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The potential for low-carbon renewable methane as a transport fuel in France, Italy, and Spain

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Introduction

Renewable methane offers the potential to displace natural gas for use in existing vehicle fleets, reducing greenhouse gas (GHG) emissions as well as emissions of air pollutants like NO_x. While the bulk of existing renewable methane comes from processes that capture the gas from the anaerobic decomposition of organic matter, a share of future renewable methane production may come from the gasification of biomass or renewable electricity-powered methane synthesis, also known as power-to-gas. The GHG impact of renewable methane and the scale of its potential adoption depend strongly on the performance of feedstocks used to produce gas and their availability.

The potential for low-carbon renewable methane is a pressing issue. Policymakers at city, regional, and national levels are considering which technology options to support for cars, trucks, and buses to help meet air-quality and climate-change mitigation goals. For light-duty vehicles, natural gas has had only limited success as all major automakers deploy electric vehicles in greater numbers. However, for trucks and urban buses especially, the role of natural gas is under active debate. Increasingly, cities are acknowledging they can now shift to electric buses and derive substantial GHG reductions and fuel savings in many cases (Dallmann, Du, and Minjares, 2017; Miller, Minjares, Dallmann, and Jin, 2017). The potential for widely available, low-cost, low-GHG renewable methane could potentially shift these debates.

Recently, the European Union finalized its recast Renewable Energy Directive for 2021-2030 (RED II), which includes ambitious targets for renewable energy in transport (General Secretariat of the Council of the European Union, 2018). EU member states must implement the directive with specific measures to promote the use of low-carbon transport fuels. Renewable methane from qualifying feedstocks is one option for helping to meet the RED II targets.

It is important that member states assess the realistic potential for renewable methane, factoring in the availability of low-carbon feedstocks necessary for production. Furthermore, the technical potential for renewable methane production may vary considerably from the volumes that are achievable at realistic levels of policy support. Constraints such as economies of scale, feedstock cost, and distribution all play important roles in determining the cost of production for renewable methane.

This study assesses the potential of renewable methane in the transport sector by 2030 in three major European countries: France, Italy, and Spain. These countries have demonstrated a particular interest in promoting renewable methane as part of their post-2020 transport decarbonization strategies. Italy currently provides special support to renewable methane from non-food feedstocks (Ministero dello Sviluppo Economico, 2018). In France, a Parisian public transport operator is investing in natural gas buses that can run on renewable methane (NGV Global News, 2018). In Spain, SEAT and Volkswagen-Audi Spain have signed

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an agreement with the Madrid Gas Network to promote compressed natural gas (CNG) vehicles and CNG infrastructure (CNG Europe, 2018b). These three countries are also among the top five markets in Europe for new vehicle sales and vehicle fleets.

The data and analysis in this paper provide a detailed methodology for determining the choice of feedstocks and calculating cost curves for renewable methane potential based on two previous studies (Searle and Christensen, 2018; Baldino, Pavlenko, and Searle, 2018). This paper addresses several questions:

1. How much renewable methane from these sources is technically possible in the EU?
2. How much renewable methane production is cost-viable?
3. How does the potential for renewable methane compare with the energy demand in these three countries?
4. What are the greenhouse gas savings associated with the technical and cost potentials of renewable methane in these countries?

Methodology

We analyze the additional technical potential for renewable methane from a variety of feedstocks, including livestock manure, sewage sludge, waste and residue biomass, and renewable power in 2030. First, we use national-level activity data for agriculture and wastewater treatment to develop an assessment of the theoretical technical potential for renewable methane production based on feedstock availability that could be supplied to any sector, transport or otherwise. Next, we incorporate bottom-up economic assessment for the cost of production and delivery to the transport fuel market to evaluate the minimum viable selling price of renewable methane across a variety of feedstocks and production modes. We then use the minimum viable selling price for each production mode in conjunction with feedstock availability and cost to estimate the cost-viable volume of renewable methane potential and the resulting GHG reductions attainable at several levels of policy support from 2020–2030. We also calculate first-order estimates of the potential for renewable methane production in 2050, which we provide in the Appendix.

FEEDSTOCK SUSTAINABILITY AND PATHWAY SELECTION

The climate benefits of renewable methane strongly depend on the upstream impacts of the feedstock used to produce the gas. Renewable methane from silage maize, for example, relies on crop land that competes with other uses and generates indirect land use change (ILUC) emissions, estimated to be 21 grams of carbon dioxide-equivalent per megajoule (gCO_2e/MJ) by Valin et al. (2015)—similar to that of some food-based biofuels. Generally, renewable methane and biofuels produced from true wastes and residues without existing uses deliver the best climate outcomes. In this analysis, we therefore focus on waste and residue feedstocks that can be converted to methane. This includes livestock manure, sewage sludge, municipal and industrial solid biogenic waste, crop and logging residues, and renewable power-to-gas.

This analysis estimates only the additional renewable methane potential relative to existing production. Diverting renewable methane from existing uses such as heat and power to transport would most likely necessitate additional energy production to replace the diverted renewable methane, and some of the net additional energy production would most likely come from unsustainable sources, such as fossil fuels and wood (Searle, Pavlenko, El Takriti, and Bitnere, 2017). We do not assess landfill gas potential because methane capture is already required on landfills in Europe, and it is thus already likely to be used in heat and power production. Furthermore, because the Landfill Directive requires reductions in landfilled waste over time, it is unlikely that additional landfill gas will be sustainably available in the future. We also do not consider feedstock to be available if it has material uses, for example use of crop residues in livestock bedding and as a soil amendment. We take estimates of the excess sustainable availability of crop and logging residues and industrial and municipal waste that are not already used for energy production, material uses, or soil protection from Searle and Malins (2016). Some livestock manure and sewage sludge is used as a soil amendment, but we consider this amount to be available for renewable methane production because the digestate resulting from anaerobic digestion is nutrient-rich and can be used as fertilizer.

In this study, we do not consider co-digestion of feedstocks, but that could be an important consideration because co-digesting feedstocks with varying carbon-to-nitrogen ratios and dry matter influences the renewable methane potential from these feedstocks (Einarsson and Persson, 2017). We assume that livestock manure and sewage sludge would be processed through anaerobic digestion, crop and logging residues and industrial and municipal waste through gasification and methanation, and renewable power through electrolysis and methanation.

Anaerobic digestion of manure or sludge produces raw biogas, a gaseous mix of approximately 50%–60% methane, with much of the remaining volume comprising CO_2, volatile organic compounds, and trace impurities. Improving the quality of this gas for distribution in the fossil gas grid and eventual use in vehicles requires purification and upgrading to enhance its energy density and to meet strict gas quality standards. Impurities can include hydrogen sulfide and water vapor, with hydrogen sulfide of particular concern because it can corrode engines (Lukehurst and Bywater, 2015).

While biogas production from anaerobic decomposition of biomass, wastes, and residues is the most mature source of renewable methane in Europe, there are alternative methods of production. Gasification converts biomass or organic wastes into syngas, a mixture of hydrogen, carbon monoxide, and carbon dioxide. The resulting syngas undergoes methanation, where carbon oxides and hydrogen are converted to methane and water using catalysts (U.S. Department of Energy, n.d.). For this analysis, we focus on the gasification of sustainably available crop and logging residues and industrial and municipal waste.

Power-to-gas comes from a family of power-to-X (PtX) processes, in which electrical energy is converted to liquid or gaseous fuels. An electrolysis process splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). To achieve climate benefits through PtX fuels, the electricity for the process must come from additional low-carbon, renewable sources, such as solar or wind. The hydrogen is then combined with captured carbon, typically from the atmosphere or a point source, to generate syngas. As with gasification, the syngas can then be converted to methane. PtX is unique compared with the other pathways assessed here

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

Feedstock	Technology pathway	GHG intensity	Reference
Livestock manure	Anaerobic digestion	-264 gCO_2e/MJ	CARB, average
Sewage sludge		19 gCO_2e/MJ	CARB, average
Municipal and industrial solid waste	Gasification and methanation	-26 gCO_2e/MJ	GREET model
Crop residues*		-6 gCO_2e/MJ	GREET model
Logging residues*		-12 gCO_2e/MJ	GREET model
Renewable electricity	Electrolysis and methanation (power-to-gas)	32 gCO_2e/MJ	Christensen & Petrenko, 2017
Fossil gas		95 gCO_2e/MJ	CARB, median value

Note: CARB = California Air Resources Board. For livestock manure, the CARB values that were used include high CO_2e reduction credits from avoided methane emissions. An asterisk (*) indicates that the feedstocks are included only in the assessment for France.

because it is more likely to be constrained by cost than by availability of feedstock—renewable electricity—within the next few decades.

After cleaning and upgrading, renewable methane must also be compressed to the pressure of the gas distribution network or for distribution in high-pressure gas bottles. Alternatively, it can be used directly at filling stations at the location of biomethane production. In those cases, it must still be compressed to at least 200 bars to exceed the pressure in natural gas vehicle fuel tanks (IRENA, 2017).

We calculate the greenhouse gas mitigation potential of using these renewable methane pathways compared with natural gas. The feedstocks, technology pathways, and lifecycle GHG intensities used in the analysis are listed in Table 1. Using the difference between the carbon intensity of fossil natural gas (95 gCO_2e/MJ) and each feedstock and pathway (Table 1), we multiply by the renewable methane production potential that we assess at two retail costs, as well as the total technical potential.

TECHNICAL POTENTIAL

Renewable Methane from Livestock Manure

To calculate the total potential renewable methane production from livestock manure, we use an assessment of overall populations of dairy cattle, non-dairy cattle, and pigs available from Eurostat.[1] We estimate methane yield using emission factors from the Intergovernmental Panel on Climate Change (IPCC) for manure management in Western Europe, including volatile solids (VS) generation, methane potential and methane conversion factor (MCF), which is the percentage of the feedstock that is converted to methane. Volatile solids represent the amount of organic matter in the manure, or material that can be converted to methane. These assumptions are presented in Table 2.

The value for the MCF was derived using a weighted average of 70% closed-pen livestock and 30% pasture livestock to take into account variation

1 Biogas production from poultry is excluded from our scope due to the high nitrogen content of poultry manure and its inhibition of methane formation (McCullough, 2018).

in manure management and specifically estimate renewable methane potential from the amount of manure that is likely to be produced in areas where it is easily collectable (IPCC, 2006). We subtract the current biogas production from the total technical potential to estimate the additional renewable methane that could technically come from pig and cattle manure. We subtract landfill gas production (EurObserv'ER, 2017), and then we estimate how much biogas production currently comes from livestock, based on information about how much different feedstocks contribute to current biogas consumption from Kampman et al. (2016) as well as Eurostat data on current biogas consumption in France, Italy, and Spain.[2]

To determine the pipeline-quality CNG yield from untreated biogas, we rely on the U.S. EPA's landfill gas cost model to assess the conversion rate for a biogas conditioning and compression unit. The model assumes a 65% conversion efficiency, factoring in methane loss from off-gassing and downtime; this conversion efficiency possibly also includes biogas that would be used to power the machine (U.S. EPA, 2018).

Table 2: Emission factors for livestock manure management

	Methane Conversion Factor (MCF)	Volatile Solids (VS) Generation	Methane Generation
	n/a	*kg VS/Animal/day*	*m^3/kg VS*
Dairy Cattle	0.56	5.1	0.24
Non-Dairy Cattle	0.56	2.7	0.17
Pigs	0.8	0.5	0.45

Source: IPCC (2006), using Western Europe values: Dairy cattle values come from Table 10A-4; non-dairy cattle, from Table 10A-5; and pigs, Table 10A-7. "Methane Generation" is the term that IPCC defines as B_0.

Table 3: Assumptions for the production of renewable methane from sewage sludge.

Sludge Characteristics	Kg Suspended Solids (SS)/kg Chemical Oxygen Demand (COD) incoming	Ratio of Volatile Solids (organic matter) to Suspended Solids (SS)	Normal cubic meters methane per tonne organic dry matter*	Reference
Primary sludge from conventional activated treatment	0.4	0.775	357.5	Andreoli, 2007; Bachmann, 2015
Secondary sludge from conventional activated treatment	0.3	0.775	215	
Anaerobic pond sludge	0.325	0.575	215	
Pond sludge after anaerobic treatment	0.08	0.575	215	

*We consider sludge from anaerobic treatment to be secondary sludge for the purpose of calculating methane emissions (Andreoli, 2007)
Note: When a range of values was provided, we present the median value. Activated sludge is the primary type of aerobic treatment in Europe (Wett and Buchauer, n.d.).

Renewable Methane from Wastewater Treatment Sludge

Wastewater is typically treated initially by filtering and through biological processes in open ponds. Sludge is the matter settled at the bottom of the ponds at the end of this process and has relatively low water content. It can be removed and transferred to an anaerobic digester to produce biogas. We do not consider the additional potential from wastewater treatment ponds themselves, which emit some methane, because the biological processes to treat the wastewater require exposure to air and sun; capping the ponds to trap the gas would interfere with these processes (Goad, 2011). We do not include industrial sources of sludge, such as paper mills, because these sources are relatively small in Italy, Spain, and France. Their methane potential is less certain than that of domestic wastewater treatment sludge, since industrial wastewater varies greatly in its organic matter composition.

For the final assessment of theoretical technical potential, we subtract the current biogas production from wastewater and sludge to estimate the additional potential. There are different organic matter compositions in sludge coming from anaerobic treatment and aerobic. Within aerobic treatment, there is also a difference in organic matter content between sludge deriving from primary and secondary treatment. This analysis incorporates both factors in our calculation of the total potential renewable methane that could be generated from sewage sludge, which we present in Table 3.

Based on national reports by the United Nations Framework Convention

2 We used Eurostat biogas consumption data from 2011 in order to better match the age of the data used in Kampman et al., 2016.

on Climate Change (UNFCCC) for Spain and France, which report anaerobic treatment for only 2% of total domestic wastewater treatment, we assume that this was the anaerobic treatment percentage for all three countries. As for biogas from livestock manure, to determine the pipeline-quality CNG yield from untreated biogas, we use the U.S. EPA (2018) landfill gas cost model to incorporate a 65% conversion rate for biogas conditioning and compression.

Biomass Residue and Waste Gasification

For Spain and Italy, we assume that all feedstock for gasification comes from biogenic wastes, using the projected sustainable availability of wastes from Searle and Malins (2016) for 2030. Waste availability is expected to decline from 2020 to 2030, but over that time period, gasification potential will be constrained by facility deployment, not feedstock availability. In France, agricultural residues and forestry residues are sustainably available for renewable methane or biofuel production. But in Italy and Spain, the sustainable availability of these resources is zero, according to Searle and Malins (2016). Because sustainable feedstock availability and facility deployment—not cost—constrain the technical potential of this pathway beyond a certain level of policy support, we assume the technical potential to be the point at which cost is no longer a limiting factor, which is discussed in greater detail in the next section.

Power-to-Gas

For the power-to-gas pathway, we assume the technical potential to be the same as the potential at the highest cost included in our analysis, which is discussed in greater detail in the next section. While there could theoretically be enough renewable electricity to produce a greater amount of power-to-gas, the technical potential is constrained by facility deployment, which along with cost constrains power-to-gas potential in the timeframe assessed here.

COST ANALYSIS

This study develops a cost curve that incorporates the cost of production for each of the six sources of renewable methane analyzed, using a slightly different methodology to project production volumes, operating expenses, and capital costs for each pathway. To estimate the minimum viable selling price for a given production system, 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. For the different renewable methane production pathways, transportation costs and technology deployment rates are treated differently, due to the varying feedstocks and differences in maturity of the technologies.

The cost modeling for this analysis is informed by a literature review to find the relevant data inputs, based on the most recent European Union-specific data when available. We assume retail prices of compressed natural gas from CNG Europe, and we assume these prices remain constant over time (CNG Europe, 2018a). All results are in 2018 Euros. Our analysis, described further below, estimates the wholesale production cost of renewable methane. To estimate retail price, we add a retail markup term calculated as the difference between CNG retail price in each country and the EU average natural gas wholesale price (World Bank, n.d.). The retail markup term reflects costs associated with building and maintaining natural gas infrastructure as well as taxes.

The discounted cash flow (DCF) analysis estimates the present-day value of future cash flows relative to the cost of a safer investment. For each subsequent year, net cash flow from the project is further discounted according to the discount rate until it reaches a terminal value. The DCF analysis uses the following formula to estimate the present-day value of a given project's future cash flows:

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots + \frac{CF_n}{(1+r)^n}$$

Wherein,

- CF_X refers to the net cash flow in year x, including fuel sales, employee salaries, facility depreciation, and maintenance.
- r is the discount rate, in this case, 5% (Agostini et al., 2016).
- n is the lifetime of the project, in this case 15 years.

The discounted cash flow analysis is used to inform our assessment of the project's value relative to the investment in capital expenses. The net present value of a given project is estimated using the following formula:

$$NPV = \sum_{(t-1)}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Wherein,

- T is the lifetime of the project, assumed to be 15 years.
- t is the time period, 1 year.
- R is the discount rate—in this case we assume a value of 15% is

necessary to stimulate investment (Bann, 2017).

- C_t is the discounted cash flow of the project—equal to DCF above.
- C_o is the CAPEX of the project.

For each project, we assess the total production costs for a given project to reach an NPV of zero, thus ensuring a 15% rate of return after factoring in discounted future cash flows. We calculate the total retail cost by adding the retail markup, which is made up of distribution costs and taxes, to the total production costs. The total retail cost is the minimum viable selling price (MSP) for the project; one can calculate the fuel subsidy that would be necessary to make the project viable by subtracting the CNG price from the total retail cost (CNG Europe, 2018a). In the results section, we present total retail costs, not the subsidies, due to different retail CNG prices in each of the member states.

There are several costs we do not take into consideration in this study, thus most likely overestimating potential at any particular retail cost level. First, 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; grid connection costs vary widely between countries, and the party responsible for paying the fees varies according to local and national regulations. Additionally, there are costs related to compliance with national permitting, planning, biosecurity, and safety regulations that we do not consider in this assessment (Lukehurst and Bywater, 2015).

Manure Management

This analysis expands upon Pavlenko and Searle (2018) to further assess the impacts of variation in farm size and transport distances on manure biogas production cost. We also incorporate data from a recent techno-economic analysis of European anaerobic digesters (Agostini et al., 2016). This pathway includes the anaerobic digestion of agricultural manure from dairy and non-dairy cattle. Poultry manure typically has a high nitrogen content, which would inhibit biogas production and is therefore excluded from this analysis. To a lesser extent, pig manure has the same problem (Gaworski et al., 2017). Moreover, the lower methane potential for pig manure relative to that of cattle suggests that with the added expense of straw or other substrates necessary to ensure anaerobic digestion, it is unlikely to be economically viable. It is very likely that little to no pig-manure renewable methane would be viable in the cost range assessed here. Thus, while we include pig manure in our assessment of the technical potential for livestock manure gas production, we do not include it in our cost supply curve.

The cost of production for manure-derived renewable methane is strongly dependent on the number of livestock at a given farm; the greater the size of the herd, the more manure in one location and the greater the economies of scale for anaerobic digestion. To incorporate this factor into the analysis, we use Eurostat data on the distribution of livestock by type and farm size for France, Italy, and Spain. The data from Eurostat was limited in resolution for large farms with more than 100 head of livestock; for this reason, we supplement this data with a more granular assessment of larger dairy farms provided by the International Food & Agribusiness Management Association.

Methane production at a given farm is proportional to the number of cattle and their type; IPCC emission factors are used to estimate the total methane production at a given farm size. This estimate of methane production is used in conjunction with CAPEX and OPEX values for anaerobic digestion derived from Agostini et al. (2016), which scale according to the power output of the digester. Agostini et al. (2016) utilize a factor of €5,700/kW of capacity to estimate CAPEX costs, along with a small additional expense of about 2% of CAPEX for the digester cover. OPEX costs for anaerobic digestion in the modeling include staffing, depreciation, insurance, and maintenance. The CAPEX and OPEX for biogas compression and conditioning are derived from the U.S. EPA's Landfill Gas Cost Model (2018) and are proportional to the methane generation rate at each farm.

For farms with between 50 and 100 dairy cattle, we assume that groups of five farms could pool resources for a shared digester, whereas farms with more than 100 head would fund their own equipment. We assume that pooled resources would become logistically difficult for larger farms as they would presumably be spread further apart. For non-dairy cattle farms, we apply Eurostat's category of farms with more than 100 head of cattle, adjusting the average head-count to factor in decreased manure production from young cattle.[3] We estimate that renewable methane yields for non-dairy farms with fewer than 100 animals would not be high enough to be economically viable given the capital costs.

Because renewable methane from manure management is often produced far from urban centers and from the natural gas grid, transport costs have a substantial impact on the

3 Cattle less than 1 year old comprised approximately 30% of non-dairy cattle and were assumed to produce 50% the manure of an adult cow.

final MSP for a given project. While in some cases CNG has been trucked to filling stations or well injection points, pipeline connections provide a longer-term, more cost-effective solution in many cases. Although Eurostat documents the size distribution of farms, it doesn't provide the farms' locations relative to the grid.

To estimate the impact of constructing pipelines, we first evaluate the average and maximum distance to a pipeline of key dairy-producing regions in the countries studied: France's Normandy, Italy's Lombardy and Emilia-Romagna, and Spain's Galicia and Asturias.[44] We then develop a normal distribution of possible distances from a farm to the natural gas grid for each of the four regions, using the average within the dairy-producing area. These distances are then multiplied by a factor for CAPEX for pipeline construction from a New York State Energy Research and Development Authority techno-economic assessment on integrating dairy biogas into natural gas grids. The pipeline CAPEX—€100,000—€200,000 per km depending on the size of the farm—is then added to a given project's total CAPEX to estimate the MSP for that project.

For each country and each farm size category, the cash flow model ran 1,000 model runs to provide a normalized distribution of possible transport distances for that size farm. The distribution of possible MSP's from those results is then used to estimate the percentage share of farms within each region that would be viable at each possible incentive rate.

Wastewater Treatment

For anaerobic digestion of primary and secondary sludge from centralized wastewater treatment facilities in Europe, OPEX and CAPEX costs are estimated using the same factors as for manure management, assuming that the sludge could be processed similarly once it leaves the wastewater treatment facility.

To estimate the MSP for renewable methane from wastewater sludge, we use the average capacity of a European wastewater treatment facility, or approximately 21,000 person-equivalents, and IPCC emission factors for methane generation from primary and secondary sludge (Gandiglio, Lanzini, Soto, Leone, and Santarelli, 2017). The methane generation for an average facility's sludge production is used to estimate the CAPEX and OPEX using data from Agostini et al. (2016). We do not assume any transport costs for this pathway as the wastewater treatment plants are assumed to be relatively close to urban centers and the natural gas grid.

Biomass Gasification and Methanation

When renewable methane is produced through gasification paired with methanation, the facility's CAPEX is dominated by the gasification equipment; methanation would most likely account for less than 5% of the total CAPEX (Gotz et al., 2016). The CAPEX and OPEX are derived from interviews conducted by Peters, Alberici, Passmore, and Malins (2016) on commercial-scale gasification. As with manure and wastewater sludge, feedstock costs for the gasification of industrial and municipal wastes were assumed to be zero. For the gasification of crop and logging residues, we use country-specific roadside feedstock cost estimates from the European Commission's Joint Research Centre using the PRIMES model (Ruiz, Sgobbi, Nijs, and Thiel, 2015). The Joint Research Centre estimates substantial collection costs for crop and logging residues. Because the cost of industrial and municipal waste is free, which contributes to a lower MSP using this feedstock compared to other feedstocks, it is used first.

We do not include renewable gas transportation costs for the gasification/methanation pathway, which are likely to be low since a gasification/methanation plant could theoretically be sited near a natural gas pipeline. However, feedstock transport costs for crop and logging residues could be significant, and as we do not include these in our analysis, we most likely underestimate the cost of renewable methane from gasification of these feedstocks.

We apply a deployment model for the gasification to methanation pathway. Total facility deployment is based on an assumption of the ramp-up capacity and resource constraints for each member state. We assume construction times of 5 years for the first facility in each country and 3 years for all subsequent facilities. We assume that a single large-scale gasification/methanation facility with a capacity of approximately 80 million liters of diesel equivalent per year would begin design and construction in the first wave in 2021 (Peters et al., 2016). No other facilities in each country begin design and construction until construction is completed on the first wave of facilities. At that point, a second round of another facility begins design and construction. The first and second rounds of facility planning and construction have one large commercial-scale facility built in each country, while subsequent rounds have two facilities each. After the first two rounds, potential becomes constrained by feedstock availability in Italy and Spain but not in France, where there is higher feedstock potential as determined by Searle and Malins (2016). Searle and

4 The mean distances ranged from 8 to 25 km depending on the country, with an overall range of 1km to 55km

Malins (2016) found that, of the feedstocks assessed, only industrial and municipal waste would be sustainably available in 2030 in Italy and Spain because of strong competing uses for crop and logging residues. The availability of biomass, as determined by Searle and Malins (2016), is presented in Table 4. France's large agricultural sector compared with those of the two other countries and its forestry sector account for the large differences observed in this table.

Table 4: Biomass availability in million dry tonnes in 2030 in France, Italy, and Spain, from Searle and Malins (2016)

Feedstock	France	Italy	Spain
Agricultural Residues	28	0	0
Forest Residues	1.9	0	0
Municipal Solid Waste	3.8	3.4	2.8

We acknowledge that these assumptions of facility deployment are somewhat arbitrary. However, we believe that such constraints are necessary to reflect limits on financing opportunities. In other words, there are a limited number of banks and other investors willing to invest in cellulosic biofuel projects, even if the projects are expected to be economically viable. This constraint also reflects 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 would be expected based on modeled economics (Miller et al., 2013).

Power-to-Gas

Our power-to-gas assessment closely follows the methodology in Christensen and Petrenko (2017) and Searle and Christensen (2018). We model three power-to-gas pathways, each with a different type of electrolyzer powered by solar energy. Capital expenses are taken from an extensive literature review provided in Searle and Christensen (2018). We project electricity prices based on a model from the National Renewable Energy Laboratory (n.d.); average capacity factors for solar power in Italy, France, and Spain; current grid fees in these countries; and our projected changes in grid fees according to the greater balancing and distribution costs with increased renewable electricity penetration. We do not include transportation costs for power-to-gas.

We find that the potential for power-to-gas using wind electricity would be much lower than using solar electricity in these three countries. We use a financial model to estimate when and in which countries power-to-gas becomes economically viable at various retail cost levels given NPV<0 and an internal rate of return of less than 15%. We also apply a deployment model, assuming that a small demo-sized plant must precede a larger commercial-scale plant for each pathway in each country. We assume that only one facility for each technology pathway can be constructed at a time in each country due to financing constraints. Given the three technology pathways, a maximum of three power-to-gas facilities could be built at the same time in each country. We assume a 4-year construction period for each facility.

Results

TOTAL TECHNICAL POTENTIAL

The total, long-term technical potential for using renewable methane by feedstock in France, Spain, and Italy in 2030 is shown in Figure 1. The figure summarizes the energy, in peta-joules, from livestock manure, wastewater sludge, power-to-gas, and gasification in the three countries. The total energy ranges are 74 PJ in France, corresponding to 1.8 billion liters of diesel equivalent (DLE) energy; 25 PJ in Italy, or 0.6 billion DLE; and 69 PJ in Spain, or 1.6 billion DLE. Livestock manure provides the majority of the technical renewable methane potential, contributing about half in Italy and around 80% in France and Spain. Wastewater sludge makes up the smallest percentage, with no potential in Spain. Kampman et al. (2016) reported significant current use of this feedstock in Spain, so we find that there is no additional potential. The power-to-gas potential is highest in Spain, followed by Italy, as these countries have relatively high capacity for solar power.

In Italy, the potential for renewable methane to meet energy consumption for all modes of transport in 2030 is low, at approximately 2%. In France, the potential is about 4%, and in Spain, about 6%. The percentage share of energy consumption in the transport sector is based on 2014 data from the International Energy Agency (2016a). We expect total energy consumption in transport to decline from the present to 2030 and thus the renewable methane potential as a share of transport energy consumption to increase. We cannot make this exact comparison, however, as we were not able to find country-specific transport energy projections for 2030.

COST-VIABLE RENEWABLE METHANE POTENTIAL

Figure 2 shows the 2030 cost-viable potential at retail cost levels of €2.90 per kilogram, or €2.22/DLE; €5.50/kg, or €4.21/DLE; and €8.10/kg, or €6.20/DLE, for each country, as well as the technical potential for renewable methane. At a retail cost of €2.90/kg, Italy would be able to meet a relatively small share of its transport sector's energy consumption with renewable methane—producing only about 1 PJ of renewable methane per year (see Figure 2). For France and Spain, our analysis finds that no renewable methane production would be cost-viable at €2.90/kg. We find that Italy's potential for renewable methane from cattle and pig manure is only half the potential of the other two countries. The cost-viable potential of renewable methane in Italy at €2.90/kg comes from sewage sludge. We find that Spain does not have any additional potential for renewable methane from sewage sludge. Renewable methane from sewage sludge is not cost-viable at €2.90/kg in France because the current retail price of compressed natural gas is higher in France, around €1.26/kg, compared with €0.99/kg in Italy and €0.94/kg in Spain (CNG Europe, 2018a). We assume that national-specific CNG retail price markups apply to renewable methane. In Italy, some amount of renewable methane could be produced and delivered to the transport fuel market with lower subsidies of approximately €2/kg, or €1.53/DLE; in France, at €2.25/kilogram, or €1.72/DLE; and in Spain, at €2.66/kg, or €2.03/DLE.

For any significant amount of renewable methane to be available to the transport fuel market, retail costs would have to be almost three times the retail price of CNG in France and almost four times in Italy and Spain. By 2030, at a very high retail cost of €8.10/kg, Italy would be able to produce only half of its total potential for renewable methane, France only 25%, and Spain only 20%.

While considering the retail costs of producing renewable methane, one should also consider Feed-in Tariffs (FiTs), which France and Italy have for biomethane production and which we did not factor into our analysis. The costs we present here are pre-incentive

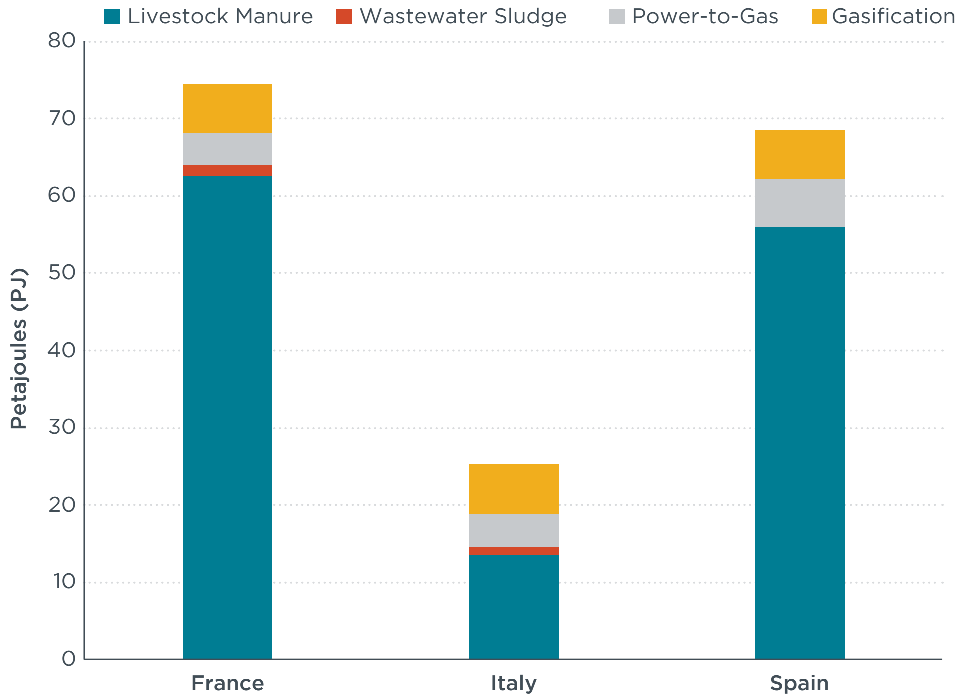

Figure 1: The total technical potential for renewable methane in Italy, France, and Spain in 2030 from livestock manure, wastewater sludge, power-to-gas, and gasification, in peta-joules (PJ).

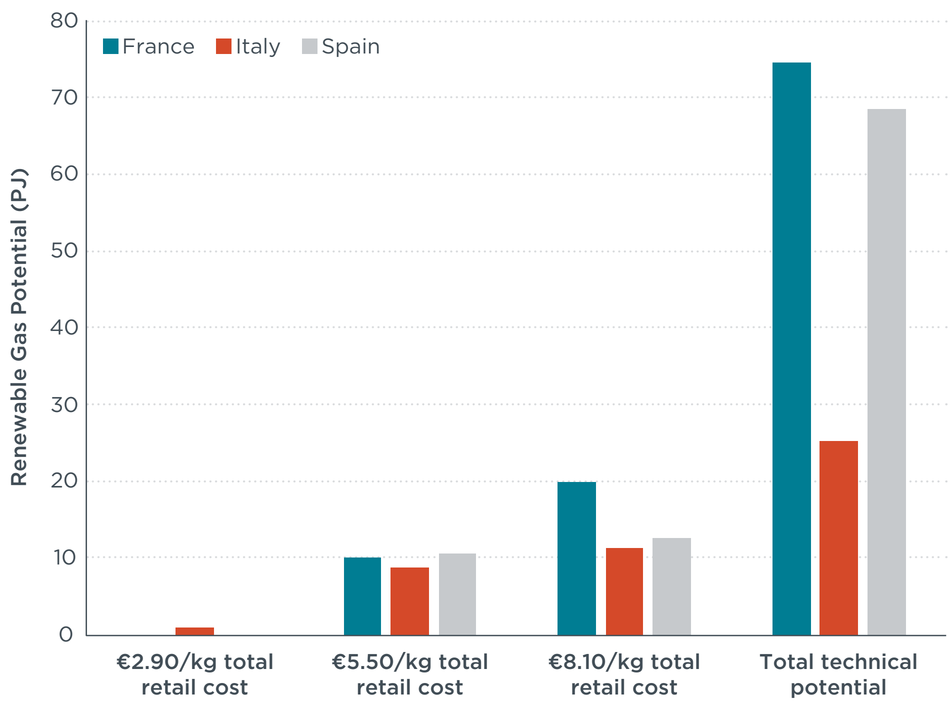

Figure 2. Total technical potential of renewable methane, as well as potential at €2.90/kg, €5.50/kg, and €8.10/kg in France, Italy, and Spain in 2030.

because incentives will most likely change in the future, especially in the timeframe under consideration. France has a FiT of €129.7/MWh, and Italy, €150/MWh. There are no tax reductions in Spain as the market for renewable methane is almost nonexistent (European Biogas Association, 2016). The bottom cost point in our analysis, €2.25/kg, translates to €193.56/MWh; thus, the existing FiTs in Italy and France could encourage production of a very small amount of renewable methane for transport when considering the retail price of CNG in these two countries—€96.86/MWh in France and €76.10/MWh in Italy.

Renewable methane from livestock manure is particularly expensive because of the high costs of transporting the gas from sometimes remote farms to gas pipelines. In France, a subsidy of €3.60/kg, or €2.75/DLE, is required to see a start of renewable methane production from dairy cows. In Italy, it would be €3.90/kg, or €2.98/DLE, and in Spain, €4.55/kg, or €3.48/DLE. Economies of scale are critical to achieve cost reductions for renewable methane from manure. However, the vast majority of farms are too small to cost-effectively produce CNG for transportation. As Figure 2 shows, cost considerations make a dramatic difference, and it is not realistic to expect that the entire technical potential of renewable methane could be delivered to the transport fuel market in these countries.

We find that in the 2020–2025 timeframe, the only available renewable methane production comes from anaerobic digestion of livestock manure and sewage sludge and power-to-gas from renewable electricity. By 2025, there is some potential to produce renewable methane using gasification of solid biomass. In Italy, France, and Spain, however, renewable methane from power-to-gas would be produced only at a retail cost of at least €4/kg, or €3.06/DLE.

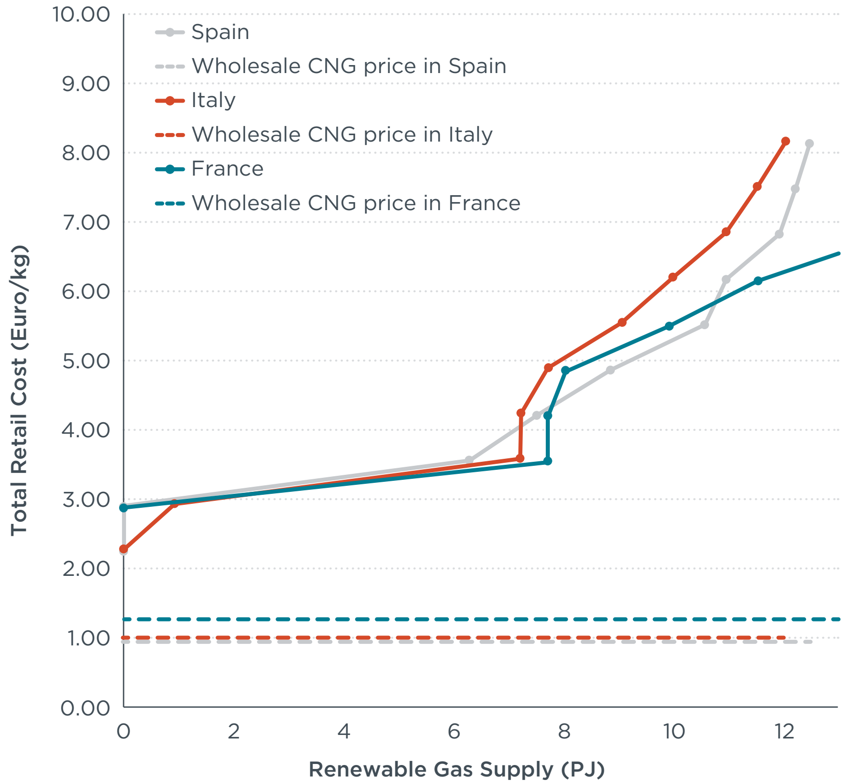

Figure 3: Total retail cost versus renewable methane supply in France, Italy, and Spain in 2030, along with wholesale price of CNG in the three countries

Figure 3 shows the retail cost curves for producing renewable methane in the three countries in 2030; the current retail prices of CNG are provided for reference. This figure demonstrates more concretely that the total estimated retail cost for renewable methane delivered as a transport fuel exceeds the retail price of CNG in every country for any amount of renewable methane supplied.

GREENHOUSE GAS MITIGATION POTENTIAL

We also assess the greenhouse gas mitigation potential if renewable methane were to displace fossil gas in the transport sector in these three countries. Figure 4 shows the total GHG mitigation potential of using all available renewable methane in France, Italy, and Spain, as well as the GHG mitigation potential when retail costs are considered, at €5.50/kg and €8.10/kg. At €2.90/kg, there was no GHG mitigation potential in France and Spain and insignificant potential in Italy, so we excluded that retail cost level from the figure.

In France and Spain, the climate benefits from using the total technical potential for renewable methane would be very high in 2030, slightly greater than 20 million tonnes of CO_2e savings per year (see Figure 4). In Italy, approximately 6 million tonnes of CO_2e annually in 2030 could be mitigated through the total technical potential. The GHG emission reductions in 2030 from the total technical potential of renewable methane are equivalent to approximately 6% of total current transport sector emissions in Italy, 19% in France, and 28% in Spain (UNFCCC, 2017a; UNFCCC, 2017b; UNFCCC, 2018). The potential reductions of GHG emissions are larger in proportion to total transport sector emissions than the potential for renewable methane relative to total transport energy because most of the potential for renewable methane comes from livestock manure, which has a negative GHG intensity (Figure 1).

At an expensive retail cost of €5.50/kg, or five time the wholesale price of natural gas in these three countries, only about 1 million tonnes of CO_2e would be saved each year in each country compared with using fossil gas. This represents less than 1% of the current GHG emissions from the transport sector in each country.

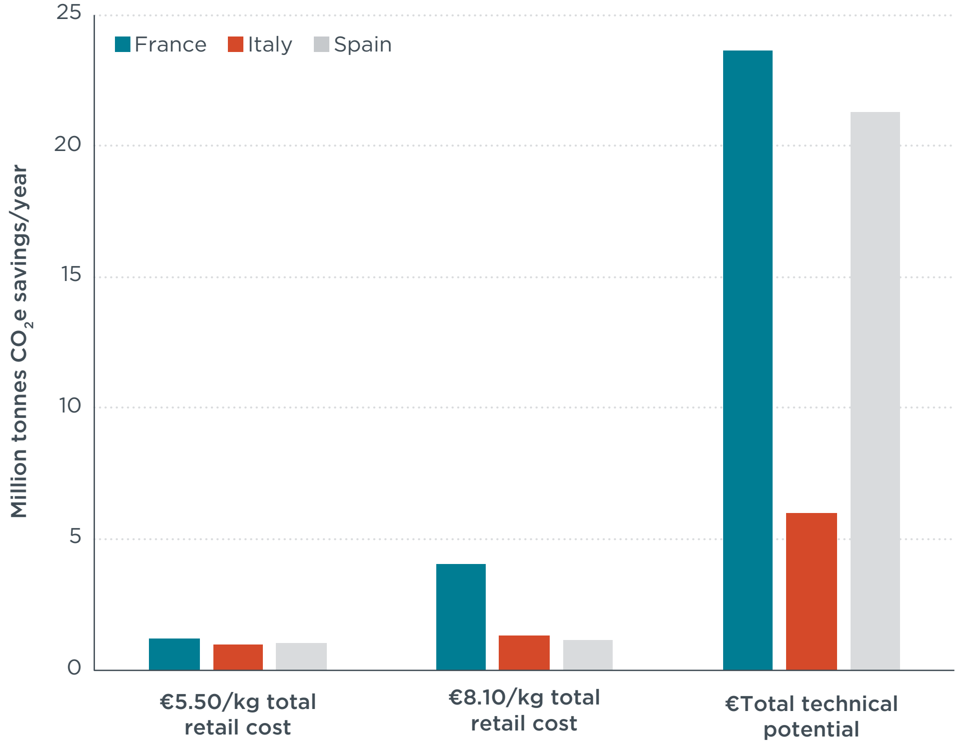

Figure 4: Greenhouse gas mitigation potential of renewable methane use in France, Italy, and Spain

Literature Comparison

Several other studies have estimated the potential for renewable methane production in Italy, France, and Spain. A 2016 European Commission study assessing the potential of renewable methane from anaerobic digestion finds that, under an "accelerated growth" scenario, the technical potential for additional renewable methane production in 2030, after subtracting 2011 renewable methane production levels) would be 167 PJ, or 4.08 billion DLE, in Italy; 176 PJ, or 4.30 billion DLE, in Spain; and 126 PJ, or 3.08 billion DLE, in France (Kampman et al., 2016). This is 6.6 times greater than our estimate for Italy, 2.6 times for Spain, and 1.7 times for France. IRENA (2017) predicted that France would be one of the top 10 biogas-producing countries in the world, generating 108 PJ, or 2.63 billion DLE, of biogas from animal waste, around 1.7 times higher than our estimate from cattle and pig manure. One methodological difference contributing to the discrepancy is that IRENA considered biogas from poultry manure, while we do not because of its high nitrogen content.

Our study does not include the potential for liquefied natural gas (LNG) in these three countries, but Kampman et al. (2016) did assess this potential. Kampman et al. (2016) estimated that LNG production would cost approximately a third more than CNG production. That study also reported that using renewable methane as LNG in a truck is less energy-efficient than using CNG in a truck, partly because of the lower vehicle efficiency of LNG trucks. LNG engines have an efficiency of 35.2% compared with 43.0% for CNG engines. In addition, higher energy consumption is required to liquefy gas compared with compressing it.

ADEME's 2018 report on the 2050 potential for renewable methane in France concludes that 300 TWh, or 1,080 PJ and 26.4 billion DLE, of renewable methane could be available in 2050 at a price that is cost-competitive with fossil gas without policy incentives (ADEME, 2018). This is eight times the technical potential for renewable methane in 2050 as found in our analysis, which estimates 39 TWh, or 142 PJ and 3.47 billion DLE, as reported in the Appendix, Table A1. The ADEME report considers a much wider range of feedstocks than our analysis, including wood, intermediary crops, sawmill and pulp mill residues, and grass, which we exclude based on environmental performance (See Methodology). In addition, the ADEME report projects far lower renewable methane production costs than our analysis and it does not consider technology commercialization and facility deployment to be a limiting factor for gasification and power-to-gas.

Conclusion

Governments and private-sector interests in France, Italy, and Spain are promoting renewable methane as a fuel source to decarbonize the transport sector in their countries. In this assessment, we ask whether renewable methane is technically feasible and cost-viable, and the extent to which renewable methane can provide greenhouse gas savings relative to fossil gas. When considering the additional potential that is technically possible from renewable methane, we find that 74 PJ could be produced in France, 25 PJ in Italy, and 69 PJ in Spain. That corresponds to 5% of 2016 natural gas consumption in France, 1% in Italy, and 7% in Spain (European Commission, 2018b). From a transport energy perspective, these potentials equate to 1.8 billion DLE for France, 0.6 billion DLE for Italy, and 1.6 billion DLE for Spain.

Our cost assessment indicates that it is highly unlikely any of the three countries will reach their technical potential for renewable methane production by 2030. There is substantial reason to believe that renewable methane from livestock manure in particular will be constrained by high costs; farms are widely distributed and many farms in the three countries suffer from poor economies of scale. After taking into account the costs of transforming waste and residue feedstocks, as well as the cost of renewable electricity in the power-to-gas pathway, we find it is likely that gasification and power-to-gas deployment will also be limited. For more information on the potential for renewable methane from electricity, see Searle and Christensen (2018).

We estimate that at a cost of €8.10/kg, renewable methane has the potential to displace CNG as fuel for only about 19,000 tractor-trailers in France, or 9% of the on-road fleet; 11,000 in Italy, or 5%; and 12,000 in Spain, or 7%.[5] Tractor-trailers are only one example of the kind of vehicle that could use the renewable methane.

In principle, using renewable methane could significantly reduce GHG emissions from the transport sector, but the high cost of production severely constrains its deployment in the three countries. At a cost of €8.10/kg, only around 1 million tonnes of CO_2e would be saved in Italy and Spain. France would generate about 4 million tonnes of CO_2e reduction annually, or about 3% of current transport sector emissions (UNFCCC, 2017b).

We find that strong subsidies of at least €3.50/kg are needed to support the use of any significant renewable methane potential in the transport sector, compared with current retail CNG prices of €0.94–€1.26/kg in these three countries. Policy support could include a suite of measures, for example capital grants combined with a fuel tax exemption. Given our findings, 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 of the transport sector.

5 We assume a vehicle kilometers travelled of 118548 for one year for a tractor-trailer, and a fuel consumption of 28 kg CNG/100 km for a tractor-trailer CNG engine, to estimate the DLE that a tractor-trailer would consume in a year. We retrieved estimates of on-road tractor-trailers for each country from Eurostat.

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Appendix

Here we present an indication of potential renewable methane production, costs, and climate impacts in the 2050 timeframe. These projections for the 2050 timeframe carry high uncertainty.

Table A1: Potential renewable methane production in France, Italy and Spain in 2040 and 2050: technical potential and potential at 3 retail cost levels, in peta-joules.

	France		Italy		Spain	
	2040	2050	2040	2050	2040	2050
€2.90/kg total retail cost	28	34	17	17	13	13
€5.50/kg total retail cost	36	64	24	31	31	46
€8.10/kg total retail cost	52	87	33	47	35	54
Total Technical Potential	110	142	47	61	91	110

Table A2: Greenhouse gas mitigation potential (million tonnes CO_2e savings per year) of using renewable methane in France, Italy, and Spain compared with fossil gas in 2040 and 2050

	France		Italy		Spain	
	2040	2050	2040	2050	2040	2050
€3.50/kg total retail cost	3.25	5.45	2.05	2.05	1.31	1.35
€8.10/kg total retail cost	7.12	10.15	3.23	4.12	2.67	3.85
Total Technical Potential	26.67	29.71	7.96	8.84	22.79	23.97