Energy 57 (2013) 76–84

Contents lists available at SciVerse ScienceDirect

Energy

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

The feasibility of synthetic fuels in renewable energy systems

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ARTICLE INFO

Article history:
Received 9 October 2012
Received in revised form
23 January 2013
Accepted 24 January 2013
Available online 26 February 2013

Keywords:
Synthetic fuels
100% renewable energy system
Transport sector
Feasibility study

ABSTRACT

While all other sectors had significant renewable energy penetrations, transport is still heavily dependent on oil displaying rapid growth in the last decades. There is no easy renewable solution to meet transport sector demand due to the wide variety of modes and needs in the sector. Nowadays, biofuels along with electricity are proposed as one of the main options for replacing fossil fuels in the transport sector. The main reasons for avoiding the direct usage of biomass, i.e. producing biomass derived fuels, are land use shortages, limited biomass availability, interference with food supplies, and other impacts on the environment and biosphere. Hence, it is essential to make a detailed analysis of this sector in order to match the demand and to meet the criteria of a 100% renewable energy system in 2050. The purpose of this article is to identify potential pathways for producing synthetic fuels, with a specific focus on solid oxide electrolyser cells (SOEC) combined with the recycling of CO_2.

1. Introduction

Shifting from oil to other fuels is not just desirable, it is necessary for a number of reasons: resources are limited, geographic distributions are uneven and the greenhouse gas emissions must be reduced. The transport sector is one of the most important sectors of our time, as well as a significant carrier and the backbone of the economic and social development in many countries. With a rapidly growing demand in the last decades, the infrastructure relied on liquid fuels and different kinds of modes and needs the transport sector represent a challenge for implementing renewable energy sources. At the moment, oil and oil products cover more than 96% of energy needs in transportation [1] and it is the only fuel that can meet the demand. The transport sector accounts for about 19% of global energy use and for 23% of energy-related carbon dioxide emissions. Under current trends, transport energy use and CO_2 emissions are projected to increase by nearly 50% by 2030 and more than 80% by 2050 [2]. Reducing reliance on oil and oil products in the transport sector is a daunting challenge [3]. Encouraging the strong decarbonisation of transport could lead to energy security which is an important goal for sustainability. While most sectors have been taking measures to reduce CO_2 emissions and shifting to renewable energy sources, the emission share for transportation has been steadily increasing.

Future energy systems will be based on high shares of fluctuating renewable energy sources and the conversion of electricity into various energy carriers will become the main concern. Research shows that 100% renewable energy scenarios are technically possible in the future [4,5]. The change from conventional energy systems to renewable energy systems reduces greenhouse gas emissions, has a positive socio-economic effect, and can create new job opportunities. Also such systems enable security of supply and reduce import dependence. Designing effective energy system will consequently result in considerable less energy for covering the same demand.

The increased need for power balancing introduced the power-to-gas technology. Power-to-gas refers to a system in which electricity is converted into hydrogen by using water electrolysis. The produced hydrogen can be stored, converted to methane and reconverted into electricity if needed. An overview of power-to-gas power plants was given in Ref. [6]. Most of the power-to-gas projects are in operation for a short while, with the exception of Germany that has put great emphasis in this technology. With two finished long run projects and five projects currently in the planning stage, Germany could be considered as a leader in this concept. However, it may not be the first option for integrating fluctuating power from renewable energy sources in the electricity grid in the smart energy system [7].

The challenge of integrating transport sector in a 100% renewable system goes along with integration of high shares of intermittent renewable sources and minimizing biomass consumption through all energy sectors. This is demonstrated in a previous studies relating to 100% renewable energy systems, in terms of

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http://dx.doi.org/10.1016/j.energy.2013.01.046

overall system [4] and heat sector [8]. Research show that is not just biofuels alone that cannot solve the transformation of the transport sector to renewable energy, it cannot be dealt with using just one specific measure or technology, but instead it has to be analysed in coherent transport scenarios [3].

While electricity is very important in the transformation of the transport sector, it cannot be used for all modes of transport and the need for liquid fuels is inevitable. In this paper the conversion of electricity into some form of synthetic fuels is proposed. The term "synthetic fuel" relates to fuel made by using electrolysis as a base process and a source of carbon to produce liquid hydrocarbon. Production cycle of synthetic fuels intertwines the heat and power sectors, with the transport sector by using carbon capture and recycling at a biomass power plant, thus providing carbon source for electrolysis. The implementation of electrolysers in the transport sector does not only provide synthetic fuels for transportation, it also provides an option for regulating the energy system. Therefore, electrolysers possibly represent a good solution for balancing and storage in renewable energy systems.

2. Methodology

The aim of this study is to create alternatives for supplying the transport sector with liquid fuels by measuring primary energy supply, biomass consumption, system flexibility, and socio-economic costs. The methodology for analysing synthetic fuel implementation can be divided into four steps: data collection, technology and fuel review, energy system analysis, and a feasibility study.

Very little literature has been identified relating to the implementation of SOECs in the future energy systems, given that the literature mostly focuses on materials, performance, and durability of the electrolysis cells as well as the modelling of SOEC stacks. Different energy system scenarios, which include SOECs, are proposed in this study. This is followed by a review of the individual stages of the production cycle. Mass and energy balances are formed based on the chemical reactions of fuel production. A separate energy/mass flow diagram for each pathway outlining the electricity, biomass, CO_2 and water needed for producing 100 PJ of the primary fuel are then presented.

The overall energy system analysis and the feasibility studies were performed using the freeware energy system analysis tool EnergyPLAN. EnergyPLAN is a deterministic mathematical tool for national or regional energy system analyses according to inputs defined by the user. The model has an input/output user-friendly interface with a wide-range of inputs, such as energy demands, production capacities, renewable energy sources and efficiency of systems. It has been used and applied for various energy system analyses, from municipality level to national energy systems [9].

The feasibility study is divided into two analyses – technical and socio-economic, both conducted from the perspective of the whole energy system. Fuel consumption is evaluated, the wind capacity integrated into the system based on the electrolyser's capacity, and the biomass consumption are determined. The socio-economic feasibility of implementing synthetic fuels in the transport sector is done by calculating socio-economic costs including costs of fuel, operation and maintenance costs and investment costs.

2.1. The reference energy system

Analysis is carried out for the transport sector in the Danish 100% renewable energy system for 2050, one of the most coherent and well analysed national energy systems, projected as a part of – Coherent Energy and Environmental System Analysis known as CEESA project [10]. The reference system is called the Recommendable scenario CEESA 2050, with the aim to minimise the biomass consumption in the transport sector to preserve it for other sectors.

3. Solid oxide electrolyser cells (SOEC)

There are several existing research and development projects on SOECs in Europe. The main research centres for SOEC are located in Denmark [11,12]. SOECs can operate as a fuel cell or as an electrolyser. The difference between the two modes of operation is that in a fuel cell mode, the cell converts the chemical energy from a fuel into electricity through a chemical reaction while in electrolysis mode the cell produces fuels such as H_2 and CO. The topic of interest for this analysis is electrolysis mode. The advantage of solid oxide electrolyte is that it conducts oxide ions, so it can oxidize CO and reduce CO_2 in addition to H_2/H_2O. This cannot be done with other types of cells, like proton exchange membrane (PEM) or alkaline cells, because their electrolytes conduct protons (H^+) and hydroxide ions (OH^-) respectively.

SOECs operate at high a temperature (around 850 °C) which has both a thermodynamic advantage and an advantage in reaction rates. One of the benefits of high temperature electrolysis is that part of the energy required for splitting reactants is obtained in the form of high temperature heat, enabling the electrolysis to occur with a lower electricity consumption. The electrolysis process is endothermic i.e. it consumes heat. High temperature electrolysis thus produces almost no waste heat, resulting in very high efficiency, significantly higher than that of low-temperature electrolysis. Operating at high temperature results in faster reaction kinetics, which reduces the need for expensive catalyst materials that is typical for low temperature electrolysis. While water electrolysis has been highly investigated thoroughly, electrolysis of CO_2 is reported on a smaller scale [13]. If steam and CO_2 electrolyses are combined in a process called co-electrolysis, the produced synthetic gas, or shortly "syngas" contains varying amounts of carbon monoxide and hydrogen. The high operating temperature and high pressure, which provides further efficiency improvements, enables the integration of a catalyst to convert the synthetic gas to synthetic fuel. The heat generated in the catalytic reaction can be therefore utilized for steam generation and recycled in the system for electrolysis [14]. The advantages of solid oxide electrolyser cells are the potential for high fuel production rates at a high efficiency, low material costs, and the possibility of co-electrolysis of H_2O and CO_2. The main disadvantage of SOECs is the durability of the cell: durable performances at high current densities remain to be proven. The SOEC performance and durability during steam and/or carbon dioxide electrolysis and used materials is thoroughly described in Refs. [15–18].

4. Fuel prioritisation in transport sector modelling

Different energy carriers for transportation require different primary energy consumption and have diverse technology requirements for their implementation. Fuels have been prioritised according to the above characteristics. Direct electrification is the most energy efficient form of transport and is the main priority in all scenarios. Electrification can provide energy security, as it can be generated by a wide variety of means. Unfortunately, many transport subsectors are not suitable for electrification and will continue to rely on liquid fuels as a result of limited energy storage, power and weight issues: for example in long distance transportation such as trucks, aviation and maritime transport [19].

Apart from electrification, the only other proposed solution for achieving a 100% renewable transport sector has, so far, been the use of biofuels that can cover subsectors that are not suitable for