Energy 90 (2015) 208–217

Contents lists available at ScienceDirect

Energy

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

Green methanol from hydrogen and carbon dioxide using geothermal energy and/or hydropower in Iceland or excess renewable electricity in Germany

Marco Kauw, René M.J. Benders, Cindy Visser*

Center for Energy and Environmental Sciences, Nijenborgh 4, 9747 AG, Groningen The Netherlands

ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form
10 May 2015
Accepted 1 June 2015
Available online 28 August 2015

Keywords:
Green methanol
Potential
CO_2 recovery
Electrolysis
Transport fuel

ABSTRACT

The synthesis of green methanol from hydrogen and carbon dioxide can contribute to mitigation of greenhouse gasses. This methanol can be utilized as either a transport fuel or as an energy carrier for electricity storage. It is preferable to use inexpensive, reliable and renewable energy sources to provide the energy needed for the green methanol production. Iceland has a large potential for such renewable energy sources. If only geothermal CO_2 may be utilized the green methanol potential in Iceland is ~340 million L/y. When all the potentially available geothermal energy and hydropower is combined the potential becomes ~2150 million L/y.

Next the scope is broadened to the European mainland using Germany as a case since its government has set strict goals for renewable electricity production. For Germany the electricity oversupply in 2050 is predicted to be 24 TWh_e/y, leading to a methanol potential of ~2360 million L/y using CO_2 from fossil fuel power plants.

In Iceland the potential of 340 million L/y of methanol as a transport fuel would supply all of the M3 demand and 75% of the M85 demand. In Germany the electricity oversupply would provide all of the M3 demand, but only 4% of the M85 demand.

1. Introduction

Increasing levels of CO_2 in our atmosphere impacting on the Earth's global temperature call for a more sustainable energy production. The European Union (EU) has set ambitious goals for GHG (greenhouse gas) emissions reduction of 80–95% by 2050. This implies that the energy sector should get about two thirds of its energy from RES (renewable energy sources). In its turn this implies that electricity production should be almost emission-free, despite an expected growth in demand [1]. Electricity from wind turbines and solar PV are expected to fulfil an important role in this transition. As these sources are intermittent surpluses of electricity need to be stored or converted to other energy carriers. Currently, H_2 (hydrogen) and CH_4 (methane) are in the picture to fulfil the role of storable energy carriers. Electricity surplus can be used to produce H_2 from water via electrolysis, or further react H_2 with CO_2 obtained from the burning of fossil fuels to synthesize CH_4 (Power-to-Gas). Apart from applying a lot of RES for electricity production there is another way to mitigate GHG emissions and meet renewable energy directives: Power-to-fuel. For this purpose the Icelandic company CRI (Carbon Recycling International) produces methanol (CH_3OH; [2]). In contrast to hydrogen and methane that could also be used as fuel methanol is a liquid which may give it some advantages (*e.g.* it can be stored at ambient temperature and atmospheric pressure). Besides blending with gasoline in cars, an application that can be started with directly as methanol is compatible with the current fuel infrastructure, or using it as fuel in fuel cells, methanol can also be used as feedstock in the chemical industry.

Currently, about 99% of all the methanol produced (global demand in 2011–2012 76,000 million L/y [3]) comes from using fossil fuels as feedstock, of which natural gas accounts for about 85% and coal for about 15%. The reasons are the relatively high hydrogen content of natural gas, the low energy consumption during the production and the relatively low investments costs. However, methanol can be produced more sustainably by synthesizing it from H_2 obtained via electrolysis and CO_2 [4]. It is no coincidence that this renewable, innovative method of synthesizing methanol is

* Corresponding author. Tel.: +31 50 363 4609.
E-mail address: c.visser@rug.nl (C. Visser).

http://dx.doi.org/10.1016/j.energy.2015.06.002
0360-5442/

applied in Iceland. This country has a large potential for producing inexpensive renewable energy (hydropower and geothermal energy). The geothermal power plants in Iceland emit CO_2 due to the degassing of volcanic magma. CO_2 from these plants can be stored easily and used for methanol synthesis. Due to the available renewable energy and CO_2, Iceland can potentially produce methanol on a large scale [5]. However, building new methanol plants in Iceland requires new geothermal wells for supplying the energy (thermal and electricity) as well as supplying the CO_2. But when not all of the released CO_2 from these (new) wells is captured and used for methanol production, this production process actually leads to an increase in greenhouse gasses.

All in all it is important to investigate both the potential for the production of green methanol and its mitigating implications using Iceland as a case. Therefore, this paper first describes the situation in Iceland. Afterwards the scope is broadened to the European mainland using Germany as case since its government has strict goals for implementation of RES in electricity production, and because CRI has announced in December 2014 that a facility will be built in Germany using captured CO_2 from a coal-fired power plant [6].

2. Methodology

This research is divided in four parts: the methanol production, the case of Iceland, the case of Germany, and methanol as a transport fuel. With relevant data from literature the H_2 and CO_2 numbers are calculated together with the energy requirements of the methanol production process. Iceland is used as case to research possible pathways for the production of green methanol (used resources, power supply, etc.) and their potential. Germany is studied for its electricity oversupply potential, as the German government plans to install a lot of renewable electricity capacity leading to an imbalance between supply and demand. The oversupply is calculated using the simulation tool PowerPlan [7,8]. With the oversupply the methanol potential for Germany can be determined. One of the uses for methanol is as transport fuel, so this potential is researched for both Iceland and Germany.

3. Results

3.1. Methanol synthesis

According to the patents of the Icelandic company CRI, they use the Lurgi methanol processes [4,9] with H_2 and CO_2 as feedstock (equation (1)). H_2 is produced by the electrolysis of water (equation (2)) and CO_2 is recovered from a geothermal power plant located in Svartsengi. These two streams are compressed to approximately 50 bars and heated to a temperature of around 498 K. After leaving the reactor vessel, a mixture of unreacted H_2/CO_2, methanol and water (by-product), flows through a heat exchanger to preheat the inlet gasses. Hereafter, this mixture flows to a preheater for the distillation system and then methanol is condensed in a condenser [10,11,12].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad \Delta H = -49 kJ/mol \quad \text{Reactor} \tag{1}$$

$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{Electrolysis} \tag{2}$$

Next, the steps in the methanol production will be described in terms of energy, starting with the two raw materials H_2 and CO_2.

3.1.1. Hydrogen production

The required energy for the electrolysis process is generated by RES. The idea of using renewable energy for producing hydrogen is not new and it was already mentioned as an option in 1975 [13]. However, the interest in renewable hydrogen production only started in the 1990s, when people became concerned about climate change and the diminishing fossil fuel reserves. Currently, there are three types of electrolyzers for hydrogen production, namely alkaline, PEM (polymer electrolyte membrane) and SOEs (solid oxide electrolyzers). Alkaline is the most mature technique, suitable for large scale, but it needs a constant input of electricity, which poses a potential problem when the facility is directly coupled to an intermittent renewable electricity supply. PEM electrolyzers are in their demonstration stages and are capable of processing a fluctuating input, thereby making them the best option for small scale commercial hydrogen production. SOEs are still in the R&D stage and they are based on high temperature electrolysis [14]. It is not known which type or brand electrolyzer unit the Icelandic company CRI uses for its production of green methanol. However, in a project of Shell and the Icelandic government, they built the world's first commercial hydrogen facility (for transport purposes) with an electrolyzer from NEL [15]. In this research it is therefore assumed that CRI also uses the highly efficient electrolyzers from NEL (bipolar alkaline) in the new commercial methanol production facilities. Table 1 presents the specifications and energy consumptions of the NEL electrolyzer. Electrolyzer units only require raw water (at ambient temperature) and electricity as an input. The purification of raw water and the separation of oxygen, hydrogen and unreacted water are included in the energy requirements of an electrolyzer unit.

3.1.2. CO_2 recovery

CO_2 can be obtained from several sources such as from flue gas of existing NG (natural gas), coal-fired or IGCC (integrated gasification combined cycle) electricity power plants; from geothermal media (Iceland); or from atmospheric air. One should keep in mind is that CO_2 recovery from power plants reduces the overall efficiency of electricity generation. This is mainly because capturing

Table 1
Specifications and energy consumptions of the bipolar alkaline electrolyzer unit NEL Atmospheric Type No. 5040 (5150 Amp DC).

Capacity [kg/day]	Conversion efficiency[a]	Energy consumption [kWh/kgH_2][b]	Product pressure [bar][c]	Energy efficiency (incl. pressure)[d]	Energy consumption without compression [kWh/kgH_2][e]	Energy efficiency (excl. pressure)[f]
1046	80%	54	30	74%	52	76%

[a] *Conversion efficiency*: the efficiency of converting water into hydrogen and oxygen. Water that has not been used in the electrolysis process is recycled. A lower conversion efficiency means a higher energy consumption [16].
[b] *Energy consumption*: the overall energy consumption in kWh/kgH_2 that is reported by the manufacturer of the electrolyzer units.
[c] *Product pressure*: the hydrogen end pressure given in bars before it is stored. In an electrolyzer unit, compression of atmospheric hydrogen is in some cases included.
[d] *Energy efficiency (incl. pressure):* the energy efficiency listed by the manufacturer. This includes compression of hydrogen.
[e] *Energy consumption without compression:* to fairly compare the energy consumption for hydrogen production, the end pressure is recalculated to atmospheric pressure because hydrogen compression is energy intensive. In this column, the energy consumption is given in kWh/kgH_2 at atmospheric pressure. For this justification, assumed is a polytrophic compression of hydrogen with an overall mechanical efficiency of 72%.
[f] *Energy efficiency (excl. pressure):* the energy efficiency of hydrogen production with an atmospheric end pressure.