The potential for low-carbon renewable methane in heating, power, and transport in the European Union

Authors: Chelsea Baldino, Nikita Pavlenko, and Stephanie Searle (ICCT), and Adam Christensen (Three Seas)
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Introduction

This study presents the potential and cost of production for renewable methane in the European Union (EU) in 2050, following a previous paper assessing the potential for renewable methane for the transport sector in France, Italy, and Spain (Baldino, Pavlenko, Searle, & Christensen, in press). Policymakers throughout the EU are evaluating their alternative energy options to help deliver on their air quality and climate change mitigation goals within the transport and stationary heating and power sectors. One of these options is renewable methane.

The recast Renewable Energy Directive for 2021-2030 (RED II; European Union, 2018) includes ambitious targets for renewable energy in all three sectors, with each EU member state required to implement the directive using specific measures that promote the use of low-carbon energy (General Secretariat of the Council of the European Union, 2018). Renewable methane from qualifying feedstocks is one option for meeting the RED II targets for the overall renewable energy target including power, heating, and transport and for the sub-target for advanced biofuels in transport. Some stakeholders have also advocated the inclusion of renewable methane and other low-carbon fuels in the vehicle carbon dioxide (CO_2) standards (ART Fuels Forum, 2018; ACEA, n.d.; NGVA Europe, 2017). As member states consider how to achieve their climate goals, they must assess the realistic potential as well as the costs for renewable methane. In 2018, the power sector is the leading user of renewable methane in the EU at 62%, with Germany, the United Kingdom, and Italy responsible for more than 77% of renewable methane production in the 28 EU member states (Kampman et al., 2016).

Proponents of renewable methane have touted its climate and air-quality benefits when displacing diesel in the heavy-duty vehicle fleet. Importantly, the feedstocks and technologies used to produce renewable methane play a large role in determining the actual climate benefits. Silage maize provides about half of the renewable methane in the European Union, but it competes with food and feed crops for agricultural land and causes substantial indirect land-use-change emissions (Valin et al., 2015). On the other hand, wastes, residues, and renewable power can be used to produce renewable methane with high reductions of greenhouse gas (GHG) emissions.

In this study we expand our previous assessment to estimate the technical and cost-effective potential for using renewable methane from sustainable feedstocks in the power, heating, and transport sectors. We assess barriers to producing renewable methane for each sector and identify the maximum amount of fossil gas that could realistically be displaced in the 2030–2050 timeframe. We also estimate the potential for GHG reductions from renewable methane in each sector. These results help to identify the role that renewable methane can have in medium- and long-term decarbonization of the European Union and the level of policy incentives that will be necessary to achieve this benefit.

Methodology

For this study, we analyze the total technical potential for renewable methane from a variety of feedstocks, including livestock manure, sewage sludge, waste and residue biomass, and renewable electricity in 2030 and 2050. We conduct a cost analysis for each feedstock and technology pathway to estimate cost-supply curves for the use of renewable methane in

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power, heating, or transport. Lastly, we estimate the maximum total potential GHG savings for renewable methane as well as the GHG savings that could be achieved at realistic levels of policy support. We conduct our analysis at the national level and present aggregated EU-level results. We present renewable methane potential in the European Union on a pre-combustion basis, or before the renewable methane is used for energy by the end user. We present our findings for two alternatives: delivering renewable gas to the gas grid for use in either the stationary heating or transport sector, or onsite combustion of renewable methane to generate electricity to be sold to the power grid.

FEEDSTOCK SUSTAINABILITY AND PATHWAY SELECTION

In this study, we assess the potential for renewable methane production only from sustainable, low-carbon feedstocks. We use the same assumptions regarding feedstock sustainability and pathway selection for renewable methane production as in Baldino et al. (in press). The three conversion pathways for renewable methane production that we assess include anaerobic digestion, thermo-chemical gasification, and power-to-gas, in which electricity is used to create methane. This study focuses on renewable methane produced from wastes and residues that do not have existing uses, including livestock manure, sewage sludge, municipal solid waste, crop residues, and forestry residues. For the power-to-gas pathway, only solar power is considered. Power-to-gas has been discussed as a potential energy storage and electrical grid balancing solution (Science Advice for Policy by European Academies, 2018). Baldino et al. (in press) provides a more detailed explanation of how we determined the choice of feedstocks and the sustainable availability of these feedstocks in our assessment.

Table 1: Low-carbon renewable methane feedstocks, technology pathways, and lifecycle GHG intensities for gaseous fuels used in the transport sector.

Feedstock	Technology pathway	GHG intensity	Reference
Livestock manure	Anaerobic digestion	-264 gCO_2e/MJ (-9.45 $kgCO_2e/m^3$)	CARB, average LCA value for dairy cows
Sewage sludge		19 gCO_2e/MJ (0.68 $kgCO_2e/m^3$)	CARB, average
Municipal and industrial solid waste	Gasification and methanation	-26 gCO_2e/MJ (-0.93 $kgCO_2e/m^3$)	Wang, 2017
Crop residues		-6 gCO_2e/MJ (-0.21 $kgCO_2e/m^3$)	Wang, 2017
Logging residues		-12 gCO_2e/MJ (-0.42 $kgCO_2e/m^3$)	Wang, 2017
Renewable solar power-to-gas in 2030	Electrolysis and methanation (power-to-gas)	26 gCO_2e/MJ (0.93 $kgCO_2e/m^3$)	Christensen & Petrenko, 2017
Renewable solar power-to-gas in 2050		12 gCO_2e/MJ (0.42 $kgCO_2e/m^3$)	Christensen & Petrenko, 2017
EU-28 Power production, grid average in 2030		68.6 gCO_2e/MJ (2.46 $kgCO_2e/m^3$*)	European Commission, 2016a; Moomaw, 2011.
EU-28 Power production, grid average in 2050		46.9 gCO_2e/MJ (1.68 $kgCO_2e/m^3$*)	European Commission, 2016a; Moomaw, 2011.
Fossil fuel-derived fossil gas		72 gCO_2e/MJ (2.58 $kgCO_2e/m^3$)	Giuntoli, Agostini, Edwards, Marelli, 2015

Note: CARB=California Air Resources Board. For livestock manure, the CARB GHG intensity values included high carbon dioxide equivalent (CO2e) reduction credits from avoided methane emissions. The gasification pathways include credits for exported electricity.

** GHG intensities for electricity are for delivered electricity, not input feedstocks.*

The feedstocks, technology pathways, and lifecycle GHG intensities used in the analysis are listed in Table 1. We use these GHG intensities to calculate the greenhouse gas mitigation potential of using these renewable methane pathways relative to either fossil gas or electricity. We assume that renewable methane replaces fossil gas in the gas grid, which is then used in the transport or heating sectors, while we consider average electrical grid power in the power sector. For heating or transport, we multiply the renewable methane volume by the difference between the carbon intensities of fossil gas and the specific feedstock and conversion pathway assessed (see Table 1). For the power sector, we calculate the GHG mitigation potential similarly, comparing renewable methane GHG intensity to that of EU grid power. We take the projected EU-level grid composition in 2030 and 2050 from the EU Reference Scenario and break this down to the national level based on 2015 grid composition in each member state from Eurostat (E3M-Lab, IIASA, & EuroCARE, 2016). We combine this with mean life-cycle power-generation emission factors for each power source from Moomaw et al. (2011) to estimate grid power GHG intensities for each member state. Table 1 provides the average grid carbon intensities in the power sector in the EU in 2030 and 2050, while the individual GHG intensities that we use for each member state are available in the Appendix in Table A1.

In our primary analysis, we do not include cover crops as a potential source for renewable methane production because there is little data on the use of cover and catch crops, also known as sequential crops, intermediate crops, green manure, winter crops, and intercrops, in Europe. We address this topic in more detail in the discussion. Although we exclude cover crops from our primary analysis, for illustration purposes we include a rough estimate of the potential that anaerobic digestion of cover crops could contribute in Europe in 2050, based on current trends. We extrapolate trends in cover cropping land area from Alliance Environnement (2017) and find that in 2050, cover cropping could involve 9%–10% of the agricultural land in Europe. Given that we do not know how many cover crops are used for fodder, we assume that half of these cover crops could be used for renewable methane production. We thus assume that 5% of agricultural land in the EU could be used to grow cover crops for renewable methane production. To estimate the total land area where these crops could be grown, we use 2016 total harvested area of all cereals, oilseeds, and pulses such as legumes in the European Union from the United Nations' FAOSTAT data source.

To estimate the yield of cover crops that could be available in 2050, we use oats as an example as they are listed as a common cover crop in Alliance Environnement (2017). We assume that oat straw is harvested before seeding, as reported in Alliance Environnement (2017). We take average EU oat yields from 2016 from FAOSTAT—weighted average by harvested area by country—and assume the same average oat-to-straw ratio as for wheat that we calculated from data in Scarlat, Martinov, and Dallemand (2010). We assume a straw yield reduction of 40% to account for growing oats at a non-optimal time of the year and of a further 20% because of physical limitations in harvesting as the harvester cannot cut below ~12 inches from the ground. We assume a 15% moisture content for oat yields based on FAOSTAT data to first calculate the dry mass yield of total straw production and then a 70% moisture content in oat straw to calculate the fresh matter yield of the cut straw. To estimate the methane yield potential from these harvested cover crops, we use the average of low and high methane production rates for the anaerobic digestion of alfalfa (Scarlat, Dallemand, and Fahl, 2018).

CURRENT USE OF RENEWABLE METHANE IN THE EU

Some renewable methane is currently produced from sewage sludge, livestock manure, and other feedstocks such as silage maize that are not included in our analysis. No significant amounts of renewable methane from gasification or power-to-gas are currently produced as there are no commercial-scale facilities using this technology. Table 2 presents the total current use of renewable methane in the EU, derived from Kampman et al. (2016) and EurObserv'ER (2017). Most of this renewable methane is used in the heating and power sectors. We calculate that the total potential for sewage sludge is only around 400 million m^3, less than what we found as the current use. There are two likely reasons for this discrepancy: 1) We most likely underestimate biogas production from sewage sludge in this study because we do not include the potential for capturing methane from the anaerobic digestion ponds themselves, although there is some evidence that very little wastewater is anaerobically treated (UNFCCC, 2017; UNFCCC, 2018). 2) Kampman et al. (2016) include industrial sewage sludge in their estimate of current use. We do not consider industrial sewage sludge in our assessment because methane potential is less certain than that of domestic wastewater treatment sludge, since industrial wastewater varies greatly in its organic matter composition. Generally, it is likely that most of the methane potential from sewage sludge is already being used for renewable methane production.

Table 2: Total current use of renewable methane in the EU, in billion m^3

Feedstock	Current Use (billon m^3)
Energy Crops	8.5
Organic Waste	2.3
Livestock Manure	1.2
Sewage Sludge	1.6
Landfill Gas	3.1

TECHNICAL POTENTIAL

The methodology for assessing the technical and cost potential for the production of renewable methane in the EU closely follows Baldino et al. (in press). Rather than estimating the additional potential for renewable methane relative to existing production, as in the previous study, here we assess the total technical potential for renewable methane in 2050. For livestock manure and sewage sludge, we first estimate the total current production of manure and sludge in EU member states and then estimate methane yields through anaerobic digestion. For use in transport or heating, we factor in losses during gas conditioning and compression. We assume that the technical potential for these pathways remains constant through 2050. For gasification, we use a deployment model to estimate the maximum production capacity of renewable methane from wastes and residues in 2030 and 2050. In most countries, renewable methane potential from this pathway becomes constrained by feedstock availability by 2050. We also use a deployment model for power-to-gas and assume the technical potential to be the potential at the highest incentive level included in our cost analysis for this pathway (more detail below). Our estimates of the technical potential of renewable methane for each sector assumes that all renewable methane feedstocks are used for one sector and not the other; for example, our technical potential estimate for transport assumes 100% of renewable methane is used in transport and none in heating or power.

For calculating the technical potential of renewable methane from livestock manure, as in Baldino et al. (in press), we use IPCC emission factors for manure management to calculate the biomethane potential from cattle and pigs. We exclude poultry manure because of the difficulty of methane formation in the anaerobic digestion of this feedstock. In Table 3 we present assumptions for volatile solid (VS) generation, methane potential, and the methane conversion factors (MCF) used to estimate the manure management emissions. The MCF is the percentage of the feedstock that is converted to methane, i.e., it is multiplied by the methane generation potential per kg VS. In this study, we expand the analysis beyond the three countries in the previous study to assess the methane potential in all EU countries.[1]

Table 3: Emission factors for livestock manure management.

	Methane Conversion Factor	VS (Volatile Solids) Generation	Methane Generation
	n/a	kg VS/Animal/day	m^3/kg VS
Western European Dairy Cows	0.56	5.10	0.24
Eastern European Dairy Cows	0.56	4.50	0.24
Eastern Non-Dairy Adult Cattle	0.56	2.70	0.17
Western Non-Dairy Adult Cattle	0.56	2.60	0.17
Pigs	0.8	0.50	0.45

COST-POTENTIAL ANALYSIS

To evaluate the relative costs of supplying renewable methane to the EU, we conduct a bottom-up economic assessment of the cost of production for each feedstock and conversion process to estimate the minimum viable selling price (MSP) of renewable methane across sectors. Next, in conjunction with feedstock availability and cost, we use the MSP for each production mode to estimate the cost-viable volume of renewable methane at several possible levels of policy support in 2030 and 2050.

We adapt the methodology used in Baldino et al. (in press) in calculating MSPs. For each technology and feedstock combination, we use a discounted cash flow model that assesses the net present value (NPV) of future returns relative to total project costs. In our analyses, retail costs and the associated levels of policy support that are necessary to make the projects viable are informed by one-time capital expenses (CAPEX), production volumes, and operational expenses (OPEX) across a given project's lifetime. Data inputs in the cost modeling for this analysis are taken from literature review, using the most recent EU-specific data available. As with the technical potential assessment, we base our cost assessment on the assumption that all the renewable methane potential goes toward that end use and not the others. All results are in constant 2018 euros. Our analysis, described further below, estimates the wholesale production cost of power and CNG for either transport or heating separately.

To estimate the value of an incentive needed for each production pathway to reach an NPV of zero, we subtract the wholesale cost of gas (for heat or transport) and grid power (for the power sector) from the MSP. We take projected CNG prices from the World Bank (2015). For power, we use wholesale prices for each member state provided in European Commission (2016b).

There are several costs we do not take into consideration in this study, thus likely overestimating the potential at any particular incentive level. We do not include the cost of pre-treatment; one study found that pre-treatment of wastewater sludge can cost between €81 and €171 per tonne of total solids (Muller, 2001). We also do not consider the cost of injecting renewable methane into the grid as grid connection costs vary widely among countries, and the party responsible for paying the fees varies according to local and national regulations. Finally, we do not take into account costs related to country-specific taxation, compliance with national permitting, planning, bio-security, and safety regulations (Lukehurst & Bywater, 2015).

Manure Management

Our cost assessment of renewable methane production from livestock manure uses the same approach in Baldino et al. (in press) but expands it to evaluate the potential from all EU countries. The methane production potential at a given farm is proportional to the number of cattle and type. We focus on the cost of production of manure-renewable methane from dairy cattle and non-dairy cattle. Although we include pig manure in our technical potential analysis, we exclude it from our cost analysis because the low methane potential per kg of pig manure greatly

1 We defined "eastern" member states to align with ministers who attended a meeting before the UNFCCC COP 23: https://unfccc.int/news/eastern-european-countries-express-full-support-for-cop23

worsens the economics of renewable methane production. Reflecting data limitations, this analysis factors in only the potential from the largest farms of more than 100 cattle. We have previously found that farms with fewer than 100 cattle are generally too small to generate sufficient manure for cost-effective biogas generation.

In this analysis, we distinguish between the methane potential for dairy and non-dairy cattle in both Western and Eastern Europe per IPCC emission factors for manure management (Table 3). We derive CAPEX and OPEX values for anaerobic digestion from Agostini et al. (2016) and U.S. EPA (2018), factoring in economies of scale; we describe this in Baldino et al. (in press). For biogas used to produce electricity, we assume only the CAPEX and OPEX costs for the digester plant. For the heating and transport energy cases, we include additional costs for biogas conditioning to grid quality and compression, as well as pipeline infrastructure for connection to the fossil gas grid. The CAPEX for the livestock methane pathway includes the cost of construction of 8 km of pipeline to connect farms to the fossil gas grid, based on the best-case pipeline cost from Baldino et al. (in press). In practice, the distance between farms and the fossil gas grid could vary significantly by farm and region, thus introducing substantial uncertainty to this method of renewable methane production.

Wastewater Treatment

We apply the same parameters as in Baldino et al. (in press) in this assessment to estimate the MSP for renewable methane from wastewater sludge. For anaerobic digestion of primary and secondary sludge from centralized wastewater treatment facilities in Europe, OPEX and CAPEX costs are estimated using the same cost factors as for manure management, assuming that the sludge could be processed similarly once it leaves the wastewater treatment facility.

Gasification and Methanation

We evaluate the costs of gasifying municipal solid waste, agricultural residues, and forest residues to generate power. For all uses, we assess gasification combined with methanation. In all cases, the facility's CAPEX is dominated by the gasification equipment; methanation would most likely be less than 5% of the total CAPEX (Gotz et al., 2016). The CAPEX, OPEX, and feedstock costs are all the same as in Baldino et al. (in press).

Because no commercial facility exists for gasification-methane production, we apply the same deployment model for this assessment as in Baldino et al. (in press). Total facility deployment is based on the ramp-up capacity and resource constraints for each EU member state. Based on Agostini et al. (2016), we assume a lifetime of 20 years for the project. The first and second rounds of facility planning and construction have only one large commercial-scale facility built in each country, while subsequent rounds include two facilities each. The total number of facilities by 2050 is constrained by resource availability in most member states, ranging from 0 to 1 facility total in some smaller countries, to 16 in some of the larger countries with substantial resource availability.

We acknowledge that these assumptions of facility deployment are somewhat arbitrary, but we include them because such constraints are necessary to reflect limits on financing opportunities. That is, there are a limited number of banks and other investors willing to invest in renewable methane projects, even if the projects are expected to be economically viable. We aim for our constraints to reflect the observed historical timeline of deployment of demonstration-scale and commercial-scale cellulosic biofuel facilities in the United States and the European Union, which has been much slower than what modeled economics have predicted (Miller et al., 2013).

Power-to-Gas

Our power-to-gas assessment, as in Baldino et al. (in press), closely follows the methodology in Christensen and Petrenko (2017) and Searle and Christensen (in press). We project power prices based on a model from the National Renewable Energy Laboratory, average capacity factors for solar power in the European Union, current grid fees in these countries, and our projected changes in grid fees according to the greater balancing and distribution costs with increased renewable power penetration.

Results

We find that economics significantly constrain the achievable potential of renewable methane. Significant policy support will be necessary to drive substantial volumes of renewable methane into transport, heating or power.

Figure 1 and Figure 2 illustrate the total technical potential, as well as the potential achievable at several incentive rates in €/m³ for the transport, heating, and power sectors, broken down by pathway in 2050. Even at high incentive levels, the cost-viable potential of renewable methane is lower than the technical potential for electricity generation, and only around half the technical potential for heating or transport.

Livestock manure offers the greatest technical potential for renewable methane across all three sectors, providing as much as 54% of the potential for the electricity generating sector and as much as 43% if the methane is injected into the gas grid for use in heating or transport. However, we find that very little renewable methane from livestock manure can be cost-viable in the transport or heating sectors at a realistic incentive rate of €1.50/m³. A much larger amount of renewable methane from this feedstock can be cost-viable in the power sector. This large difference in potential for using renewable methane from livestock manure among the three sectors is largely attributable to high costs of transporting renewable methane from farms to the fossil gas grid via pipelines.

Figure 2 shows cost curves for these two scenarios in 2050, illustrating the amount of renewable methane that could be delivered at varying incentive levels in €/m³. At most volumes of renewable methane production, it is more expensive to bring renewable methane to the grid than to use it for generating electricity.

Figure 3 presents the potential for renewable methane at an incentive level of €1.75/m³ as well as the total technical potential for the power sector and the transport or heating sectors in 2030 and 2050. These figures show how the potential for renewable methane increases over time. The difference in potential in 2030 versus 2050 demonstrates how gasification and power-to-gas, as emerging technologies with high CAPEX, will require more time to develop. We estimate very little potential for renewable methane from these pathways in the 2030 timeframe. Anaerobic digestion, on the other hand, is already a mature technology, so we assume that the full potential of renewable methane production from livestock manure and sewage sludge at each cost level could be available by 2030. Anaerobic digesters also have relatively low CAPEX, so the availability of financing options would not be likely to constrain expansion of this pathway.

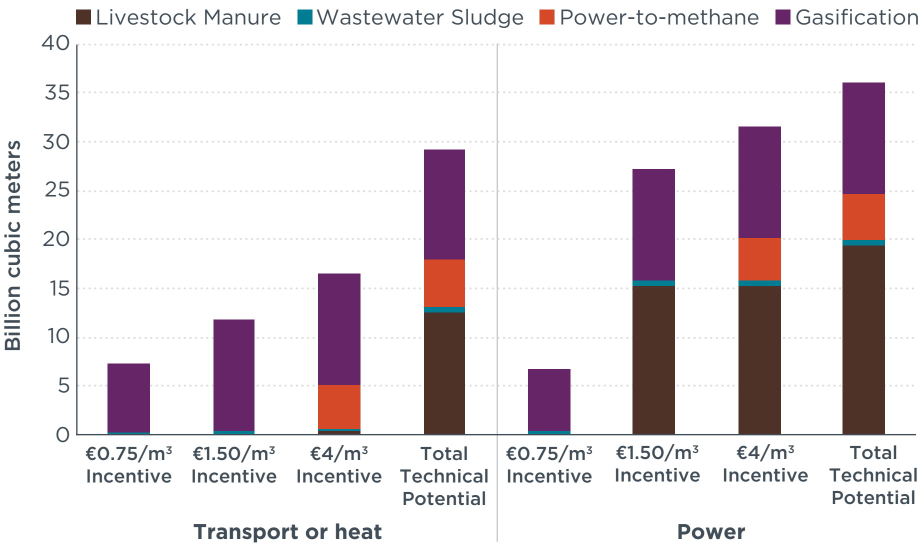

Figure 1: Total technical potential and economically viable potential of renewable methane delivered for transport or heating, or power, with varying levels of policy incentive (constant 2018 €) in 2050; for comparison, the current average EU natural gas price is €0.20/m³

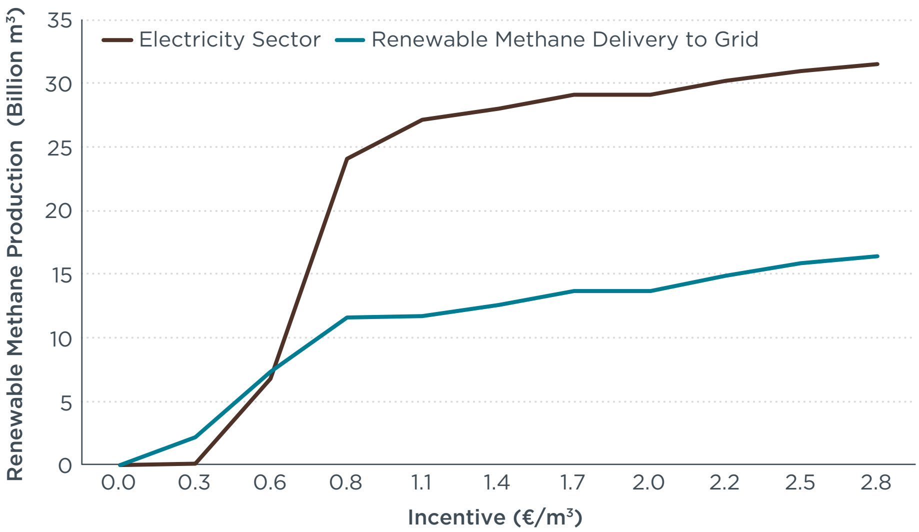

Figure 2: Renewable methane potential (billions of cubic meters) vs. incentive value (€/m³ of natural gas) for heating or transport, or power in 2050

We find that renewable methane delivered to the fossil gas grid, where it would be used primarily by the heating or transport sectors, could replace approximately 12% of the total projected methane demand in 2050 if its full technical potential were utilized (European Commission, 2016a). Renewable methane could fulfill 7% of transport energy demand, 10% of demand for energy for residential heating, or 3% of demand in the power sector in 2050.

GHG MITIGATION POTENTIAL

Renewable methane has a high potential to reduce GHG emissions particularly in the electricity sector. Figure 6 illustrates the technical greenhouse gas mitigation potential for renewable methane and the savings achievable at an incentive level of €1.75/m³ in 2050 for heat or transport and power. Higher GHG savings are most cost-effectively achievable in the power sector because it can more easily use renewable methane from livestock manure – a pathway with extremely high GHG reductions from avoided raw manure methane emissions. For heating or transport, it is not cost effective to use more than a small fraction of livestock manure potential at any incentive level, so the very high GHG savings from this pathway are not realistically available in these sectors. Though the overall greenhouse gas mitigation potential is positive for the power sector, there are some specific feedstocks where renewable methane performs worse in terms of GHG intensity than the predicted power mix in 2050. This is because we project a few member states to have extremely low power-grid GHG intensities in 2050.

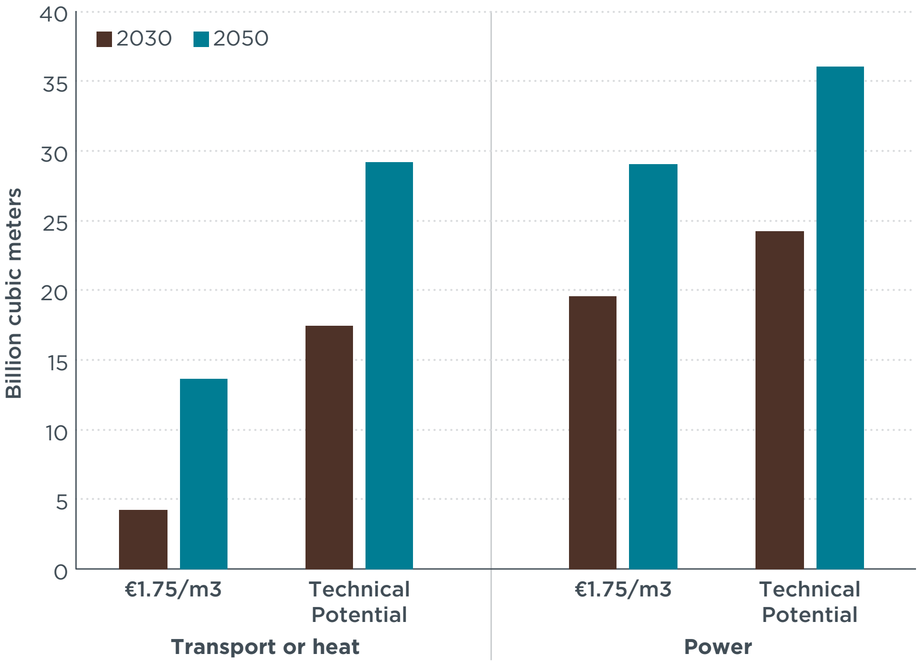

Figure 3: Total renewable methane supply available for transport or heat, or power, at an incentive level of €1.75/m³ in 2030 and 2050, shown alongside the total technical potential.

Discussion

One of our key findings is that it is much more cost-effective to use renewable methane from livestock manure in the power sector than in the heating or transport sectors. The prohibitively high transportation cost of bringing renewable methane to the fossil gas grid severely limits the realistic potential of using this pathway for transport or heating. For this reason, the realistic GHG mitigation potential of using renewable methane in the power sector vastly outweighs that of using it for heating and power.

Another key finding is that high levels of policy support will be necessary to support these pathways. Some policy support measures in place today contribute toward renewable methane production, but we do not include these incentives in our cost analysis because they are likely to change before 2050. Existing incentives, however, can help provide context for our findings. As an example, France currently offers a feed-in tariff, or a guaranteed purchase price, of as much as €0.22/kWh of electricity derived from manure biogas, equivalent to roughly €0.70/m³ for methane on a pre-combustion basis (Najdawi, 2017). In our analysis, we start to see renewable methane potential increase at this incentive level and above (see Figure 2). The current incentive level in France is thus sufficient to drive some production of renewable methane, but not nearly the full technical

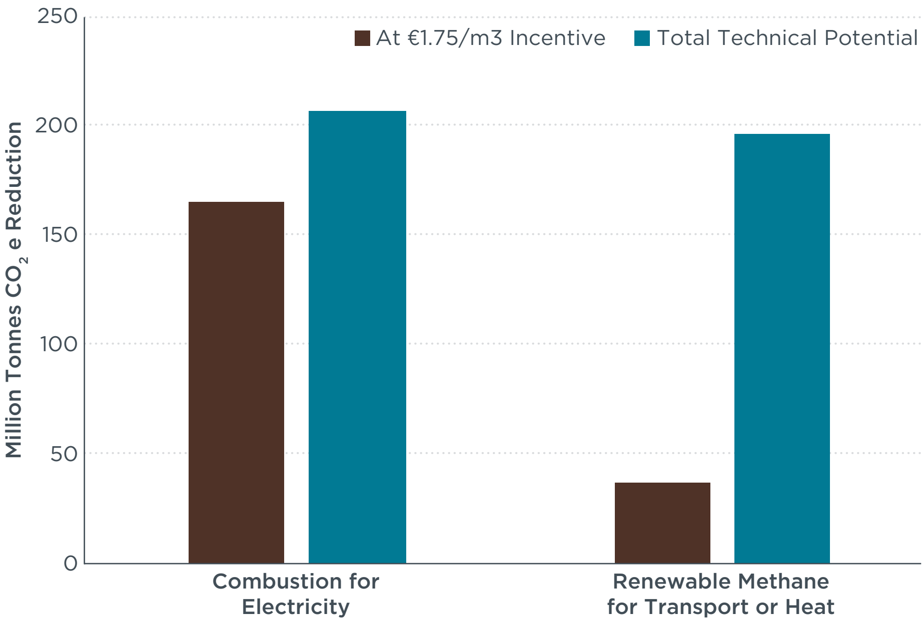

Figure 4: Greenhouse gas mitigation potential of renewable methane for transport or heating, or power in 2050 at an incentive level of €1.75/m³.

potential of the country. This is consistent with what we observe in France and other EU countries that support renewable methane. It is clear that higher incentive levels would be needed to increase renewable methane penetration.

In transport, we find that renewable methane is a particularly expensive decarbonization strategy. Policy support of €1.50/m^3 would be needed to encourage a small amount of renewable methane in transport, and €4/m^3 of policy support would be needed to drive a substantial level of penetration. These support levels are roughly equivalent to subsidies of €1.50 and €4 per liter of diesel equivalent or a carbon price of €580–€1,350 per tonne of CO_2e abated. If renewable methane were used to deliver GHG reductions toward the EU's vehicle CO_2 standards, it would cost €90–€230 per gCO_2e saved per kilometer over the lifetime of a vehicle.[2] Compared with the €95 per gCO_2e per km penalty for not complying with the proposed 2030 standards, it seems unlikely that renewable methane will represent a cost-effective strategy for meeting those standards (European Commission, 2018).

THE POTENTIAL FOR RENEWABLE METHANE FROM COVER CROPS

Other studies of EU renewable methane potential include cover crops as a feedstock (van Melle et al., 2018; ADEME, 2018). In our primary analysis, we do not include this feedstock as a potential source for renewable methane production because there is little data on the use of cover crops.

The most recent EU-wide data collected on these crops was in the Farm Structure Survey in 2010, which indicates that cover crops are not common in Europe. Using this survey data, Alliance Environnement (2017) finds that only 3.24% of arable land in the EU (excluding France and Lithuania because of lack of data) has cover and catch crops. There is also little data on changing trends in cover cropping over time in the EU, making it difficult to predict the potential. Based on agricultural land use information from the Alliance Environnement (2017) report, we estimate that cover crops will have increased by almost 3% to covering 6% of arable land in 2030, using this study's baseline scenario.[3] Based on this trend, we would still not expect a large fraction of arable land to be double-cropped in 2050. As a part of its study, Alliance Environnement (2017) conducted interviews with farmers to determine why they do not plant cover and catch crops. In many regions in the EU, including France and Germany, it is not possible to plant catch or cover crops after maize because the harvest season occurs too late in the year before winter. Moreover, cover crops tend to be low-yielding crops such as forage radish and yellow mustard and generally do not produce seed because of the short duration available for their growth. In many cases, Alliance Environnement reported that farmers do not harvest cover crops at all and plough them into the soil when preparing fields for the main crop, presumably because of the low yields and value of these crops. Given these barriers, we do not expect cover and catch crops to be a significant feedstock source for renewable methane production.

Furthermore, the use of existing cover crops for renewable methane production introduces concerns over indirect emissions from material displacement. We would expect that diverting cover crops from existing uses, such as animal fodder, to renewable methane production would lead to indirect land use change (ILUC) (Takriti, Malins, & Searle, 2016). We would also expect that cover crops would cause significant GHG emissions associated with their cultivation, especially because of low yields.

To better compare our results with those of others in the literature, for illustrative purposes we include a rough estimate of renewable methane potential from cover crops. We estimate that, at most, 1.4 billion m^3 of renewable methane per year could be available from cover cropping in 2050, which would add just 4% to our calculated technical renewable methane potential.

COMPARISON WITH LITERATURE

In a study commissioned by gas transport companies and renewable methane producers, van Melle et al. (2018) estimate the 2050 EU renewable methane potential to be more than three times higher than in the present study—122 billion m^3 per year, compared with our estimate of 36 billion m^3 of technical potential for power, or 29 billion m^3 of gas delivered to the grid for use in heating or transport. One-third of the total potential in this study comes from cover and catch crops. Van Melle et al. (2018) assume that 50% of the current harvested area of wheat and maize in the EU, excluding the Nordic countries, the Baltic countries, and Ireland) can be double-cropped with silage maize and triticale, a wheat-rye hybrid, delivering 40% the yield of the main

2 This calculation assumes the following: vehicle efficiency of 0.0363 L/km (what would typically be needed to meet the 95 gCO_2e/km standard for 2021 (Regulation (EC) No. 333/2014); 15-year vehicle lifetime; 117,000 km annual distance driven by each car (Odyssee-Mure, n.d.).

3 We calculate a 34% increase in cover cropping for the European Union excluding France using data from Alliance Environnement, 2017: 2,051,600 ha in 2010 to 2,757,451 ha in 2015. Assuming a linear increase in cover cropping to 2030, and, similarly, extrapolating the very slight decrease in total arable land area to 2030 (from Eurostat data), we calculate that 6% of arable land would have catch and cover cropping in 2030 in a baseline scenario.

crop. These assumptions contrast strongly with the findings from our literature review of substantial barriers to expanding energy double-cropping (Alliance Environnement, 2017). Van Melle et al. (2018) do not cite evidence suggesting that it is likely or even possible that their assumption on cover crop production can be achieved.

Compared with the present analysis, the authors fail to account for realistic limitations on biogas production from anaerobic digestion related to losses in renewable methane conditioning and compression. Van Melle et al. (2018) also assume gasification yields of 0.55 m^3 of renewable methane per kg feedstock, a four-fold increase compared with their 2015 assessment of a futuristic, nth of a kind (that is, matured technology), gasification and Fischer-Tropsch plant without any specific justification for the assumption. Fischer-Tropsch synthesis, a cleaning and refining process, is not necessary for combusting syngas, which is a mix of predominantly carbon monoxide and hydrogen. Removing this part of the process should improve yields by only around 25% (Brynolf, Taljegard, Grahn, & Hansson, 2017; Hannula, 2015; Schemme, Samsun, Peters, & Stolten, 2017). Another major difference between the present study and van Melle et al. (2018) is that our study accounts for the limitation of facility deployment rate to 2050, whereas van Melle et al. (2018) assume that enough facilities will be built to process all available feedstock in 2050. In addition to cover cropping, these differences account for most of the discrepancy between the results of van Melle et al. (2018) and those of the present study.

METHANE LEAKAGE DURING RENEWABLE METHANE PRODUCTION

Gas leakage is also an important consideration when evaluating the GHG performance of renewable methane. There is little empirical data on methane leakage from biogas plants, and stakeholders have reported that leakage is uncertain (CARB, 2015).

Measuring total CH_4 emissions from a renewable methane facility is expensive and time-consuming. Based on information from a limited number of academic studies, the IEA (Liebetrau, Reinelt, Agostini, & Linke, 2017) found that biogas plants can present both systemic and accidental emissions of methane. For instance, plants that store digestate, a by-product of biogas production, in open tanks emit a continuous stream of methane (Giuntoli et al., 2017). Other systemic leakages can derive from flanges, which are connecting and fortifying pieces on pipes, and as gas diffusion from the tanks' membrane covers. Accidental leaks are often linked to over-pressure in the digester, leading to biogas being vented or flared. The range of methane leakages emerging from studies that have tried to quantify it is between 0.001% and 1.11% of the biomethane produced, although one study noted a major leak of 5% due to improper operation (Liebetrau et al., 2017). Kollamthodi et al. (2016) found methane leakage of 1.2% from the anaerobic digester, 0.5% for upgrading biomethane, and 0.1% for injecting biomethane into the grid. The Joint Research Centre assumes a leakage rate of 3% from gas conditioning after anaerobic digestion, also assuming that this leaked methane is flared, which reduces its climate impact because flaring converts most methane to carbon dioxide, a less potent greenhouse gas.

Further leaks can occur when combusting gas for use in heating, power, or transport. In a gas engine for combined heat and power, leakages can occur because of uncombusted methane released through the exhaust, known as "methane slip." Liebetrau et al. (2017) found an average leakage estimate of 1.89% of input gas through methane slip across the literature. Another study reported on methane leaks in vehicles, finding that gas-spark ignition engines emit around 1% of the methane delivered to the engine, while compression-ignition engines emit 2%–3% of the methane (Aschmann, 2014). Leakage can also occur from gas-tight storage tanks, digesters, and digestate storage when methane can diffuse through the membranes. The reported range of methane leakage in the literature was 0.22% to 4% (Liebetrau et al., 2017).

These estimates of leakage from renewable methane production and use are similar to those for fossil gas. Like renewable methane, there is considerable uncertainty around leakages from the production of conventional fossil and shale gas, and the numbers are most likely underestimated. The broad range of leakage estimates for fossil gas include 0.4% for extraction and processing (Kollamthodi et al., 2016), 1.14% for life-cycle emissions of conventional gas and 1.21% for shale gas (CARB, 2015), 0.2%–10% with a mean of 2.2% for natural gas supply chains (Balcombe, Anderson, Speirs, Brandon, and Hawkes, 2015), and 12% for shale development (Howarth, 2015).

Given these uncertainties, we conduct a sensitivity analysis to assess the effect of leakage on our results based on values from a CARB Low Carbon Fuel Standard pathway calculation. We find that for a small sewage sludge digester, the carbon intensity of renewable methane with no leakage would be 0.64 $kgCO_2e/m^3$, which provides GHG savings of 75% compared with fossil gas. If there were a 5% leakage rate, the carbon intensity would be 1.54 $kgCO_2e/m^3$, which provides GHG savings of only 40% compared with fossil gas. With a leakage rate of 11%, this pathway for a small digester would not have any GHG savings compared with fossil gas. For a bigger digester, CARB provides a lower carbon intensity value, so in this case, there would need to be an even higher leakage rate for the digester to not provide any GHG savings compared with fossil gas.

We caution against drawing any strong conclusions from this sensitivity analysis. The lack of robust data on methane leakage lends considerable uncertainty to the overall climate impacts of renewable methane and fossil gas. Even a relatively small rate of leakage can undermine the GHG benefits of renewable methane pathways, except for manure biogas, which has significant climate benefits even with moderate methane leakage. Much more data collection is needed to confirm or revise the estimated GHG intensities for both renewable and fossil gas assumed in this study.

Conclusions

Not all renewable methane is created equal. It is important that policy-support measures distinguish among the different feedstocks and technological pathways and prioritize renewable methane production from the lowest-carbon options. Primary considerations are the sustainability and GHG intensity linked to different feedstocks. Using livestock manure for renewable methane can deliver very large GHG savings because of avoided methane emissions from the management of raw manure, without compromising the economic and ecological functions of manure fertilization. Using other sustainable wastes and residues and renewable power for gas production can also deliver strong climate benefits if methane emissions are limited through careful plant design.

We find that sustainable renewable methane can make only a small contribution to decarbonizing the EU energy economy. It can have a much stronger role in delivering GHG reductions in the power sector compared with heating and transport. We find a total technical potential for renewable methane in the EU in 2050 of 36 billion m^3 per year for power generation. Alternatively, the same resource base could supply 29 billion m^3 to the heating or transport sectors. These volumes would cover 7% of transport energy demand, 10% of energy demand for heating, and 3% of demand in the electrical generation sector in 2050.

Strong policy support would be needed to overcome the cost challenges of producing renewable methane. Even with generous incentives, economics will limit renewable methane deployment. With a high policy incentive of €1.75/m^3, 78% of the total technical potential for power could be achieved in 2050, while only 43% of the total technical potential for the heating or transport sectors could be achieved due to the higher cost of transporting renewable methane to the gas grid. With this level of incentive, CO_2e emissions could be reduced by as much as 166 million tonnes annually by 2050 if renewable methane were used for power generation.

Overall, we find that renewable methane can play a modest role in decarbonizing the EU's long-term energy supply. Renewable methane production should be seen as one strategy in a suite of measures, such as efficiency improvements, electrification, and use of other low-carbon alternative fuels, that must be implemented to achieve long-term decarbonization.

References

ADEME. (2018). Gas independence in France in 2050: A 100% renewable methane mix in 2050? Study Summary. Retrieved from http://www.ademe.fr/sites/default/files/assets/documents/renewable-gas-mix-2050-010521.pdf

Agostini, A., Battini, F., Padella, M., Giuntoli, J., Baxter, D., Marelli, L., Amaducci, S. (2016). Economics of GHG emissions mitigation via biogas production from Sorghum, maize and dairy farm manure digestion in the Po valley. *Biomass and Bioenergy* 89: 58-66.

Alliance Environnement. (2017). On payments for agricultural practices beneficial for the climate and environment. Retrieved from: https://ec.europa.eu/agriculture/sites/agriculture/files/fullrep_en.pdf

ART Fuels Forum. (2018). Position Paper: Post 2020 Light Vehicle CO_2 Regulations Initiative. Available at: http://artfuelsforum.eu/wp-content/uploads/2018/03/ART-Fuels-Forum_Passenger-Cars_Position-paper_Mar_2018.pdf

Aschmann, V. (2014), Einflussfaktoren auf die Kohlenwasserstoffkonzentration im Abgasbiogasbetriebener Blockheizkraftwerke(BHKW) [Influences on the concentration

of hydrocarbons in the exhaust gas of biogas-driven combined heat and power units (CHPU)], in: VDI Berichte 2214 - Emiss. 2014 Stand - Konzepte - Fortschritte, VDIVerlag GmbH, Düsseldorf, pp. 193 – 201.

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2015). The natural gas supply chain: The importance of methane and carbon dioxide emissions. Retrieved from http://www.sustainablegasinstitute.org/wp-content/uploads/2015/09/SGI_White_Paper_methane-and-CO2-emissions_WEB-FINAL.pdf?noredirect=1

Baldino, C., Pavlenko, N., Searle, S., & Christensen, A. (In press). *The potential for low carbon renewable methane a transport fuel in France, Italy, and Spain*. The International Council on Clean Transportation.

Brynolf, S., Taljegard, M., Grahn, M., and Hansson, J. (2017). “Electrofuels for the Transport Sector: A Review of Production Costs.” *Renewable and Sustainable Energy Reviews*.

California Air Resources Board (CARB). (2014). Low carbon fuel standard (LCFS) pathway for the production of biomethane from the mesophilic anaerobic digestion of wastewater sludge at a publicly-owned treatment works (POTW). Retrieved from: https://www.arb.ca.gov/fuels/lcfs/121514wastewater.pdf

California Air Resources Board (CARB). (2015). Low carbon fuel standard re-adoption: Natural gas carbon intensity and other CA-GREET model adjustments. Retrieved from: https://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040315presentation.pdf

Christensen, A., & Petrenko, C. (2017). *CO_2-based synthetic fuel: Assessment of potential European capacity and environmental performance.* Retrieved from the International Council on Clean Transportation, https://www.theicct.org/sites/default/files/publications/CO2-based-synthetic-fuel-EU-assessment_ICCT-consultant-report_14112017_vF_2.pdf

Dalsøren, S.B., Myhre, G., Hodnebrog, Ø., Myhre, C., Stohl, A., Pisso, I.,..., Wallasch, M. (2018). Discrepancy between simulated and observed ethane and propane levels explained by underestimated fossil emissions. Retrieved from https://www.nature.com/articles/s41561-018-0073-0

EurObserv’ER. (2017). Biogas Barometer. Retrieved from https://www.eurobserv-er.org/category/all-biogas-barometers/

European Commission. (2016a) EU reference scenario 2016: Energy, transport and GHG emissions, trends to 2050. https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

European Commission. (2016b). Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Energy prices and costs in Europe. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2016:769:FIN

European Commission. (2018). COM/2017/676 - Proposal for a Regulation of the EP and of the Council setting emission performance standards for new passenger cars and for new light commercial vehicles as part of the Union’s integrated approach to reduce CO2 emissions from light-duty vehicles and amending Regulation (EC) No 715/2007 (recast). Retrieved from http://ec.europa.eu/transparency/regdoc/?fuseaction=list&n=10&adv=0&coteId=1&year=2017&number=676&version=F&dateFrom=&dateTo=&serviceId=&documentType=&title=&titleLanguage=&titleSearch=EXACT&sortBy=NUMBER&sortOrder=DESC2017

E3M-Lab, IIASA, & EuroCARE. (2016). *EU Reference Scenario 2016: Energy, transport, and GHG emissions trends to 2050.* Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf.

European Automobile Manufacturers Association (ACEA). ACEA Position Paper: Post-2021 CO_2 Regime for Passenger Cars. Available at: https://www.acea.be/uploads/publications/PC_CO2_ACEA.pdf

European Union. (21 June 2018). Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources - Analysis of the final compromise text with a view to agreement. Retrieved from http://www. consilium.europa.eu/register/en/content/out?&typ=ENTRY&i=LD&DOC_ID=ST-10308-2018-INIT

Food and Agriculture Organization of the United Nations. (2018). “Food and agriculture data.” Retrieved from http://www.fao.org/faostat/en/#home

General Secretariat of the Council of the European Union. (2018, June21). Interinstitutional file: Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources - Analysis of the final compromise text with a view to agreement. Retrieved from http://www.consilium.europa.eu/register/en/content/out?&typ=ENTRY&i=LD&DOC_ID=ST-10308-2018-INIT

Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2015). Institute for Energy and Transport, Joint Research Centre Report. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/ead42a9c-3105-4046-a401-9f1ca27a3bf5

Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2017). Solid and gaseous bioenergy pathways: Input values and GHG emissions. Version 2. Joint Research Centre Science for Policy Report. Retrieved from https://publications.europa.eu/en/publication-detail/-/publication/1893b3a1-3f61-11e7-a08e-01aa75ed71a1/language-en/format-PDF/source-76654754

Gotz, M., Lefebvre, J., Mors, F., Koch, A.M., Graf, F., Bajohr, S., Reimert, R., and Kolb, T. 2016. Renewable Power-to-Gas: A technological and economic review. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0960148115301610

Hannula, I. (2015). "Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis." *Biomass and Bioenergy* 74: 26–46.

Howarth, R. (2015). Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: Implications for policy. Retrieved from: https://www.eeb.cornell.edu/howarth/publications/f_EECT-61539-perspectives-on-air-emissions-of-methane-and-climatic-warmin_100815_27470.pdf

Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Brückmann, R., Maroulis, G.,..., & Elbersen, B. (2016). Optimal use of biogas from waste streams: An assessment of the potential of biogas from digestion in the EU beyond 2020. A CE Delft, Eclareon, and Wageningen Research report. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf

Kollamthodi, S., Norris, J., Dun, C., Brannigan, C., Twisse, F., Biedka, M., & Bates, J. (2016). The role of natural gas and biomethane in the transport sector. A Ricardo Report. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2016_02_TE_Natural_Gas_Biomethane_Study_FINAL.pdf.

Liebetrau, J., Reinelt, T., Agostini, A., & Linke, B. (2017). Methane emissions from biogas plants: methods for measurement, results and effect on greenhouse gas balance of electricity produced. IEA Bioenergy Task 37 Report, Retrieved from http://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf.

Lukehurst, C., & Bywater, A. (2015). Exploring the viability of small scale anaerobic digesters in livestock farming. IEA Bioenergy. Retrieved from http://www.ieabioenergy.com/publications/exploring-the-viability-of-small-scale-anaerobic-digesters-in-livestock-farming/

Van Melle, T., Peters, D., Cherkasky, J., Wessels, R., Mir, G., & Hofsteenge, W. (2018). Gas for climate: How gas can help to achieve the Paris Agreement target in an affordable way. An Ecofys Report. Retrieved from https://www.gasforclimate2050.eu/files/files/Ecofys_Gas_for_Climate_Feb2018.pdf.

Miller, N., Christensen, A., Park, J. E., Baral, A., Malins, C., & Searle, S. (2018). *Measuring and addressing investment risk in the second-generation biofuels industry.* The International Council on Clean Transportation: http://www.renewablejetfuels.org/sites/renewablejetfuels.org/files/resources/reports/ICCT_AdvancedBiofuelsInvestmentRisk_Dec2013.pdf.

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., & Verbruggen, A. (2011.) Annex II: Methodology. In IPCC: Special Report on Renewable Energy Sources and Climate Change Mitigation.

Muller, J.A. (2001). Prospects and problems of sludge pre-treatment processes. Water Science Technology, 44(10), 121-128.

Najdawi, C. (2017). RES Legal: Promotion in France. Retrieved from http://www.res-legal.eu/search-by-country/france/tools-list/c/france/s/res-e/t/promotion/sum/132/lpid/131/

Natural & bio Gas Vehicle Association (NGVA Europe). (2017). PRESS RELEASE: NGVA Europe on the proposal for a Regulation setting CO_2 emission performance standards for new heavy-duty vehicles. Available at: https://www.ngva.eu/wp-content/uploads/2018/05/2018-05-18-PR-NGVA-Europe-on-HDVs-CO2-standards.pdf

NYSERDA. (2006). Biogas Processing: Final Report. Retrieved from: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Reports/NYSERDA_final_report_Biogas_Processing.pdf

Odyssee-Mure, n.d. Sectoral Profile- Transport. Retrieved from http://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html

Scarlat, N., Martinov, M., & Dallemand, J.F. 2010. "Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use." *Waste Management* 30(10): 1889-97.

Scarlat, N., Dallemand, J.-F., & Fahl, F. (2018). Biogas: Developments and perspectives in Europe. *Renewable Energy* 129(A): 457-472.

Schemme, S., Samsun, R.C., Peters, R., & Stolten, D. (2017). "Power-to-fuel as a key to sustainable transport systems–an analysis of diesel fuels produced from CO_2 and renewable electricity." *Fuel* 205: 198–221.

Science Advice for Policy by European Academies. (2018). "Novel carbon capture and utilization technologies: Research and climate aspects." Expert report convened by the European Commission Group of Chief Scientific Advisors, Scientific Opinion No. 4/2018. Retrieved from https://www.sapea.info/wp-content/uploads/CCU-report-May2018-3.pdf

Takriti, S., Malins, C., & Searle, S. (2016). *Understanding options for ILUC mitigation*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/sites/default/files/publications/ILUC-Mitigation-Options_ICCT_nov2016.pdf.

United Nations Framework Convention on Climate Change. (2017, July). Report on the review of the report to facilitate the calculation of the assigned amount for the second commitment period of the Kyoto Protocol of Spain. Note by the expert review team. Retrieved from https://unfccc.int/sites/default/files/resource/docs/2017/irr/esp.pdf.

United Nations Framework Convention on Climate Change. (2018, April). Report on the individual review of the annual submission of France submitted in 2017. Note by the expert review team. Retrieved from https://unfccc.int/sites/default/files/resource/fra.pdf.

U.S Environmental Protection Agency. (2018). LFGcost-Web-Landfill Gas Energy Cost Model. Retrieved from https://www.epa.gov/lmop/lfgcost-web-landfill-gas-energy-cost-model

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., ..., & Fulvio, F. (2015). The land use change impact of biofuels consumed in the EU. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf

Wang, M. (2017). GREET® Model. The greenhouse gases, regulated emissions, and energy use in transportation model. GREET 1 Series (Fuel-Cycle Model). Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Retrieved from https://greet.es.anl.gov/greet_1_series

Werner, S. (2016). European District Heating Price Series. An Energiforsk Report, Retrieved from Euroheat and Power, https://www.euroheat.org/publications/reports-and-studies/european-district-heating-price-series/

World Bank. (n.d.). “Research - Commodity Markets.” http://www.worldbank.org/en/research/commodity-markets.

Appendix

Table A1: Predicated GHG intensities for grid electricity for each member state in kgCO_2e per cubic meter (delivered electricity, not input feedstocks)

Country	2030 Grid Emissions	2050 Grid Emissions
Austria	1.22	1.15
Belgium	2.82	2.41
Bulgaria	2.98	1.41
Croatia	1.89	1.24
Cyprus	7.62	4.31
Czech Republic	1.37	0.77
Denmark	0.12	0.12
Estonia	7.26	4.14
Finland	0.66	0.53
France	0.54	0.48
Germany	2.93	1.28
Greece	4.00	2.54
Hungary	4.75	3.45
Ireland	4.39	3.26
Italy	3.37	2.34
Latvia	0.05	0.07
Lithuania	0.11	0.13
Luxembourg	3.20	3.23
Malta	9.95	9.95
Netherlands	5.14	3.83
Poland	1.13	0.82
Portugal	3.08	1.97
Romania	1.59	0.73
Slovakia	0.73	0.82
Slovenia	0.13	0.14
Spain	2.48	1.59
Sweden	0.10	0.11
United Kingdom	3.83	3.05

Table A2: Total technical potential in million cubic meters of renewable methane, by country

Country	Total technical potential for the power sector (million cubic meters)	Total Technical Potential for the transport or heat sectors (million cubic meters)
Austria	676	534
Belgium	1177	935
Bulgaria	1007	963
Croatia	418	374
Cyprus	235	223
Czech Republic	876	791
Denmark	1159	808
Estonia	165	148
Finland	841	777
France	4448	3478
Germany	4903	3740
Greece	594	558
Hungary	760	658
Ireland	909	652
Italy	2177	1712
Latvia	372	347
Lithuania	470	424
Luxembourg	185	175
Malta	183	181
Netherlands	1518	1039
Poland	2044	1550
Portugal	860	757
Romania	2263	2045
Slovakia	573	541
Slovenia	260	237
Spain	3333	2456
Sweden	717	633
United Kingdom	2888	2439