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A methodological comparison for estimating renewable gas potential in France

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Summary

Renewable gas is discussed frequently as part of a strategy to decarbonize Europe's energy system and reduce dependence on conventional natural gas. In a previous analysis, ICCT found that there is a limited potential for renewable gas to decarbonize France's transportation sector, and that it would be prohibitively expensive, even with strong policy support (Baldino et al., 2018, which we refer to as "the ICCT analysis" in this paper). Another analysis by Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME, 2018) found that 100% of France's transportation energy needs in 2050 could be met cost-effectively with renewable gas. In this working paper, we compare in detail the methodologies and assumptions in these two studies to elucidate the large difference in results.

ADEME (2018) estimated the technical potential for renewable gas (including both renewable methane and hydrogen) in 2050 as roughly 16 times the value reported in ICCT's analysis. ADEME concluded that 293 terawatt-hours (TWh) could be available at a relatively low price, whereas ICCT concluded that only 22 TWh of renewable gas is cost-viable even with a very high government policy incentive (e.g., subsidy) of €7.50/kg. This amount of policy support is more than 7 times the current wholesale price of natural gas in France.

The main differences between the ICCT analysis and ADEME's are the identification of low-carbon feedstocks and assumptions about production costs and technology deployment. These are the most important differences:

1. The ADEME analysis assumes that all renewable gas feedstocks are climate-neutral. This does not align with the vast majority of scientific literature, which shows that forest stemwood in particular does not provide a climate benefit relative to fossil fuels over a 20-year time frame. The ICCT analysis does not include the potential for renewable gas from stemwood or other feedstocks associated with high-lifecycle greenhouse gas (GHG) emissions.
2. The ADEME analysis includes intermediate crops. The ICCT analysis excludes intermediate crops due to a lack of data on the sustainable availability of these resources in France.
3. Relative to ICCT's analysis of methane production costs, the ADEME analysis assumes lower costs for some technologies and omits some cost terms. The ICCT analysis finds that renewable methane, from livestock manure in particular, will be constrained by high costs. For example, farms are widely distributed and affected by poor economies of scale.
4. The ICCT analysis accounts for deployment limitations for the gasification and power-to-gas conversion pathways, whereas the ADEME analysis does not. ICCT's assumptions of facility deployment are designed to reflect limits on financing opportunities for advanced, capital-intensive technologies.

In this paper, we include a sensitivity analysis that attempts to align ICCT's methodology with ADEME's. We adjust select assumptions to match ADEME's where that study's approach is reasonable or superior to ICCT's. In this sensitivity analysis,

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we find that the technical potential for renewable gas in transport in France could be 70 TWh, or almost twice ICCT's initial assessment. This potential is still vastly lower than the 620 TWh technical potential reported in the ADEME baseline 2050 scenario.

Introduction

The French government's energy package sets a target for 10% of the gas sector to be renewable by 2030 (Le Dû, 2017). Local governments are also supporting the use of methane in transportation; for example, a Parisian public transport operator is investing in natural gas buses that can run on renewable methane (NGV Global News, 2018). As a result of this policy momentum, multiple studies have since been released assessing the potential for renewable gas in France and the European Union at large. Here, we compare in detail the methodology in a recent ICCT study (Baldino, Pavlenko, Searle, & Christensen, 2018, which we refer to as "the ICCT analysis") that estimates the potential for renewable gas in France in 2050 to a recent Agence de l'Environnement et de la Maîtrise de l'Énergie analysis (ADEME, 2018).

Figure 1 illustrates the difference in renewable gas potential between ADEME (2018) and the ICCT analysis, showing the cost-viable potential in ADEME (2018) along with the total technical potential for renewable gas from the ICCT analysis. For comparison, it also includes results from the ICCT analysis for the cost-viable potential of renewable gas with several levels of policy support, such as (for example) a subsidy of a given amount in addition to the market price of natural gas for use in transport. ADEME (2018) concludes that 620 terawatt-hours (TWh) of renewable gas, including both renewable methane and hydrogen, could be available in 2050, versus ICCT's estimate of 39 TWh of renewable methane. ADEME estimates that 293 TWh could be available at a relatively low price. In contrast, ICCT estimated that the bulk of renewable methane availability was cost-constrained. At ICCT's highest policy support level (€7.50/kg), the study estimated that only 22 TWh of renewable gas is cost-viable.

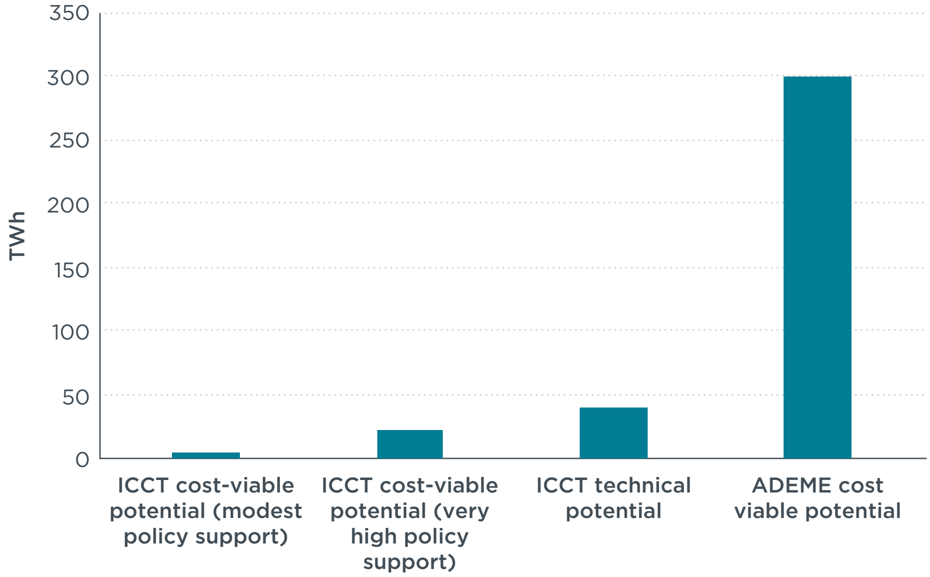

Figure 1. Cost-viable potential and total technical potential for renewable methane gas from the ICCT analysis (Baldino et al., 2018) and ADEME (2018).

This paper evaluates the methodological decisions and assumptions of both studies in an attempt to explain the large differences in results. It is important for policymakers to understand the differences in methodologies between these studies in order to have a realistic understanding of the potential for low-carbon renewable gas in France.

We begin by discussing fundamental differences in the scope and methodological framework of the ICCT and ADEME studies, focusing on the ADEME 2050 baseline scenario. Next, we assess the differences in assumptions regarding anaerobic digestion technology and its associated feedstocks and leakage rates, gasification and its associated feedstocks, and power-to-gas (PtG). We conclude with a sensitivity analysis of ICCT's study aimed at reconciling select methodological differences between the two studies.

Differences in overarching study scope and methodological framework

Although both ICCT's and ADEME's assessments estimate the long-term potential for renewable gas in France, the two analyses differ in scope and rely on different sets of assumptions. Figure 2 illustrates the total technical potential for renewable gas from both studies broken down by feedstock. The ADEME assessment includes a number of feedstocks not included in the ICCT study.

The ICCT study conducted a bottom-up analysis based largely on feedstock availability. According to the bulk of existing lifecycle assessment literature, renewable methane and biofuels produced from true wastes and residues without existing uses deliver the best climate outcomes, so ICCT focused on these feedstocks in its analysis. ICCT did not consider the use of purpose-grown crops, such as silage maize, that could compete with food crops for limited cropland because indirect land-use change (ILUC) emissions would undermine some of the climate benefits from renewable methane (Valin et al., 2015). The ICCT analysis estimated the potential availability of livestock manure, sewage sludge, municipal and industrial solid biogenic waste, crop and logging residues, and renewable PtG (Figure 2). ICCT assumed that livestock manure and sewage sludge are converted into biogas and then conditioned into renewable methane prior to import into the natural gas grid, whereas the remaining feedstocks are gasified, followed by methanation into synthetic methane.

ADEME presented several scenarios in its study; here, we focus on ADEME's baseline scenario for 100% renewable gas, called "100% R&REn (Renewable and Recovered Energies)." According to the authors, this is intended as an "extreme scenario" where, in 2050, the gas sector in France would be completely renewable (personal communication, November 2018). ADEME drew upon a wider range of feedstocks than did ICCT, including feedstocks that we believe evidence suggests do not offer significant climate benefits relative to fossil gas. This includes wood from forests, intermediate crops, and forestry by-products (sawmill and pulpmill residues, including sawdust and black liquor, and grass) (Figure 2). ICCT did not include forestry by-products because these materials already have existing uses in stationary heat and power generation as well as some material uses. ADEME assumed that there would be no biomass-derived energy used by the stationary heat and power sector or by the wood products sector, which could make these by-products available for renewable gas production. It also appears that to achieve the maximum technical potential claimed to be possible for PtG (~200 TWh), ADEME assumed a carbon tax of €1,000/tonne CO_2 (Figure 2).

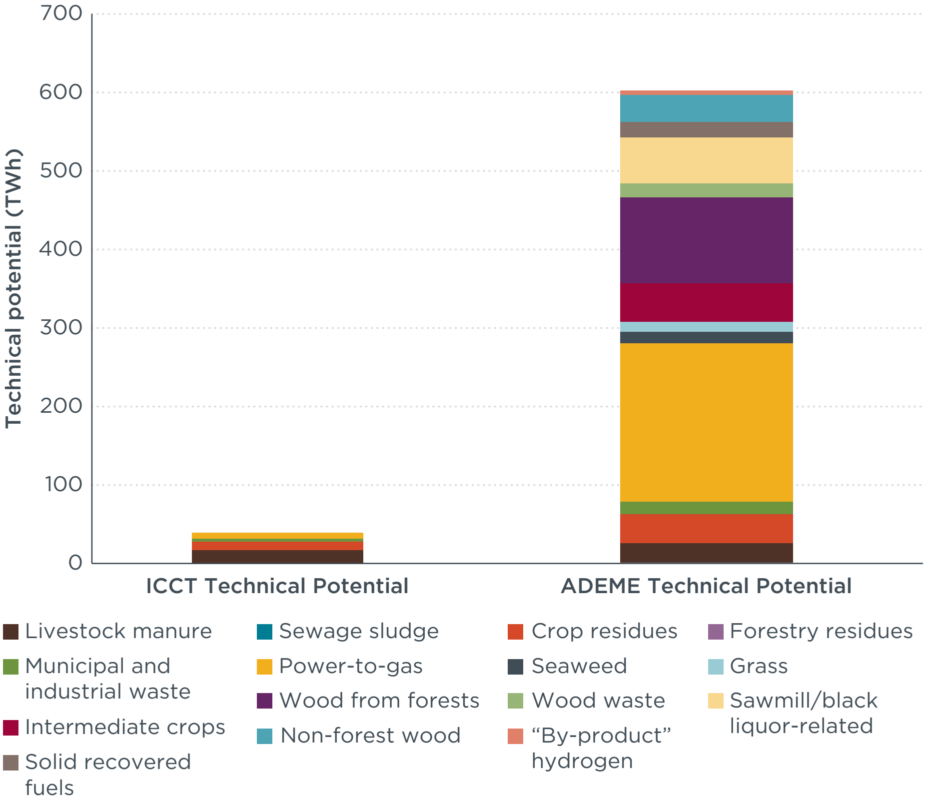

Figure 2. Total technical potential estimated by the ICCT analysis (Baldino et al., 2018) and by ADEME (2018), broken down by feedstock. This potential is called "Primary resources available in 2050" in the ADEME analysis.

Using its baseline scenario, ADEME conducted a top-down study, working backward from France's projected 2050 gas demand of 300 TWh. ADEME used a cost optimization approach to estimate how that demand is met through renewable energy sources. ADEME considered future policy changes and climate change effects, such as how a carbon tax of €200/tonne CO_2 could reduce costs, and how climate change would affect the yields of cover crops as well as the times of year during which they could be planted. In contrast, the ICCT analysis did not make any assumptions about future policy; rather, it developed an assessment of the costs inherent to each feedstock and technology, and then assessed the value of policy incentives necessary for each renewable methane source to become cost-viable relative to natural gas.

To develop its 293 TWh estimate, the ADEME study relied heavily on the work of Couturier, Charru, Doublet, and Pointereau (2016) and Caullet (2015) as well as several internal reports to which we do not have access, although we did communicate with the authors of ADEME (2018) and Couturier et al. (2016) to better understand their methodology.

ANAEROBIC DIGESTION

Anaerobic digestion is a well-documented conversion pathway for producing biogas, and there are numerous examples of anaerobic digestion projects worldwide, usually for on-site biogas combustion. Generally, it is cheaper to combust biogas onsite for electricity and heat than to condition, compress, and inject it into the natural gas grid, which can often be located far from farms. In our review of differences in the methodologies for the anaerobic digestion pathway in the two studies, we focus on livestock manure, because ADEME (2018) arrived at a potential for livestock manure that is 10 times ICCT's when considering costs [27 TWh, versus 2.6 TWh at the highest level of policy support in the ICCT analysis (€7.50/kg)].

The methane potential of livestock manure varies according to manure handling, region, and the type of animal that is producing manure. For the cost-constrained livestock manure methane potential analysis, ICCT used a granular breakdown of France's dairy farm distribution by size, in conjunction with cost data for anaerobic digestion, to assess the cost of supplying dairy manure–derived renewable methane to the natural gas grid. This approach factors in the reality that most dairy farms in France are relatively small in size and would not be able to produce biogas cost-effectively. As a result of the costs associated with constructing and running an anaerobic digester, plus the cost of transporting the resulting biomethane to the grid, ICCT found that production of biomethane from livestock manure is not cost-viable for farms with fewer than 100 cows. For reference, farms of this size are much larger than the median size of farms in France; only 2.6% of farms in France have more than 500 cows.

For this pathway, ICCT assumed that groups of five farms could pool resources for a shared digester if they had a total of 50 to 100 dairy cattle, whereas farms with more than 100 head would fund their own equipment. This is because pooled resources would become logistically difficult for larger farms, as they would presumably be spread farther apart. In contrast to ICCT, ADEME assumed that livestock manure biogas could be produced using economies of scale, regardless of the underlying farm sizes in France and their geographic distribution. ADEME assumed that manure-derived biogas production would occur at a centralized, large facility. Further, ADEME assumed that livestock manure could be delivered at zero cost to the anaerobic digester because of the value of the resulting digestate that could be returned to the farm, presumably allowing for much more flexibility in their modeling of the size of the anaerobic digesters and their distance from farms. However, this does not account for costs of transporting the manure.

Yazan et al. (2018) reported that the distance the manure needs to be transported is an important factor, because manure has a very low value. When assessing the profitability of exchanging manure and digestate between a biogas producer and a farm, Yazan et al. found that only a large-scale farm (producing more than 20,000 tonnes of manure per year) would find this exchange profitable if the biogas producer paid the farmer to receive the manure, or if manure disposal costs were greater than €10 per tonne of manure. Einarsson and Persson (2017) assumed that the maximum economically viable distance for transporting substrates, including manure, was 15 km. These findings contrast with the assumption in ADEME (2018) that manure could be pooled from dozens of farms with zero transport costs.

The differences in assumptions around manure pooling likely explain part of the difference in cost potential between the two studies. In addition, the digester cost is very low compared to the cost cited by Agostini et al. (2016) which was used in the ICCT analysis. ADEME (2018) provides an example of anaerobic digester costs in 2050: A digester with a flow rate of 200 Nm^3/hour, located 30 km from the injection point on the network and producing 17 GWh per year, could be built with capital expenses (CAPEX) of €959,000 and operating expenses of €205,000 per year. This scale for facility size assumed in ADEME (2018) is very large relative to the size of dairy farms in France, which have a median of 50 dairy cows per farm. For reference, Agostini et al. (2016) found that for an output of 13 GWh of methane (pre-combustion), the manure of 3,000 cows was needed, or 60 median-size farms' worth of dairy cows.

Agostini et al. (2016) consulted farmers, suppliers, and the literature to provide costs, and calculated that the digester at a 13 GWh facility would cost at least several million euros. In addition, a meta-analysis developed by the EU Sub-Group on Advanced Biofuels estimates a CAPEX cost of €1,500 to €2,000/kW of power from anaerobic digesters; this equates to a cost of €3.2 to €4.5 million for a 17 GWh project, assuming 8,000 hours of operation. ADEME's assumption on digester CAPEX thus diverges substantially from the literature (European Commission, 2017).

Another key difference between the ICCT analysis and ADEME (2018) is the way in which biogas is conditioned, compressed, and distributed to the grid. The ADEME study assumed that in some cases, gas would be trucked from the farm to the pipeline in bottles, and in other cases a pipeline could be constructed; it is unclear from the ADEME study how its levelized cost modeling determined the preferred means of transporting. The study that ADEME (2018) cited on how gas would be transported from the farm to the pipeline focused on transporting biomethane by bottles in a truck, so this may be the method that was primarily used in its modeling (Laurent, Benchimol, & Guianvarc, 2016). After an extensive literature search for the costs of transporting biomethane to the grid, the ICCT analysis focused on pipeline construction as the means to transport biomethane to the grid. Hjort and Tamm (2012) found that for distances of less than 30 km, transporting biomethane via pipeline is much more cost-effective than trucking it in most cases. Dairy biogas farmers in California have conveyed that shipping biomethane via truck is viewed as a short-term solution, whereas pipeline construction is considered a meaningful, long-term means to transport biomethane to the gas distribution grid.

For the construction of a pipeline 10 cm in diameter (i.e., DN100), ADEME used cost estimates from GRTgaz of €200 to €900 per meter, whereas ICCT used data on pipeline installation costs from NYSERDA (2006), which reported that approximately €119 per meter would be necessary for a pipeline closer to 2.5 cm in diameter. The NYSERDA study included the pipe costs and installation, plus an additional 50% for fittings and valves. It is unclear which exact considerations went into this cost assessment in ADEME (2018), as it is not clear which GRTgaz report it was citing for this information. The authors of ADEME (2018) reported that the average distance from farm to pipeline in France is 5 to 7 km, which is similar to the 8 km that the ICCT analysis found. Hjort and Tamm (2012) assumed costs of 1500 SEK per meter (€140,000 per km) for large, regional pipelines, and 700 SEK per meter (€65,000 per km) for smaller distribution pipelines, which is comparable to ICCT's estimate of €119,000 per km. ICCT's per-km cost estimates for pipelines do not differ much from those in ADEME (2018), so it is likely that the difference in potential from livestock manure lies in the assumptions made about the aggregate quantity and length of pipelines necessary to bring livestock manure–derived renewable methane to the grid.

Research shows that co-digestion with agricultural residues does improve the yield of biogas relative to using pig or cow manure alone (Wei et al., 2019; Wu, Yao, & Zhu, 2010). It appears from personal communication with the authors of the ADEME study that they assume co-digestion for agricultural residues with livestock manure for anaerobic digestion; however, the ICCT analysis assumed that cow and pig manure would be digested alone, without any other substrates. Wei et al. (2019) found that a 1:1 ratio of cow manure to corn straw (on a volatile-solids basis) increases biogas yield, relative to using cow manure as a mono-substrate, by a factor of 1.4. Therefore, we conducted a sensitivity analysis to determine how those remaining agricultural residues in France that would not be gasified in 2050 because of facility deployment restraints could be digested along with the livestock manure to improve yields. Because the mass of remaining agricultural residues available in France for co-digestion exceeds the available livestock manure (12 million tonnes of volatile solids) in 2050, we find that the technical potential available from livestock manure could be 40% higher. However, this does not consider the costs associated with transporting the crop residues to the anaerobic digesters. Even with the improvement in yield that co-digestion would provide, there is still the problem of economies of scale for smaller dairy farms and their geographic distribution.

The ICCT analysis also assumed a conversion rate of 65%, which comes from a U.S. EPA landfill energy cost model that assumes the use of a small-scale single-membrane system (U.S. EPA, 2018). Because this might be a conservative estimate, in the sensitivity analysis below, we included a 90% conversion rate for all anaerobic digestion to match the assumption in ADEME (2018).

Gasification

A large difference between the two analyses is their methodological approach toward gasification and methanation. Both ADEME and ICCT assumed *n*th-of-a kind gasification facilities with reduced CAPEX and improved yields relative to current demonstration facilities. Yields for the facilities that were modeled in the ICCT analysis are around 1,655 kWh methane per tonne of dry biomass, whereas ADEME assumed much higher yields of around 3,000 kWh methane per tonne of dry biomass. This assumption came from a Gaya resource that is not publicly available.

ICCT did not include transportation costs for the gasification/methanation pathway, which would likely be low because a gasification/methanation plant could theoretically be sited near a natural gas pipeline. ADEME (2018) appears to have used a similar assumption. ICCT also did not include feedstock transport costs for crop and logging residues, which could be substantial. ICCT's overall costs for the gasification pathway may thus be an underestimate.

In contrast to ADEME's approach, ICCT's analysis adopted a deployment model for the gasification-to-methanation pathway to consider the ramp-up capacity of these facilities. ICCT assumed the following scenario: A single large-scale gasification/methanation facility with a capacity of approximately 80 million liters of diesel equivalent per year begins design and construction in the first wave in 2021 (Peters, Alberici, Passmore, & Malins, 2016). No other facilities 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, whereas subsequent rounds have two facilities each, with a construction time of 5 years for the first facility and 3 years for all subsequent facilities. The ICCT analysis acknowledges that these assumptions of facility deployment are somewhat arbitrary, but they reflect limits on financing opportunities. That is, even if the projects are expected to be economically viable, there are a limited number of banks and other investors willing to invest in cellulosic biofuel projects. We removed deployment assumptions in the sensitivity analysis.

Gasification feedstocks

FOREST BIOMASS

Around 80 TWh of renewable gas in ADEME's analysis, a large fraction of total potential, is from "wood from forests." ADEME assumed carbon neutrality of this feedstock and all other feedstocks in its analysis. This assumption contrasts with the majority of the scientific literature, which is summarized in a recent Joint Research Centre study that shows that harvesting stemwood from forests for bioenergy purposes increases lifecycle GHG emissions relative to fossil gas over a reasonable time frame (Agostini, Giuntoli, & Boulamanti, 2014). Figure 3 combines all the estimates of carbon payback time for stemwood and whole trees (i.e., it does not include logging residues) reviewed in Agostini et al., 2014, showing how the vast majority of studies find that this payback period exceeds a typical time frame for low-carbon fuel policies (20 to 30 years). That is, in a 20- to 30-year period (20 years is used in the European Union's Renewable Energy Directive and the recast of the Renewable Energy Directive carbon accounting), using stemwood or whole trees for heat, power, or transport fuel produces greater GHG emissions than using fossil fuels. For this reason, ICCT excluded this feedstock.

The carbon payback times for use of logging residues (e.g., treetops and small branches) or salvage logs (e.g., from insect infestations) are much lower than for use of stemwood or whole trees. ADEME's analysis and ICCT's analysis both included logging residues. However, these feedstocks are still not carbon-neutral, and their use for energy leads to some lifecycle GHG emissions due to a reduction in forest carbon stocks and soil carbon (Agostini et al., 2014).

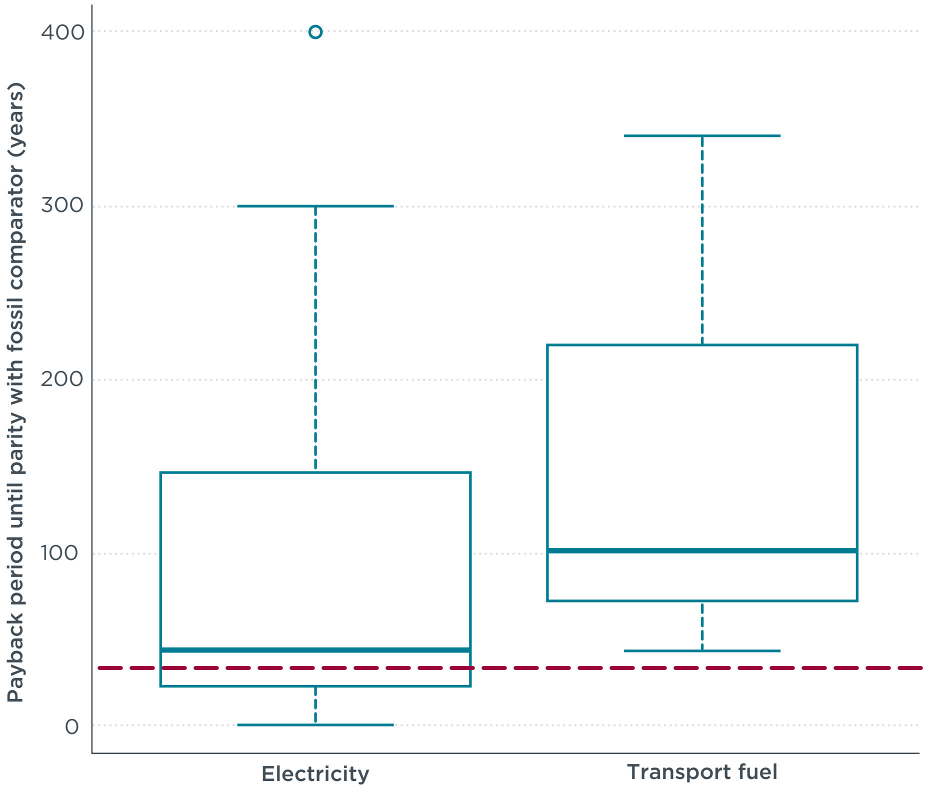

Figure 3. Summary of estimates of carbon payback time for stemwood and whole trees reviewed in Agostini et al. (2014). The dashed red line represents a 30-year payback time. The bold line through the box represents the median carbon payback time; the lower and upper hinges (the top and bottom of the box) represent the first and third quartile (25th and 75th percentiles) of the distribution. Whiskers extend to the smallest and largest values no further than 1.5 times the interquartile range outside the box. The small circle represents an outlier, i.e., a value exceeding the 75^{th} percentile plus one-and-a-half times the interquartile range.

Logging residues may account for some fraction of "wood from forests" in ADEME's analysis. However, the amount of "wood from forests" included in ADEME's scenario is considerably larger than the amount of logging residues produced annually that can be sustainably harvested without a negative impact on soil quality in France, which was estimated in a previous study (Searle & Malins, 2016). Thus, it is likely that a majority of the amount of "wood from forests" in ADEME's study would be stemwood.

Caullet (2015) is heavily cited in ADEME (2018) during discussions about using forest biomass in renewable gas. Caullet (2015) is a discussion paper and does not present or substantially review evidence on the lifecycle GHG performance of forest biomass. In Annex 4, Caullet argued that bioenergy from forest biomass cannot be considered carbon-neutral and that carbon payback times are generally 20 to 100 years. That is, during this time period, forest bioenergy is more carbon-intensive than fossil fuels, and substantially longer than 20 to 100 years will be required before forest bioenergy delivers substantial carbon savings over fossil fuels. Caullet also argued strongly that use of forest biomass in long-lived wood products delivers much stronger climate benefits than using the same wood for energy production. This is because in addition to substituting for carbon-intensive products such as concrete, the carbon in the biomass remains sequestered for years or decades in wood products, whereas when it is used for energy, it is immediately emitted to the atmosphere. At the same time, Caullet asserted that harvesting wood for use in wood products increases forest productivity, but Searle and Giuntoli (2019) found that increased demand for forest biomass historically has been associated with only a small increase in forest productivity, if any at all.

ADEME (2018) also cited Roux et al. (2017), which included several scenarios for harvesting wood for bioenergy. All of the scenarios in Roux et al. (2017) found that forest bioenergy causes a reduction in forest carbon stocks and results in carbon debt. No other studies were cited in the ADEME study in its discussion on the climate performance of forest bioenergy.

FORESTRY BY-PRODUCTS

ICCT excluded forestry by-products from the analysis because of previous research showing that these resources have high indirect emissions caused by their diversion from existing uses (Malins, 2017; Searle, Pavlenko, El Takriti, & Bitnere, 2017). Most of these resources are currently combusted for heat and power by the industries that produce them. For example, crude tall oil can be combusted directly on site for energy recovery for the pulpmill lime kiln. Diverting these feedstocks from their existing uses would cause a shuffling of fossil fuel use: Less fossil gas would be used, but perhaps more coal would be used, with no net climate benefit.

ADEME (2018) included these feedstocks in its assessment, which contribute to the 9 TWh of cost-viable potential from refuse-derived fuel. The authors assumed that in 2050, materials such as sawdust and black liquor will not be needed for heat and electricity, which would mean that pulpmills and sawmills will voluntarily start purchasing grid electricity and heat (assuming that is 100% renewable in 2050) instead of combusting forestry by-products (personal communication, November 2018).

GRASSES GROWN ON LOW–CARBON STOCK LAND

ADEME (2018) assumed that pasture land is decreasing in France, and that climate change will make it impossible for livestock to forage in the summer. ADEME argued that using grass for bioenergy will help to consolidate grazing systems and make foraging easier (personal communication, November 2018). The ICCT analysis does not include grass or any other cellulosic energy crop grown on available unused land because (1) there is not enough data available for a robust estimate of the land area in France that could be sustainably available for energy crops, and (2) using the scarce amount of data available, a study from the Institute for European Environmental Policy estimates very limited energy crop potential in the European Union (Allen et al., 2014, 2015).

AGRICULTURAL RESIDUES

ICCT assumed that agricultural residues such as wheat straw would be converted to methane by gasification and methanation. ADEME (2018) assumed that agricultural residues would be used in anaerobic digestion, with the digestate returned to the soil (personal communication, November 2018). The ICCT analysis did not include anaerobic digestion of agricultural residues, because these materials have a much lower moisture content than is typically necessary for feedstocks for anaerobic digestion technology (Einarsson & Persson, 2017). To determine the amount of agricultural residues that would be available in France for gasification, the ICCT analysis used a detailed previous study on the sustainable availability of agricultural residues in individual European member states, including France. That study found that 28 million tonnes of agricultural residues would be available for new energy uses in 2030, and the ICCT analysis assumed the same amount for the year 2050 (Searle & Malins, 2016). Combined with cost modeling and considering ramp-up times and deployment, ICCT found that 10 TWh of renewable methane from crop residues could potentially be available in France in 2050. ADEME (2018) found that 31 TWh of renewable gas could come from agricultural residues. We believe that the primary factors leading to different potentials from agricultural residues in the two studies are the different conversion pathways (anaerobic digestion versus gasification) used, as well as constraints on gasification facility deployment in the ICCT analysis.

ALGAE

ADEME (2018) considered algae as a viable feedstock for gasification and found that 14 TWh of renewable methane will be available from this feedstock in 2050. The ICCT analysis did not include algae for a variety of technical and financial reasons. There are currently no commercial-scale producers of algae-derived biofuels, and the technical parameters and cost of this feedstock are poorly understood. The most promising technology for processing micro- and macroalgal feedstock is hydrothermal processing, which includes hydrothermal gasification, but this technology is still in a nascent stage and costs for mass cultivation of algae remain high. At present, hydrothermal processing of other feedstocks, particularly biowaste, is more promising (Biller & Ross, 2016).

INTERMEDIATE CROPS

The primary ICCT analysis did not include intermediate crops, also known as cover crops, as a potential source for renewable methane production because there is little data on the use or potential sustainable availability of these crops.

The potential for increasing intermediate cropping is not clear; more than half of all croplands in Europe were already double-cropped at some point over the period 2001–2012, and in general double cropping is increasing in practice globally (Estel et al., 2016). Using intermediate crops that would have been grown anyway to supply increasing global food and feed demand would divert those resources from other uses, with resulting ILUC emissions.

The main environmental risk with intermediate cropping is diversion to biofuels of resources that would have been used in food and feed. France already has some double-cropping, and some of the double crops produced on that land may already be used for food and feed (Estel et al., 2016). If crops that are already used are diverted to biofuel production, the result will be a gap in supply for food and feed, leading to crop expansion elsewhere (i.e., ILUC). Furthermore, intermediate cropping as a general practice (i.e., not directly associated with biofuel demand) is increasing globally. Therefore, in the absence of French bioenergy demand, we would expect to see an increase in double-cropping in France. That increase in double-cropping will be driven by an increase in demand for food, feed, and to some degree, bioenergy demand in other countries, so if we are diverting that commodity to use in bioenergy, there will be ILUC. Low-ILUC renewable gas from double-cropping is only possible if the use of intermediate cropping is increased in areas where it would not be practiced without the specific incentive of using it for domestic renewable gas production.

It appears that one of the primary reasons ADEME (2018) found such high potentials from intermediate crops is that the study assumed that climate change will affect yields and sowing dates for these crops in the future. In particular, it appears that ADEME assumed that wheat will be harvested earlier in 2050, meaning that more summer intermediate crops can be grown after that harvest (personal communication, November 2018). The ICCT analysis made no assumptions about how climate change will affect production of agricultural resources, because climate change is already occurring, so any increase in double-cropping due to climate change will occur in the absence of renewable gas demand; an increase in double-cropping due to climate change thus cannot be attributed to renewable gas. ADEME (2018) assumed yields of 4 to 6 tonnes per hectare for intermediate crops, which is around 2 to 3 times the average yields in France of common intermediate crops identified in Alliance Environnement, 2017 (FAO, 2019).

Power-to-gas (PtG)

The largest difference in overall potential between the ADEME analysis and ICCT's assessment stems from differing views on the potential for renewable electricity to generate renewable gas. ICCT's estimate is taken from a previous ICCT study on the potential for electrofuels from PtG in Europe (Searle & Christensen, 2018). That study conducted a cost projection of electricity prices for each EU member state through 2050, along with cost data taken from a literature review on the capital and variable costs of electrolysis and methanation. That study assumed that the capital costs include €0.6 to €0.8 million/MW for an electrolyzer and €1.77 million for a methanation unit of 5 MW capacity. Table 25 in ADEME (2018) reported similar CAPEX costs, around €1 million/MW.

Although both the ICCT analysis and the ADEME study started from a similar baseline with respect to capital costs, ADEME estimated higher potential for PtG in 2050 than did ICCT's assessment (90 TWh compared to ICCT's 7.7 TWh), a factor of ~11 difference. This likely stems from differences in the studies' respective approaches toward the cost of renewable electricity. ICCT drew upon average per-kWh cost estimates for renewable electricity from the grid as well as from off-grid installations, whereas ADEME assumed that the PtG pathway would be the "adjustment variable" to balance supply of renewable gas and demand, which it estimated would be 300 TWh in 2050 in France.

It appears that ADEME assumed a carbon tax of €200/tonne CO_2 in order to conclude that the cost-viable potential for PtG would be 90 TWh, which would increase the price of natural gas and thus make PtG competitive at a higher selling price. ADEME (2018) also included revenue from energy storage, known as smoothing, and ICCT's analysis did not. The ICCT analysis assessed absolute costs and reported the total level of policy support that would be necessary to make PtG cost-competitive. The ICCT analysis found that no PtG would be cost-viable with an implied policy support level equivalent to €200/tonne CO_2e, and that a significantly higher level of policy support would be necessary to support substantial PtG volumes.

To estimate renewable electricity prices, ICCT assessed internal wind and solar price projections, both off grid and on grid, assuming roughly 50% and 10% reductions in solar and wind levelized costs from the present to 2050, respectively, plus taxes and a modest increase in grid fees for renewables balancing costs. The ICCT analysis found that the potential for PtG using wind electricity would be much lower than using solar electricity in France. ADEME used a model that optimizes for a 100% renewable energy mix; the lower range of electricity prices it used is "lower than the market value, assuming that the PtG is a new and flexible usage at marginal cost for the whole electricity system" (personal communication, November 2018). The higher range of electricity prices is based on an average of spot market prices.

Similar to ICCT's assessment of the potential for the gasification conversion pathway, ICCT's PtG assessment included ramp-up times and facility deployment constraints, whereas ADEME (2018) did not. ICCT assumed that a small demo-sized plant must precede a larger commercial-scale plant for each pathway, and that only one facility for each technology pathway can be constructed at a time because of financing constraints. Further assumptions were that a maximum of three PtG facilities could be built at the same time and each facility would require a 4-year construction period. The ICCT analysis used a financial model to estimate when PtG would become economically viable at various wholesale cost levels, given a positive net present value and an internal rate of return of less than 15%.

Another minor difference between the two analyses is the difference in efficiency of PtG conversion. ADEME assumed a 66% conversion rate for electricity to CH_4 using this pathway, whereas ICCT assumed a conversion rate ranging between 48% and 62%, depending on the type of electrolyzer.

ADEME also assumed that much more excess electricity would be available for use in this pathway, which is an important difference in ADEME's and ICCT's assessments, because both studies found that electricity is one of the biggest components of cost for this pathway, and excess electricity is free. It appears that ADEME assumed that 3,200 to 3,700 hours of excess electricity would be available per year when spot prices are low (personal communication, November 2018). The ADEME study also included income from sales of excess heat from the process, whereas ICCT did not find that the process would create enough heat to consider this factor.

The ICCT analysis also did not consider injection of hydrogen into the grid, given limits on direct injection of hydrogen. Had ICCT considered the potential from the production of hydrogen alone, slightly more renewable gas would have been produced, because the efficiency loss during the methanation step would be avoided.

Sensitivity analyses

We performed a sensitivity analysis on the results of the ICCT analysis to align ICCT's methodology with ADEME's for select differences where we agree that ADEME's approach is superior or reasonable, shown in Figure 4. Even with these adjustments, we found that ICCT's assessment of France's renewable gas potential is still much lower than the potential in ADEME (2018). This sensitivity analysis takes into account:

1. a 90% conversion yield for anaerobic digestion (increasing the potential from livestock manure and sewage sludge both by approximately 40%),
2. the potential for intermediate crops,
3. the potential for energy crops on low–carbon stock land,
4. no gasification deployment limits.

With these changes, the technical potential for renewable gas in transport in France grows to 70 TWh, nearly double the value in the initial ICCT analysis. This potential is still much lower than the 620 TWh technical potential reported in the ADEME baseline 2050 scenario, as well as its estimate of 293 TWh for the cost-viable potential.

Although there is a lack of data and projections on the growth of intermediate cropping, we created a projection for 2050 based on the limited evidence available in a study commissioned by the European Commission (Alliance Environnement, 2017). That study presented some evidence that the prevalence of intermediate cropping may be increasing over time. Extrapolating from this data, we estimate that intermediate cropping could be practiced on 10% of cropped fields in Europe in 2050. We assume that half of this area would be available for renewable gas production without displacing food and feed; there is no data available on the fraction of all intermediate crops used for food and feed. We chose oats as a representative intermediate crop because it is one of the few common intermediate crops identified in Alliance Environnement (2017) for which yield data is available (European Commission, 2019). Oats grown as intermediate crops likely do not grow normally, however, because of the adverse winter conditions and short growing season. For example, Alliance Environnement (2017) reported that intermediate crops are typically harvested or plowed under before producing seed. To estimate biomass production from winter-grown oats, we thus subtracted grain production using the harvest index for wheat from Scarlat, Martinov, and Dallemand (2010), further assuming a 40% yield penalty for growing in adverse conditions overwinter, and a 20% harvesting loss for the amount of stubble that occurs under the height of the harvesting blade. We find that 3 million fresh tonnes of intermediate biomass would be available per year. This corresponds to 3 TWh of renewable gas per year, as shown in Figure 4. This increases ICCT's total methane potential by 6% and is much smaller than the potential of renewable gas from intermediate crops estimated by ADEME, 51 TWh.

For cellulosic energy crops, referred to as "grass" in ADEME's assessment, we relied on an assessment of sustainable land availability and energy crop potential (Allen et al., 2014). That study reported an EU-wide energy crop potential, and we scaled this to France on the basis of France's proportion of total agricultural land in Europe. We assumed that cellulosic energy crops would be subjected to gasification followed by methanation, and used the same yields as for agricultural residues. We estimate that 2 TWh could come from these energy crops, which is much lower than ADEME's estimate of 13 TWh.

Because ICCT's analysis only focused on the transport sector, it accounts for renewable gas that is already used in other sectors. Currently produced sewage and manure renewable gas is mostly used for heat and power, and this resource should not be considered sustainably available for use in the transport sector. If this renewable gas were diverted from its existing uses in heat and power, another energy source, which is likely to be at least in part fossil gas, would be needed to replace it in those uses. However, this assumption does not substantially affect ICCT's total technical potential relative to ADEME's. If we instead consider the total technical potential without subtracting current uses of sewage sludge and livestock manure, the results would also have only changed slightly—a 24% increase in the potential from sewage sludge, from 0.4 TWh to 0.5 TWh, and a 3% increase in the potential from livestock manure, from 17.4 TWh to 18.0 TWh—making a very small difference in the potential relative to ADEME (2018).

We could consider two additional changes. Agricultural residues can be mixed with livestock manure and co-digested in anaerobic digesters, which could increase the methane yield from agricultural residues relative to gasification and methanation. In the primary ICCT analysis,

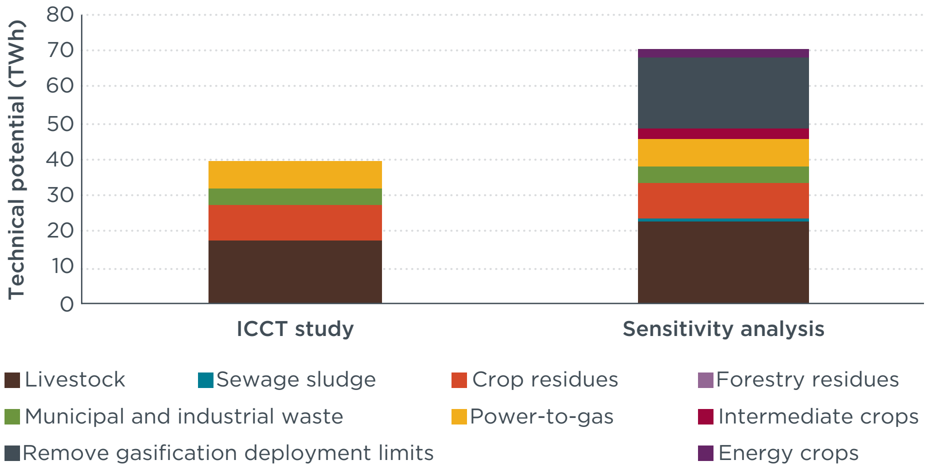

Figure 4. Sensitivity analysis results.

not all sustainably available agricultural residues were used in gasification because of facility deployment limits. Were there still to be a limit on the deployment of gasification technology, an additional 40% could be added to the livestock manure potential for the co-digestion that could occur using remaining, sustainably removed crop residues. This increase in the ICCT renewable gas estimate is similar to the increase resulting from the removal of facility deployment limits. The ICCT analysis also did not consider injection of hydrogen into the grid, given limits on direct injection of hydrogen due to safety and material integrity concerns, such as the durability of certain metals present in gas infrastructure (IRENA, 2018). Slightly more renewable gas would be produced if the ICCT analysis had considered the potential from the production of hydrogen alone, because the efficiency loss during the methanation step would be avoided. Keeping all of the other assumptions constant in the ICCT analysis, we find that when all gas production from the PtG pathway goes to production of hydrogen alone, 10 TWh of hydrogen gas could be produced, around 1.3 times the 7.7 TWh of CH_4 from PtG in the ICCT analysis. This is lower than the potential reported by ADEME (2018) by a factor of 9.

Conclusions

The ICCT analysis quantified the availability and cost of supplying renewable methane to the transportation sector in France in 2050 in a bottom-up assessment. The ADEME study, on the other hand, presented a top-down analysis to determine the most cost-effective way that 100% of France's gas demand could be met with renewable resources. The ICCT analysis found that even with a very high government incentive of €7.50/kg, only 22 TWh of renewable gas could be delivered to the gas grid for use in transport in France, compared to ADEME's cost-viable estimate of 293 TWh. When we tried to align ICCT'S methodologies by adopting those of ADEME's assumptions that may be reasonable or superior to ICCT's in a sensitivity analysis, there was still a very large discrepancy in ICCT's renewable gas potential estimates.

The main differences between the ICCT analysis methodology and ADEME's are the identification of low-carbon feedstocks and assumptions concerning production costs and technology deployment. In particular, ADEME's study makes several assumptions about policies and climate change in the future that would increase renewable gas potential, whereas the ICCT analysis considers only current trends. Overall, we find that several of ADEME's assumptions and methodological choices are not well supported by evidence. ADEME's assumption that all feedstocks are carbon-neutral, including forest biomass, does not align with the vast majority of scientific literature showing that forest biomass does not provide a climate benefit in a 20-year time frame relative to fossil fuels. There is little evidence to support ADEME's strong assumptions on the future availability of intermediate crops; furthermore, their use in energy can conflict with uses in food and feed, leading to ILUC. It is unclear exactly how ADEME's modeling leads it to such different cost estimates relative to ICCT's, but it appears that ADEME omits some important cost terms from its analysis, such as the cost of transporting manure to centralized digesters. At the same time, we acknowledge that ICCT's assumptions of facility deployment for gasification and PtG are somewhat arbitrary, but they reflect limits on financing opportunities that are important when considering the future availability of advanced gas conversion technologies.

It is vitally important for renewable energy policies to be based on realistic expectations about the potential volumes, costs, and lifecycle GHG impacts of the energy sources they support. Overly optimistic policy targets can lead to the use of unsustainable resources and high costs. This methodological comparison finds that ADEME's conclusion that 100% of gas in 2050 can be renewable, cost-competitive, and climate-neutral is very optimistic, given the available evidence on renewable gas sources.

Glossary

Anaerobic digestion: A commercially mature technology that produces methane from wet feedstocks such as manure and sewage sludge.

Biogas: Gaseous fuels produced from biomass, including energy-carrying gas, that is primarily methane and mixtures that are partially methane produced from biomass feedstocks through anaerobic digestion, gasification, or other processes. Raw biogas typically contains a mix of approximately 50 to 60% methane, with much of the remaining volume comprising CO_2, volatile organic compounds, and trace impurities.

Biomass: Organic matter, particularly from plants and animals, that could be used as a source of energy.

Biomethane: Biogas that has been cleaned so that only methane (CH_4) remains.

Black liquor: A by-product from pulp production, which is mostly used to make paper; a lignin-rich slurry created when ground wood is washed in chemicals to separate lignin from the cellulose fibers that make up pulp.

By-product: Secondary product made in the manufacture or synthesis of a different product.

Carbon payback period: The point at which the forest carbon stock from increased removal of wood for energy is balanced over time by the GHG savings that derive from replacing fossil fuels relative to a no-bioenergy scenario.

Digestate: The material that remains after anaerobic digestion.

Feedstock: A raw material that can fuel a machine or industrial process.

Gasification: The conversion of biomass or organic wastes; for example, the organic fraction of municipal solid waste converted into syngas. This syngas is a mixture of hydrogen (H_2), carbon monoxide (CO), and CO_2. See Baldino, Berg, Pavlenko, and Searle (2019) for more information.

Hydrothermal processing: After pretreatment, a biomass slurry is heated and pressurized to convert it to bio-crude. Bio-crude is an intermediary product that is then hydroprocessed in a manner similar to conventional crude to produce drop-in fuels. See Baldino et al. (2019).

Indirect land use change (ILUC): When absolute levels of feedstock production rise in response to a biofuels policy, this will generally require an increase in land that is put to agricultural use. Because these changes can happen at some distance from the location of biofuel feedstock cultivation, they are referred to as being indirect.

Intermediate crops: Crops planted in addition to a main crop to manage soil erosion, fertility, and quality, as well as water, weeds, pests, diseases, and biodiversity in agriculture. Also known as cover crops, sequential crops, green manure, winter crops, and intercrops.

Methanation: The conversion, at temperatures of 700° to 1,000°C and with a nickel catalyst, of carbon monoxide and hydrogen to methane and water.

Power-to-gas: A set of processes that convert electrical energy to liquid or gaseous fuels, using either CO_2 or CO as a feedstock. Includes power-to-liquids and power-to-gas. See Baldino et al. (2019).

Sawdust: Residue from producing sawed wood in a sawmill.

Spot market price: The current price at which an item is bought or sold for immediate payment and delivery.

Stemwood: The wood of the stem(s) of a tree, i.e., the aboveground main growing shoot(s).

Wheat straw: The stalk left over after wheat grain is harvested.

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