1 June 2019.

[32] Strauch, S., Krassowski, J., Singha, A.. Biomethane guide for decision makers. Project GreenGasGrids 2013;Fraunhofer UMSICHT, Research Group Biogas technology, Osterfelder Strasse 3, 46047 Oberhausen, Germany.

[33] BIOGAS3 Consortium. European legislative and financial framework for the implementation of small-scale biogas plants in agro-food & beverage companies. 2016. Intelligent Energy Europe (IEE) Programme.
[34] Agency, D.E.. The Danish subsidy scheme for the use of biogas. The Ministry of Energy, Utilities and Climate, Denmark 2018;URL: https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark; accessed date 1 June 2019.
[35] RES LEGAL Europe. Legal sources on renewable energy. Berlin, Germany 2018;URL: http://www.res-legal.eu/; accessed date 1 June 2019.
[36] Klein, A., Held, A., Ragwitz, M., Resch, G., Faber, T.. Evaluation of different feed-in tariff design options: Best practice paper for the international feed-in cooperation. Energy Economics Group & Fraunhofer Institute Systems and Innovation Research, Germany 2008;URL: http://www.feed-in-cooperation.org/wDefault_7/wDefault_7/download-files/research/best_practice_paper_2nd_edition_final.pdf; accessed date 1 June 2019.
[37] EEA. Energy support measures and their impact on innovation in the renewable energy sector in Europe. Tech. Rep.; European Environment Agency; 2014.
[38] Haas, R., Resch, G., Panzer, C., Busch, S., Ragwitz, M., Held, A.. Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources–lessons from eu countries. Energy 2011;36(4):2186–2193.
[39] BMUB. The 2012 Amendment of the Renewable Energy Sources Act (EEG 2012). Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2012;URL: https://www.bmel.de/SharedDocs/Downloads/EN/Publications/EEG-Amendment2012.pdf?__blob=publicationFile; accessed date 1 June 2019.
[40] BMUB. The 2014 Amendment of the Renewable Energy Sources Act (EEG 2014). Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2014;URL: https://www.bmwi.de/Redaktion/EN/Downloads/renewable-energy-sources-act-eeg-2014.pdf?__blob=publicationFile&v=1; accessed date 1 June 2019.
[41] Horschig, T., Adams, P.W., Röder, M., Thornley, P., Thrän, D.. Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses. Appl Energ 2016;184:840–852.
[42] Hustveit, M., Frogner, J.S., Fleten, S.E.. Toward a model for the swedish-norwegian electricity certificate market. In: European Energy Market (EEM), 2015 12th International Conference on the. IEEE; 2015, p. 1–5.
[43] Held, A., Ragwitz, M., Gephart, M., de Visser, E., Klessmann, C.. Design features of support schemes for renewable electricity. European Commission, DG ENER 2014;URL: https://ec.europa.eu/energy/sites/ener/files/documents/2014_design_features_of_support_schemes.pdf; accessed date 1 June 2019.
[44] SEAI. Accelerated capital allowance. Sustainable Energy Authority of Ireland 2018;URL: https://www.seai.ie/energy-in-business/accelerated-capital-allowance/; accessed date 1 June 2019.
[45] Timilsina, G.R., Csordás, S., Mevel, S.. When does a carbon tax on fossil fuels stimulate biofuels? Ecol Econ 2011;70(12):2400–2415.
[46] Torrijos, M.. State of development of biogas production in Europe. Procedia Environ Sci 2016;35:881 – 889.
[47] Scarlat, N., Dallemand, J.F., Fahl, F.. Biogas: developments and perspectives in Europe. Renew Energ 2018;129:457–472.
[48] Daniel-Gromke, J., Rensberg, N., Denysenko, V., Stinner, W., Schmalfuß, T., Scheftelowitz, M., et al. Current developments in production and utilization of biogas and biomethane in Germany. Chem-ing-tech 2018;90(1-2):17–35.
[49] Bayer, B., Schäuble, D., Ferrari, M.. International experiences with tender procedures for renewable energy–A comparison of current developments in Brazil, France, Italy and South Africa. Renewable Sustainable Energy Rev 2018;95:305–327.
[50] Abdmouleh, Z., Alammari, R.A., Gastli, A.. Review of policies encouraging renewable energy integration & best practices. Renewable Sustainable Energy Rev 2015;45:249–262.
[51] Kitzing, L., Mitchell, C., Morthorst, P.E.. Renewable energy policies in Europe: Converging or diverging? Energ Policy 2012;51:192–201.

[52] Jenner, S., Groba, F., Indvik, J.. Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries. Energ Policy 2013;52:385–401.

[53] Pablo-Romero, M.d.P., Sánchez-Braza, A., Salvador-Ponce, J., Sánchez-Labrador, N.. An overview of feed-in tariffs, premiums and tenders to promote electricity from biogas in the EU-28. Renewable Sustainable Energy Rev 2017;73:1366–1379.

[54] IEA and IRENA. IEA/IRENA joint policies and measures database. International Energy Agency Policies and Measures Databases 2018;URL: https://www.iea.org/policiesandmeasures/renewableenergy/; accessed date 1 June 2019.

[55] Engdahl, K.. Biogas policies, incentives and barriers: a survey of the strategies of three European countries. Master's thesis; Lund University, Department of Technology and Society; 2011.

[56] Larsson, M., Grönkvist, S., Alvfors, P.. Upgraded biogas for transport in Sweden–effects of policy instruments on production, infrastructure deployment and vehicle sales. J Clean Prod 2016;112:3774–3784.

[57] Lemonde, M.. Sweden: a pioneer in natural gas vehicle, NGV and BioNGV. Biogas World 2018;URL: https://www.biogasworld.com/news/vehicle-ngv-biongv-sweden/; accessed date 1 June 2019.

[58] Raven, R., Gregersen, K.. Biogas plants in Denmark: successes and setbacks. Renewable Sustainable Energy Rev 2007;11(1):116–132.

[59] Goulding, D., Power, N.. Which is the preferable biogas utilisation technology for anaerobic digestion of agricultural crops in Ireland: Biogas to CHP or biomethane as a transport fuel? Renew Energ 2013;53:121–131.

[60] Browne, J., Nizami, A.S., Thamsiriroj, T., Murphy, J.D.. Assessing the cost of biofuel production with increasing penetration of the transport fuel market: A case study of gaseous biomethane in Ireland. Renewable Sustainable Energy Rev 2011;15(9):4537–4547.

[61] Murphy, J.D., Power, N.M.. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenergy 2009;33(3):504–512.

[62] Dillon, E., Moran, B., Lennon, J., Donnellan, T.. Teagasc National Farm Survey 2017 Results. Teagasc; 2018. URL: https://www.teagasc.ie/media/website/publications/2018/NFS2017_web.pdf; accessed date 1 June 2019.

[63] EPA. Ireland's Environment 2016 – An Assessment. Environmental Protection Agency; 2016. URL: http://www.epa.ie/pubs/reports/indicators/irelandsenvironment2016.html; accessed date 1 June 2019.

[64] EBA. EBA's position on digestate within the Nitrates Directive. European Biogas Association 2014;URL: http://european-biogas.eu/wp-content/uploads/2014/12/Digestate-in-the-Nitrates-Directive_EBA-Position-paper.pdf; accessed date 1 June 2019.

[65] Huttunen, S., Kivimaa, P., Virkamäki, V.. The need for policy coherence to trigger a transition to biogas production. Environmental Innovation and Societal Transitions 2014;12:14–30.

[66] Qi, A., Holland, R.A., Taylor, G., Richter, G.M.. Grassland futures in Great Britain–productivity assessment and scenarios for land use change opportunities. Sci Total Environ 2018;634:1108–1118.

[67] Whittaker, C., Hunt, J., Misselbrook, T., Shield, I.. How well does miscanthus ensile for use in an anaerobic digestion plant? Biomass Bioenergy 2016;88:24–34.

[68] Trabold, T., Babbitt, C.W., editors. Sustainable Food Waste-to-Energy Systems. Academic Press; 2018.

[69] DAERA. Northern Ireland Local Authority Collected Municipal Waste Management Statistics. Department of Agriculture, Environment and Rural Affairs the Northern Ireland Executive 2018;URL: https://www.daera-ni.gov.uk/articles/northern-ireland-local-authority-collected-municipal-waste-management-statistics; accessed date 1 June 2019.

[70] Dragivcevic, V., Miletic, M., Pavkovic, B.. Investigation on possibilities for biogas production from organic waste on the Croatian island of Krk. Tehnicki vjesnik/Technical Gazette 2015;22(3).

[71] Korres, N.E., Singh, A., Nizami, A.S., Murphy, J.D.. Is grass biomethane a sustainable transport biofuel? Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy 2010;4(3):310–325.

[72] Smyth, B.M., Murphy, J.D.. The indirect effects of biofuels and what to do about them: the case of grass

biomethane and its impact on livestock. Biofuels, Bioprod Biorefin 2011;5(2):165–184.

[73] McEniry, J., Crosson, P., Finneran, E., McGee, M., Keady, T., O'Kiely, P.. How much grassland biomass is available in Ireland in excess of livestock requirements? Irish J Agr Food Res 2013;:67–80.

[74] Warren, C.R., Burton, R., Buchanan, O., Birnie, R.V.. Limited adoption of short rotation coppice: The role of farmers' socio-cultural identity in influencing practice. J Rural Stud 2016;45:175–183. URL: https://doi.org/10.1016/j.jrurstud.2016.03.017; accessed date 1 June 2019.

[75] Sherrington, C., Moran, D.. Modelling farmer uptake of perennial energy crops in the UK. Energ Policy 2010;38(7):3567–3578. URL: https://doi.org/10.1016/j.enpol.2010.02.034; accessed date 1 June 2019.

[76] Convery, I., Robson, D., Ottitsch, A., Long, M.. The willingness of farmers to engage with bioenergy and woody biomass production: A regional case study from Cumbria. Energ Policy 2012;40:293–300. URL: https://doi.org/10.1016/j.enpol.2011.10.009; accessed date 1 June 2019.

[77] Blanco-Canqui, H.. Growing dedicated energy crops on marginal lands and ecosystem services. Soil Sci Soc Am J 2016;80(4):845–858. URL: https://doi.org/10.2136/sssaj2016.03.0080; accessed date 1 June 2019.

[78] Pulighe, G., Bonati, G., Colangeli, M., Morese, M.M., Traverso, L., Lupia, F., et al. Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean regions. Renewable Sustainable Energy Rev 2019;103:58–70. URL: https://doi.org/10.1016/j.rser.2018.12.043; accessed date 1 June 2019.

[79] Shortall, O.. "Marginal land" for energy crops: Exploring definitions and embedded assumptions. Energ Policy 2013;62:19–27.

[80] Gerwin, W., Repmann, F., Galatsidas, S., Vlachaki, D., Gounaris, N., Baumgarten, W., et al. Assessment and quantification of marginal lands for biomass production in Europe using soil quality indicators. SOIL 2018;4:267–290.

[81] Foley, P., Crosson, P., Lovett, D., Boland, T., O'Mara, F., Kenny, D.. Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. Agriculture, Ecosystems & Environment 2011;142(3-4):222–230. URL: https://doi.org/10.1016/j.agee.2011.05.010; accessed date 1 June 2019.

[82] Edwards-Jones, G., Plassmann, K., Harris, I.. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. J Agric Sci 2009;147(6):707–719. URL: https://doi.org/10.1017/S0021859609990165; accessed date 1 June 2019.