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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

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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.

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

* 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).

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power-to-gas/liquid concepts; both since gases and liquids are 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

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