Journal of Cleaner Production 129 (2016) 548–555

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Electricity-based plastics and their potential demand for electricity and carbon dioxide

Ellen Palm*, Lars J. Nilsson, Max Åhman

Environmental and Energy Systems Studies, Department of Technology and Society, Lund University, Box 118, SE-221 00 Lund, Sweden

ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form
9 March 2016
Accepted 31 March 2016
Available online 19 April 2016

Keywords:
Electrification
CCU
Ethylene
Propylene
Fossil-free plastics

ABSTRACT

In a future fossil-free circular economy, the petroleum-based plastics industry must be converted to non-fossil feedstock. A known alternative is bio-based plastics, but a relatively unexplored option is deriving the key plastic building blocks, hydrogen and carbon, from electricity through electrolytic processes combined with carbon capture and utilization technology. In this paper the future demand for electricity and carbon dioxide is calculated under the assumption that all plastic production is electricity-based in the EU by 2050. The two most important input chemicals are ethylene and propylene and the key finding of this paper is that the electricity demand to produce these are estimated to 20 MWh/ton ethylene and 38 MWh/ton propylene, and that they both could require about 3 tons of carbon dioxide/ton product. With constant production levels, this implies an annual demand of about 800 TWh of electricity and 90 Mton of carbon dioxide by 2050 in the EU. If scaled to the total production of plastics, including all input hydrocarbons in the EU, the annual demand is estimated to 1600 TWh of electricity and 180 Mton of carbon dioxide. This suggests that a complete shift to electricity-based plastics is possible from a resource and technology point of view, but production costs may be 2 to 3 times higher than today. However, the long time frame of this paper creates uncertainties regarding the results and how technical, economic and social development may influence them. The conclusion of this paper is that electricity-based plastics, integrated with bio-based production, can be an important option in 2050 since biomass resources are scarce, but electricity from renewable sources is abundant.

© 2016 The Author(s). Published by Elsevier Ltd. All rights reserved.

1. Introduction

Before petrochemistry, most organic materials and chemicals were derived from biogenic feedstock. Today, nearly all of these materials and chemicals are derived from fossil feedstock. In the long-term, to meet the vision of a fossil-free circular economy, fossil fuels and feedstock will have to be phased out. The time frame for attaining this varies between countries, but the adopted 2 °C target implies zero emissions before the end of this century. For the EU the aim is that greenhouse gas emissions should be reduced by 80–95% by 2050 and reach zero in the decade thereafter (European Commission, 2011). This will have profound effects on the petrochemical industry as not only the emissions need to be drastically reduced, but also the feedstock (naphtha derived either as refinery by-products or from natural-gas) will be affected by the phase out of fossil fuels for transport. Furthermore, there will be an increasing demand for reducing the embedded carbon dioxide (CO_2) emissions in the feedstock itself.

One idea that has gained considerable traction in recent years is to develop new technologies for a bio-based economy, including bio-based plastics. Although bio-based plastics hold much promise, they are not free from challenges and in the long-term, perhaps the greatest limitation is resource scarcity and competing uses for biomass and land (Mülhaupt, 2013; Tsiropoulos et al., 2015).

Another fossil-free option for producing plastics, fuels and chemicals is to use renewable electricity, water and carbon dioxide as a feedstock through Carbon Capture and Utilization (CCU). In contrast to biomass, there are essentially no resource constraints for renewable electricity and it is increasingly competitive compared to fossil and nuclear options (IPCC, 2011).

One driving factor for several of the key technologies used in CCU is the need for a more flexible electricity demand as a result of the increased production of variable renewable electricity. The challenge of variable electricity production has generated interest in power-to-gas/liquid concepts; both since gases and liquids are

* Corresponding author.
E-mail addresses: Ellen.Palm@miljo.lth.se (E. Palm), Lars_J.Nilsson@miljo.lth.se (L.J. Nilsson), Max.Ahman@miljo.lth.se (M. Åhman).

http://dx.doi.org/10.1016/j.jclepro.2016.03.158
0959-6526/© 2016 The Author(s). Published by Elsevier Ltd. All rights reserved.

easier to store than electricity, but also since gases and liquids can be useful in applications where electricity is not suitable (Aresta et al., 2013) Thus, electricity-based production is likely to become an important alternative to bio-based production in a fossil-free world. An electricity-based process, in contrast to a bio-based process, can use various sources of carbon. For production of hydrocarbons without flows of fossil carbon this means tapping into flows of biogenic carbon, or possibly use of air capture. For this reason, the electricity-based processes are likely to be deeply integrated with the bio-based processes. Using carbon dioxide as a feedstock is not new, the global annual use in the chemical industry is around 200 Mton, mainly in production of urea (Schüwer et al., 2015). Other applications such as methanol (CH_3OH) and polymer production are growing, but starting from very low levels (Aresta et al., 2013). Some specific examples of demonstrated applications include polyurethane from Covestro (Covestro, 2015), 'blue crude' from Sunfire (Sunfire, 2015) and methanol produced from Carbon Recycling International (Carbon Recycling International, 2015).

There is an emerging literature on CCU options and technologies for a variety of applications (Graves et al., 2011; Hoekman et al., 2010; Jensen et al., 2007; Liu et al., 2009; Ogura, 2013; Ren et al., 2008; Stünkel et al., 2012; Styring et al., 2014). However, the option of using renewable electricity, water and carbon dioxide as feedstock for chemicals and materials is still relatively unknown and unexplored, and CCU is generally assumed as negligible compared to other mitigation options (IPCC, 2014). The same is true for electricity used to replace fossil fuels and feedstock in other basic material industries, such as iron and steel (Lechtenböhmer et al., 2015; Åhman and Nilsson, 2015).

The overall aim of this paper is to fill a part of this gap by exploring the CCU option for plastics and calculate the potential future electricity and carbon dioxide demand in the EU for a 100% shift to electricity-based plastic production. For this purpose, a continued use of plastics and constant production levels (57 Mton/year) of ethylene (C_2H_4) and propylene (C_3H_6) are assumed. Future efficiencies and yields are estimated based on the literature and used as a basis for calculating potential electricity and carbon dioxide demands. Rough cost estimates are made, and the future prospects for electricity-based plastics to become competitive are discussed. The structure of this paper is as follows: first, general information on the current and future production of plastics and bio-based plastics is presented, second the production methods for electricity-based plastics are presented and third the potential cost, electricity and carbon dioxide demand is presented. The final sections include a discussion on limitations and uncertainties followed by conclusions.

2. Current and future plastic production

Global plastic production has increased from 200 to over 300 Mton over the past 10 years, with projections for continued future increase (Plastics Europe, 2015). The growth is driven mainly by increasing demand in developing regions such as Asia, Africa and South America (UNEP, 2012). Assuming that a global population of 8–9 billion people consume plastics at the present average EU level of more than 100 kg/capita, the world would use about 1000 Mton/year of plastics. The EU plastics industry also predicts continued growth in global demand, but does not expect the increased production to be located in Europe (Cefic, 2013). The EU production is instead expected to remain relatively constant and therefore it is assumed in this paper that the total EU production in 2050 is similar to the present, i.e., 57 Mton/year. Furthermore, no major changes in the product mix are assumed. Ethylene and propylene are the largest bulk chemicals and plastic raw materials, with an annual EU production of 16 Mton and 13 Mton respectively (Eurostat, 2013). In the detailed analysis of this paper, focus is set on these two alkenes since the great majority of them are used as direct or indirect feedstock for more than half of all plastics, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polyvinylchloride (PVC).

The assumption that the EU plastic production will remain constant seems plausible also given recent trends in efforts to improve resource efficiency. The EU plastic production has fluctuated around 60 Mton/year over the past decade, and it does not seem to be influenced by import, population increase or recycling rates. In the past decade there has been a positive trade balance and an increase in plastic recycling, but no significant increase in production (Plastics Europe, 2015). Goals are set to increase recycling even further, with the target that no plastic should end up in landfills and that 80% of plastic packaging should be recycled by 2025 (European Commission, 2014). Improved resource efficiency and recycling can reduce the demand for plastic production from virgin feedstock, but future plastic production levels can still be assumed to be stable due to for example increased utilization related to population growth.

3. Bio-based production

Production of bioplastics is getting increased attention from both public and private actors. However, the term bioplastics often leads to confusion because it includes both plastics that are bio- and fossil-based. A plastic can be a bioplastic in three different ways; (1) bio-based and non-biodegradable, (2) bio-based and biodegradable or (3) fossil-based and biodegradable. This paper only considers bio-based plastics, both biodegradable and non-biodegradable, since the aim is to explore the implications of a fossil-free plastic production. Bio-based plastics are still in their infancy and subject to substantial development efforts. They have so far mostly been used in special applications, but the range of applications is expected to increase through recent technical advances, such as production of conventional plastics from biomass. The most prominent example is polyethylene from sugarcane ethanol (C_2H_5OH) from Brazil (Braskem, 2015). Global projections of bio-based plastic production vary, but all estimates project a future increase. At present the annual bio-based plastic production is around 1 Mton, but it is projected to increase to between 6 and 12 Mton in 2020 (European Bioplastics, 2013; Nova-Institute, 2015). Even though the expected increase is large, bio-based plastics will only account for a few per cent of the global plastic production with the current projections.

Bio-based plastics when entirely based on sustainable biomass feedstock and renewable energy will reduce carbon dioxide emissions, but the limited amount of suitable land and the competition between food, feed, fuel and material makes biomass a scarce resource (Tsiropoulos et al., 2015). Critics of bio-based plastics also point out problems with intensified farming, extensive use of water and fertilizers, deforestation and increased greenhouse gas emissions due to grassland conversion (Mülhaupt, 2013).

Replacing the fossil feedstock for the current global demand for platform chemicals, that mainly form plastics (275 Mton), is estimated to require between 17 and 40 EJ of biomass (Cherubini and Strømman, 2011). Scaling that up to a future global production of 500–1000 Mton of plastics results in a biomass feedstock need of 30–150 EJ. This biomass need represents a relatively large share of the estimated 50 to 500 EJ global biomass potential (IPCC, 2011). Other estimations present an even lower biomass potential (75–215 EJ), underlining the point of scarcity even further (Saygin et al., 2014).

In a scenario where plastics do not compete with food or contribute to deforestation, a possible feedstock for bio-based plastics would be by-products and residues from agriculture and forestry

(Álvarez-Chávez et al., 2012). One example is the planned production of polyethylene based on by-products from the forest industry (SEKAB, 2015). However, on a global level residues and by-products only amount to about 50 EJ; in other words, the lower number in the IPCC biomass potential range noted above, and they also have competing uses. Thus, it seems prudent to also consider electricity and carbon dioxide as a future non-fossil option for plastics.

4. Electricity-based production

Fossil-free production of drop-in quality ethylene and propylene from electricity and carbon dioxide can be done in different ways. The method on which the calculations are based is chosen for its relatively high selectivity, where selectivity means the percentage of carbon feedstock that ends up in the desired product. The electricity-based ethylene and propylene production method is illustrated in Fig. 1 and the subsequent sections contain explanations of the process condition and electricity demand. In summary, the production starts with the most energy consuming step namely the formation of methane (CH_4) via a combined solid oxide electrolysis cells (SOEC) and Sabatier reaction. This is followed by the ethylene production via oxidative coupling of methane (OCM), and the propylene production via methanol to propylene (MTP), both of which use methane as feedstock.

The feedstock needed is composed of electricity, carbon dioxide and water and for the final products to be fossil-free these inputs must be so as well. The calculations are based on assumptions that include future possible improvements in efficiencies, C-conversion and selectivity. This paper considers the utilization, and not the capturing, of carbon dioxide; therefore, the energy use for capturing, transporting or processing the carbon dioxide is not included. Another assumption is that the unreacted carbon dioxide and methane is circulated without leakage. The electricity and carbon dioxide demand are further explained and calculated in Section 5 and 6, but in summary it is allocated to the ethylene, propylene and the hydrocarbon by-products (stream 9 in Fig. 1) based on the share of carbon in the product. The electricity allocation is divided in two parts, first the share of electricity needed to produce the methane used in the final product and then the electricity needed for the specific process. The sum of the two makes up for the total electricity need. The allocation of the carbon dioxide regard the carbon used per product or process, where the carbon content of the methane is recalculated to CO_2-equivalents.

4.1. Hydrogen and methane formation

The first process step in the formation of electricity-based ethylene and propylene is a Solid Oxide Electrolysis Cell (SOEC) where water is split into hydrogen (H_2) and oxygen (O_2) (see Reaction 1 and Fig. 1). The reaction takes place under high temperatures (600–900 °C) leading to thermodynamic advantages that substantially reduce the electricity need. However, electricity still accounts for about 70% of the production cost (Jensen et al., 2007). The SOEC technology is not yet available on an industrial scale and the main challenge is to develop electrode materials to further reduce the electricity use and decrease the degradation to prolong the lifetime of the cell (Jensen et al., 2013).

$$2H_2O \rightarrow 2H_2 + O_2 \tag{R.1}$$

All the hydrogen produced in the SOEC is used in the Sabatier reaction, but only a small amount of the oxygen is used within the process (see stream 2 and 3 in Fig. 1). The majority of the clean and separated oxygen is therefore available for other industrial applications. The current efficiency and electricity need for commercially available electrolysis, such as alkaline electrolysis and proton exchange membrane electrolysis, is around 50–70% and 4 to 7 kWh/Nm^3 hydrogen gas (Ursua et al., 2012). However, by 2050 it can be expected that SOEC will be commercially available with a process efficiency of about 85% and an electricity need of perhaps 3.5 kWh/Nm^3 hydrogen gas (Mogensen, 2014).

The second step, the methane formation takes place via a catalytic methanation in a Sabatier reaction that produces methane and water from hydrogen and carbon dioxide (see Reaction 2 and Fig. 1). The reaction is exothermic, meaning that it produces heat, and due to thermodynamics the temperature in the Sabatier reaction should be below 500 °C (Gao et al., 2012). The brackets in the flowchart in Fig. 1 illustrate that a co-location of the SOEC and the Sabatier reaction is highly favourable, since the waste heat from the exothermic Sabatier reaction can be used in the SOEC and thereby decrease the total energy need. As can be seen in Reaction 2, the Sabatier reaction has an inefficient hydrogen use and only half the hydrogen turns to methane. Another disadvantage with the Sabatier reaction is that the CO_2-conversion is low, meaning that some of it leaves unreacted and hence the recirculation is important (Hoekman et al., 2010).

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \tag{R.2}$$

The electricity need to form methane from water and carbon dioxide, including the SOEC and the Sabatier reaction, can be expected to be 12 kWh/Nm^3 methane by 2050. This is a decrease of about 2–6 kWh/Nm^3 compared to the current electricity need of 14–18 kWh/Nm^3 methane (De Saint Jean et al., 2014; Sunfire, 2015).

4.2. Ethylene formation

The third step of the electricity-based plastic production is the ethylene formation via Oxidative Coupling of Methane (OCM) using the methane and oxygen from the previous steps (see Reaction 3 and Fig. 1). The OCM-process consists of three stages: a reactor, a

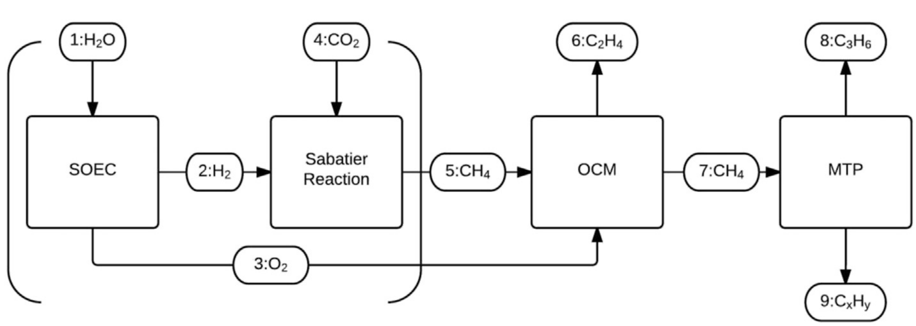

Fig. 1. Illustration of the process from water [1] and carbon dioxide [4], via methane [5] and [7], to ethylene [6] and propylene [8].

CO_2-removal and a C2-separation. The carbon-conversion in the reactor is low, therefore the unreacted methane is both circulated internally to increase the carbon-conversion and used as feedstock for the next process step, the propylene formation (Stünkel et al., 2012). Also, regardless of the use of optimized catalyst and process conditions some of the input methane will oxidise to carbon dioxide (Jašo et al., 2012). The carbon dioxide separated from the stream is a clean and useful feedstock that could be used to lower the carbon dioxide need in the Sabatier reaction. However, the amount is low and therefore does not have a great impact on the overall performance.

$$2CH_4 + O_2 \rightarrow C_2H_4 + 2H_2O \quad \text{(R.3)}$$

By 2050 a methane conversion of 35% and a selectivity for ethylene of 85% can be assumed, meaning that 35% of the input methane will react and that 85% of this will form ethylene (Arndt et al., 2012). The electricity consumption of the process is low and depends mostly on the pressure in the reactor and the CO_2-removal; it is assumed to be 40 kWh/ton ethylene by 2050. Regarding the carbon dioxide need for the ethylene production, it is derived from the methane utilization and the carbon dioxide residue in the reaction, resulting in 3 tons of CO_2/ton ethylene.

4.3. Propylene formation

The final process step of the electricity-based plastic feedstock is the propylene formation through a Methanol to Propylene (MTP) process consisting of a series of reactions and intermediates. As seen in the flowchart (Fig. 1) the propylene feedstock consists entirely of the unreacted methane from the OCM. The key steps in the MTP are methane and oxygen forming methanol and dimethyl ether (CH_3OCH_3) prior to the propylene formation (see Reaction 4 and Fig. 1) (Hadi et al., 2015). The formation from methane to methanol occurs in two steps, via syngas, and requires oxygen and energy (8.3 MWh/ton methanol) (Ren et al., 2008). A direct conversion would be more energy efficient, but the technology is not expected to have a breakthrough any time soon even though this is subject to extensive research efforts (Holmen, 2009).

$$CH_4 \rightarrow CH_3OH \rightarrow \mathrm{CH_3OCH_3} \rightarrow C_3H_6 \quad \text{(R.4)}$$

The MTP process strongly depends on well-functioning catalysts, but still struggle with low selectivity, and the end stream does not only contain the desired propylene, but also water and a mix of hydrocarbon by-products. Assuming that a development of catalysts will reduce the formation of unwanted hydrocarbons, the selectivity for propylene is expected to be 55% by 2050. The expected distribution of the carbon selectivity is presented in Table 1 and shows that the stream, except the 55% propylene, will contain around 20% butylenes (C_4H_8) and 14% hydrocarbons consisting of five or more carbon atoms (C5+) (Hu et al., 2012). For example, butylenes are important monomers in the production of the plasticizer polybutene, but even though the hydrocarbon by-products might not directly be used for plastic production, they are valuable energy-containing chemicals that can be used for other purposes, although this is not further investigated here. Applying the allocation method for the electricity and carbon need, the MTP process results in an electricity consumption of 19 MWh/ton of propylene and a carbon dioxide need of 3 tons of CO_2/ton of propylene.

4.4. Summary of results

The outcome of applying the processes described above on a completely electricity-based EU production of ethylene and propylene by 2050 is shown in Table 2. The annual mass [Mton] and energy flow [TWh] of the flowchart (Fig. 1) show that 208 Mton water, 127 Mton carbon dioxide and 1210 TWh could result in 16 Mton ethylene, 13 Mton propylene and 11 Mton hydrocarbon by-products. The hydrocarbon by-product consists mainly of butylenes, a variety of alkanes and aromatics in accordance with Table 1. Due to the carbon content in the products and the mass relationship between carbon dioxide and hydrocarbons in general, the carbon dioxide need will be almost equal for all products, 3 tons of CO_2/ton hydrocarbon.

Table 2 also shows that the largest energy use takes place in the integrated SOEC and the Sabatier reaction. The ethylene and propylene formation in the OCM and MTP require less energy, but are more inefficient regarding C-conversion and selectivity. Not all flows are shown in the flowchart in Fig. 1 or in Table 2 since some flows are not used in the process, including excess oxygen or water leaving the Sabatier reaction, the OCM or the MTP.

5. Electricity needs

Based on the detailed assessment of electricity-based ethylene and propylene production, the electricity need is allocated to each energy-containing product and the results are scaled up to estimate the potential electricity needs for the total EU production of the intermediates and plastics. The electricity need for the methane and methanol production is allocated to each stream (i.e., 16 Mton ethylene, 13 Mton propylene and 11 Mton hydrocarbon by-products) based on carbon use as described in Section 4. Meaning that the electricity need per product is a sum of the SOEC and Sabatier process and the OCM for the ethylene or the MTP for the propylene and hydrocarbon by-product (see Table 2 for process electricity need). The ethylene production (16 Mton) accounts for 42% of the carbon use, which results in 318 TWh (Eq. (1)) as well as a specific consumption of 20 MWh/ton of ethylene. Regarding the propylene (13 Mton) the corresponding numbers are 32%, 490 TWh (Eq. (2)) and 38 MWh/ton, and the hydrocarbon by-products (11 Mton) account for 25% of the carbon use, 401 TWh (Eq. (3)) and 37 MWh/ton.

$$\text{Ethylene} \quad (0.42{*}759TWh) + 1TWh = 318TWh \quad \text{(Eq.1)}$$

$$\text{Propylene} \quad (0.32{*}759TWh) + (0.55{*}450TWh) = 490TWh \quad \text{(Eq.2)}$$

$$\text{Hydrocarbon by-products} \quad (0.25{*}759TWh) + (0.45{*}450TWh) = 401TWh \quad \text{(Eq.3)}$$

Excluding the hydrocarbon by-products, the EU production of ethylene and propylene (29 Mton) by 2050 would require 808 TWh.

Table 1
The distribution of the end stream in the MTP process presented in carbon percentage, showing that the largest flows after the desired product propylene are butylenes and C5+. Adapted from (Hu et al., 2012).

	Methane	Ethane	Propane	Ethylene	Butane	Butylenes	C5+	Aromatics	Propylene
Selectivity [C%]	1	0.5	0.5	4	3	20	14	2	55

Table 2
The annual mass flow, electricity need, process efficiency, C-conversion and selectivity for producing ethylene and propylene in the EU by 2050.

	SOEC and Sabatier				OCM		MTP		
Nr: Substance	1:H_2O	2:H_2	3:O_2	4:CO_2	5:CH_4	6:C_2H_4	7:CH_4	8:C_3H_6	9:C_xH_y
Total weight [Mton]	208	23	18	127	46	16	27	13	11
Electricity need		759 TWh				1 TWh		450 TWh	
Process efficiency		85%							
C-conversion		60%				35%		100%	
Selectivity						85%		55%	

Note: 208 Mton water and 127 Mton carbon dioxide result in 16 Mton ethylene, 13 Mton propylene and 11 Mton hydrocarbon by-products. Note that not all substances are present in Table 2 or Fig. 1. For example, the water (103 Mton + 18 Mton) leaving the Sabatier reaction and OCM. The same goes for the carbon dioxide (2 Mton) produced in the OCM as well as the excess oxygen (165 Mton) from the SOEC. The total electricity need for each process clearly shows that the electrolysis and Sabatier reaction consume the most electricity, 759 TWh in comparison with 1 and 450 TWh. The C2- and C3-formation in the OCM and MTP are rather inefficient regarding conversion and selectivity, respectively.

This is almost equivalent to one-fourth of the gross EU electricity production in 2012 (Eurostat, 2014). It also compares to the total non-energy feedstock in petrochemistry in 2012 that was 860 TWh, where 66% of the physical (Mton) production was ethylene and propylene (Eurostat, 2012, 2013).

For scaling up the electricity need to the production of all plastics in the EU a rough assumption is made that all other plastic raw materials such as benzene and styrene will require an equivalent of the average specific consumption of ethylene and propylene at 29 MWh/ton. It is also assumed that there is no substantial weight difference between the raw material and the resulting plastic material, as well as that no additional electricity is used in the polymerization processes. Under these assumptions, the total electricity use for producing all EU plastics (57 Mton) in 2050 would be 1615 TWh, with a range from 1400 to 1900 TWh.

Plastics has a high energy content and currently the fossil energy and feedstock need for the global plastic production is estimated to amount for around 8% of the global oil and gas production (Hopewell et al., 2009). Thus, it is not surprising that it requires much energy in the form of feedstock to produce plastics, irrespective of whether the feedstock is petroleum, biomass or electricity and carbon dioxide.

The assumed technical improvements by 2050 may result in an electricity need that could be about 600 TWh lower (see Table 3). The difference between 2050 and 2014 depends mainly on the expected development of the SOEC electrolysis. Although 1615 TWh is a large amount of electricity, it is relatively little compared to the technical potential for renewable electricity from wind and solar, which amounts to tens of thousands of TWh in Western Europe (IPCC, 2011). As noted earlier, the electricity used for this process is assumed to be based on renewables; otherwise, the plastic as such cannot be considered renewable.

Table 3
The electricity need for producing ethylene, propylene and all plastics in the EU by 2050 (improved technology) and 2014 (current technology) shows that the expected technology improvement lowers the total electricity need by about 600 TWh.

	2050		2014	
	[TWh]	[MWh/ton]	[TWh]	[MWh/ton]
Ethylene	318	20	532	33
Propylene	490	38	590	46
Ethylene + Propylene	808	20 and 38	1122	33 and 46
Remaining raw materials	807	29	1081	39
All plastics	1615	29	2203	39

Note: The remaining plastic raw materials are assumed to have an electricity need of the average value between ethylene and propylene (29 MWh/ton), if instead the extreme values are applied (20 or 38 MWh/ton) it results in an electricity need for all plastics by 2050 that ranges between 1400 and 1900 TWh.

6. Carbon dioxide needs

In a circular economy carbon dioxide is expected to move from being a pollutant that is discharged into the atmosphere creating climate change to become a carbon resource for fuels, chemicals and plastics. This section explores how much carbon dioxide the EU would need annually to sustain the assumed level of plastics production in 2050 and what the sources of carbon dioxide may be with no fossil fuel use.

The reactions and mass balances in Section 4 showed that the carbon dioxide use per ton of product is about 3 tons CO_2/ton ethylene or propylene. The resulting total carbon dioxide demand for the production of 29 Mton ethylene and propylene is 94 Mton CO_2 (see Table 4). The results are scaled up to the total EU plastic production, assuming that the carbon dioxide use per ton of feedstock monomers is equal for all plastics (i.e., 3 tons of CO_2/ton). Once again the potential difference in weight of the feedstock and the total weight of all final products is not considered. Based on these assumptions, the total annual need of carbon dioxide to cover the EU plastic production is estimated to between 180 and 190 Mton (see Table 4). As expected, the carbon dioxide demand will not differ much between 2014 and 2050, since the carbon dioxide and methane are re-circulated internally the mass balance is not affected much by technology development.

The potential sources of carbon dioxide can be both fossil and non-fossil and although air capture removes any scarcity argument, it would be convenient to capture carbon dioxide in more concentrated streams. In a circular economy concentrated non-fossil carbon sources may come from combustion of biomass and municipal waste (including end-of-life plastics), or the production of ethanol or upgrading of biogas. The potential size of such specific streams in 2050 are unknown today, though some rough estimates can be made of future potential biogenic carbon flows.

The current annual use of biomass for energy in the EU is about 3 EJ (European Commission, 2013). Emission factors for oil and coal that are well documented are on the order of 75 $kgCO_2$/GJ and 90 to 100 $kgCO_2$/GJ. Direct emission factors for corresponding biofuels such as tall oil and solid wood fuels when burned are in the same

Table 4
The carbon dioxide need for ethylene, propylene and all plastics in the EU by 2050 and 2014 does, as expected, not vary with improved technology.

	2050	2014
	CO_2 [Mton]	CO_2 [Mton]
Ethylene	53	54
Propylene	41	41
Ethylene + Propylene	94	95
Remaining raw materials	90	91
All plastics	184	186

range (Paulrud et al., 2010). A simple assumption of 100 $kgCO_2$/GJ average emissions for EU biomass indicates that current emissions of biogenic carbon dioxide are about 300 Mton/year. Even if future use of biomass for energy may be two to three times higher and waste combustion provides an additional source, this indicates that there may be competition for concentrated bio-based carbon dioxide sources in a fossil-free future.

7. Cost and competitiveness

Given that is it possible from a technological and resource point of view to produce plastic feedstock from electricity, water and carbon dioxide, a cost and competitiveness comparison between fossil-, bio- and electricity-based ethylene is motivated. Ethylene prices show considerable variation over time, but a global market price for fossil ethylene is assumed to be 1100 USD/ton (915 EUR/ton). Bio-based ethylene is produced from bioethanol in Brazil at prices around 1200 USD/ton (1000 EUR/ton) and from substantially more costly bio-feedstock such as sugar beets in the EU, or with more advanced technologies based on woody biomass in the US at costs ranging from 1900 to 2600 USD/ton (1600–2170 EUR/ton) (IRENA, 2013). There are no published cost estimates for the production of entirely electricity-based ethylene or propylene starting with carbon dioxide and water. In the rough estimate of this article (with 20 MWh/ton ethylene), the electricity cost alone (at 60 EUR/MWh) would represent 1200 EUR/ton ethylene, thus suggesting that total production costs may be 2000 EUR/ton or more.

Using electricity and carbon dioxide as the main feedstock for ethylene and propylene production will only make sense under a very strict climate policy where fossil feedstock is completely phased out. The two main non-fossil feedstock options available then are biomass or electricity and carbon dioxide. For discussing future costs, electricity-based production is compared with bio-based production using thermo-chemical conversion of woody biomass. These production routes share the intermediate products syngas and/or methane as a feedstock for further synthesis to ethylene and propylene, which allows for comparison at this stage. For syngas and methane production there are current and future cost estimates for both electricity and bio-based production.

Current production costs for bio-based methane are roughly 80 EUR/MWh (Åhman, 2010). Future projections assuming substantially lower technology cost and increased conversion efficiencies estimate a potential long-term cost of 36–55 EUR/MWh (Van der Meijden et al., 2011; Åhman, 2010). These costs depend strongly on feedstock costs, and the range reflects future biomass feedstock prices ranging from 7 to 20 EUR/MWh (IRENA, 2013).

The estimated current production cost for methane from electricity and carbon dioxide is 120–180 EUR/MWh (Benjaminsson et al., 2013; Krause et al., 2013). Future estimates assume lower technology costs and higher efficiencies as through, for example, the development of SOEC technology. Future cost estimates for electricity-based methane range from 55 to 100 EUR/MWh. The low cost estimate assumes a very low future electricity price of 11 EUR/MWh, and the higher estimate assumes a more realistic (but still relatively low) electricity price of 30–35 EUR/MWh (Mogensen, 2014; Reinchert, 2012).

The comparison between cost estimates for intermediate methane production suggests that in order for bulk production of electricity-based ethylene to become competitive with bio-based ethylene, the electricity prices need to be very low (perhaps below 30 to 35 EUR/MWh) and, at the same time, the price of biomass would be need to be substantially higher than today (perhaps above 30 to 40 EUR/MWh). This change in relative price between electricity and biomass is possible in a future where competition for scarce biomass resources is strong and if low cost renewable electricity technologies are successfully developed. The potential for solar power is huge, and future costs may well decrease to 30 to 40 EUR/MWh (IPCC, 2011). One possible scenario is that solar PV becomes a backstop technology that indirectly through, for example electricity-based methane, determines the willingness to pay for, and thus the price of, biomass feedstock.

8. Discussion

The analysis shows that a complete shift to electricity-based plastics in the EU is possible in principle from a resource and technology perspective. To put the result into context uncertainties, technology developments, alternative processes and the need for integration between electricity and bio-based routes are discussed below. However, switching plastic production to renewable feedstock only solves one environmental problem associated with plastics. Other issues such as land and ocean littering, hazardous additives and resource inefficient use of plastics are not addressed in this paper, nor are they solved via a change of feedstock.

Except known limitations with the production method, such as low selectivity and high electricity consumption, the long time frame of the analysis imply further uncertainties. For example, the process steps exist in more or less industrial scale at present, but the entire integrated process has, to the authors' knowledge, not yet been tested. This creates uncertainties in how the scaling might affect the electricity and raw material consumption. Further, the assumption that there are no differences in weight and energy use between the feedstock and the final plastic is rather general, since more energy is probable to be needed in the polymerization process, and the additives also account for an amount of the plastic weight. Thus, the results of the electricity and carbon dioxide demand are to be regarded as a first estimate of a future electricity-based plastic production. The same is true for the cost and competitiveness, were the results indicate that the production cost for ethylene, propylene and plastics could become 2 to 3 times higher. However, in this paper the carbon dioxide is assumed to be for free, both regarding capturing, possible cleaning and transportation. This may not be the case depending on development of emission targets, carbon tax, oil and electricity pricing, etc. implying that cost may be even higher. However, the material cost is often low in comparison to the product price, meaning that high prices on plastics are not likely to be a problem for the overall economy (Rootzén, 2015). Another influencing factor and possible uncertainty is the technology development, but the technologies can be expected to develop irrespective of potential future applications in the plastics industry. For example, power-to-gas/liquid solutions dealing with the increased need to store power from variable electricity production are likely to drive the development of electrolysis and methanation processes. Thus, the key process steps and technologies for electricity-based plastics are essentially general-purpose technologies that have a broad range of applications.

The process studied in this paper is not the only option, alternative routes of producing hydrocarbons exist and they all entail different advantages and limitations. One alternative process is producing syngas (CO and H_2) in co-electrolysis, where carbon dioxide and water react simultaneously in a high-temperature SOEC device. The syngas produced in this efficient, but not yet mature, technology can be used for ethylene and propylene production via a modified Fischer–Tropsch reaction (Graves et al., 2011). The method has the benefit, in comparison with the chosen route, of being less complex regarding catalysts, but it results in a mixture of olefins and has lower selectivity for ethylene and propylene (Ampelli et al., 2015). Another more developed process option is producing methanol for the MTP process directly from syngas, without forming methane. However, this process does not easily allow for process integration with production of ethylene from methane.

A co-evolution and integration between electricity and bio-based production of chemicals and materials is possible. The bio-based production has a lower electricity demand and can be integrated with the electricity-based production as a carbon source. The H_2 and CO_2 economy of producing plastics basically necessitates that integration. An application to integrate early may be to boost bio-based processes with hydrogen from electrolysis. Thermo-chemical gasification and biological processes for methane production both have a surplus of carbon dioxide, and adding hydrogen can therefore increase the yield. Thus, electricity and biomass are options that complement rather than compete with each other. In the near term niche markets may develop, such as CCU polyurethane, but in the longer term it is likely that bulk drop-in material such as ethylene and propylene from renewable sources will be an important part of phasing out petrochemistry.

9. Conclusions

In a fossil-free future, electricity from renewable sources may become an important input for producing hydrogen and hydrocarbons, not only for fuel and power storage, but also as feedstock for the production of plastics. This paper explores a scenario where the current EU plastic production (57 Mton/year) remains constant, but is completely electricity-based. The key findings are that the total demand for electricity for such a production in 2050 could be 1400 to 1900 TWh and the carbon dioxide demand could be around 180 Mton. These figures are based on scaling up the results of a detailed assessment of electricity-based ethylene and propylene production, which was found to have a specific electricity demand of 20 MWh/ton and 38 MWh/ton respectively. Furthermore, both ethylene and propylene require about 3 tons of carbon dioxide/ton of product.

The analysis suggests that a complete shift to electricity-based plastics is possible from a resource and technological perspective, but that production costs may be 2 to 3 times higher than today. However, the long-term analysis imposes uncertainties and both the cost and resource requirements may vary depending on aspects such as development of technology, material efficiency and oil and electricity pricing.

Electricity-based plastics production is still a relatively unexplored option and more research and development is needed to advance the key technologies involved and to understand the potential role of electricity-based plastics in a fossil-free circular economy. Further studies could involve environmental assessments of the technology, integration between the electricity and bio-based economies and fundamental research on the process technologies. Nonetheless, it can be concluded that electricity-based plastics, integrated with a bio-based production, is an important option for a future with scarce biomass resources, but abundant electricity from renewable sources.

Acknowledgements

The authors wish to thank the Swedish Energy Agency for financial support through the project 'Green industrial transitions'(Grant number P38271-1) and the anonymous reviewers for their constructive comments. Support from MISTRA for the research programme Sustainable Plastics and Transition Pathways (STEPS) is also gratefully acknowledged.

References

Åhman, M., 2010. Biomethane in the transport sector—an appraisal of the forgotten option. Energy Policy 38, 208–217.

Åhman, M., Nilsson, L.J., 2015. Decarbonising industry in the EU – climate, trade and industrial policy strategies. In: Dupont, C., Oberthur, S. (Eds.), Decarbonisation in the EU: Internal Policies and External Strategies.

Álvarez-Chávez, C.R., Edwards, S., Moure-Eraso, R., Geiser, K., 2012. Sustainability of bio-based plastics: general comparative analysis and recommendations for improvement. J. Clean. Prod. 23, 47–56.

Ampelli, C., Perathoner, S., Centi, G., 2015. CO2 utilization: an enabling element to move to a resource-and energy-efficient chemical and fuel production. Philos. Trans. Royal Soc. Lond. A Math. Phys. Eng. Sci. 373, 20140177.

Aresta, M., Dibenedetto, A., Angelini, A., 2013. The changing paradigm in CO2 utilization. J. CO2 Util. 3, 65–73.

Arndt, S., Otremba, T., Simon, U., Yildiz, M., Schubert, H., Schomäcker, R., 2012. Mn–Na2 WO4/SiO2 as catalyst for the oxidative coupling of methane. What is really known? Appl. Catal. A General 425, 53–61.

Benjaminsson, G., Benjaminsson, J., Rudberg, R.B., 2013. Power-to-Gas–a Technical Review. Tech. rep.. Svenskt Gastekniskt CenterAB (SGC).

Braskem, 2015. Green Products. http://www.braskem.com.br/site.aspx/green-products-EURO.

Carbon Recycling International, 2015. Resource Efficiency by Carbon Recycling. http://www.carbonrecycling.is/.

Cefic, 2013. European Chemistry for Growth. Unlocking a Competitive, Low Carbon and Energy Efficient Future.

Cherubini, F., Strømman, A.H., 2011. Chemicals from lignocellulosic biomass: opportunities, perspectives, and potential of biorefinery systems. Biofuels Bioprod. Biorefining 5, 548–561.

Covestro, 2015. Carbon Dioxide – a New Raw Material. http://www.covestro.de/en/Projects-and-Cooperations/CO2-Project.aspx.

De Saint Jean, M., Baurens, P., Bouallou, C., 2014. Parametric study of an efficient renewable power-to-substitute-natural-gas process including high-temperature steam electrolysis. Int. J. Hydrogen Energy 39, 17024–17039.

European Bioplastics, 2013. Bioplastics – Facts and Figure.

European Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions a Roadmap for moving to a Competitive low Carbon Economy in 2050. EuropeanUnion. COM/2011/0112 final. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0112.

European Commission, 2013. Renewable energy progress report. EuropeanUnion. COM(2013)175 final.

European Commission, 2014. Proposal for a Directive of the European Parliament and of the Council Amending Directives 2008/98/EC on Waste, 94/62/EC on Packaging and Packaging Waste, 1999/31/EC on the Landfill of Waste, 2000/53/EC on End-of-life Vehicles, 2006/66/EC on Batteries and Accumulators and Waste Batteries and Accumulators, and 2012/19/EU on Waste Electrical and Electronic Equipment. EuropeanUnion. COM/2014/0397 final - 2014/0201 (COD).

Eurostat, 2012. EU Energy Balances. Annual.

Eurostat, 2013. Statistics on the Production of Manufactured Goods. Annual.

Eurostat, 2014. Net Electricity Generation, 1990–2012 YB14. Annual.

Gao, J., Wang, Y., Ping, Y., Hu, D., Xu, G., Gu, F., Su, F., 2012. A thermodynamic analysis of methanation reactions of carbon oxides for the production of synthetic natural gas. RSC Adv. 2, 2358–2368.

Graves, C., Ebbesen, S.D., Mogensen, M., 2011. Co-electrolysis of CO2 and H2O in solid oxide cells: performance and durability. Solid State Ionics 192, 398–403.

Hadi, N., Niaei, A., Nabavi, S., Shirazi, M.N., Alizadeh, R., 2015. Effect of second metal on the selectivity of Mn/H-ZSM-5 catalyst in methanol to propylene process. J. Industrial Eng. Chem. 29, 52–62.

Hoekman, S.K., Broch, A., Robbins, C., Purcell, R., 2010. CO2 recycling by reaction with renewably-generated hydrogen. Int. J. Greenh. Gas Control 4, 44–50.

Holmen, A., 2009. Direct conversion of methane to fuels and chemicals. Catal. Today 142, 2–8.

Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Philosophical Trans. R. Soc. B Biol. Sci. 364, 2115–2126.

Hu, S., Shan, J., Zhang, Q., Wang, Y., Liu, Y., Gong, Y., Wu, Z., Dou, T., 2012. Selective formation of propylene from methanol over high-silica nanosheets of MFI zeolite. Appl. Catal. A General 445, 215–220.

IPCC, 2011. Special Report on Renewable Energy for Climate Change Mitigation. SREEN, Geneva.

IPCC, 2014. Climate change 2014: mitigation of climate change. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P. (Eds.), Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (UK and New York).

IRENA, 2013. Production of Bio-ethylene. Technology Brief.

Jašo, S., Sadjadi, S., Godini, H., Simon, U., Arndt, S., Görke, O., Berthold, A., Arellano-Garcia, H., Schubert, H., Schomäcker, R., 2012. Experimental investigation of fluidized-bed reactor performance for oxidative coupling of methane. J. Nat. Gas Chem. 21, 534–543.

Jensen, S.H., Larsen, P.H., Mogensen, M., 2007. Hydrogen and synthetic fuel production from renewable energy sources. Int. J. Hydrogen Energy 32, 3253–3257.

Jensen, S.H., Hauch, A., Knibbe, R., Jacobsen, T., Mogensen, M., 2013. Modeling degradation in SOEC impedance spectra. J. Electrochem. Soc. 160, F244–F250.

Krause, H., Mulker-Syring, G., Henel, M., 2013. Power-to-gas Concepts for Energy Storage in Gas Infrastructure. DVGW-EDGaR, Arnhem, NL.
Lechtenböhmer, S., Nilsson, L.J., Åhman, M., Schneider, C., 2015. In: Decarbonising the Energy Intensive Basic Materials Industry through Electrification – Implications for Future EU Electricity Demand, SDEWES 2016, 10th Conference on Sustainable Development of Energy. Water and Environment Systems, Dubrovnik.
Liu, J., Zhang, C., Shen, Z., Hua, W., Tang, Y., Shen, W., Yue, Y., Xu, H., 2009. Methanol to propylene: effect of phosphorus on a high silica HZSM-5 catalyst. Catal. Commun. 10, 1506–1509.
Mogensen, M., 2014. Production of green fuels using solid oxide electrolysis cells: status and perspectives. In: 3rd Conference on CO2 as a Feedstock for Chemistry and Polymers. Essen, DE.
Mülhaupt, R., 2013. Green polymer chemistry and bio-based plastics: dreams and reality. Macromol. Chem. Phys. 214, 159–174.
Nova-Institute, 2015. Bio-based Polymers – Production Capacity will Triple from 3.5 Million Tonnes in 2011 to Nearly 12 Million Tonnes in 2020.
Ogura, K., 2013. Electrochemical reduction of carbon dioxide to ethylene: mechanistic approach. J. CO2 Util. 1, 43–49.
Paulrud, S., Fridell, E., Stripple, H., Gustafsson, T., 2010. Uppdatering Av Klimatrelaterade Emissionsfaktorer, (Update of Climate-related Emission Factors (In Swedish)). SMED Nr 92.
Plastics Europe, 2015. Plastics – the Facts 2015. An Analysis European Plastics Production, Demand and Waste Data.
Reinchert, F., 2012. Wind-to-gas-to-money? Economics and Perspectives on the Power to Gas Technology, Development and Planning. Aalborg University.
Ren, T., Patel, M.K., Blok, K., 2008. Steam cracking and methane to olefins: energy use, CO2 emissions and production costs. Energy 33, 817–833.
Rootzén, J., 2015. Pathways to Deep Decarbonisation of Carbon-intensive Industry in the European Union-techno-economic Assessments of Key Technologies and Measures. Chalmers University of Technology.
Saygin, D., Gielen, D.J., Draeck, M., Worrell, E., Patel, M.K., 2014. Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers. Renew. Sustain. Energy Rev. 40, 1153–1167.
Schüwer, D., Arnold, K., Bienge, K., Bringezu, P.D.S., Echternacht, L., Esken, A., Fischedick, P.D.-I.M., Geibler, D.J.v, Höller, S., Merten, F., Perrey, K., Pastowski, A., Pietzner, K., Schneider, C., Terrapon-Pfaff, J.C., Viebahn, D.P., 2015. CO2 Reuse NRW – Evaluating Gas Sources, Demand and Utilization for CO2 and H2 within the North Rhine-Westphalia Area with Respect to Gas Qualities. Wuppertal Institute.
SEKAB, 2015. Närodlad Plast – Är Det Möjligt? (Locally Grown Plastics – Is it Possible?).
Stünkel, S., Trivedi, H., Godini, H.R., Jašo, S., Holst, N., Arndt, S., Steinbach, J., Schomäcker, R., 2012. Oxidative coupling of methane: process design, development and operation in a mini-plant scale. Chem. Ing. Tech. 84, 1989–1996.
Styring, P., Quadrelli, E.A., Armstrong, K., 2014. Carbon Dioxide Utilisation: Closing the Carbon Cycle. Elsevier.
Sunfire, 2015. Closing the Carbon Loop. http://www.sunfire.de/.
Tsiropoulos, I., Faaij, A., Lundquist, L., Schenker, U., Briois, J., Patel, M., 2015, 90. Life cycle impact assessment of bio-based plastics from sugarcane ethanol. J. Clean. Prod. 114–127.
UNEP, 2012. Global Chemical Outlook – towards Sound Management of Chemicals.
Ursua, A., Gandia, L.M., Sanchis, P., 2012. Hydrogen production from water electrolysis: current status and future trends. Proc. IEEE 100, 410–426.
Van der Meijden, C., Rabou, L., Van der Drift, A., Vreugdenhil, B., Smit, R., 2011. Large Scale Production of Bio Methane from Wood. International Gas Union Research Conference IGRC, Soeul, South Korea, pp. 19–21.