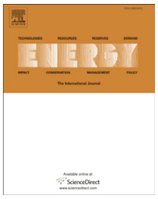
ARTICLE IN PRESS

Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

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



Synthetic fuel production costs by means of solid oxide electrolysis cells

Iva Ridjan*, Brian Vad Mathiesen, David Connolly

Department of Development and Planning, Aalborg University, Denmark

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form
21 February 2014
Accepted 1 April 2014
Available online xxx

Keywords:
Synthetic fuels
100% Renewable energy system
Flexible system
Biomass scarcity
Transport

ABSTRACT

The purpose of this paper is to provide an overview of fuel production costs for two types of synthetic fuels – methanol and methane, along with comparable costs for first and second generation biodiesel, two types of second generation bioethanol, and biogas. When analysing 100% renewable systems, the intermittent nature of renewable energy sources needs to be taken into consideration, so flexible solutions that can provide an option for regulating the energy system by balancing and storing excess electricity are essential. Coupled with the limitations of biomass resources and the need for the sustainable use of it, the solution that fits both concerns needs to be prioritized. The model analysed in this article is a 100% renewable scenario of Denmark for 2050, where the data for the transport sector has been changed to estimate the fuel production costs for eight different fuel pathways. The results confirm that synthetic fuel pathways reduce the demand for biomass, while simultaneously increasing the flexibility of the energy system by enabling a high share of wind energy. The most interesting finding is that the production costs of synthetic fuels are comparable with petrol production costs once the associated CO_2 emissions are included.

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1. Introduction

Over the decades emissions from the transport sector have been increasing while no significant renewable energy penetrations have been implemented. Due to the many different modes in the transport sector, flexible solutions that can be implemented in the existing infrastructure, completely adapted to liquid fuels, would be preferred. While there is a large potential for electric vehicles for personal cars, other modes of transport such as trucks and ships require fuels in a liquid or gaseous form. The focus traditionally has been on biofuels such as bio-diesel and bio-ethanol, as the only recommended supplements for the liquid fuel production [1]. The reason why biomass is interesting for the transport sector is that it can be converted to fuels with a high energy density. Implementation of biofuels raised discussions about their actual effect on the environment [2], such as the risk of interfering with food production, deforestation, and changes in land-use [3]. The comparison of biofuel emissions and their fossil equivalents was analysed in Ref. [4] which has raised the question of the sustainability of these fuels. However, there are many uncertainties on how to calculate lifecycle emissions for biofuels, which caused concerns on the accuracy of the real results [5]. Recent research in 100% renewable energy systems heightened the need to consider fuels in which you can limit the use of biomass when including the transport sector in the energy system analysis [6].

When switching to renewable sources their intermittent nature needs to be taken into consideration. The implementation of sources such as wind and solar energy requires balancing capacity that can enable extensive penetration into the grid. Electrolysers can convert electrical energy to chemical energy in the form of fuels, which enables electrolysers to substitute fossil energy in different ways. In combination with carbon from biomass conversion in the heat and power sector it enables production of liquid or gaseous fuels that can be either used in other energy sectors that require high energy density fuels or reused for power generation. The benefit of converting electricity into a form of liquid/gas fuel via electrolysis provides flexibility in terms of system regulation.

There are different types of electrolysers that can be used in the process of synthetic fuel production: alkaline, PEM (polymer exchange membrane) and SOEC (solid oxide electrolysis cell). The reason why alkaline and PEM electrolysers are not the one of interest is because of their lower efficiency compared to the solid oxide electrolyser cells, along with the fact that they can only be

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* Corresponding author.
E-mail addresses: iva@plan.aau.dk (I. Ridjan), bvm@plan.aau.dk (B.V. Mathiesen), david@plan.aau.dk (D. Connolly).

http://dx.doi.org/10.1016/j.energy.2014.04.002
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Please cite this article in press as: Ridjan I, et al., Synthetic fuel production costs by means of solid oxide electrolysis cells, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.04.002

used for steam electrolysis. However, these electrolysers could be a possible transition solution as solid oxide electrolyser cells are still not commercially available. Even though the SOECs are still not commercialized the technology has been demonstrated and tested in a period of 9000 h [7]. The high operation temperature of SOEC (>800 °C) results in faster reaction kinetics, which reduces the need for expensive catalyst materials. The SOEC could potentially operate in reverse as a fuel cell (SOFC) and therefore provide more options for balancing the energy system. The advantage of SOEC compared to other electrolyser technologies is that it conducts oxygen ions so they enable CO_2 electrolysis. SOEC can also generate synthetic gas by conducting co-electrolysis, the combined electrolysis of carbon dioxide and steam. However, this process is more complicated than separate steam and CO_2 electrolysis, and overall reaction pathway is not clearly defined [8].

Throughout this paper the term synthetic fuel will refer to a fuel that does not include the use of fossil fuel in the production process, and instead it is produced by combined use of electrolysers with carbon source. The carbon source can come either through: the recycling of CO_2 from a stationary energy-related/industrial process, or from the biomass gasification. The CO_2 recycling or biomass “boosting” (upgrading the energy content of biomass with hydrogen) for renewable fuel production would open the door to renewable energy in the transport sector, which was previously not accessible in the form of liquid fuels, with the exception of biofuels. Moreover this way of fuel production enables flexible fuel choice, as produced syngas can be converted to various liquid or gaseous fuels. One of the main advantages of some synthetic liquid fuels such as methanol and DME (dimethyl ether), is that implementation requires a limited change in the infrastructure: these typically include alterations of the vehicles and existing fuelling stations to a new type of fuel.

The synthetic fuel production is still at an early stage of development when combining renewable sources and CO_2 recycling. However, the George Olah Renewable Methanol Plant in Iceland has started the production of methanol via carbon recycling from a geothermal power station, using a technology called ETL (Emission to Liquid) [9]. Biomass gasification to fuels is already demonstrated in Sweden and there are a few projects planned for its commercialization. The BioDME project has already demonstrated the production of bio-DME and bio-methanol from the gasification of black liquor in 2011 [10]. The first commercial biomass to methanol plant, which gasifies biomass residues, will be inaugurated in Hagfors, Sweden and plans to start production in 2014/2015 [11]. Methane production from forest biomass is a key focus in the Bio2G project and a plant is planned in the Öresund region [12]. Two more methanol plants, based on wood gasification and black liquor gasification are planned to be built by Rottneros Biorafinery AB [13]. Therefore, although the hydrogenation of CO_2 and biomass are relatively new concepts for the production of fuels, there are already a number of large-scale plants either in operation or at the planning phase.

In this paper eight different fuel production pathways are analysed in the 100% renewable energy system and their fuel production costs are compared. The three synthetic fuel pathways (biomass hydrogenation, CO_2 hydrogenation and co-electrolysis) were analysed both for methanol and methane production, while the other three pathways (biodiesel – 1st and 2nd generation, bioethanol – 2nd generation with and without C5 sugar utilization and biogas) are analysed as separate cases. The synthetic fuel pathways using CO_2 recycling process (CO_2 hydrogenation and co-electrolysis) analysed in this article use CO_2 emissions from the biomass combustion in the heat and power sector as their carbon source.

The scenarios of the energy system have been allocated the same names as pathways implemented in the transport sector. The infrastructure costs, such as building new gas networks for transporting gaseous fuels, CO_2 or syngas, were not included in the cost calculation because the aim of the article is to give an overview of the fuel production costs and not the overall implementation costs of these fuels in the system. The flexibility of the different pathways is compared with the level of wind energy integration as the determining factor and the sensitivity analysis of biomass use is conducted to highlight the importance of conscientious use of biomass in the future energy systems.

The objective of this paper is to determine the fuel production price for different synthetic fuels and their competitors by providing an overview of all production chain elements that are forming the fuel price. The study provides the enhanced knowledge of the production chain components and related costs which enabled the more detailed modelling of synthetic fuels in the energy system. The focus of this study is narrowed in order to get the clear picture of the production costs and the competitiveness of the newly proposed fuels. The present study confirms previous findings [14] and contributes by giving the insight of the fuel price formation.

2. Methodology

The model analysed in this article is taken from the Danish 100% renewable scenario for 2050 [6] where the data for the transport sector has been changed in order to get the overview of costs for different renewable fuels that can be implemented. The obtained results include the costs of the production units, fuel handling costs, associated CO_2 emissions costs, and the feedstocks needed for the production. All the analysed scenarios are 100% renewable energy systems.

The scenarios have been analysed using the energy system analysis tool EnergyPLAN [15] to analyse different fuel types in the energy system. EnergyPLAN was chosen because it includes the balancing of the system in its fuel costs calculations. This aspect was important because electrolysers enable high share wind integration; therefore the costs are more accurate when including balancing costs. All scenarios were analysed with technical optimization, meaning that the fuel consumption is minimized. This is important due to the level of biomass resource used in the scenarios. The system in all scenarios was balanced in terms of CEEP (critical excess electricity production) and the gas balance, so the scenarios could be comparable. The balancing of the gas grid includes import and export, utilisation of gas storage and regulation strategies to minimise the exchange of gas to and from the system. The model operates in a way that it reduces the demand for natural gas with the produced biogas and/or syngas so the output is a biogas/syngas grid instead of a natural gas grid due to the analysis of 100% renewable systems. The scenarios vary depending on the pathways implemented in the transport sector, but in terms of primary energy supply the variations are mainly the ability to integrate wind capacity and the biomass demand for fuel. All the scenarios have closed self-sufficient energy systems.

Many previous studies have been carried out using EnergyPLAN such as analysing high shares of intermittent sources particularly wind power on the system [16], DH and CHP [17], analysis of alternative transport technologies [18–20] and analysis of 100% renewable energy systems [6,21–24]. The tool is a free-ware software that is updated regularly so it can implement the newest technologies in energy systems. The latest updates are new facilities of waste-to-energy technologies in combination with geothermal and absorption heat pumps, new costs data, different biomass conversion plants such as biogas, biomass gasification, biodiesel and ethanol plants, new facilities for grid gas (natural gas/bio/syngas) and additional grid stabilisation options. Furthermore,

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