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The Potential for Electrofuels Production in Sweden Utilizing Fossil and Biogenic CO_2 Point Sources

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This paper maps, categorizes, and quantifies all major point sources of carbon dioxide (CO_2) emissions from industrial and combustion processes in Sweden. The paper also estimates the Swedish technical potential for electrofuels (power-to-gas/fuels) based on carbon capture and utilization. With our bottom-up approach using European databases, we find that Sweden emits approximately 50 million metric tons of CO_2 per year from different types of point sources, with 65% (or about 32 million tons) from biogenic sources. The major sources are the pulp and paper industry (46%), heat and power production (23%), and waste treatment and incineration (8%). Most of the CO_2 is emitted at low concentrations (<15%) from sources in the southern part of Sweden where power demand generally exceeds in-region supply. The potentially recoverable emissions from all the included point sources amount to 45 million tons. If all the recoverable CO_2 were used to produce electrofuels, the yield would correspond to 2–3 times the current Swedish demand for transportation fuels. The electricity required would correspond to about 3 times the current Swedish electricity supply. The current relatively few emission sources with high concentrations of CO_2 (>90%, biofuel operations) would yield electrofuels corresponding to approximately 2% of the current demand for transportation fuels (corresponding to 1.5–2 TWh/year). In a 2030 scenario with large-scale biofuels operations based on lignocellulosic feedstocks, the potential for electrofuels production from high-concentration sources increases to 8–11 TWh/year. Finally, renewable electricity and production costs, rather than CO_2 supply, limit the potential for production of electrofuels in Sweden.

Keywords: carbon dioxide, CO_2 recovering, carbon capture and utilization, carbon recycling, power-to-gas, alternative transportation fuels

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HIGHLIGHTS

- Sweden emits 50 million metric tons of CO_2 per year from different types of point sources, the vast majority of which is emitted at low concentrations.
- Of this, 65% is from biogenic sources, most of which are located in southern Sweden.
- Currently, the high-concentration sources of CO_2 in Sweden can provide a potential 1.5–2 TWh electrofuels/year (2% of current transportation demand).

- The Swedish potential for electrofuels is currently limited by the electricity required and production costs rather than the amount of recoverable CO_2.

INTRODUCTION

Anthropogenic greenhouse gas (GHG) emissions need to be reduced in order to limit global climate change and reach ambitious climate targets (Pachauri et al., 2014). Carbon dioxide (CO_2) emissions can be reduced by using less fossil fuels or by using fossil fuels in combination with carbon capture and storage (CCS) or carbon capture and utilization (CCU) [e.g., Cuéllar-Franca and Azapagic (2015), Wismans et al. (2016)]. In Sweden, the overall national vision is for zero net emissions of GHG to the atmosphere by 2050 (likely to be changed to 2045), along with a fossil fuel-independent vehicle fleet by 2030 (Government offices of Sweden, 2009; Swedish Government Official Reports, 2016). An extensive official investigation commissioned by the Swedish government has concluded that a range of options are needed to reduce CO_2 emissions from the transport sector, including biomass-based liquid and gaseous fuels (biofuels) along with hydrogen and electricity produced from renewable energy sources (Swedish Government Official Reports, 2013).

However, neither government nor academia have explored electrofuels (i.e., power-to-gas/fuels or synthetic hydrocarbons produced from CO_2 and water using electricity), extensively. Interest in electrofuels is on the rise, both in the literature (Graves et al., 2011; Mohseni, 2012; Nikoleris and Nilsson, 2013; Taljegård et al., 2015)[1] and in terms of demonstration plants in the EU, in some cases, including CO_2 capture (Gahleitner, 2013). Studies mainly investigate electrofuels as a (i) technology for storing intermittent electricity [e.g., Streibel et al. (2013), de Boer et al. (2014), Vandewalle et al. (2014), König et al. (2015), Qadrdan et al. (2015), Varone and Ferrari (2015), Zakeri and Syri (2015), Zhang et al. (2015), and Kötter et al. (2016)], (ii) fuel for transport [e.g., Connolly et al. (2014), Ridjan et al. (2014), Larsson et al. (2015)], or (iii) means of producing chemicals [e.g., Ganesh (2013), Perathoner and Centi (2014), and Chen et al. (2016)]. Different types of energy carriers [e.g., methane, methanol, DME (dimethyl ether), gasoline, and diesel] can be produced, which makes electrofuels a potentially interesting option for all transport modes, especially shipping, aviation, and long distance road transport, where the potential for other renewable fuel options, such as electricity and hydrogen, may be limited. Electrofuels may allow increased use of biofuels, if the CO_2 associated with their production is used for production of electrofuels instead of being emitted to the atmosphere (Mignard and Pritchard, 2008; Mohseni, 2012; Hannula, 2015, 2016).

CO_2 emissions can be captured from various point sources, including industrial processes that produce CO_2, such as biofuel production (including anaerobic digestion and fermentation), natural gas processing, steel plants, and oil refineries, fossil and biomass combustion in heat and power plants, or directly from the air.

Many studies have estimated CO_2 emissions from point sources in China [e.g., Chen and Chen (2010), Liu et al. (2010), Zhang and Chen (2014)]. Zhang and Chen (2014) used a bottom-up approach to estimate CO_2 emissions from fuel combustion and the main industrial processes at 7.7 Gt CO_2 per year in 2008, with coal as the main source. The potential global supply of CO_2 from point sources is estimated in Naims (2016). The total estimated global capturable CO_2 supply from point sources amount to approximately 12.7 Gton of CO_2 (Naims, 2016). High purity point sources (e.g., fermentation of biomass and ammonia production) and other low cost sources (e.g., bioenergy, natural gas, and hydrogen production) represent in total approximately 0.3 Gton of CO_2. Naims (2016) further indicates that there is enough CO_2 to meet the estimated global CO_2 demand in the near and long term.

In Austria, the iron and steel, cement industry, and power and heat industries are the largest point sources of CO_2 emissions (Reiter and Lindorfer, 2015). Biofuel production, a relatively modest point source at about 113 kton in 2013, is considered the most suitable Austrian source for power-to-gas application by Reiter and Lindorfer (2015). A German feasibility study by Trost et al. (2012) identifies a large potential for biogenic CO_2 sources, including biogas upgrading, bioethanol plants, and sewage treatment plants. Trost et al. (2012) also found a substantial electrofuels potential of over 130 TWh fuel per year in the form of methane produced using CO_2 from industrial processes and biogenic sources. Reiter and Lindorfer (2015) and Trost et al. (2012), both conclude that availability of CO_2 will not be a limiting factor for using power-to-gas as a balancing strategy for intermittent renewable power sources (wind power and photovoltaics) in Austria or Germany.

In Sweden, carbon capture is currently implemented at, for instance, Agroetanol in Norrköping. Agroetanol produces grain-based ethanol; the resulting CO_2 is purified and sold to the AGA Gas AB. Detailed quantification of current and/or future Swedish CO_2 emissions from point sources is, however, lacking in the scientific literature, and there are no assessments of the technical potential for Swedish production of electrofuels. Electrofuels may represent an interesting option in Sweden, that is a forest-rich country, due to the ambitious GHG emission reduction targets in general and specifically in the transport sector. Assessing the Swedish potential for CCS and CCU requires detailed knowledge of the stationary CO_2 emissions. The overall impact on CO_2 emissions of the production and use of electrofuels mainly depends on the electricity-related CO_2 emissions. The Swedish electricity production consists mainly of hydro power and nuclear power implying relatively low GHG emissions.

The overall aim of this paper is to map and quantify stationary Swedish CO_2 emissions by concentration, origin, and geographical distribution, as well as investigate the potential for CCU. Specifically, we aim to (i) map and quantify the major point sources of CO_2 emissions from industrial and combustion processes in Sweden with a bottom-up approach and estimate the technical potential for CO_2 capture or recovery and (ii) estimate the technical potential for production of electrofuels

[1] Brynolf, S., Taljegård, M., Grahn, M., and Hansson, J. (2017). Electrofuels for the transport sector: a review of production costs. *Renew. Sust. Energ. Rev.* (Submitted).

in Sweden, as an example of CCU. We analyze the potential for biofuels-related CO_2 in the future (a 2030 scenario), since the use of biomass and biofuels is expected to increase and use of fossil fuels decrease. Additionally, we estimate the potential demand for CO_2 and electricity corresponding to the use of electrofuels for road transport, heavy trucks, and shipping, at scale, in order to give a first indication of the potential role for electrofuels in transportation in Sweden.

MATERIALS AND METHODS

This section describes the methodology for estimating both CO_2 emissions from major point sources and the potential for capturing and using the emissions.

Assumptions about the CO_2 Sources Included

CO_2 emission sources can be divided into diffuse sources (e.g., transport and agriculture) and point sources (e.g., factories and power production). This study uses a bottom-up approach to estimate CO_2 emissions from the following point sources in Sweden:

- Industrial process plants (including iron and steel, non-ferrous metal, oil and gas refineries, lime and cement, pulp and paper, chemical, metal, and other similar plants)
- Heat and power production (including biomass, waste, and fossil fuel-fired plants)
- Biofuels production facilities (including ethanol, biogas, and more advanced biofuels).

Emissions data for year 2013 from the European Environment Agency's "European Pollutant Release and Transfer Register" (European Environment Agency, 2015) was used to estimate (i) the available amount of CO_2 and (ii) the share of fossil and biogenic CO_2, for Swedish point sources, including all sources emitting 0.1 million metric tons of CO_2 per year or more. Other CO_2 sources are assumed to be negligible (except in the case of biofuels production). The concentration of CO_2 for each type of sources was estimated using (Chapel et al., 1999; Bosoaga et al., 2009) (see **Table 1**). For the purposes of analysis, the concentrations were divided in three ranges: low (<15 vol%), medium (15–90 vol%), and high (>90 vol%).

For biofuels plants, the CO_2 estimates are based on data gathered by Swedish Energy Agency and Energigas Sverige (2015) and Grahn and Hansson (2015) in 2012–2013. Also, the sources emitting less than 0.1 million metric tons of CO_2 per year are included in the case of biofuels since these are relatively pure and, therefore, well suited for electrofuels production. In most biofuels production processes, there is a surplus of CO_2 and the CO_2 is of high purity (Xu et al., 2010). When biogas is upgraded to transport fuel quality, a cleaning step to remove CO_2 is included, resulting in a relatively pure stream of CO_2. The CO_2 emissions from domestic biofuel production in a 2030 scenario are estimated based on biofuels production scenarios from Grahn and Hansson (2015) and on scenarios for anaerobic digestion and gasification-based biogas production from Dahlgren et al. (2013). Grahn and Hansson (2015) assessed the potential contribution of domestically produced biofuels for transport in Sweden in 2030 based on a mapping of the prospects for current and potential Swedish biofuel producers. Some of the planned biofuels production plants included in the scenario for 2030 have been canceled or put on hold and are, therefore, excluded in this study.

The 2030 scenario was constructed exclusively for biofuel plants because these represent a relatively pure stream of CO_2 of particular interest in electrofuels production, and because the use of biofuels is expected to increase in the future. For many biofuels, no extra major purification step is needed in the capture process, which leads to a relatively low capture cost. This can also be assumed for the case of biogas since CO_2 is already removed when biogas is upgraded to transport fuel quality. This can be compared to the CO_2 capture cost linked to processes requiring an extra purification step like steel and iron, ammonia, refinery, cement, and fossil or biomass combustion plants estimated at $20€_{2015}$–$170€_{2015}$/ton CO_2 in the short term (10–15 years) and $10€_{2015}$–$100€_{2015}$/ton CO_2 in the more long term (Damen et al., 2007; Finkenrath, 2011; Kuramochi et al., 2012, 2013; IEA, 2013). Even though it has been

TABLE 1 | The type of CO_2 stream, CO_2-concentration range, range of CO_2 emissions per unit, and share of recoverable CO_2, for different point sources in Sweden based on European Environment Agency (2015).

Production facility and location	Type of CO_2 stream	Typical concentration	Process CO_2 emissions (kton/year) for smallest and largest plant	Recoverable share (%)
Oil and gas refineries	Flue gases, by-product	3–13 vol%[a]	122–1,573	90
Power and heat production	Flue gases	3–13 vol%	104–1,990	90
Iron and steel production	Flue gases	Approx. 15 vol%	102–1,540	90
Non-ferrous metal production	Flue gases	Approx. 15 vol%	101–256	90
Cement and lime production	Flue gases, by-product	Approx. 14–33 vol%	110–1,940	90
Production of chemicals	Flue gases, by-product	3–13 vol%[a]	13–620	90
Pulp and paper production	Flue gases	Approx. 15 vol%	165–1,740	90
Waste treatment or incineration	Flue gas	Approx. 10 vol%	105–837	90
Fermentation-based biofuels	By-product	Pure stream	0.11–154	100
Anaerobic digestion-based biofuels	By-product	>90 vol-%	0.14–21	54
Gasification-based biofuels	By-product	>90 vol-%	1.84–37	100
Other	Flue gas	3–13 vol%	134	90

For CO_2 concentration and recoverability references, see Section "Availability of CO_2 for Carbon Capture and Utilization."
[a]Minor amounts of CO_2 are available at higher concentrations (up to 100 vol%).

indicated that the cost for carbon capture represents a relatively modest share (a few percent) of the total electrofuel-production cost unless air capture is assumed (Graves et al., 2011; Tremel et al., 2015; Varone and Ferrari, 2015; see text footnote 1), using CO_2 from biofuel production represent an attractive source for electrofuel production since more pure streams will likely be used first for economic reasons and the domestic biofuel actors, representing a considerable biofuel production capacity, in order to comply with sustainability requirements need to improve their production processes in terms of CO_2 emissions.

Table 1 presents the type of CO_2 stream, typical concentration of CO_2, the range of CO_2 emissions per unit, and the amount of recoverable CO_2, for different point sources. **Table 2** includes a list of all the biofuel production facilities in operation in 2015, their production capacity and associated CO_2 emissions, and the corresponding information for the biofuels plants planned by 2030. **Table 3** summarizes the main assumptions used in estimating the amount of CO_2 that is available for recovery from current and future biofuels plants.

Availability of CO_2 for CCU

In order for CO_2 to be used to produce electrofuels, the gas needs to be separated from other substances in emissions from industrial and combustion processes, such as sulfur dioxide. The concentration of CO_2 in power plant flue gases is relatively low (<15 vol%) (Chapel et al., 1999); for process-related emissions, e.g., in the lime and cement industry, CO_2 concentrations are somewhat higher (14–33 vol%) (Bosoaga et al., 2009) (see **Table 1**). In this study, we assume that 90% of the CO_2 from medium- (15–90 vol%) and low- (<15 vol%) concentration CO_2 sources is recoverable (Chapel et al., 1999). Current CO_2 capture technologies do not usually capture all the CO_2 as this is too expensive and requires too much energy.

In biofuels production processes (fermentation, anaerobic digestion, gasification), relatively pure streams (>90 vol%) of CO_2 are available in latter cases due to the demand for high fuel purity in the transport sector. We assume that 100% of the CO_2 from biofuel plants is recoverable and could be converted into fuel. Approximately 54% of the biogas produced in Sweden is upgraded for the transportation sector (Swedish Energy Agency and Energigas Sverige, 2016), which means that CO_2 capturing technology already exist on several Swedish anaerobic digestion facilities. Another opportunity for anaerobic digestion-based biogas plants is to feed raw biogas to a methanation reactor, thereby combining biogas upgrading and electrofuels production (Johannesson, 2016). Biogas plants that currently do not upgrade their gas are generally small implying high costs for upgrading and currently supplying other markets than the transport sector, making them less suitable as a source of CO_2 for electrofuels production. Therefore, only CO_2 from biogas-upgrading plants is considered in this study. For simplicity, we assume that the share of upgraded biogas of total biogas production by 2030 remains at 54%.

Geographic Distribution of CO_2 Emissions

The CO_2 emission sources have been mapped and categorized by concentration and geographical area. The geographical areas are those used for the Swedish electricity market, i.e., four price areas (SE1, SE2, SE3, and SE4) (Swedish Energy Markets Inspectorate, 2014) (see **Figure 1**). The electricity price areas were implemented in Sweden in order to control the transmission of electricity between regions and to promote the construction of power generation and transmission capacity in and to areas with electricity deficits. On average, the northern parts of the country (SE1 and SE2) are characterized by an excess of electricity production due to the available hydropower resources and relatively

TABLE 2 | Biofuels production facilities and associated CO_2 emissions.

Production facility and location	Biofuel	Biofuel production (GWh/year)	Process CO_2 emissions (ton/year)	Reference[a]
Facilities operational in 2015				
Agroetanol, Line 1, Norrköping	Ethanol	391	53,466[b]	Axelsson et al. (2014) and Grahn and Hansson (2015)
Agroetanol, Line 2, Norrköping	Ethanol	1,126	154,014[b]	Axelsson et al. (2014) and Grahn and Hansson (2015)
ST1, Göteborg	Ethanol	34	4,617	Axelsson et al. (2014) and ST1 (2016)
SEKAB, Örnsköldsvik	Ethanol	64	7,807	Arvidsson and Lundin (2011) and Grahn and Hansson (2015)
SP, pilot plant, Örnsköldsvik	Ethanol	0.9	109	Arvidsson and Lundin (2011) and Grahn and Hansson (2015)
LTU Green Fuels, pilot plant, Piteå[c]	DME	6	1,836	Pettersson and Harvey (2012) and Grahn and Hansson (2015)
GoBiGas, Göteborg Energi, Göteborg	Gasification-based biogas	180	36,900	Heyne (2013) and Grahn and Hansson (2015)
Swedish anaerobic digestion-based biogas production (277 plants)	Biogas	1,686	245,680	SGC (2012) and Swedish Energy Agency and Energigas Sverige (2016)
Additional production capacity until 2030				
Fermentation	Ethanol	3,300	402,033	Hansson and Grahn (2013)
Anaerobic digestion	Biogas	4,600	672,342	SGC (2012), Dahlgren et al. (2013), and Hansson and Grahn (2013)
Gasification	Biogas, methanol, DME	4,050	1,023,260	Dahlgren et al. (2013) and Hansson and Grahn (2013)

[a] *References for the amount of biofuels produced and the estimated CO_2 emissions per unit of fuel are provided here.*
[b] *CO_2 produced at Agroetanol in Norrköping is currently purified and sold to the AGA Gas AB.*
[c] *The closure of this pilot plant was announced in April 2016.*

TABLE 3 | Main assumptions for assessing CO_2 availability from current and future biofuels plants in Sweden.

Production technology	Assumed amount of available CO_2 per GWh biofuel
Fermentation	Cereal based: 136.8 ton CO_2/GWh (Axelsson et al., 2014) Lignocellulose based: 121.7 ton CO_2/GWh (Arvidsson and Lundin, 2011)
Anaerobic digestion	Upgraded biogas: 145.7 ton CO_2/GWh (SGC, 2012)
Gasification	Black liquor gasification: 305 ton CO_2/GWh (Pettersson and Harvey, 2012) Indirect gasification: 206 ton CO_2/GWh (Heyne, 2013)

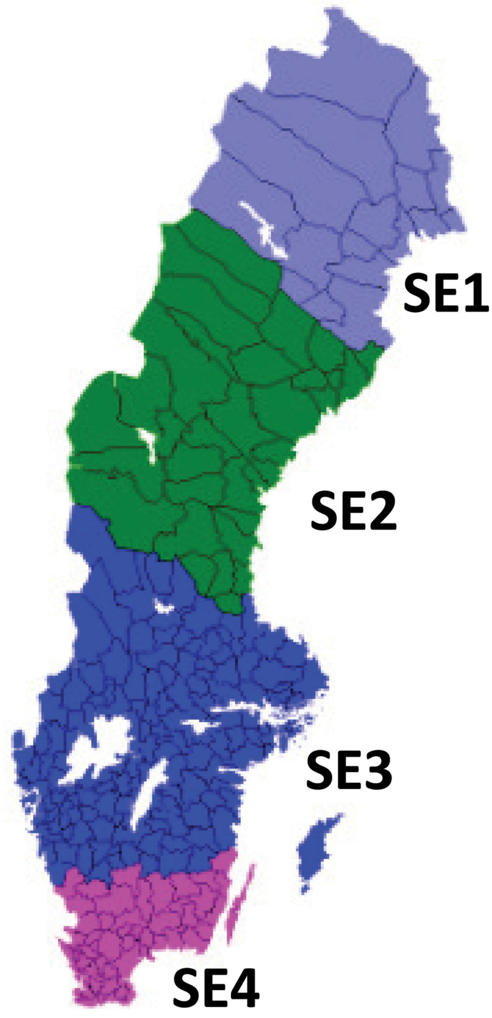

FIGURE 1 | The electricity price areas (SE1, SE2, SE3, and SE4) in Sweden, which are used to illustrate the geographic distribution of the CO_2 emissions. Figure based on SCB (2015).

low overall power consumption. In the southern parts (SE3 and SE4), electricity consumption often exceeds production, which leads to relatively higher electricity prices in these areas (Nord Pool, 2016).

Electrofuel-Production Efficiency and Cost

The focus in this study is on electrofuels in the form of methane, methanol, and DME since these are the most discussed electrofuels in the literature (see text footnote 1), are of interest for the relevant transport sector (shipping and trucks), and include fuels in liquid and gaseous form. The amounts of CO_2 and electricity necessary for the types of electrofuels included in this study are given in **Table 4** and are based on lower heating value (LHV).

Table 4 also presents cost ranges for 2015 and 2030 estimated in the base case reference scenario in Brynolf et al. (see text footnote 1). The electricity-to-fuel efficiency of the electrofuel-production process strongly depends on the type of electrolyzer and the future development of production technologies. Alkaline electrolysers have efficiencies in the range of 43–69% today, while the most efficient electrolysers are expected to reach efficiencies above 80% based on LHV (Smolinka et al., 2011; Benjaminsson et al., 2013; Grond et al., 2013; Mathiesen et al., 2013; Bertuccioli et al., 2014; Hannula, 2015; Schiebahn et al., 2015). Combining this with the efficiency for fuel synthesis yields electricity-to-fuel efficiencies in the 30–75% range for methane, methanol, and DME, this corresponds to an electricity demand of 1.33–3.33 MWh electricity/MWh electrofuel.

Brynolf et al. (see text footnote 1) suggest costs for different electrofuels (methane, methanol, DME, gasoline, and diesel) in the span of $120€_{2015}$–$1,050€_{2015}$/MWh_{fuel} and $100€_{2015}$–$430€_{2015}$/MWh_{fuel} in 2015 and 2030, respectively. However, in the base case of the reference scenario representing average data, the same costs are $200€_{2015}$–$280€_{2015}$/MWh_{fuel} and $160€_{2015}$–$210€_{2015}$/MWh_{fuel} in 2015 and 2030, respectively. The most important factors affecting the production cost of electrofuels are the capital cost of the electrolyzer, the electricity price, the capacity factor of the unit, and the lifetime of the electrolyzer. The base case reference scenario assumes alkaline electrolyzer with a capital cost of $600€_{2015}$/kW_{el}, capacity factor of 80%, lifetime of the electrolyzer at 25 years, carbon capture cost at $30€_{2015}$/ton, and electricity price of $50€_{2015}$/MWh. A capacity factor at 80% implies that the plant is run the major part of the year. However, if electrofuels are used to balance intermittent renewable power production (i.e., there is production only when there is a surplus of power from these sources), the capacity factor will be reduced. This will not influence the estimated technical potential for production of electrofuels in Sweden in this study, but it will lead to increased electrofuel-production costs [which is further assessed in Brynolf et al. (see text footnote 1)]. In the case of a carbon capture cost at $10€_{2015}$/ton representing more pure streams like biofuels operation, the production cost of electrofuels is reduced by approximately 3%. In their review of the literature, Brynolf et al. (see text footnote 1) also found that the cost of capturing CO_2 generally is a minor factor in the total production cost of electrofuels representing less than 10% (when not considering CO_2 capturing from air). CO_2 can be captured from various industrial sources with costs ranging from about $10€_{2015}$ to $170€_{2015}$/ton CO_2, depending on the CO_2 concentration (Damen et al., 2006, 2007; Finkenrath, 2011; Goeppert et al., 2012; Kuramochi et al., 2012, 2013; IEA, 2013; see text footnote 1). This indicates that from an economic point

TABLE 4 | Estimated values for CO_2 and electricity demand per unit of electrofuel and production cost for 2015 and 2030 (based on literature review and base case reference scenario by Brynolf et al. (see text footnote 1) representing average data and based on lower heating value, for assumptions see the text).

Electrofuel	Fuel synthesis efficiency (%)	CO_2 per unit of fuel (t/MWh_{fuel})	Electricity per unit of fuel (MWh_{el}/MWh_{fuel})	Production cost 2015 (€$_{2015}$/MWh_{fuel})	Production cost 2030 (€$_{2015}$/MWh_{fuel})
Methane	77[a]	0.21	2.00	200	160
Methanol	79[b]	0.28	1.93	210	160
DME	80[b]	0.27	1.95	210	160

[a]Mohseni (2012), Grond et al. (2013), Schiebahn et al. (2015), and Tremel et al. (2015).
[b]Hannula and Kurkela (2013) and Tremel et al. (2015).

of view, all CO_2 sources (except from pure air) might be of interest for electrofuel production in the future.

RESULTS

CO_2 Emissions in Sweden

In Sweden, major stationary point sources currently emit approximately 50 Mton CO_2 per year. Of this, about 45 Mton CO_2 is recoverable (see **Figure 2**). Our analysis includes 148 facilities, with 14 U emitting more than 1 Mton CO_2/year, 88 U emitting between 1 Mton and 100 kton CO_2/year, and 47 U emitting less than 100 kton/year.

Figure 2 shows the distribution of CO_2 emissions among different types of point sources. Pulp and paper plants and heat and power plants are the two major types of point sources, corresponding to 23 Mton CO_2 (45% of the total) and 11.5 Mton CO_2 (23% of the total) per year, respectively. In total, biogenic sources account for 65% or 32 Mton of CO_2 emissions per year. The high share of biogenic CO_2 is mainly due to the extensive use of biomass in producing pulp, paper, heat, and power and from waste treatment and incineration. Emissions from biofuel production represent a small share of the current total amount of available CO_2, with approximately 0.5 Mton of recoverable CO_2 per year. According to Andreas Gundberg, Innovation manager at Lantmännen Agroetanol, CCU has already been implemented at the main Swedish ethanol producer representing approximately 90% of the total Swedish ethanol production capacity. The emissions from this ethanol production (about 100 kton/year) are included in the analysis.

Figure 3 shows the amount of CO_2 available and the corresponding potential production of electrofuels in the form of methanol at different CO_2 concentrations in Sweden in 2013 and in 2030. The majority of the CO_2 is available at low and medium concentrations, equally spread between the categories low and medium but mainly below 20 vol%. A small share of the CO_2, mainly from the biofuels industry, is available at higher, significantly more accessible, concentrations.

About 90% of the high-concentration emissions come from sources in geographic region SE3, along with about 60% of the rest of the CO_2 emission sources (see **Figure 4**). Anaerobic digestion and ethanol production from agricultural crops currently dominate biofuels production, and these are mostly located in densely populated areas (producing biogas from digestion of sewage sludge and food waste) or in proximity to agricultural operations (farm-based ethanol and biogas production), which are mainly found in southern Sweden. However, electricity prices in the southern parts are currently less favorable than further north where hydropower resources and lower demand create

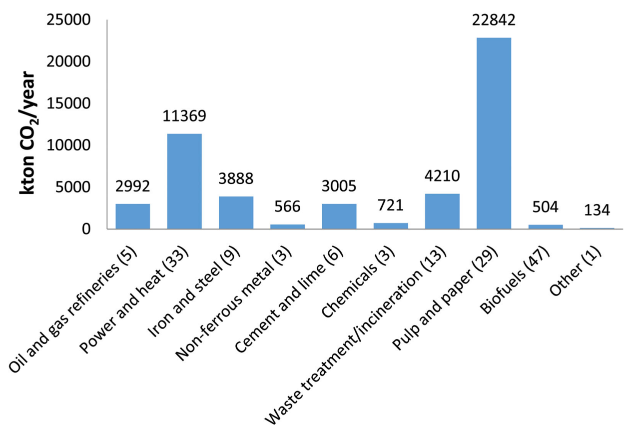

FIGURE 2 | **Current recoverable CO_2 from major point sources in Sweden, based on European Environment Agency (2015), Grahn and Hansson (2015), and Dahlgren et al. (2013).** In total, 149 point sources are included; the number of plants in each category is given in parenthesis.

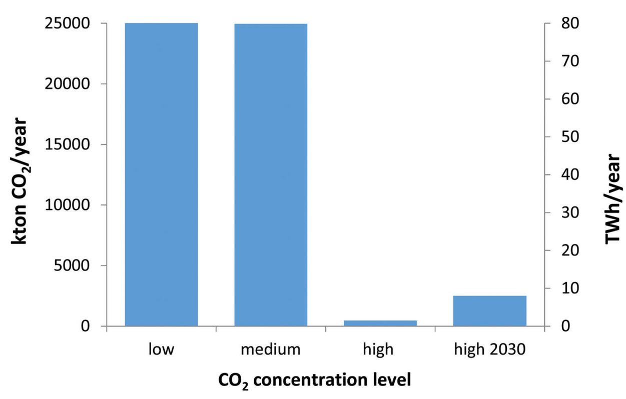

FIGURE 3 | **Recoverable CO_2 and potential for production of electrofuels in the form of methanol at three different concentration levels (low: <15 vol%, medium: 15–90 vol% and, high: >90 vol%) in 2013 and at high concentration in 2030.**

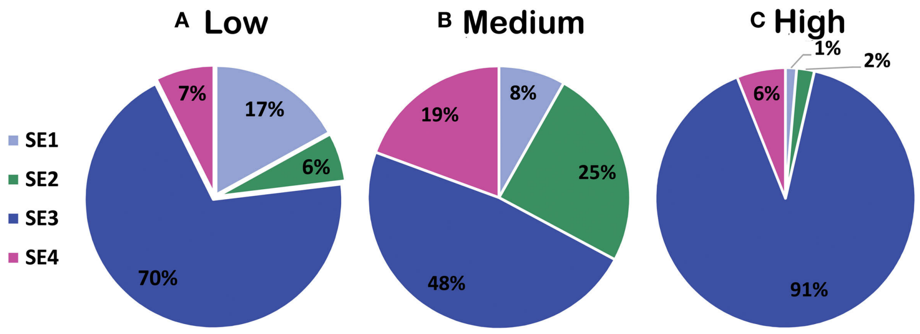

FIGURE 4 | **CO_2 point sources by region and concentration level**. **(A)** Low, **(B)** medium, and **(C)** high.

an excess of electricity while the transmission capacity to the southern industrial and population centers is limited.

The projected large-scale introduction of biofuels based on lignocellulosic feedstocks should entail higher shares of high-concentration CO_2 emissions in the northern regions, SE1 and SE2, if plants are located near feedstock resources.

The biofuels sector is expected to grow significantly in Sweden during the coming years in order to achieve national climate and transport targets. **Figure 5** illustrates the current and estimated amount of CO_2 available for electrofuels production from different biofuel production technologies and a minor share of others sources available by 2030 in Sweden based on Dahlgren et al. (2013) and Hansson and Grahn (2013). Only CO_2 from the production of upgraded biogas is included. In 2030, the CO_2 originates mainly from gasification, anaerobic digestion, and fermentation-based biofuels production (utilizing both cereals and lignocellulosic biomass and considering recent implementation plans). In 2030, these sources could potentially yield 2.2 Mton CO_2 for electrofuels production (approximately 5.5 times the amount currently available). The largest increase in production capacity is expected with the large-scale implementation of a variety of biomass-gasification-based biofuels, such as synthetic natural gas, DME, or methanol from lignocellulosic biomass. Ethanol produced from lignocellulosic feedstocks could also potentially generate large amounts of highly concentrated biogenic CO_2.

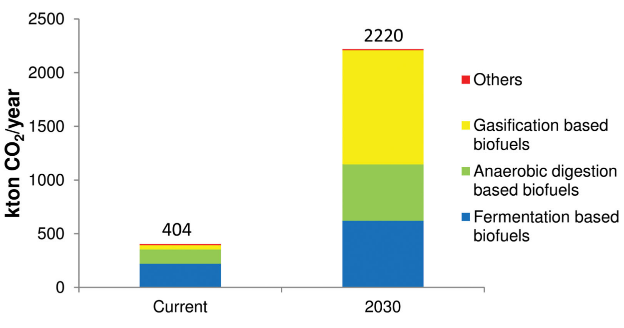

FIGURE 5 | **CO_2 from high CO_2 concentration sources (>90 vol-%) today and in 2030**.

The high-concentration sources, represented mainly by biofuel plants, suffice to provide only about 2% of the current demand for transportation fuels (corresponding to 1.5–2/year, see **Figure 6**). Converting the high-concentration emissions to electrofuels would require about 3–4 TWh of electricity (2–3% of the current national production). In 2030, the potential production of electrofuels in the form of methane, methanol, and DME from high-CO_2 sources is 8–11 TWh (see **Figure 6**). This corresponds to approximately 9–13% of the current demand for transportation fuels and would require about 15–21 TWh of electricity (10–14% of current electricity production).

Table 5 shows the requirements for meeting the current Swedish fuel demand for (non-air) transport with electrofuels in the form of methanol. As seen in **Table 5**, about half of the recoverable CO_2 (23 Mton) would be needed to supply the entire current Swedish road transport demand with electrofuels in the form of methanol (assuming a conversion factor of 0.275 ton CO_2/MWh methanol). The corresponding amount of CO_2 needed to satisfy the entire fuel demand from heavy trucks and all domestic and international shipping currently bunkering in Sweden is estimated to be about 5 and 6 Mton CO_2, respectively. This implies that in the case of large-scale introduction of electrofuels for road transport (including heavy trucks), heavy trucks only, or shipping in Sweden, the supply of CO_2 is not a limiting factor.

Swedish Production Potential for Electrofuels

Using all the currently recoverable CO_2 from the point sources identified in this study to produce electrofuel in the form of methane would yield approximately 224 TWh per year. This corresponds to approximately 2.5 times the current Swedish demand for transportation fuels [approximately 85 TWh per year in 2014 (Swedish Energy Agency, 2015b)]. For electrofuels with lower conversion efficiencies (e.g., methanol and DME), production could instead cover about twice the current demand. Producing 224 TWh per year of electro-methane requires about 448 TWh of electricity (assuming 2 MWh_{el}/MWh_{fuel}), which corresponds to three times the current Swedish electricity generation [149 TWh (Swedish Energy Agency, 2015a)].

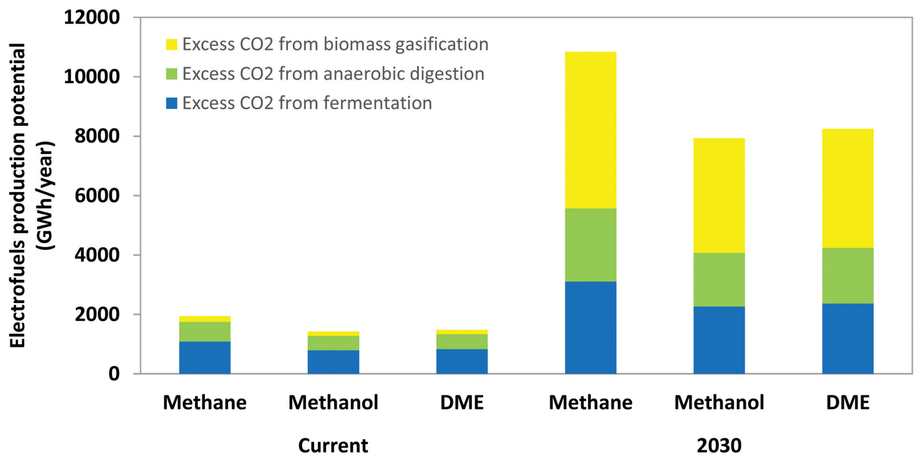

FIGURE 6 | **Production potential for electrofuels in the form of methane, methanol and DME from current and future biofuel plants with high CO_2 concentrations**.

TABLE 5 | **Outputs and inputs to electrofuels production if fulfilling the fuel demand with electrofuels in the form of methanol in three different transport modes.**

	Road transport	Heavy trucks	Shipping
Fuel demand 2014 (TWh)	85 (Swedish Energy Agency, 2015b)	18 (Swedish Government Official Reports, 2013)[a]	21 (Swedish Energy Agency, 2015b)[b]
Electrofuel replacement (%)	100	100	100
Electrofuel production			
Methanol (TWh)	85	18	21
Electrofuel requirements			
Electricity (TWh)	164	35	41
Carbon dioxide (Mton)	23	5	6

For electricity and CO_2 demand per unit of electrofuel see ***Table 4****.*
[a]*Expected to increase to approximately 25 TWh by 2050.*
[b]*Represents the total Swedish use of bunker fuels in 2014 of which 96% was used for international sea transport.*

However, meeting the entire current road transport demand with electrofuels would require about 164 TWh_{el} of electricity (with methanol at 1.93 MWh_{el}/MWh_{fuel}). This would more than double the current demand for electricity. To meet the current Swedish fuel demand for passenger cars (at about 41 TWh) (Swedish Government Official Reports, 2013) with electrofuels in the form of methanol would require approximately 11 ton CO_2 and 79 TWh_{el} of electricity. For comparison, if the entire passenger car fleet were replaced by electric vehicles, the increased demand for electricity would be approximately 10 TWh (based on Swedish Government Official Reports, 2013).

Using electrofuels for the heavy truck sector and for shipping bunker fuel sold in Sweden would require about 35 and 41 TWh_{el}, respectively. For comparison, in 2014, domestic power generation was 150 TWh (SCB, 2016). Further, the goal is to increase domestic generation from renewable sources by about 30 TWh by 2020, compared to 2002 figures and current production of renewable electricity is approximately 85 TWh (SCB, 2016). Large-scale introduction of electrofuels would require a major increase in the supply of electricity from renewable energy sources.

DISCUSSION AND CONCLUSION

This study shows that Swedish point sources emit approximately 50 million metric tons of CO_2 per year, 65% of which is biogenic in origin. The potentially recoverable emissions amount to 45 Mton. The main point sources are in the pulp and paper industry along with heat and power, while emissions from biofuel production (with relatively high concentrations of recoverable CO_2) amounted to 0.5 Mton CO_2 in 2015, with an estimated potential for 2.2 Mton CO_2 in 2030. Thus, the potential streams of relatively pure CO_2 are modest, at least in the near term. Currently, the potential yield from these sources is 1.5–2 TWh of electrofuels per year, corresponding to approximately 2% of the current Swedish demand for transportation fuels.

However, in Sweden, all types of CO_2 emissions, whether fossil or biogenic, and whether low-concentration or high, are of interest in terms of CCU (although carbon capture can be expected to first be applied to systems with higher concentrations of CO_2 because capture costs are somewhat lower for these, generally speaking). In the case of electrofuels, as mentioned earlier, it has been indicated that the cost for carbon capture represents a relatively modest share of the total electrofuel-production cost which makes the purity of the CO_2 sources less important. However, CO_2 from biofuel operations seem like an attractive source since biofuel actors strive to reduce their CO_2 emissions due to sustainability requirements. Further, biomass-related CO_2 emissions are expected to increase in the future, since the use of biomass for energy is expected to increase while fossil CO_2 emissions are expected to decrease.

We conclude that the Swedish supply of CO_2 does not have to be a limiting factor for the potential future production of electrofuels for the Swedish transport sector, even if the current supply of pure CO_2 streams is limited. However, there might be other limiting factors such as the associated electricity demand.

As indicated in the introduction, electrofuels represent a potential long-term energy storage option and could, therefore, be of interest in terms of managing grid-integration of more intermittent renewable energy sources (e.g., wind and solar power). But large-scale introduction of electrofuels in the transport sector would in turn represent a huge new demand for electricity. The direct use of electricity needed to supply the entire current transport demand for passenger cars would increase current electricity demand by 10%, while using electrofuels would require increasing the Swedish electricity generation by about 60% to meet the same transport demand (Swedish Energy Agency, 2015b). The electrofuels production process and combustion engine are simply that much less efficient than electric motors. Therefore, large-scale introduction of electrofuels might potentially increase the challenge of balancing intermittent renewable generation, rather than help solve it with long-term energy storage, since an increased demand for power would most likely be met with new wind power installations in Sweden. Producing electrofuels only part of the year is one option to limit this problem. However, according to Brynolf et al. (see text footnote 1), the production cost of electrofuels increases drastically per megawatt hours fuel when the capacity factor (i.e., actual production as share of total production capacity) of the wind turbines is decreased. Thus, the benefit of using electrofuels for balancing renewable energy need to be further assessed.

The production cost of different electrofuels is also a limiting factor for the potential future production of electrofuels in Sweden. The literature contains a fairly broad range of estimates, but the most important factors in the production cost of electrofuels are the capital cost of the electrolyzer, the electricity price, the capacity factor of the unit, and the lifetime of the electrolyzer (see text footnote 1).

The majority of the current CO_2 sources are located in southern Sweden, which is also the case for the current CO_2 sources with relatively pure CO_2 emissions. However, from the perspective of the electric-grid, electrofuels production may be more suitable in the northern parts of Sweden where there is generally a surplus of power generation and lower electricity prices. An increasing demand for electricity in southern Sweden might put additional pressure on the transmission capacity from north to south. Future biofuel plants based on forest biomass (as included in the 2030 scenario) are expected to be located mostly in northern Sweden and, therefore, represent an interesting source of CO_2 for production of electrofuels.

From a climate perspective, it might be preferable to capture and store CO_2 underground, using CCS technology, and not convert CO_2 into a fuel that after combustion will be released to the atmosphere again (van der Giesen et al., 2014; Sternberg and Bardow, 2015). If the CO_2 has been captured from burning fossil fuels, CCS will avoid increased CO_2 concentration, and if the CO_2 is captured from burning biomass (or from air), CCS will decrease the atmospheric CO_2 concentration, *ceteris paribus*. Today, however, there are several obstacles that have to be overcome before CCS could be available at a large scale, including public acceptance (Oltra et al., 2010; Dütschke, 2011). CCS is also only applicable for relatively large CO_2 sources and storage possibilities depend on geological prerequisites.

The overall impact on CO_2 emissions of the production and use of electrofuels mainly depends on the electricity-related CO_2 emissions and what the fuels replace (van der Giesen et al., 2014; Sternberg and Bardow, 2015). van der Giesen et al. (2014) conclude that for some production paths, the climate impact is worse than for fossil fuels, and achieving a net climate benefit requires using renewable electricity and renewable CO_2 sources. Sternberg and Bardow (2015) evaluate electrofuels relative to the case in which the same amount of CO_2 is instead either emitted or stored. They find that electrofuels can at best only make a small contribution to mitigation compared to other available solutions and that using CO_2 emissions for electrofuels is worse from a climate perspective compared to storing them. It would be interesting to more thoroughly study the environmental impact of electrofuels compared to other CCU technologies with a lifecycle perspective. For example, the amount of CO_2 emissions from electricity production will depend on (i) the time perspective (for example using a marginal or average electricity mix) and (ii) the geographical boundaries of the electricity supply. However, GHG emissions from electricity production are expected to decrease significantly as a consequence of stringent energy and climate policies changing the mix of energy sources.

To summarize, electrofuels are limited by electricity demand rather than the demand for CO_2 and, at scale, require a substantial amount of renewable electricity at relatively low cost. The GHG impact of electrofuels compared to other options, in particular CCS, needs to be further assessed.

AUTHOR CONTRIBUTIONS

JH is the main author; planned the work and led the writing. RH was responsible for the mapping and quantification of the major Swedish point sources of CO_2 emissions and contributed to further assessments and paper writing. SB, MT, and MG contributed with the electrofuel-production characteristics, participated in the assessment, and contributed to paper writing.

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