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Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis

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ABSTRACT

Using a life cycle perspective, potentials for greenhouse gas emission reductions using various power-to-x processes via electrolysis have been compared. Because of increasing renewable electricity production, occasionally surplus renewable electricity is produced, which leads to situations where the price of electricity approach zero. This surplus electricity can be used in hydrogen, methane and methanol production via electrolysis and other additional processes. Life cycle assessments have been utilized to compare these options in terms of greenhouse gas emission reductions. All of the power-to-x options studied lead to greenhouse gas emission reductions as compared to conventional production processes based on fossil fuels. The highest greenhouse gas emission reductions can be gained when hydrogen from steam reforming is replaced by hydrogen from the power-to-x process. High greenhouse gas emission reductions can also be achieved when power-to-x products are utilized as an energy source for transportation, replacing fossil transportation fuels. A third option with high greenhouse gas emission reduction potential is methane production, storing and electricity conversion in gas engines during peak consumption hours. It is concluded that the power-to-x processes provide a good potential solution for reducing greenhouse gas emissions in various sectors.

1. Introduction

Climate change due to increased greenhouse gas (GHG) emissions is one of the greatest global environmental challenges. Energy production by fossil fuel combustion is the most significant source of GHG emissions, comprising approximately 65% of global GHG emissions [17]. Various targets have been set for overcoming the problems, such as the EU 20-20-20 target for reducing GHG emissions, increasing the use of renewable energy and to improve energy efficiency [16]. This has led to rapidly increasing production of renewable energy.

Increased renewable energy production may in turn lead to situations where electricity production is occasionally at a higher level than electricity consumption. This has already happened for instance in Germany, Scotland and Denmark, where there is relatively high capacity for producing both wind and solar power. According to Neslen [41] on windy conditions Denmark have been able to exceed domestic electricity consumption with wind power. The same also happened in Scotland during 2016 [56]. It is likely that similar challenges will also appear in other regions in the near future.

According to Plessmann et al. [45] global 100% renewable decentralized electricity supply scenario is feasible at decent cost but requires electricity storages. The chief problem is that renewable electricity production peaks occur only temporarily and separately from consumption peaks. Therefore, the price of electricity may drastically fall during those surplus electricity production hours. Also, storage resources or dispatchable generation methods are needed in order for grid operators to balance demand and supply on a real-time basis [34]. This surplus electricity can be stored and used in several ways, depending on the energy form required as an outcome of the storage. When it is desirable to use surplus electricity later in the form of electricity, it can be stored in pumped hydro storages, compressed air storages or batteries. These processes are more detailed explained by Sternberg and Bardow [52], Beaudin et al. [4] and Ma et al. [35]. However, battery technology is not yet where it needs to be for storing electricity and balancing energy systems on a large scale [29]. A new solution could be to produce liquid or gaseous fuels by means of using sur-

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Nomenclature

CH_3OH	methanol
CH_4	methane
CO_2	carbon dioxide
EPA	U.S. Environmental Protection Agency
GaBi	LCA software
GHG	greenhouse gas
H_2	hydrogen
H_2O	water
EC	European Commission
ISO	International Organization for Standardization
LCA	life cycle assessment
MEA	monoethanolamine
O_2	oxygen
PtX	power-to-X

plus electricity via electrolysis. These fuels could provide a large energy storage capacity and an option to move energy from the electricity markets to other sectors, such as transportation. A recent techno-economic comparison of different energy storage options have been carried out by Amirante et al. [2]. The study shows rapid development in different storage options.

The production of hydrocarbons and hydrogen would allow for the use of hydrogen storage options and hydrogen utilization instead of direct electricity storing and power-to-power options. Further, hydrogen production also facilitates the production of other chemicals, such as methane and methanol, which have even better storage characteristics [53]. All these options to produce something from renewable electricity via electrolysis and additional processes are referred to as PtX (Power-to-X) in this paper. In addition to balancing electricity systems, hydrogen, methane and methanol have multiple utilization alternatives for energy, transportation, fertilizers and materials. Global markets for these commodities are tremendous [18,37].

Hydrogen can be produced through various types of electrolysis processes. At the moment, the focus of research is on reducing capital costs and integrating the compression of hydrogen into an electrolysis process [57]. Methane can be produced via a thermochemical catalytic or biological methanation of hydrogen. Thermochemical catalytic methanation has been viewed as a more potential option in the near future. Etogas started a 6 MW thermochemical catalytic methanation process in 2013 in Germany, which can be regarded as mature technology [47]. The good availability of natural gas, have been seen to limit large scale methanation plants [25]. Methanol can be produced with the hydrogenation of carbon monoxide and carbon dioxide by using catalysts, which is also mature technology [3]. Various pilot-scale demonstration plants have confirmed the possibility to produce methanol from CO_2 captured from flue gas, and H_2 from electrolysis [54]. In addition, Mitsui Chemicals is working with a 100,000 t methanol plant that uses CO_2 from flue gas and H_2 from the photochemical splitting of H_2O [38].

There are relatively few life cycle assessment (LCA) studies related to surplus electricity utilization in different products and energy options. Denholm and Kulcinski [13] have compared different electricity storage options from a life cycle perspective. Their conclusions is that electricity generation method have the highest contribution on climate change. However they did not include PtX processes in their study. The most thorough study has been carried out by Sternberg and Bardow [52], who have compared GHG emissions results from various PtX processes. They found that the highest GHG emission reductions can be achieved by surplus electricity use in heat pumps or in electric vehicles. However, they did not include hydrogen compression electricity consumption in their study, and there are various options for heat recycling also not included in their study. One of the key process steps of PtX is CO_2 capture. Sternberg and Bardow [52] did not include CO_2 capture-related GHG emissions in the overall emissions of PtX products. Therefore, its importance from a GHGs standpoint is unclear. Oliveira et al. [44] did an LCA comparison of various electricity storage methods. Their conclusion is that from climate change perspective electricity production methods have the highest contribution to the results. Spath and Mann [51] studied GHG emissions from hydrogen production via electrolysis utilizing renewable electricity. Their conclusion was that in the operational phase, emissions are minimal, and that the majority of emissions are related to the construction phase. Galindo et al. [23] compared the economy of conventional methanol production with that of methanol production from CO_2, and they concluded that conventional methanol production is less expensive. They also collected data from previous studies on the GHG emissions of methanol production from CO_2. According to the previous studies, 1 kg of methanol produced from CO_2 leads to 0.8 kg of CO_2 emissions. Since then, development has occurred in the methanol conversion process. Schaaf et al. [48] conclude that methane production from surplus electricity and storage in natural gas grids enables a high balancing option for the electricity system. Clemens et al. [10] have studied photocatalytic methane and methanol production from CO_2. The weak point of this process is the high water consumption, which may limit its use, especially in dry regions. There may also be economic limitations as Bydny et al. [8] study shows that PtX options cannot be operated profitably for bridging the balancing markets for power and gas currently without subsidizes.

Due to the various utilization options and PtX routes, deciding how surplus electricity should be utilized is challenging. We still lack knowledge about the ways and means that hold the most potential for utilizing surplus electricity via PtX routes especially compared to traditional production ways. In this paper, our focus is on GHG emission reductions from these routes. Some are more direct, such as conventional hydrogen, methane, and methanol replacement with PtX products. However, backed by political decisions and economic support, these fuels could also be utilized as replacement of fossil-based transportations fuels or in various energy production options. The aim of this research is fourfold: (1) to calculate the GHG balance for various PtX options; (2) to compare, for the same products, GHG emissions from PtX methods to GHG emissions from alternative production methods; (3) to provide recommendations for how PtX processes should be utilized in order to gain the highest GHG emission reductions; and (4) to discuss the potential of PtX commodities for replacing conventional fossil fuel-based systems globally.

This paper gives novel information related to GHG emission reductions for PtX processes and products compared to those produced by fossil energy. The conclusions of the paper can help researchers, companies and decision makers to develop more sustainable electricity systems that are linked to fuel production.

2. Materials and methods

In this chapter at first general principles for the life cycle assessment model have been presented. The second part of this chapter presents detailed assumptions and data used in the model.