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A holistic view of biomethane: Insights from a systematic review of biomethane in Ireland

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Abstract

Biomethane is gaining traction as a possible renewable alternative to fossil gas. Due to its interconnection with food and waste systems and the decentralised nature of its production it is a complex energy source that should be considered within the broader energy-environment-society nexus it occupies. To map this complexity, we conduct a systematic review of research on biomethane in Ireland from which we develop insights on biomethane that go beyond the Irish context. Our research complements existing cross-country studies which, due to their geographic scope, have focused more on specific elements of the biomethane life cycle than the interplay between them. We find that the national context substantially shapes the potential for and impacts of a biomethane industry. However, even within a single-country context, there is strong uncertainty around the scale of biomethane's energy and carbon abatement potential. Our research also highlights the importance of a socio-ecological systems level analysis of biomethane as it has wide-reaching positive and negative social and environmental impacts that, at least in the Irish case, have so far been understudied. Finally, we highlight the need for a long-term vision of the space biomethane will occupy in an energy system since it is frequently portrayed as an interim solution until other technology matures.

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1 Introduction

Energy use contributes 73.2% of global greenhouse gas emissions [99] and is therefore the main target of decarbonisation measures. While electrification and the generation of low-carbon electricity through renewables is considered the cornerstone of this process [58], modern bioenergy[1] is estimated to contribute as well [58, 20]. This is due to its ability to act as a direct substitute for fossil fuels, often without requiring major adjustments from the end user, making it a candidate for hard-to-abate sectors [58]. At the same time, the use of waste, for example through use of livestock waste, means it can not only reduce energy emissions but emissions from other sources as well. However, bioenergy

[1] Modern bioenergy refers to biogases, including biomethane, liquid biofuels, and other more recent ways of consuming energy from organic materials. [58, pp. 56 & 77]

remains controversial due to the scope of negative consequences in the case of poor implementation. This includes emissions from land use change, impacts on biodiversity, land being unavailable for food crops, and infringement of the rights of Indigenous Peoples, among others [15, p. 88].

Biomethane is one such bioenergy source which is gaining increasing attention due in part to its ability to directly substitute for fossil/natural gas. Biomethane is an upgraded form of biogas, a gas that is typically produced through anaerobic digestion (AD) of organic feedstocks, including the organic fraction of municipal solid waste, energy crops, and livestock waste. The biogas obtained in this way consists mainly of methane (50-70%) and carbon dixoide (30-50%) [5]. It then undergoes a process of cleaning and upgrading, resulting in a gas that is over 95% methane [5]. This so-called biomethane is virtually identical to fossil gas and can therefore be used in existing fossil gas networks or in other applications currently using fossil gas.

Even though the production of biomethane is technologically mature [38], it currently only makes up 0.1% of total gas demand worldwide [57, pp. 21]. However, upgrading of biogas to biomethane has become increasingly attractive given improvements in upgrading techniques and a limited market for the heat produced when burning biogas for electricity generation [103], as well as the recently high gas prices. Several countries have now set medium-term targets for biomethane production [59, pp. 137-140] and the International Energy Agency (IEA) has identified a global biomethane potential of 730 Mtoe based on feedstock availability [57, p. 6]. Given these developments, and the enormous potential for growth in biomethane production, it is important to map the debate surrounding biomethane in order to inform decisions on if and how to pursue this path.

Past reviews of the scientific literature on biomethane have generally presented in-depth assessments of defined elements of the biomethane life cycle, rather than cross-cutting socio-economic and environmental considerations. For example, there have been a large number of reviews investigating the benefits of feedstock choice and pre-treatment [138, 127, 72, 74] as well as biogas production and upgrading technologies [90, 102, 5, 98, 89, 72, 81].

However, reviews drawing on research in a large number of country contexts are not able to address the complexities and uncertainties that emerge from a holistic, spatially situated approach. This is demonstrated by the fact that the few reviews which do address broader environmental and social concerns limit their analysis to a small number of countries [see e.g., 104, 139].

This is in part because the implementation of a biomethane industry is inherently country specific. For example, the growth of energy crops depends on a country's climate and soil conditions [118, p. 2038]. Additionally, the desirability of a biomethane industry likewise depends on a country's existing (gas) infrastructure and policy landscape [96, 115].

As a result, understanding the interplay between different elemnts of the biomethane lifecycle and mapping key research themes, points of contention and research gaps or omissions requires country-specific research. This is what we aim to do with this systematic review of research on biomethane in Ireland. While the initial findings are specific to the Irish context, we broaden the analysis and identify wider key themes and debates as they emerge from the review. These are of interest to researchers, policymakers, and stakeholders in different national contexts.

Ireland has only recently developed a National Biomethane Strategy [28] and represents an interesting case study since it is a country with a large agri-food sector, especially as regards livestock [27]. As such, there is a need to reduce emissions from agriculture to comply with EU climate targets [50, 51] but there is also a high availability of animal manure and grassland as feedstock for biomethane production [92]. Nevertheless, the biomethane industry in Ireland is currently very limited, with only one injection point into the gas grid up and running [45, p. 18]. Yet, importantly for our research, the literature on biomethane in Ireland is well-developed, providing a strong basis for a systematic review.

To holistically map the energy-environment-society nexus that a biomethane industry would occupy in Ireland, we review the potential of biomethane based on feedstock availability, different end uses, possible infrastructure constellations, costs, and wider environmental, social, and economic sustainability considerations. Section 2 presents the systematic literature review methods. Section 3 outlines the results from the review, presenting an in-depth analysis of each of the key themes split between the spatially-situated findings in an Irish context and the overarching findings that transcend the country context. In section 4, we discuss the wider implications of our findings and conclude.

2 Methods

For this study, we included both peer-reviewed academic articles listed in the Web of Science and grey literature. Although grey literature can be considered of less consistent quality, since it usually does not undergo peer review and can represent vested interests, we chose to include it here since much of the research done on biomethane in Ireland has been conducted by state or other non-academic bodies.

Different search mechanisms were employed for the different document types (see figure 1). For the academic articles, the Web of Science was searched for the search string ‘Biomethane AND (“Ireland” OR “Irish”)’. This relatively simple search string was used with the aim of capturing all articles related to biomethane in an Irish context and yielded 221 articles. For the grey literature, the term ‘Biomethane Ireland’ was searched in both Google and Ecosia to identify the organisations that provided information on biomethane and their websites were subsequently searched for publications. The publications found through this process were saved if they fulfilled certain base inclusion criteria (see table 1).

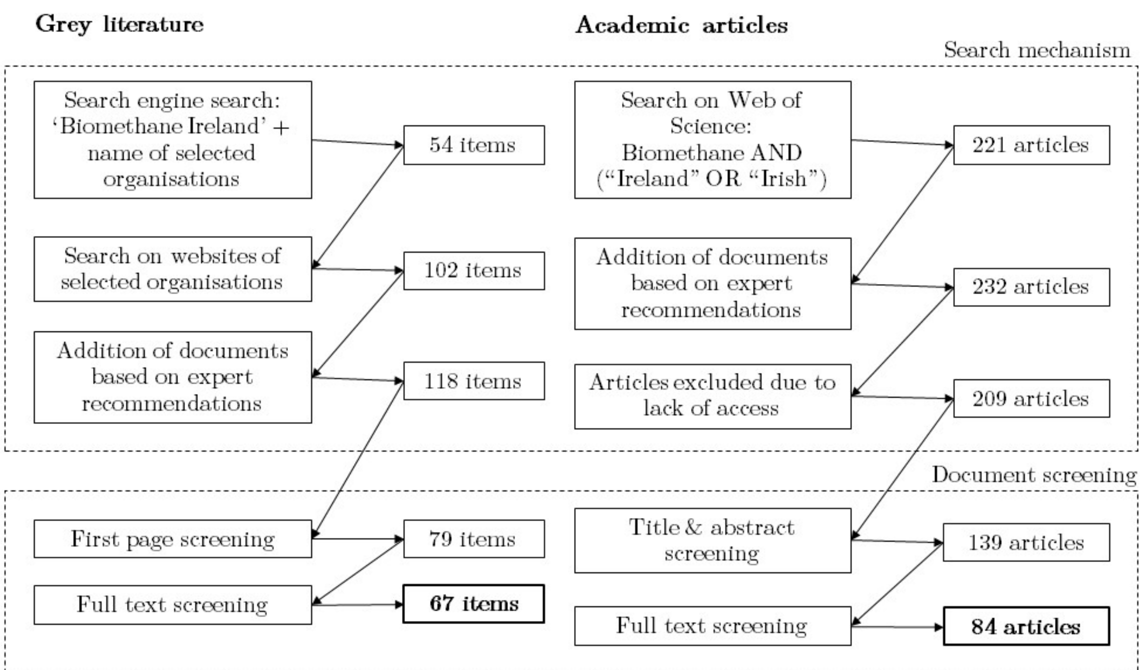

Figure 1: Sampling and screening process for the systematic literature review. The ‘selected organisations’ were identified through a first search engine search using the keywords ‘Biomethane Ireland’.

Table 1: Inclusion and exclusion criteria for the search process and document screening

	Grey literature	Academic articles
Search	Inclusion criteria: • Published documents • From official website of a selected organisation • Focus on Republic of Ireland • Most up-to-date version of regularly published reports etc. Exclusion criteria: • News articles, blog posts, sponsored links, academic articles • From websites not connected to selected organisations • Older versions of reports etc.	Inclusion criteria: • Reference to biomethane and Ireland Exclusion criteria: • Published after December 2023 • Unable to access article
First screening	Inclusion criteria: • Analyses biomethane in Ireland from an economic, social or environmental perspective • For grey literature: research-based reports or policy documents Exclusion criteria: • Purely engineering paper with no immediate societal implications • Slide deck	
Full-text screening	Inclusion criteria: • Analyses biomethane in Ireland from an economic, social or environmental perspective Exclusion criteria: • Does not specifically research the Irish context • Only looks at biogas without specific reference to biomethane as a separate product	

Then, two rounds of document screening were conducted. First, title and abstract were screened for academic articles and the first page for the grey literature, followed by a full text screening. Table 1 presents the inclusion and exclusion criteria at each step of the process and figure 1 illustrates the number of publications eliminated. The final sample consisted of 67 grey literature documents and 84 academic articles.

The documents remaining after the full-text screening were initially coded deductively. We used a coding structure which covers all stages of the biomethane life cycle as well as the various impacts that might arise from a biomethane industry (see table 2 for an overview and Appendix A for the full code book). The results were largely the original findings of the reviewed literature, but in some cases the reviewed articles act as secondary sources if they cite an original article that is not included in the sample because it does not fulfill the selection criteria. For the second stage of coding, all the coded segments within each category were collected and themes identified inductively within each code. These themes are both a finding in and of themselves and form the structure for the analysis (an overview can be found in Appendix B). They give an overview of the key questions surrounding the development of a biomethane industry. Finally, overarching insights were developed inductively from the findings within the themes. While the details of the implementation are likely country-specific and function more as a case study, we expect the themes and overarching insights gleaned from them to be applicable to other country contexts, some more broadly, while others likely apply mainly to countries which are similar to Ireland in certain characteristics, depending on the findings.

Table 2: Coding structure for the documents selected for review

Biomethane life cycle	Possible sources of biomethane Possible uses of biomethane Storage requirements for biomethane
Costs & impacts	Costs of biomethane production and use Carbon abatement potential Abatement costs for biomethane Other effects of biomethane production and use

3 Results

This section is structured according to the major codes with the exception of abatement cost, which is integrated into a combined section due to low numbers of results. For each code, the inductively developed themes are presented with their findings, followed by the overarching insights.

3.1 Biomethane feedstocks in Ireland

This section presents the results of the sub-theme "feedstock availability, distribution, and characteristics", which was identified under the code "sources of biomethane". This theme combines research on the different types of feedstocks of relevance for Ireland and their overall theoretical and practical availability, which is the basis for assessing a country's overall biomethane potential. Other themes and sub-themes from the "sources of biomethane" code were found to align better with other sections and are presented there (see Appendix B for an overview).

3.1.1 Feedstock availability, distribution, and characteristics

Biomethane can be produced from organic waste and/or energy crops. Energy crops include food crops, e.g., beets, as well as grass (silage). Although there was initially some research into using food crops for biomethane production in Ireland [3, 49, 88, 85], more recent analysis has shifted away from considering them as a biomethane feedstock. This is partly due to the low and declining share of tillage land in Ireland, making the remaining crops more desirable for use as food or fodder [114, p. 40]. Additionally, the use of food crops for energy has come under global scrutiny for putting pressure on food systems and for concerns over negative environmental impacts [65, p. 8].

Grass, or specifically grass silage, has garnered a lot of attention in Ireland for use as biomethane feedstock due to the fact that 60% of the total land area of Ireland is grassland [21]. Currently, this land is used for grazing, and feed during the winter months. The grass for biomethane is expected to be made available either by an intensification of land use and/or a reduction in the livestock herd, freeing up grass for other uses [117, 128, 31, 55, 107, 114]. Estimates of the amount of energy this excess grass can provide as biomethane vary widely across the reviewed literature, however, the majority of publications calculate an amount between 0.6 and 6.3 TWh/year, with a small number estimating much higher amounts. The variation is due to different assumptions for grass yield per hectare, the area of grassland available, and whether economic/logistical factors are taken into consideration. Economic/logistical factors in particular make a substantial difference, meaning practical estimates are generally much lower than theoretical ones. Grass yield assumptions are largely a factor of land management, in particular fertilizer application, while grassland availability depends on the area released, due to changes in the size of the national herd, or excluded, for environmental or suitability considerations. Economic and logistical factors primarily include distance to the gas grid, economic incentives provided, and overall financial viability of AD and biomethane upgrading plants.

Aside from energy crops, organic waste has the potential to contribute to biomethane production. Along with grass silage, waste products are considered 'second-generation' feedstocks as they do not require land to be diverted from food production. The waste feedstocks most frequently discussed in the reviewed literature are animal slurry and manure. These have a large theoretical potential in Ireland due to the structure of the agricultural sector, with significant meat and dairy production [22, 23]. The total theoretically possible slurry and manure resource could provide about 4 TWh/year [129, 9] whereas the total practical energy is estimated to be around 0.5 TWh/year [129, 107]. The two main reasons for this drop from theoretical to practical resource are 1) the low energy density of slurries and the large number of small farms, meaning much of the resource is not accessible economically and 2) the long grazing period of cattle and sheep during which slurry is not collected [107, p. 55; 68, p. 39].

In addition to this, industrial process waste, the organic fraction of municipal solid waste (OFMSW), and sewage sludge are considered as feedstocks for biomethane production in Ireland. The industrial process wastes which have been analysed in the reviewed studies primarily include milk processing and slaughterhouse waste [13, 129, 31, 84, 3, 93, 94, 64, 30, 114].The only study making a quantitative estimate of the energy potential of milk processing waste puts it at 0.05 TWh/year based on data from the largest facilities [3]. For slaughterhouse waste, estimates of theoretical potential are consistently between 0.3 and 0.4 TWh/year [31, 84, 93], while the practical potential ranges between 0.04 [30] and 0.1 TWh/year [31]. This is likely due to the restrictions placed on animal by-products and the use of processed animal protein and fats for bio-diesel production [13].

OFMSW mainly represents food and garden waste from domestic and commercial premises. At about 180 kg of waste per person and year [32][2], this is a substantial resource: the theoretical potential is estimated to be between 0.59 [3] and 0.97 TWh/year [84], with the majority around 0.69 TWh/year. The practical potential, constrained by the number of households and commercial premises with access to food bins and the percentage of food waste sorted into these bins, is estimated to be in the range of 0.16 [13] to about 0.37 TWh/year [114, 2030 estimate] with values increasing over time as uptake improves [107]. This increased uptake is partly due to government policy which aims to reduce

[2] This has since fallen to 146kg [34].

the amount of OFMSW going to landfill, although the majority is diverted to composting, not AD [9, p. 3].

Sewage sludge is a by-product of wastewater treatment which is high in energy and therefore an attractive feedstock for anaerobic digestion. Biomethane upgrading might be of interest to larger plants (>100 Nm3/h) but is less likely to be viable for smaller ones [62, p. 10], but there is no current assessment of possible biomethane potential.

Finally, where organic waste has been landfilled, landfill gas develops directly in the landfill sites and can be collected and upgraded to biomethane as well. This is not an efficient use of organic waste if other options are available, but is an attractive option where landfilling has already occurred [24; 65, p. 8].

Seaweed is another possible feedstock in Ireland. Due to eutrophication, large blooms of seaweed wash up on beaches along the the east coast of Ireland [2]. This beach cast seaweed is typically removed from beaches due to its strong smell. As such, it is a waste product which can be used for AD. However, to scale up biomethane production from seaweed, most research suggests cultivation, in which case seaweed would act as an energy crop. The exact potential of cultivation so far remains uncertain, with a wide range of estimates from 19 - 700 GJ/ha/a [4, 3, 121, 122].

Figure 2 summarizes the various energy potentials from these feedstocks as identified in the reviewed studies. It is clear that biomethane from grass silage is associated with the highest biomethane potential with a practical resource of anywhere between 1 and 13 TWh/year from grass silage alone. If only biomethane from waste products is used, the total energy available from biomethane is much lower, likely around 1 TWh/year.

3.1.2 Overarching findings from the reviewed literature on biomethane feedstocks in Ireland

From these results we identified a few overarching findings which likely apply beyond the Irish context as well. The first is the large discrepancy that often appears between theoretically possible and practically accessible feedstock amounts. Depending on the economic, technical, logistical, and other factors taken into consideration, even assessments of what is practically feasible diverge widely. This is most starkly seen in the case of grass silage in the Irish case but applies to waste as well. For example, the amount of OFMSW available is dependent on the uptake of waste separation.

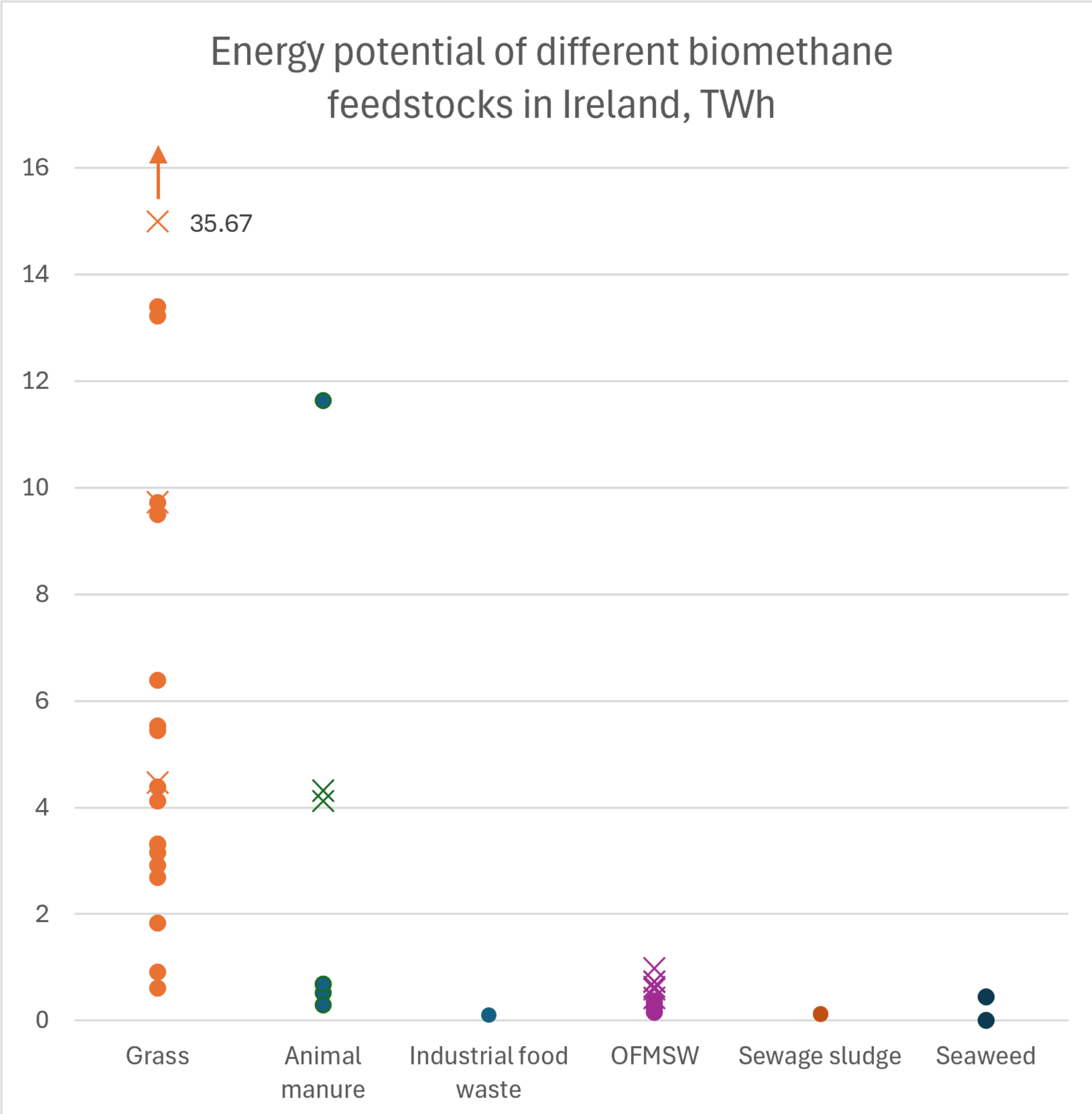

Figure 2: Energy potential from the different available biomethane feedstocks in Ireland. Each marker represents one estimate from one of the reviewed papers. Where papers assessed different scenarios, multiple markers were typically included. Crosses are theoretical or technical availability, dots are practical or economic availability, taking into consideration logistics, uptake, and/or economic viability.

Second, over time research has moved away from so-called 'first generation' feedstocks, which refers to energy crops in direct competition with the use of land for food production, and towards 'second generation' feedstocks which do not directly compete for land. The latter include waste products, but often lignocellulosic materials such as grass silage, which have a land footprint but are not seen as competing directly with food crops, are considered as second generation as well.

Third, the energy potential from energy crops, here mainly grass silage, far exceeds the potential from waste products. As a result, they have received significant research attention. However, the use of energy crops may have environmental disadvantages and therefore energy potential should not be the only criterion to consider (see sections 3.5 and 3.6).

Finally, this section highlights the importance of considering biomethane development within a national context. The parameters and assumptions used to assess feedstock potential are often country-specific. For example, livestock-related feedstocks play a major role in Ireland due to the importance of livestock, and, in particular, beef and dairy farming in Ireland. This includes grass silage from pastures and animal manure, but also wastes from slaughterhouses or milk processing plants. Similarly, the time cattle spends grazing outdoors reduces the availability of slurry, and legislation on landfills and composting affects how much OFMSW is available for biomethane production.

3.2 Uses of biomethane in Ireland

Biomethane is virtually identical to fossil gas and its end uses therefore align with the end uses of fossil gas. The themes identified are: (1) Power generation, (2) heat, (3) transport, and (4) other uses. For each of these end uses we present findings on specific uses that are particularly suited to biomethane, what the technical requirements are, how much demand for biomethane there could be and whether biomethane could meet this demand. Additionally, one theme identified in the academic literature was an ongoing debate on the use of biomethane in transport as opposed to its use for heat based on the Renewable Energy Directive (RED).

3.2.1 Biomethane for power generation

Power generation is currently the largest source of demand for fossil gas in Ireland, but this is assumed to fall over the coming years, largely due to the expansion of wind and solar power generation [46, p. 37]. The power sector is therefore not identified by the literature as a priority for biomethane use in the long run [31, 76, 112]. Very few of the reviewed sources consider the use of biomethane for power generation and none in great detail.

3.2.2 Biomethane for residential and industrial heat

Most of the reviewed documents considering biomethane for heat see the role of biomethane primarily in providing high-temperature heat to energy-intensive industries which cannot electrify or otherwise decarbonise easily, such as the cement industry, as well as hard-to-decarbonise buildings [see, e.g., 52, 112]. However, this role is somewhat dependent on technological developments, notably on hydrogen, policy decisions on technology support, and alternative technology options, such as high temperature heat pumps [113].

The use of biomethane for heat requires limited changes to the gas network. For end users that are off the gas grid, transportation of containerised biomethane in trucks would likely have to be developed [141, 112]. Where biomethane is injected into the gas grid, renewable gas certificates are used to assign it to a specific end use [40, p. 165].

Current fossil gas demand for heat in industrial, commercial, and residential use in Ireland is around 25 TWh/year [46, p. 37], with 15.1 TWh/year from industry and 7 from residential use [112, p. 24]. As outlined in the reviewed studies, demand for biomethane will depend on both the development of demand for gas for heat, and on the roll-out of alternatives, primarily hydrogen, to meet this demand. The scenarios the Sustainable Energy Authority of Ireland (SEAI) has developed for low-carbon gas demand range from a maximum demand of around 30 TWh/year, if the focus is put on decarbonising gas, to a minimum of 5 TWh/year, under high electrification [112]. In these scenarios, hydrogen is introduced in the 2030s and becomes the dominant low-carbon gas since it represents a scalable alternative [112]. A small role for biomethane could remain in the transport of containerised biomethane to off-grid locations [112].

3.2.3 Biomethane for transport

The reviewed literature concurs that the best use of biomethane in transport is for heavy duty vehicles, such as long-haul heavy goods vehicles (HGVs) and long-distance buses as these consume a disproportionate amount of energy[3] and currently have no viable decarbonisation options [46, 45, 78, 109, 53, 48]. The reviewed literature estimates that battery electric and hydrogen-powered HGVs will likely only become available around 2030, so biomethane is considered an interim solution for a 10-15-year period [45, p. 35; 109; 53]. Additionally,

[3] While HGVs and buses only made up 4% of registered vehicles in 2021, they emitted about 20% of total CO2 emissions from transport [46, p. 35].

some sources point to the benefits of using biomethane in local transport around biomethane upgrading plants [24, p. 146; 10].

To use biomethane in transport, additional fuelling and transport infrastructure will be required, as well as compatible vehicles. This is outlined further in section 3.3.3.

Energy demand from HGVs was 9.26 TWh in 2021, 19.1% of transport final energy demand [111, p. 54]. However, the use of fossil gas, let alone biomethane, in transport is so far very limited. Forecasts of future demand in the literature vary. [82] calculate a demand of between around 3.5 and 10.5 TWh/year by 2050. However, they assume uptake of biomethane by light goods vehicles (LGVs) which is unlikely given that LGVs have alternatives, such as battery electric power. A study commissioned by Gas Networks Ireland estimates a peak at around 3 TWh/year in 2035 with a relatively smooth increase to the peak from 2020 and a similarly smooth decrease thereafter until 2050 due to zero-emission options taking over around that time [45, p. 13]. A further study recommends aiming for 5 TWh/year of biomethane in heavy transport in order to achieve a 51% reduction in transport emissions by 2030 [78, p. 4]. Overall, a maximum peak demand between 3 and 10 TWh of biomethane can likely be expected from the transport sector.

3.2.4 Use of biomethane in transport vs heat in the Renewable Energy Directive

Along with technical considerations, decisions on the end use of biomethane are shaped by legislation. A few of the reviewed academic studies point to the role of the Renewable Energy Directive [RED; 75, 76]. The authors argue that the RED encourages biomethane use in transport. They reason that emissions savings criteria in heat include the full life cycle, whereas for transport the emissions savings are calculated from cradle to tank, without including the conversion efficiency of fossil gas engines in the calculation [75, p. 9]. Additionally, the requirements for emissions savings from heat are higher (80% for installations starting operations from 2026) than for transport (65%) [75, p. 10]. As a result, biomethane for use in transport cannot exceed emissions of 32.9 g CO2eq/MJ, whereas for heat this is 14.4 g CO2eq/MJ [76, 75]. This creates an economic incentive for use in transport that is not fully connected to actual emissions savings.

3.2.5 Overarching findings from the reviewed literature on end uses of biomethane in Ireland

One overarching theme identified is therefore the interim position biomethane occupies as an energy source, which is likely to apply outside of the Irish context as well. Across possible applications, biomethane is identified as a relatively quick solution for hard-to-abate uses, such as for HGVs and high-temperature heat in industry, but only until other technological options mature. Consequently, since wind and solar power are already mature, power generation has received less attention from the reviewed literature. Once options such as hydrogen, high-temperature heat pumps or electric HGVs develop, biomethane is likewise predicted to cease being the first choice for industry and transport. The reasons given for this are the lack of scalability due to limited feedstock supply and the fact that it is not considered a zero-emissions energy source, unlike hydrogen and electricity. Much of the reviewed literature then expects the use of biomethane to be phased out as the alternatives are phased in, although a small role for biomethane in heat might remain in supplying containerised biomethane to off-grid locations.

3.3 Biomethane infrastructure and logistics in Ireland

In this section, the results of the overarching technology & infrastructure theme from the 'sources of biomethane' code will be presented together with some infrastructure-related insights from the 'uses of biomethane in Ireland' code. These components are clustered to provide a comprehensive overview of the infrastructure and logistical requirements for a biomethane industry in Ireland. While this topic was not specifically coded for during document analysis, it emerged as a relevant theme within several different codes. Three different sub-themes were identified: (1) Location of anaerobic digesters and biomethane upgrading units, (2) injection into the gas grid, and (3) integrated (circular economy) systems.

3.3.1 Location of anaerobic digesters and biomethane upgrading units

With the exception of pig and poultry farming, farms in Ireland are generally small, dispersed, and often located more than 10 km from the gas network [106, p. 19; 140; 43; 68, p. 39; 141, p. 10]. This creates logistical issues for farm-based feedstock as it is neither economically nor environmentally viable to transport cattle and pig slurries or grass silage over long distances [107, 110, 44, 114].

This is due to its generally high liquid content and low energy density, with a maximum haulage distance of 10 km recommended [107, 110]. As a result, AD plants may have to be located close to farms rather than the gas grid. Biomethane upgrading must consequently occur through on-site upgrading, mobile upgrading, or through transport of biogas to a centralised upgrading plant [92, p. 255]. For other feedstocks, energy densities are usually higher, allowing for longer transport distances and more flexibility with the placement of AD and upgrading plants [94].

3.3.2 Injection into the gas grid

Two main approaches to injecting biomethane into the gas grid are discussed in the reviewed literature. The first option, for cases where a biomethane plant is located close to the gas grid, is direct grid connection [43, 46, 41, 118].

If this is not possible or desired, plants at a greater distance from the gas network can make use of the so-called virtual pipeline, namely trucks transporting containerised biomethane to a central grid injection point. A variant of this option is mobile upgrading, where biogas is collected from AD plants by a mobile upgrading unit which then transports the upgraded biomethane to a grid injection point, although at the cost of significantly higher emissions [140].

Wider questions on the availability of the gas network to biomethane are considered by some of the reviewed sources as well. This includes whether the gas grid will convert to hydrogen in the long run, and what options this leaves for biomethane usage of the grid [45, 112], or whether parts of the grid itself will be decommissioned over time, leaving containerised biomethane transport through trucks as the most prominent option [120, pp. 18-19].

3.3.3 Use in transport

There are different pathways through which biomethane can be used in transport. However, most of the reviewed documents focus on the potential to replace compressed natural gas (CNG), likely due to the comparative ease of implementation. For use as bio-CNG, biomethane can be supplied to a fuelling station directly from an upgrading plant, by transport via the gas grid, or by trucking of compressed biomethane in cylinders [48, 67, 13, 31]. In all cases, biomethane must be compressed to upwards of 200 bar for use in CNG vehicles [88, 31]. A hurdle identified by most authors is the current lack of refuelling infrastructure and CNG vehicles in Ireland [49, 129, 48, 78, 76, 75].

3.3.4 Integrated (circular) systems

In addition to the standard biomethane production pathways, many of the reviewed articles suggest integrated systems which combine biomethane production with other production processes, often in an attempt to maximise resource use and valorise by-products.

One frequently discussed option is the biomethanation with hydrogen, or 'power to gas' pathway [60, 1, 77, 133, 134, 132, 76, 67, 54, 100, 33]. In this pathway, hydrogen is combined with the carbon dioxide present in biogas to increase the biomethane produced. This is seen as a way to make use of the CO2 by-product while increasing biomethane production as well as using otherwise curtailed electricity [133, 76].

Another variation on the upgrading step is microalgal, or photosynthetic, upgrading [11, 137, 134]. In this case, the carbon dioxide to be removed during upgrading is fixed by microalgae, which in turn can be used as a feedstock for biogas or as a food source [11, 137].

Other systems, such as integrated AD and pyrolysis systems for the production of biochar [100, p. 11], or the integration of gasification and AD [134], have also been proposed. The feasibility of these variations will likely depend on a case-by-case analysis for each planned biomethane production project but could potentially provide significant greenhouse gas emissions savings along with other economic and environmental benefits.

3.3.5 Overarching findings from the reviewed literature on biomethane infrastructure and logistics in Ireland

This section again highlights the country-specific considerations related to biomethane roll-out. Where low-energy density agricultural feedstocks are used, the location of farms as well as the extent of the existing gas grid majorly affect the availability of resources and the costs of transporting biomethane. While most of the reviewed studies rely heavily on the existing gas grid for the distribution of biomethane, questions on the long-term viability of this option emerge. The replacement through hydrogen or the decommissioning of (sections of) the gas grid would mean producers and consumers have to rely on transport through a 'virtual grid', changing the associated costs and emissions. Such a long-term perspective will be relevant in other countries with an extensive existing gas grid as well, although a lower reliance on agricultural feedstocks may lead to more flexibility in locating biomethane plants.

3.4 Cost of biomethane production and consumption in Ireland

Several themes were identified in the code ‘cost of biomethane production and consumption in Ireland’. These were (1) CAPEX, (2) OPEX, (3) the cost/price of biomethane, (4) the overall profitability of biomethane production, and (5) financial support for biomethane production. Additionally, the results of the sub-theme ‘feedstock cost’ from the code ‘sources of biomethane’ was included in this section under ‘OPEX’. The five themes cover the major sources of costs to biomethane producers and consumers as well as the economic viability of biomethane production and financial support measures.

3.4.1 CAPEX for AD, cleaning, upgrading, and transportation to place of end use

Most values for the specific CAPEX calculated from the reviewed literature fall between 1.5 and 4 million € / MW (see specific CAPEX in Figure 3). Due to economies of scale, the specific CAPEX decreases as throughput increases.

The cost for the anaerobic digester is the largest component, upwards of 60% of the CAPEX [136, 13]. As a result, factors affecting the cost of the anaerobic digester, such as digester size, feedstock type, and technology [13, pp. 4541-4542] have a substantial impact on overall CAPEX. The costs for cleaning and upgrading comprise between 15 and 30% of total CAPEX, a function of technology used and scale of the upgrading plant. Compression and distribution, including connection to the grid, where applicable, make up a small proportion of the overall cost, only around 5%, with values ranging between 0.1 million € and just under 2 million €, depending in part on the type of distribution selected and distance to the grid, as well as whether injection is into the distribution network (lower cost) or the transmission network (higher cost due to higher compression).

3.4.2 OPEX for AD, cleaning, upgrading, and transportation to place of end use

The OPEX of biomethane production is composed of a range of main expenses, namely feedstock costs, energy costs, overhead and cost of capital. The costs from these components vary with the scale of biomethane production, the type(s) of feedstocks used and the technology deployed. As with the CAPEX, the OPEX benefits from economies of scale [see e.g., 106]. The cost of feedstocks displays

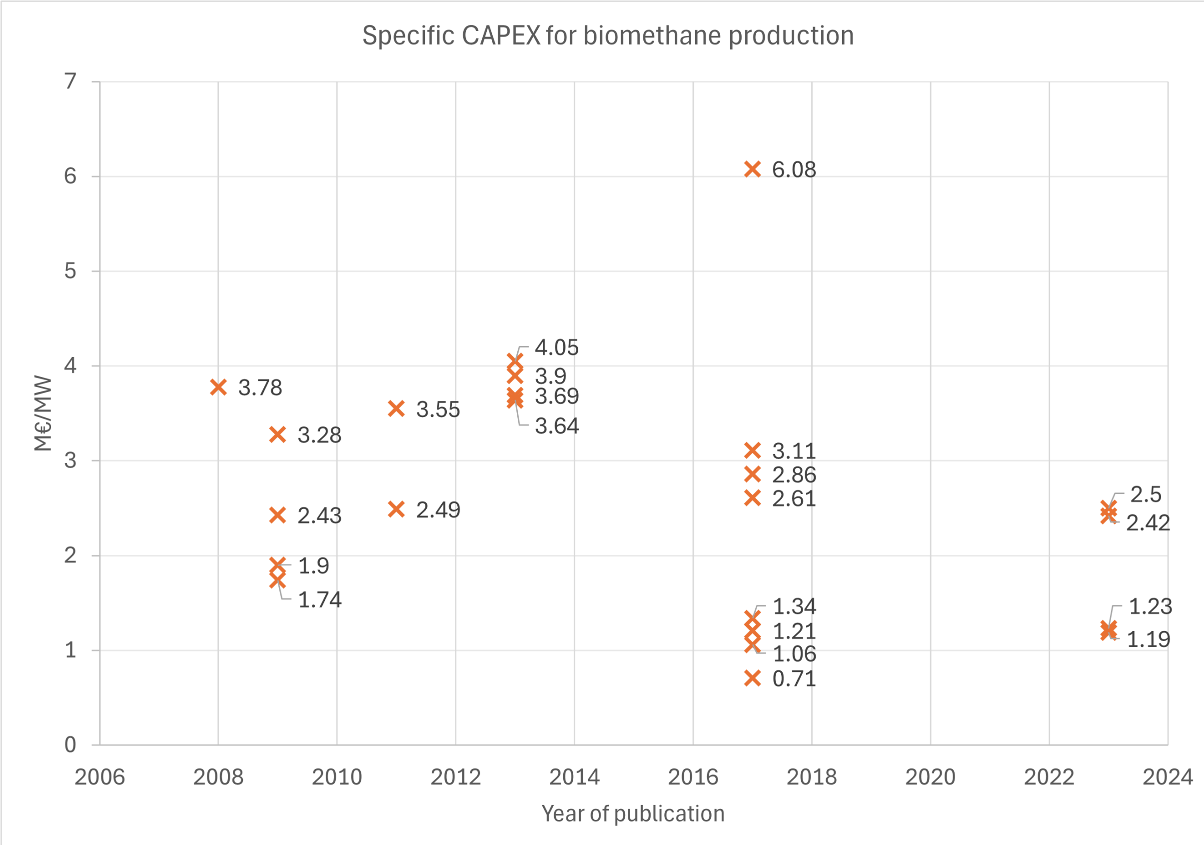

Figure 3: Specific CAPEX for AD, cleaning, upgrading, and transportation to place of end use. Source: Largely own calculations based on cost and capacity figures from the reviewed literature. The year on the x-axis represents the year of publication of the reviewed studies.

a particularly wide variation, with food waste estimated to bring in a gate fee of up to around 70 € per tonne [83, 13, 94], while animal manure is considered to be largely free, with the exception of transport costs [43, 56, 92, 107, 106, 32, 11, 114, 95], and the purchase of energy crops incurs costs of up to 100 € per tonne [see e.g., 86] (see figure 4 for an overview of feedstock costs). Fluctuation in price according to technology is largely a question of reducing energy demand from upgrading facilities through novel technological approaches, although new components, such as hydrogen, can introduce new operating costs as well [see e.g., 137, 136]. The contribution of each of the four main cost categories to the total OPEX ranges between around 10 and 50%. If hydrogen is used for biomethanation, the cost of hydrogen dominates, making up over 60% of the total [136].

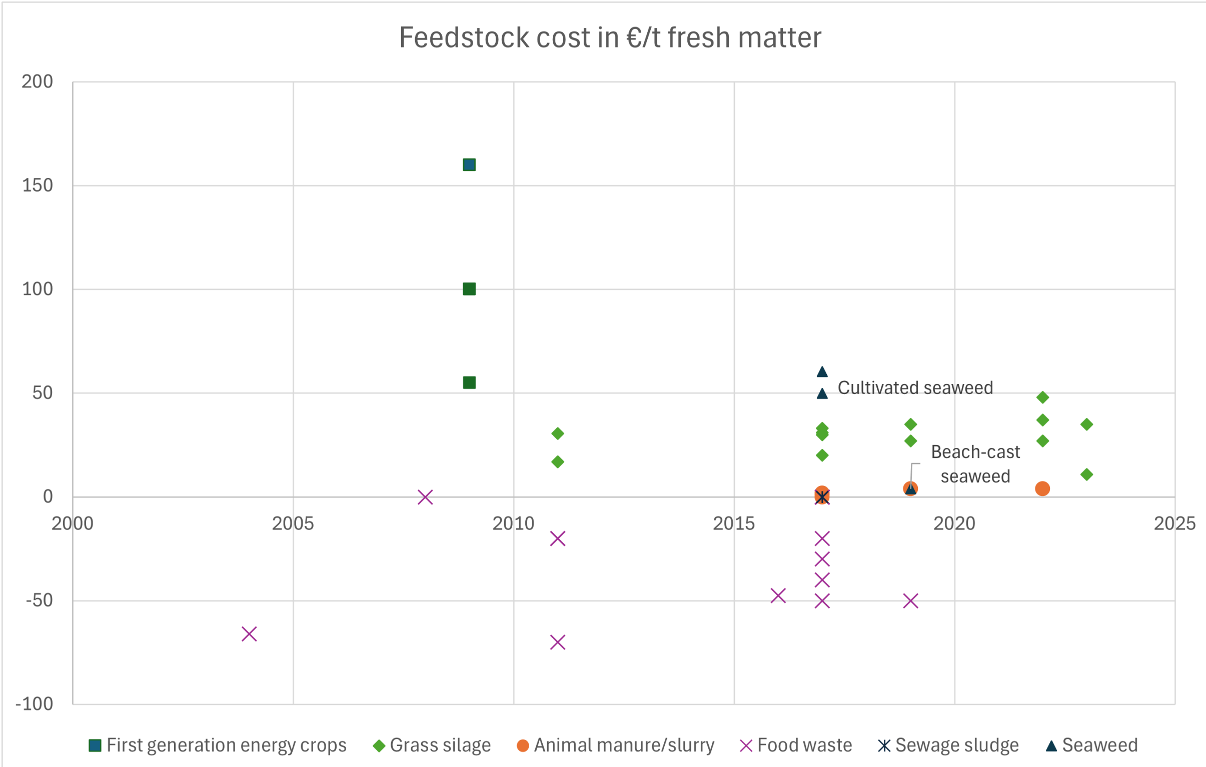

Figure 4: Feedstock costs taken from the reviewed literature. Where a document analysed a cost range, the median or average values were used. Source: Reviewed literature. The year on the x-axis represents the year of publication of the reviewed studies.

The reviewed studies calculate the specific OPEX as a function of either feedstock or energy generated, with values of around 50 - 100 € per tonne of feedstock [95, 86, 88] and generally around 1 € per cubic meter of biomethane [49, 88, 86], although these values rely largely on older sources.

3.4.3 Biomethane minimum selling price

The average minimum selling price (MSP), or levelised cost of energy, for biomethane, based on the reviewed literature, is 0.91 € per cubic metre of biomethane [86, 49, 123, 122, 133, 31, 79, 33, 136, 95, 112, 12, 73, 53, 132, 106, 92, 48, 13, 116, 32, 94, 24, 87, 122, 29]. The breakdown for the individual feedstocks can be found in figure 5. While there is some variation in MSP, about 80% of the estimates fall between 0.3 and 1.4 € per cubic metre, that is 2.84 and 13.27 €cents per kWh with a mean of 8.63. This is approximately double the wholesale fossil gas price since after the energy crisis in 2021-2023 [130].

The estimates from the literature are stable over time, however, they have not been adjusted for inflation. This may be the result of more recent calculations relying on older cost estimates or indicate a decrease in cost over time.

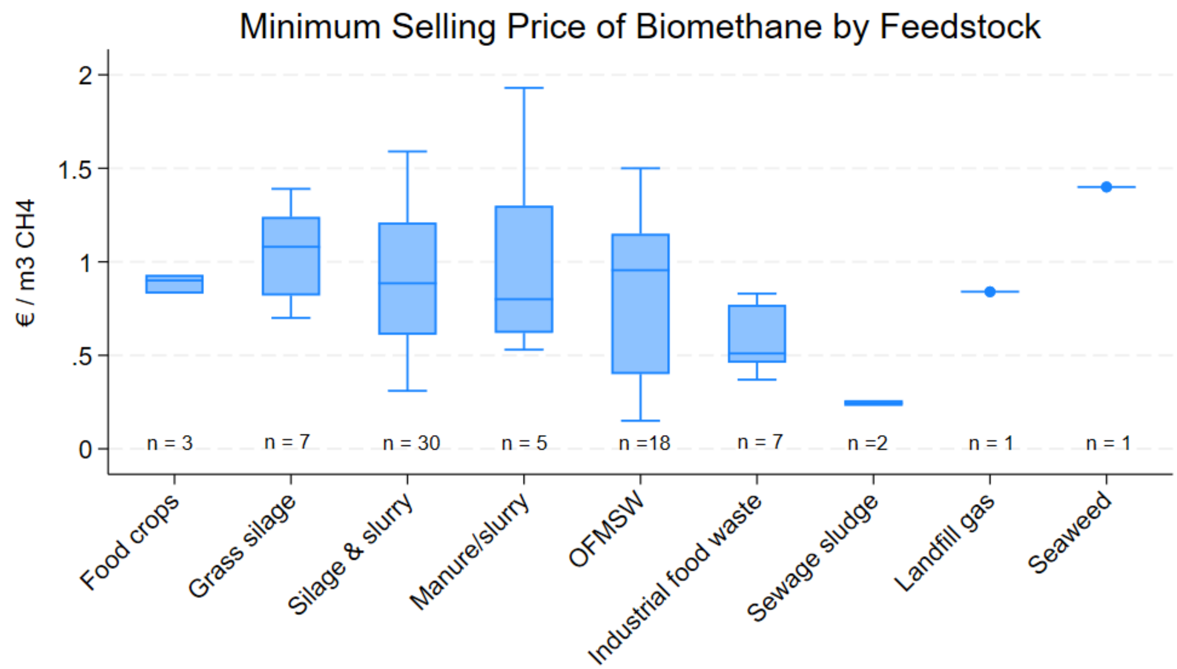

Figure 5: Minimum selling price of biomethane according to the cost estimates in the reviewed literature. Some values are not included in the graph as they could not be attributed to one of the feedstock categories. None of the values are adjusted for inflation.

3.4.4 Profitability of biomethane agriculture and production

At 30 € per tonne, grass silage for biomethane is not an attractive option economically for most farmers, as other land uses are more profitable [42]. Beef farms are the most promising candidates for such a switch as they have comparably lower profit margins while retaining good quality soil [42, 118].

Likewise, biomethane production is currently largely not economically viable without financial supports [116, 43, 92, 24, 49, 86, 68, 32, 106, 31], although some limited constellations present opportunities for profitable biomethane production. These are existing wastewater sludge [108, archetype BM H] as well as the broader category of integrated production systems which combine biomethane production with further processes, such as biorefinery or biomethanation using hydrogen, to improve the economics of the overall production process. These are presented as profitable in several analyses [11, 126, 132, 33] but still face significant uncertainty regarding the cost of inputs, primarily hydrogen but also electricity and microalgae nutrient medium, and the selling price of co-products, such as spirulina or biochar.

Across all reviewed studies, economies of scale meant that larger facilities were more likely to be profitable while smaller ones struggled, even under high financial support and low feedstock cost scenarios [95, 12, 92, 24, 84, 49, 32].

3.4.5 Financial support for biomethane production

As outlined above, the reviewed studies highlight the need for financial supports if a biomethane industry is to be developed in Ireland and several support schemes already exist. As part of the National Biomethane Strategy, the Irish government introduced capital grant supports for biomethane production [28]. On the demand side, vehicle gas, and therefore biomethane, is exempt from the excise duty on vehicle fuel and the Renewable Transport Fuel Obligation (RTFO) requires suppliers of road transport fuels to include a minimum of 21% of renewable transport fuels across their fuel mix [70].

Further to these policies, the government is developing a Renewable Heat Obligation. This policy will be similar to the RTFO but target heating fuel suppliers [28, p. 18].

In addition to these planned and existing policies, several policy suggestions are made in the reviewed literature to support the development of a biomethane industry. These include a feed-in tariff [68, p. 41; 123, p. 9; 108, pp. 38-41; 139, p. 5] and reduced interest rates for loans [139, p. 5]. Overall, the level of the financial support required was assessed to be between 33 and 103 €/MWh (i.e., 3.3 - 10.3 €cents per kWh) [32, 92]. Furthermore, several authors highlighted the need for a clear regulatory framework, for example regarding construction and operation of biomethane transport and injection facilities, and clearer information for biomethane producers [68, p. 41; 108, pp. 36-37; 139, p. 6].

3.4.6 Overarching findings from the reviewed literature on costs of biomethane production and consumption

An initial insight from this section is that the financial element of biomethane production has received a lot of attention, at least in Ireland, so there is a wide range of estimates to draw on even for countries in which limited prior research has been conducted.

However, as with previous estimates, for example in the case of feedstock availability, cost estimates vary widely. In this case, though, this does not seem to reflect uncertainty but rather the wide variation in technology, feedstock, scale, and transport arrangements which are possible.

Differences based on feedstock used show how country-specific differences in terms of feedstock availability carry through to the price. Nevertheless, estimates of the final selling price do not, for the most part, seem to differ significantly between feedstocks. This may be due to other factors outweighing the differences in feedstock costs or the range of scenarios assessed within each feedstock category.

In any case, multi-million investments will likely be required for any one set of biomethane production infrastructure, indicating significant upfront costs which have been frequently highlighted in the reviewed literature. Similarly, the operating costs are likewise in the region of a few million euro per year.

The reviewed literature shows that both energy crop production and the biomethane industry itself are generally not profitable, outlining the need for financial incentives with many different (complementary) instruments already in operation or suggested in the literature.

3.5 Abatement potential of biomethane in Ireland

Four themes emerged from the code ‘abatement potential of biomethane in Ireland’: (1) sources of emissions savings, (2) sources of emissions, (3) net emissions savings and (4) total abatement potential. Additionally, the results from the code ‘cost of carbon abatement from biomethane’ were included.

3.5.1 Sources of emissions savings from biomethane production and use

The emissions reduction achieved compared to fossil fuels depends mainly on feedstocks, technology and the end use of by-products.

Where waste feedstocks are used, the avoided emissions from other forms of waste treatment are a large contributor to overall emissions savings. For OFMSW, some of the reviewed literature highlights the emissions avoided had the waste had gone to landfill [76, p. 3; 129, p. 4645]. However, a 2017 SEAI report considers these savings to be negligible compared to composting [106, p. 46]. If animal manure or slurries are used, the estimated value for avoided emissions from their storage and land application ranges from 59.5 - 124.4 gCO2eq/MJ [36, 53, p. 17] for mono-digestion of slurry, with lower values of around 8 - 12 gCO2eq/MJ if co-digested with grass silage [114, p. 62; 92, p. 255].

If grass is used as a feedstock, the carbon sequestered by grassland is sometimes included as emissions savings [97; 42; 117; 88; 82; 142; 53; 136; 76; 114, p. 18; 44, p. 13; 31, p. 29] at a rate of approximately 22 gCO2e/MJ for biomethane from the mono-digestion of grass [based on the sequestration rate in [117, 142, 76, 84] and the calculation from 82, p. 60]. Additionally, if the land used and income gained from grass silage leads to a reduction in the national herd, this may reduce carbon emissions by around six times that of carbon sequestration [42, p. 6], although [117] highlights that there are likely indirect effects that could attenuate these benefits if consumption habits do not change.

At the other end of the process, the replacement of other, often emissions-intensive, goods with by-products from the biomethane production process can be a substantial contributor to emissions savings. The most commonly cited option in the reviewed literature is that of using digestate to replace mineral fertiliser, with savings of 12 kgCO2e per tonne of digestate [11, p. 6]. However, if slurry is used as a feedstock, digestate will not only replace chemical fertiliser but also slurry which would otherwise have been landspread as fertilizer, thus altering the associated emissions savings.

The main contribution to emissions reductions in most cases remains the displacement of fossil fuels. These savings depend on the fuel that biomethane is displacing, such as petrol for transport or fossil gas for heating. For example, [97] estimate a saving of 79 gCO2e/MJ for the replacement of petrol.

3.5.2 Sources of emissions from biomethane production and use

The emissions savings from biomethane are partially offset by emissions that occur as a result of biomethane production. For example, if digestate isn't used as replacement fertiliser, the production and use of mineral fertiliser to replace slurry can lead to greenhouse gas emissions [7, 114, p. 60], which the SEAI estimates to be around 7 gCO2e/MJ [114, p. 62].

Where energy crops are used as feedstock, their cultivation is a source of emissions. In particular, where an intensification of land use is pursued to achieve the required feedstock amounts [139, p. 9; 42, p. 9; 76]. The emissions from grass production are estimated to be around 19 g CO2e/MJ biomethane [31, 76]. The main share of such emissions arises as a result of (increased) use of fertiliser [139, 80, 142, 11, 136, 65, p. 7].

The emissions from parasitic energy demand of biomethane production and transport depend on a range of factors such as transportation distances and technologies employed, as well as the energy source used to satisfy parasitic demands. As a result, estimates vary widely, with values between 5 and 40 gCO2e/MJ [76, 136, 36, 31].

Fugitive methane emissions throughout the process are largely identified as a substantial source of emissions. Assessments of the extent of methane leakage vary between less than 1% and up to 15%, with most values under 4% of total methane production [49, 97, 76, 13, 33, 68, 63], equating to between 10 and 100 gCO2e/MJ [97, p. 1408; 136, p. 11; 35; 31, p. 39]. The values depend strongly on the digestate storage systems (open or closed) and whether off-gas from upgrading is combusted [63, 105, p. 48].

Finally, there is the question of greenhouse gas emissions from the combustion of biomethane. While some studies account for these emissions [29, 97, 83, 26], many do not, pointing to the fact that the CO2 released is so-called biogenic CO2, i.e., CO2 which was initially absorbed from the atmosphere by the organic matter that is used as feedstock, creating a neutral emissions cycle [53, p. 17; 11; 133, p. 497; 114, p. 18].

3.5.3 Net emissions from biomethane and compliance with the Renewable Energy Directive

The net emissions from biomethane vary according to the factors described above. To be considered a renewable fuel under the RED, biomethane will have to reach a maximum of 32.9 gCO2e/MJ for transport and 14.4 gCO2e/MJ for heat [76, Table 5].

Meeting both thresholds is likely to only be easily achieved through the mono-digestion of animal manure/slurry, due to avoided emissions [76, 133, 48, 36, 123, 105, 106, 31]. For other feedstocks, optimal management and accounting assumptions[4] are often required to achieve sufficient emissions savings. For example, limiting methane losses is required if OFMSW and the co-digestion of grass silage and cattle slurry are to have a chance of reaching the emissions threshold for heat, although they are both likely to meet the transport threshold [142, 53, 92, 8, 11, 136, 18, 114, 105, 76, 13, 35, 106]. For first generation energy crops, mono-digested grass silage, and algae, meeting the threshold for heat is almost impossible and even the threshold for transport is unlikely to be met [76, 128, 117, 101, 82, 133, 55, 13, 114, 31, 26, 97, 123, 105, 35].

[4] Accounting assumptions refer, for example, to the allocation of emissions between different end products.

3.5.4 Abatement cost

Seven of the reviewed documents presented estimates of marginal abatement costs associated with different biomethane production assumptions. These estimates vary drastically with values ranging from around -200 € to almost +500 €. The lowest cost assessments assumed high gas prices, low feedstock costs, and, in one case, that co-products in a polygeneration system will replace emissions-intensive alternatives [136, 33, 124, 12]. Higher costs are associated with lower gas prices, the use of more expensive feedstocks, more expensive technologies, and the use for heat, not transport [32, 124].

3.5.5 Overarching findings from the reviewed literature on the abatement potential of biomethane

We identified several findings within the abatement section that should apply beyond Ireland. A central element is the high level of uncertainty that surrounds any abatement estimates found in the literature. This follows the trend from previous sections but is even more prominent here.

First, the calculation of emissions (reductions) is dependent on what scenario is used as a comparison. For example, is organic waste considered to go to landfill or to be composted? Does digestate replace artificial fertilisers or slurry? Does the produced biomethane replace diesel or fossil gas?

Additionally, there are uncertainties on how and whether to include indirect (land-use) effects. For example, should the emissions reductions from changes to the cattle herd be attributed to biomethane? And if they are, should the supply-chain effects be considered as well? [76] find that, if consumption habits do not change, emissions may even increase as a result of these reduced exports being replaced by other sources. How far to extend the scope has so far received limited attention in the reviewed literature.

Related to this is the question of whether the benefits of good-practice land-use changes, which are not necessarily contingent on biomethane production, should count towards the produced biomethane. An example of this would be multi-species swards which lead to a reduced need for nitrogen inputs but can be implemented regardless of whether grass is used for biomethane.

Similarly, the reviewed literature shows that much of the emissions savings depends on the management of the biomethane production process, such as the monitoring of methane leaks and the use of state-of-the-art technology. There is a high level of uncertainty around fugitive emissions and they can be a deciding factor in determining emissions.

Despite these uncertainties, it is clear that waste crops, in particular slurry, are likely to meet stringent emissions reductions requirements if some basic steps are taken, such as closed digestate storage and off-gas combustion. On the other hand, energy crops require co-digestion with a large proportion of waste to have a chance of meeting the same requirements.

Overall, as identified for the cost of biomethane and the total abatement potential, the abatement cost of biomethane is highly dependent on feedstock, technology, and end use, but also on accounting choices and gas prices. As a result, it is hard to provide a generally applicable cost range which likely makes decisions around biomethane more complicated for policymakers.

3.6 Other costs and benefits of biomethane production and consumption in Ireland

Alongside energy generation and carbon abatement, the reviewed texts identified other effects resulting from biomethane production, although often not in great detail. These were grouped into two overarching themes, (1) social/economic impacts and (2) environmental impacts. This section helps provide a more holistic overview of advantages and disadvantages of biomethane production.

3.6.1 Social/economic impacts

'Ease of implementation' is frequently mentioned in the reviewed literature as an advantage of biomethane. This is due firstly to the use of grass silage as feedstock, since most farmers in Ireland already cultivate grass [141, p. 4; 47, pp. 27-28; 76, p. 5; 107, p. 45; 55, p. 317; 135, p. 426; 118, p. 2037; 88]. Secondly, biomethane production technology is at high market and technology readiness, and already in widespread commercial use [53, p. 19; 131, p. 13]. Additionally, gas grid infrastructure is in place to transport it to end users [46; 64, p. 4; 123, p. 40; 41, p. 159]. The same is true for (heat) end users who need make no changes if they are already using fossil gas [46, p. 12; 45; 112; 16, p. 131; 123, p. 40f; 93, p. 237; 41, p. 159]. However, this likely does not apply to use in transport where significant infrastructural investment will be required, e.g., in gas-powered vehicles [32, p. x]

Another sub-theme with overwhelmingly positive associations is that of 'income and employment', especially in rural communities. One benefit mentioned in the reviewed literature is increased and diversified farm incomes as a result of energy crop cultivation, use of manure and slurries, and on-farm production of biogas or even biomethane [44, p. 8; 110, p. 1; 76, p. 12; 139, p, 8; 69, p. 1; 66, p. 12; 64, p. 4; 77, p. 2; 31, p. 13; 36]. However, these benefits are only mentioned but not quantified or subject to more in-depth analysis. In contrast, some analysis has been conducted on the creation of both direct and indirect jobs related to biomethane. These studies find that several thousand jobs could be created, primarily in rural areas [106, 69, 76, 42].

Another sub-theme identified in the reviewed literature is 'energy security'. Biomethane is considered to contribute to energy security by reducing import dependence, and the associated price volatility, as well as through its decentralized production locations [46, 106]. Additionally, the literature highlights that biomethane is dispatchable and can therefore balance variable renewable generation in addition to providing a use for surplus electricity through the biomethanation pathway [67].

Where waste feedstocks are used to produce biomethane, the contribution to 'waste management and a circular economy' was identified as a major benefit. According to the reviewed literature, using waste feedstocks can reduce pressure on landfills, enable the reuse of the resources contained in waste, and reduce negative effects resulting from other forms of waste disposal [54, 91, 9, 7, 69, 32, 131]. However, a 2017 SEAI study highlights composting as another circular economy waste management option which should be considered as well [106, p. 46].

'Improvements to farming output' is a further sub-theme identified within the reviewed literature. One argument put forward is that co-products from biomethane production, mainly digestate but also biochar, can improve soil quality, thereby increasing crop yields [33, p. 49; 106, p. 47; 44, p. 43]. Multi-species swards, which are sometimes advocated for for grass silage production, have also been shown to improve crop yields as well as animal growth and health and reduce the need for fertilizer use in the long run [44]. However, their implementation is not limited to biomethane feedstock production. Another benefit identified is the reduction of plant and animal pathogens as well as weed seeds through the anaerobic digestion process, although additional thermal treatment of digestate is required before landspreading according to [116, p.1].

3.6.2 Environmental impacts

The reviewed literature stated that the impact of biomethane production on 'air quality' was positive based on two pathways. The first is lower odour levels as well as lower particulate matter formation from digestate than from manures and slurries [66, 7, 106, 61]. The second is reduced particulate and other emissions from CNG-based transport compared to fossil fuel cars [123; 129, p. 4645; 13, p. 4546; 128, p. 1016; 101].

For 'soil quality', most of the reviewed sources mention a positive impact of digestate application. The benefits listed include increased soil organic carbon, increased soil microbial activity, and improved nutrient uptake, among others [37, pp. 126-127; 46, p. 12; 33, p. 49; 66; 44, p. 44]. Another factor affecting soil quality is the land use change which can be associated with biomethane feedstock cultivation. Here, the reviewed literature recommends avoiding the intensification of land use, such as by moving from unimproved grassland to improved grassland, or introducing energy crops on marginal land, as this would lead to a reduction in soil organic carbon and an increase in erosion [47; 110, p. 14; 80, p. 361].

The impact of biomethane production on 'biodiversity' is largely tied to the use of grass silage as feedstock. The major factor impacting biodiversity identified by most of the reviewed literature is the negative impact of productivity improvements, such as the (intensive) cultivation of peaty soils, marginal land, extensive grassland, and other high nature value land, on biodiversity [114, p. 43; 44, p. 27; 47; 80, p. 361; 107, p. 45]. The use of multi-species swards is frequently put forward as a solution to enhance biodiversity, with the reviewed authors acknowledging the biodiversity benefits of this approach, but only to replace existing mono-cultures, not as a substitute for natural and semi-natural areas [44, 47]. Other approaches put forward to address biodiversity concerns are: excluding environmentally sensitive areas, avoiding major land-use change, and requiring protection of biodiversity-enhancing features [114, 47]. The overall impact on biodiversity remains unclear, with some of the reviewed literature calling for further research [17, p. 102; 47].

Regarding 'terrestrial acidification and water eutrophication', which are the result of nitrogen, and other nutrient, emissions, the reviewed literature is even more mixed. As acknowledged by several sources, fertiliser use in general contributes to nitrogen emissions and therefore increased fertiliser use for energy crops may lead to an increase in acidification and eutrophication [68, p. 3; 47, p. 35; 8]. However, the key question emerging from the reviewed literature is the relationship between nitrogen emissions from raw slurry and digestate. If the latter is lower than the former, then the impact of nitrogen can be reduced through biomethane production from slurries. However, the reviewed literature does not give a clear answer to this question. The two studies assessing overall impact on eutrophication and acidification do not come to conclusive results [7, 26]. Multi-species swards and good farm management practices, such as injection of fertiliser into the soil, are recommended in the literature to minimise harmful effects [61, p. 20; 44; 47, p. 9].

In terms of 'water use', feedstock and technology emerge as key factors in determining the overall impact in the reviewed literature. Energy crops are generally seen as requiring large amounts of water for irrigation, although likely less so in Ireland than in drier regions [9, p. 6; 47]. Overall, [11] identify very different water use levels, both significantly above and below the water required for fossil gas, depending on biomethane production technology.

Several of the reviewed documents highlight 'land use and land use change' as a sensitive topic surrounding biomethane. While some sources consider biomethane to have a large land footprint [11, 47], [53, p. 19] characterize it as comparatively low when contrasted with other biofuels. One issue several authors associate with the question of land use is the debate on whether biomethane feedstock cultivation reduces available arable land for food production [25; 42, p. 9; 80; 49, p. 122]. Within the reviewed Irish literature, this is largely not seen as a concern when either wastes or grass are used as a feedstock. Some documents present a reduction in the national herd as a way to enable grass use without encroaching on arable land [78, p. 4; 88, p. 505; 125, pp. 47-48], whereas others suggest an intensification of grasslands as a way of achieving sufficient yields for both livestock and energy use [44, p. 7; 25, p. 1749; 128, p. 1016; 117, pp. 168-169]. However, several sources also highlight the environmental benefits associated with a small herd size as well as the harm associated with a change of land use to intensive grassland management [7, p. 2; 47; 78, p. 4; 66, pp. 9-10; 31, p. 13; 128, p. 1016].

3.6.3 Overarching findings from the reviewed literature on other costs and benefits of biomethane production

The large number of impacts discussed in the reviewed literature make it clear that it is important to evaluate a biomethane industry from a broader perspective. Focusing only on energy provision and greenhouse gas emissions does not give a full picture.

We find that socio-economic impacts are generally identified as positive, whereas for environmental impacts a lot hinges on how a biomethane indutry is implemented. This may be a less generalisable finding as it is also tied to the current state of industry and agriculture in Ireland. It may, however, provide some insights to countries which are similar to Ireland in those regards.

Additionally, when comparing results across the reviewed literature, the net effect in some areas, especially environmental, are unclear or even contradictory and require further research. This applies, for example, to the impact on biodiversity and nitrogen pollution.

Finally, as has been mentioned in section 3.5, any kind of impact depends on the alternatives against which the biomethane pathway is compared. For example, when looking at benefits for waste management, are we comparing anaerobic digestion to landfill or to composting? When evaluating the nitrogen pollution benefits of multi-species swards, are these in comparison to a grass monoculture or semi-natural grassland?

Overall, the reviewed literature shows that the impacts of implementing a biomethane industry are multi-dimensional and go beyond the frequent focus on biomethane as a renewable energy source.

4 Discussion and conclusion

4.1 The role of national context

The overarching insights from across the different sections highlight that the potential, form, and cost of a biomethane industry is dependent on a country's national context. This starts with waste feedstocks whose availability depends on what organic waste is produced and how much of it is collected, which is shaped by national diets, norms, and waste management legislation. For example, in our case study of Ireland, agricultural wastes played an important role due to the large livestock sector. In turn, the cultivation of energy crops depends on the available land area and what alternative demands are placed on it, as well as a country's climate, soil, and more. Beyond feedstocks, the existence, or not, of an extended gas network affects both ease and cost of biomethane transport, and the final use of the gas is similarly affected by whether, for example, gas-powered vehicles and gas boilers are already in use. As an example of how these differences come into play even in neighboring countries, [139, Table 2] outline the different biomethane production and use profiles of a number of European countries.

4.2 Strong uncertainty around biomethane energy and abatement potential

One point that emerged strongly from the reviewed literature is the high degree of uncertainty on biomethane energy and abatement potential, and cost. Estimates of potential fluctuated widely between different analyses (by a factor of upwards of 20 in the case of grass silage) due to different economic, technical, logistical, sustainability, and other factors being taken into account.

The emissions and emissions savings associated with biomethane are subject to substantial uncertainty as well. Most of these factors are linked to accounting/assessment conventions. For example, what is the scope of the analysis? Should indirect (land use) effects be counted? How are emissions allocated between the different end products? [12] demonstrate the impact of different accounting approaches, where choosing an economic emissions allocation or an energy-based one leads to emissions thresholds either being met or exceeded.

Additionally, the question arises whether good-practice land use changes which might be implemented in the context of biomethane production but are not contingent on it should count towards biomethane's abatement potential or other biomethane-related impacts, e.g., on biodiversity. Further, good management practices are often a necessary requirement to meet RED emissions thresholds [31, 35]. From a policy perspective this highlights the importance of regulating such practices, although such regulation should be approached with care as it may lead to negative backlash among farmers [6, 39]. For researchers the question arises whether it is realistic to assume good management practices as even with regulation compliance is not guaranteed [119, 19].

Finally, the choice of comparison scenario has, in our review, several times been underlined as an important criterion to consider. For example, comparing anaerobic digestion as a waste management option to landfilling vs composting will lead to different results. This applies to other environmental impacts beyond abatement potential as well. There is no convention on whether to use the current status quo, the most likely future path, or the best-case alternative as comparison. However, in any case, this should be critically reflected on as part of any research in this area and based on this research we would suggest that a comparison with multiple alternatives could be the best-practice option.

Overall, there needs to be transparency in the communication of assumptions, given the existing uncertainty and the decisive difference they can make when evaluating biomethane.

4.3 Socio-ecological systems level analyses of biomethane needed

This review has demonstrated the importance of looking at biomethane beyond the energy and abatement potential. There is a wide range of social/economic and environmental impacts to consider that call for a more holistic analysis. While many of the reviewed papers mentioned additional impacts, these are often based on assumptions with little in-depth research behind them. In particular, environmental impacts remain under-researched in Ireland with conflicting assessments in some areas. This is a research gap that needs to be filled if policymakers are to make fully informed decisions on biomethane implementation.

4.4 Long-term vision for biomethane required

An inherent tension emerges from this review regarding the long-term role of biomethane as an energy source. It is frequently portrayed as an interim energy source before alternatives, such as electricity-powered HGVs, high-temperature heat pumps, and hydrogen, replace it over time. At the same time, biomethane production is associated with high upfront costs and is currently largely not profitable but reliant on incentives provided by the government. Consequently, investment is likely to be unattractive if the future of biomethane is uncertain. At the same time, there are limits to the scale of biomethane production, if environmental sustainability is to be taken seriously, as it relies on the input of waste. A long-term vision of the role of biomethane in the energy system could help coordinate policies to address these future challenges and would de-risk investment, as well as preventing a short-term policy approach focused only on growing the biomethane industry. Other, cross-country research has likewise called for a "clear strategic vision" for biomethane [139] indicating that this is a wider issue, at least in Europe.

4.5 Limitations and future research

There are some limitations to this study. For one, as a case study, the conclusions we draw are based on a single country context, the trade off to being able to conduct such a holistic analysis. We identify several ovearching insights that we believe are applicable beyond the Irish context, but more research is needed to verify this. It is also important to note that, due to resource constraints, the coding was undertaken only by one researcher which has been shown to be less reliable than double-coding [14, 71]. Despite these limitations, we believe that the insights shared here provide a good basis for reflection for biomethane policy development, and point to several fruitful lines of further research. We have shown that there is significant uncertainty around the energy and abatement potential of biomethane and that a long-term perspective of and research on biomethane as a part of socio-ecological and energy systems is required to make biomethane a success story.

Data availability

A list of the reviewed documents as well as the results of the quantitative coding can be made available upon request. The reviewed documents themselves cannot be provided directly but are largely freely accessible online.

Appendix

Appendix A

CODE BOOK

IMPORTANT: Code references to biomethane only, not generic references to biogas unless it is clear from the text that this is specifically in reference to biomethane.

1. **Possible sources of biomethane**
    a. What are they? Examples: Wastewater, grass, cover crops
    b. How abundant are they in Ireland?
    c. Where are they found?
    d. (Any information about associated costs should be coded here and under costs of biomethane production.)
2. **Possible uses of biomethane**
    a. Where can biomethane replace natural gas? Which households are suited to biomethane?
    b. What industries/sectors are particularly suited to biomethane uptake?
    c. Direct injection into the gas grid or transported by car?
    d. What are the other options in these areas? E.g., synchronous condensers for the power grid.
3. **Carbon abatement potential**
    a. Natural gas / other fossil fuels displaced and carbon content of these displaced fuels.
    b. Methane emissions avoided and associated carbon content.
    c. Include references to any carbon emissions as well, e.g., from burning the biomethane, from leaks during transport and storage, etc.
    d. Include all information on energy generated by biomethane, energy lost during the process, energy balance etc.
4. **Costs of biomethane production and use** (divided by different sources and different actors)
    a. Cost of production / import
    b. Cost of infrastructure
    c. Cost to consumers (resulting biomethane gas price)
    d. Profit from biomethane
    e. Changes in cost/profit/income compared to other energy sources.
5. **Abatement costs for biomethane production** (combination of production (+ infrastructure) costs and carbon abatement potential)
    a. Marginal abatement cost curves or any other references to abatement costs
6. **Storage requirements for biomethane**
    a. Any reference to storage requirements (associated costs should be coded here and under costs of biomethane production and use).
    b. Include references to lack of storage requirements (e.g., due to decentralized nature of biomethane production).
7. **Other effects of biomethane production and use**
    a. On biodiversity, farm income, inequality, etc.

If a document has no information on any of these parameters, make a note of that fact.

If an article looks at Ireland as well as other countries, only include sections referring to Ireland.

Appendix B

Table 3: Inductively developed themes

Codes	Overarching themes	(Sub-)Themes
Sources of biomethane	Feedstocks	Feedstock availability, distribution, and characteristics (3.1)
		Feedstock cost (3.4)
		Emissions and emissions savings (3.5)
		Other effects (3.6)
	Technology and infrastructure (3.3)	Technology
		Integrated systems
Uses of biomethane (3.2)		Biomethane for power generation
		Biomethane for heat (residential and industrial)
		Biomethane for transport
		Other uses of biomethane

Table 3: Inductively developed themes - continued

Codes	**Overarching themes**	**(Sub-)Themes**
Combination of results from: *Sources of biomethane (technology & infrastructure)* *Storage* *Uses of biomethane*	Biomethane infrastructure and logistics (3.3)	Location of anaerobic digesters and biomethane upgrading units Injection into the gas grid Storage Integrated (circular economy) systems
Storage requirements for biomethane (3.3)		
Costs of biomethane production and use (3.4)		CAPEX OPEX Cost/price of biomethane Profitability of biomethane production
Carbon abatement potential (3.5)		Sources of emissions savings Sources of emissions Net emissions savings Total abatement potential
Abatement costs (3.5)		

Table 3: Inductively developed themes - continued

Codes	Overarching themes	(Sub-)Themes
Other effects of biomethane production and use (3.6)	Social/economic impacts	Production of co-products
		Ease of implementation
		Income and employment
		Energy security
		Waste management and circular economy
		Improvements to farming output
		Air quality
		Soil quality
	Environmental impacts	Biodiversity
		Terrestrial acidification and water eutrophication
		Water use
		Land use and land use change

Note: Numbers in parentheses represent the respective sections of the article.

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