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 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 electrification [20,21]. However, there are a number of concerns relating to biofuel production in 100% renewable energy systems, such as the availability of adequate land. Even though this problem is well reported [22,23], many biofuel technologies are well established on the market, primarily because they can be used directly or with slight modifications in the existing combustion engines that are available on the market today. Many biofuels are subsidized to encourage a 10% penetration in the transport sector by 2020, in line with European Union targets. All EU members have either quota obligations and/or tax exemptions for implementing biofuels [24]. There are some concerns about the extent to which biofuels really influence emission reductions. A recent study which focused on air pollution effects of biofuels supply chains indicates that NO_x and NH_3 emissions of biofuels can sometimes be higher than their reference fossil fuels emissions – fossil diesel and gasoline [25].

The conversion of electricity into liquid fuels via electrolysis could be beneficial in the future transport sector because output gas can be catalysed into various types of fuels. Synthetic fuels overcome land-use problems, have no interference with the food supply, and provide solution for supply related issues of conventional fuels and biofuels. Methanol and DME are chosen as the most promising types of fuels, primarily due to the well-known chemical synthesis for producing these kinds of fuels and since they can be used in existing internal combustion engines with relatively few modifications. Where possible, produced fuel from syngas is assumed to be methanol because it is the simplest and lightest alcohol. It is also possible to use methanol as a petrol substitute in Otto engines due to its high octane rating, and methanol cars are a well-known technology. For example, methanol flexible fuel vehicles were available in the United States from the mid-1980s to the late 1990s [26]. Today, China is the leader in using methanol for transportation with five different methanol gasoline mixtures available on the market – M5, M10, M15, M85 and M100 [26]. Moreover, methanol is a platform chemical used to produce a range of other chemicals and fuels so it is a flexible solution. DME can be used as an alternative to conventional diesel, and it is often characterized as one of the most promising alternative automotive fuel solutions due to the more efficient diesel engines. The first DME fuelled heavy vehicle was developed by Volvo as a part of the development plan in the period from 1996 to 1998 [27]. The conversion losses during dehydration of methanol to DME are gained due to the higher efficiencies of diesel engines compared to petrol engines. Therefore, the results for methanol and DME are similar and no distinction was made. It was assumed that methanol/DME could be used directly in all modes of transport except aviation. Although methane is often considered as the easiest fuel to convert from syngas, it is not included in this analysis, because it is assumed that the application of methane is too expensive since the existing transport-fuel infrastructure is designed for liquid fuels [10].

5. Production cycle of synthetic fuels

The production cycle of synthetic fuels is divided into three steps as shown in Fig. 1: carbon and energy source, dissociation of oxides and fuel synthesis.

To provide the carbon source in order to avoid direct usage of biomass in the transport sector, carbon-capture and recycling (CCR) or air capturing are proposed. The difference between CCR and air capturing is that latter is not connected to any specific carbon source. CCR refers to a biogenic carbon dioxide from a stationary energy-related or industrial process, in this case from biomass combustion in the heat and power sector [28]. The analysis here is conducted with a post-combustion process, since this method is today more established for CO_2 capture than the others [29]. A previous analysis has shown that carbon capture and storage (CCS) is not a suitable way to decrease CO_2 emissions and it does not fit into the long-term sustainable solution based on renewable energy [30]. By using carbon-capture and recycling technology to capture and reuse the produced biogenic CO_2 expensive storage options are avoided. Air capturing is excluded from the analysis here since CCR is currently a cheaper alternative to synthetic trees [31,32]. From a technical perspective carbon trees would only require approximately 5% more electricity than CCR [31] so system costs are probably the only significant variation in the results of the whole system. With captured CO_2 from the atmosphere, the proposed production process of synthetic fuels could enable a closed-loop carbon-neutral fuel. The concept of carbon capturing and recycling is important not just because of the issue of global warming, but also since there may be a carbon shortage when implementing a 100% renewable system [33].

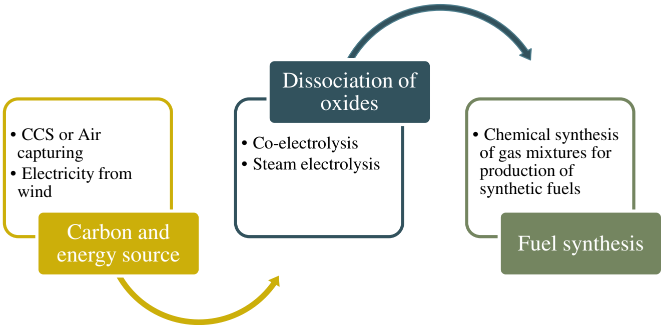

Fig. 1. Production cycle of synthetic fuels.

The electricity which enables the electrolysis process is provided by wind turbines. This option is chosen not only because Denmark is a leader in modern wind energy, with 28% of electricity produced from wind in 2011 [34], but also due to the fact that the integration of electrolysers in the transport sector enables the regulation of intermittent electricity sources.

After capturing the CO_2, the main step in the production cycle represents the conversion of electricity to fuel. This process is called dissociation of oxides, and it can be conducted with steam electrolysis or co-electrolysis by using electricity from wind turbines. Electrolysis performs the dissociation in a single step. The production cycle finishes with a chemical synthesis of the gas mixtures produced from the electrolyser into desired fuel.

6. Synthetic fuel pathways

After identifying the cycle steps needed for the production of synthetic fuels, two pathways are proposed here with four variations, as illustrated in Fig. 2. The first pathway is the *Co-electrolysis of steam and* CO_2 and the second one is the *Hydrogenation of* CO_2. Co-electrolysis is a combined process of steam and CO_2 electrolysis. Hydrogenation of CO_2 involves steam electrolysis and then a reaction of hydrogen with recycled CO_2. A key advantage of these pathways is that they finish with chemical synthesis. This means that a variety of fuels can be then be produced, because syngas can be transformed to many different fuels depending on different catalysts. The principal objective of these pathways is to create a liquid fuel which does not require any direct biomass input.

As it can be seen from the flow charts in Figs. 3 and 4 the same amount of carbon dioxide is required for the production of fuel from both pathways proposed here, so the same amount of electricity is also necessary for the carbon capturing and recycling system. The electrolyser efficiencies assumed are reduced by 5% to

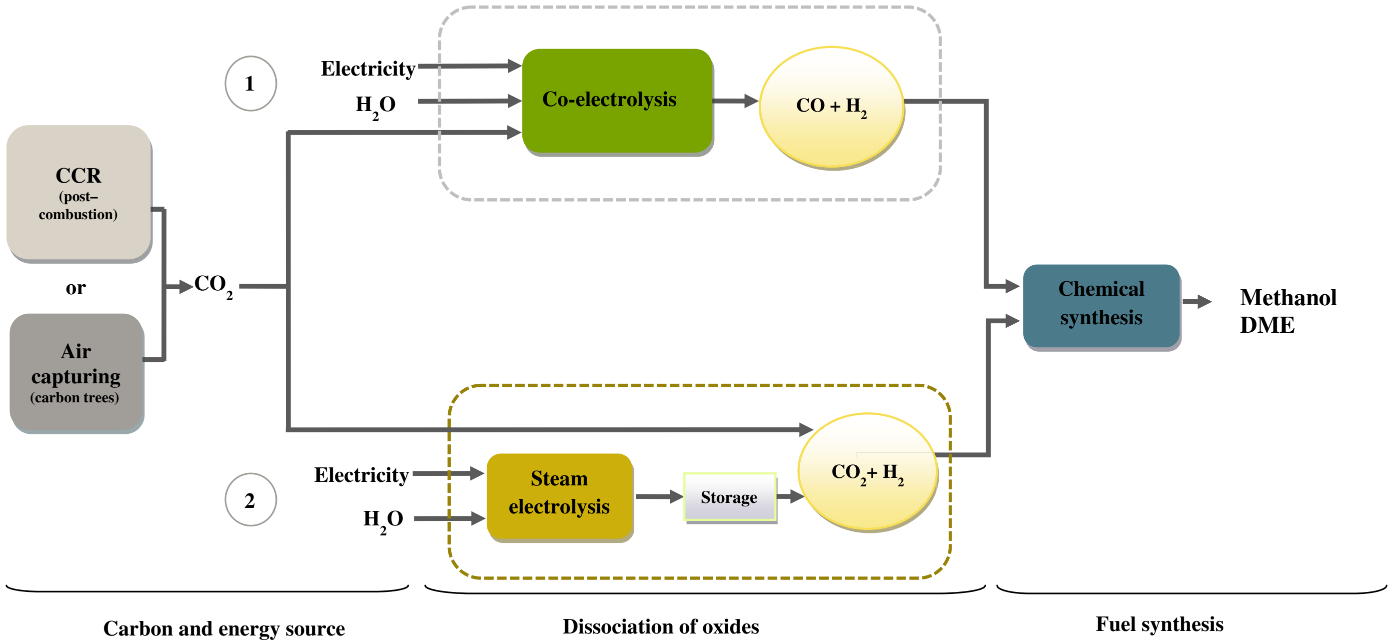

Fig. 2. Pathways for production of synthetic methanol or DME; 1 – Co-electrolysis, 2 – CO_2 hydrogenation.

account for storage and chemical synthesis losses. In the hydrogenation of CO_2 pathway, the synthesis of methanol produces excess water which can be recycled back to the electrolyser. The calculations for both pathways assume that dry willow biomass is used in the power plants with an assumed CO_2 capture rate of 1.63 Mt CO_2/Mt biomass.

7. Alternatives to synthetic fuels

Two biofuels scenarios that have direct usage of biomass for producing liquid fuels are included in the analysis here: *Hydrogenation of biomass* and *Conventional biodiesel.*

7.1. Hydrogenation of biomass

The principal objective in this pathway is to create a liquid fuel from biomass, which is boosted by hydrogen from steam electrolysis [see Fig. 5]. In this way, the liquid energy potential of the biomass resource is maximized. It is more preferable than the conventional production of biofuels due to the fact that it consumes less biomass and allows the integration of more wind in the system. The hydrogenation of biomass is a well-known process for upgrading the energy content and energy density of biomass with hydrogen. The hydrogenation of biomass involves gasifying the biomass into a syngas, which subsequently reacts with hydrogen.

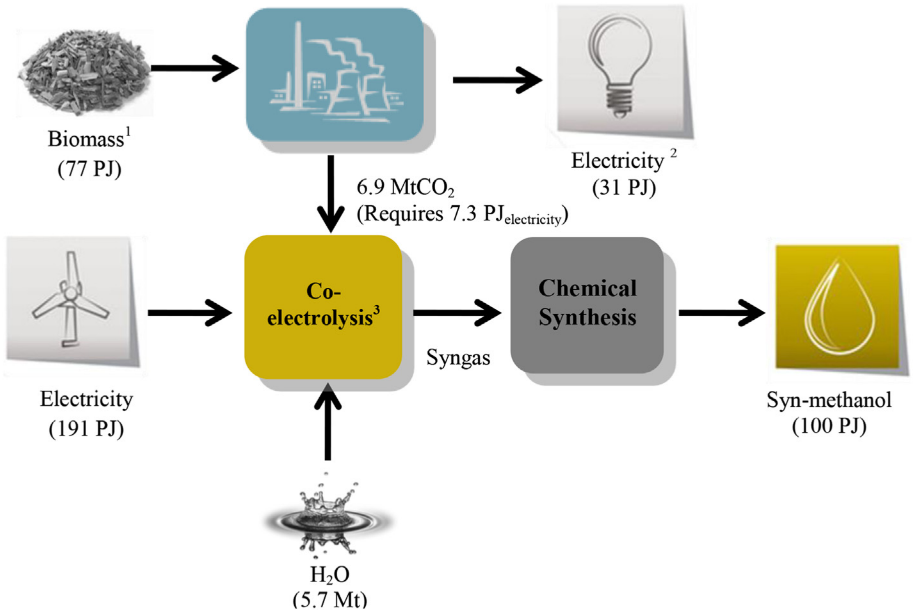

Fig. 3. Co-electrolysis scenario. [1]Based on dry willow biomass. [2]Assumed an electricity generation efficiency of 40%. [3]Assumed an electrolyser efficiency of 78% [35], minus 5% accounts for storage and chemical synthesis losses.

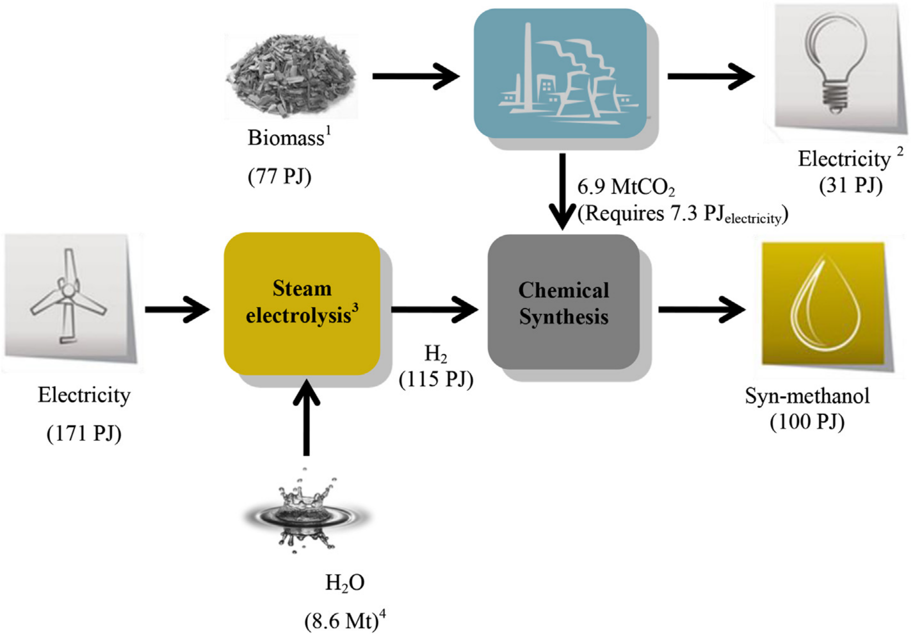

Fig. 4. Hydrogenation of CO_2. [1]Based on dry willow biomass. [2]Assumed an electricity generation efficiency of 40%. [3]Assumed an electrolyser efficiency of 73% [36], minus 5% accounts for storage and chemical synthesis losses. [4]This does not include the excess water which can be recycled from the hydrogenation process.

Biomass gasification is a high-temperature process (500–1400 °C) for converting complex hydrocarbons of biomass into a combustible gas mixture in the presence of gasification agents such as oxygen, air, steam or a combination of them [37].

7.2. Conventional biodiesel

This pathway is a response to the Technology Roadmap – Biofuels for Transport [21], which is based on the BLUE Map Scenario from the Energy Technology Perspectives 2010 report [38], this proposes cost effective strategies for reducing greenhouse-gas emissions by half by 2050. The scenario suggests that a considerable share of the required volume will come from advanced biofuel technologies that are not yet commercially deployed. However, the biodiesel path in our analysis is an extreme case of the conventional production of biodiesel in 2050. Conventional biodiesel production is the only scenario that does not include electrolysers in the production process in this study.

8. Energy system analysis

All scenarios analysed here are 100% renewable scenarios for 2050, without any fossil fuel input. Hence, the pathways modelled for this analysis represent extreme cases of replacing all of the liquid fuel demand with synthetic fuels, biofuels, or bio-diesel. The total predicted fuel demand in 2050 is 138 PJ/year (which is equal to

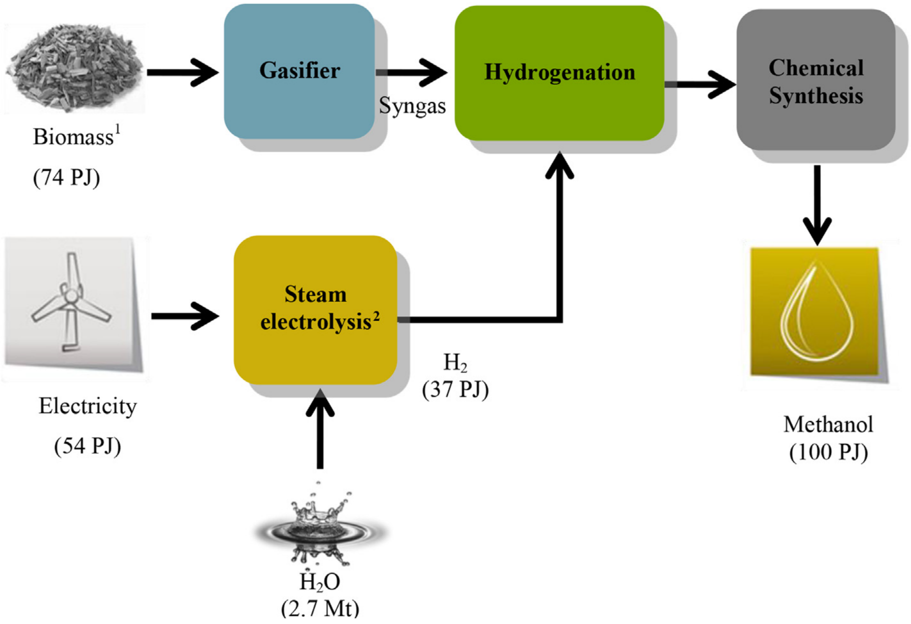

Fig. 5. Hydrogenation of biomass. [1]Based on straw/wood chips. [2]Assumed an electrolyser efficiency of 73% [36], minus 5% accounts for storage and chemical synthesis losses.

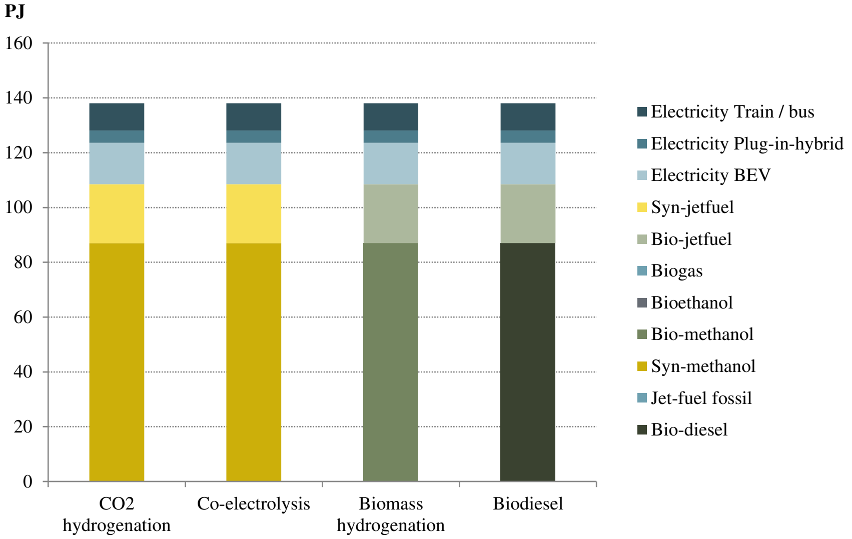

Fig. 6. Energy consumed by fuel type for the proposed pathways.

38 TWh/year) and it is kept the same in all scenarios [see Fig. 6]. In general, 21% of the consumption is met by the electrification of the transport sector, with different types of electric vehicles and electrically powered trains, while the rest is covered by different kinds of liquid fuels depending on the scenario. Due to the specific requirements for aviation fuels, a different type of fuel is required compared to the other transport modes. To account for this additional loss of 10% was added when fulfilling the aviation fuel demand.

The energy system analysis is carried out by focussing on four criteria for measuring the feasibility of implementing these scenarios: primary energy supply, system flexibility, biomass use and socio-economic costs.

9. Results

The biomass consumption for the whole energy system in each scenario is illustrated in Fig. 7. It can be seen that the *Co-electrolysis* scenario uses the least biomass possible – 193.2 PJ, while in the *Biodiesel* scenario the biomass consumption is almost 280 PJ. For the transport sector only, this ratio is even worse at the expense of the *Biodiesel* scenario, due to the fact that *CO_2 Hydrogenation* and *Co-electrolysis* have no direct biomass input in the transport sector.

Systems are compared by fixing the installed onshore capacities to 4454 MW. From the energy system perspective, 20–25% wind power can be integrated without significant changes to the system, while the integration of more wind requires the implementation of technologies that could facilitate wind power integration [10]. Installed offshore wind capacities are strongly connected with the addition of electrolysers in the system [see Fig. 8]. The implementation of electrolysers in the system enables a flexible and efficient integration of larger amounts of renewable energy into the transport sector. As it was expected, the *Co-electrolysis* pathway represents the most flexible scenario with 14,203 MW integrated off-shore wind turbines. It is evident from the results that the *Biodiesel* scenario can utilise a small amount of wind energy compared to the rest of the scenarios. In total, the *Biodiesel* scenario has approximately four times less off-shore wind (3444 MW) than the *Co-electrolysis* scenario. This is due to the much larger electricity demands and energy storage capacities available in the scenarios that include electrolysers. All scenarios that utilise electrolysers have higher wind shares in primary energy supply (up to 49%) than the *Biodiesel* scenario with 21%.

The flexibility of the system is also measured by adding more wind power to the system. A rise in CEEP indicates that there is a lack of flexibility in the system. The offshore wind capacities in scenarios are adjusted so the CEEP for all scenarios is 0.5 TWh/year.

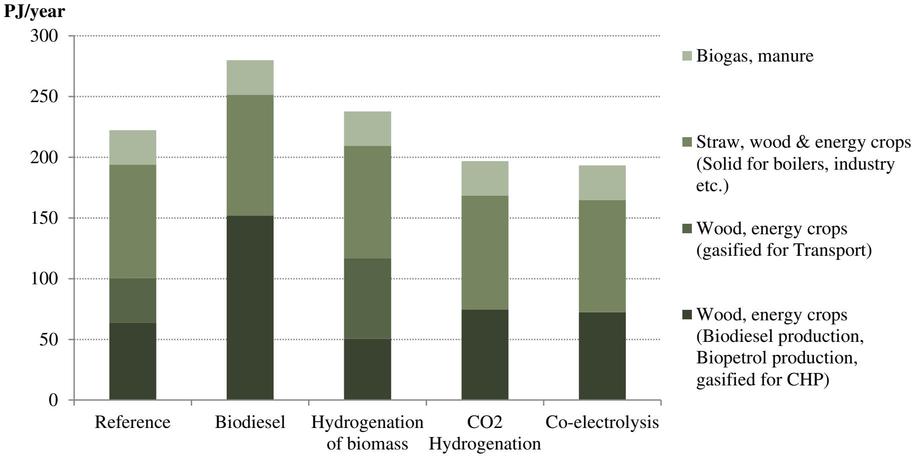

Fig. 7. Biomass use in overall energy system.

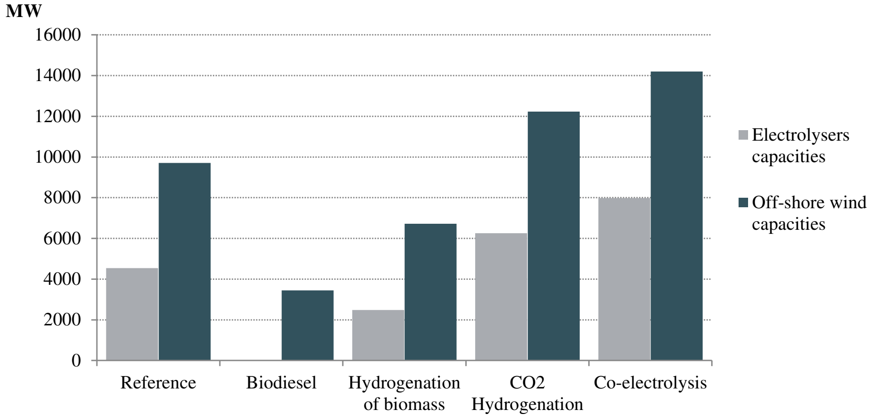

Fig. 8. Installed electrolysers and off-shore wind capacities.

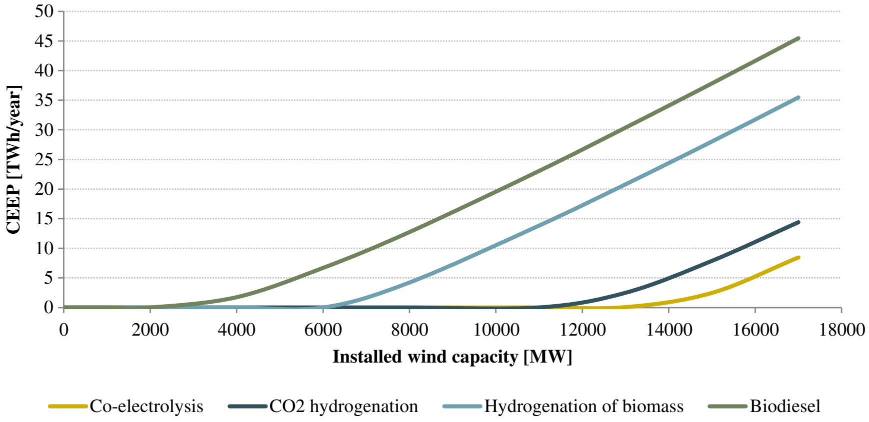

Fig. 9. Increasing wind integration by different scenarios.

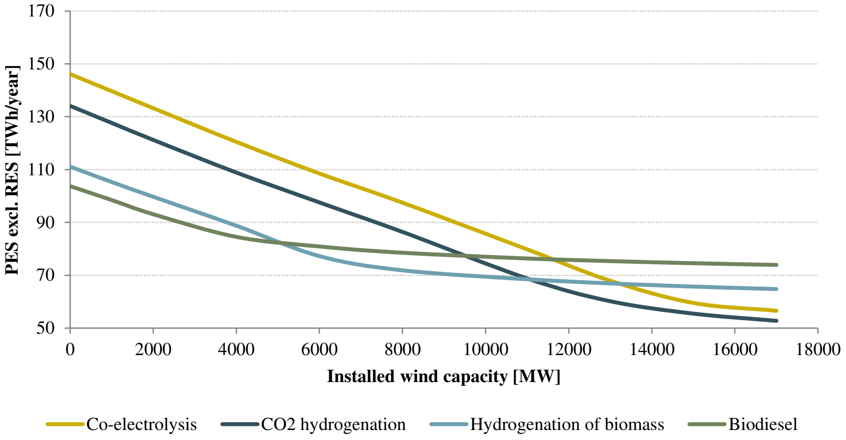

Fig. 10. Biomass fuel consumption for all scenarios.

As it is presented in Fig. 9, the *Biodiesel* scenario is the least flexible one, followed by the *Hydrogenation of biomass*. The integration of more wind capacities than presented here in the results leads to the further increase of CEEP. However, by increasing the storage capacities CEEP can be reduced.

In relation to the primary energy supply (PES), the scenarios differ only in their utilisation of biomass and offshore wind power, while the use of the rest of renewable energy sources is identical.

Table 1
Fuel prices used in analysis [10].

€/GJ	Straw/wood chips	Energy crops
Low price level	4.04	5.52
Medium price level	5.52	7.40
High price level	8.34	11.84

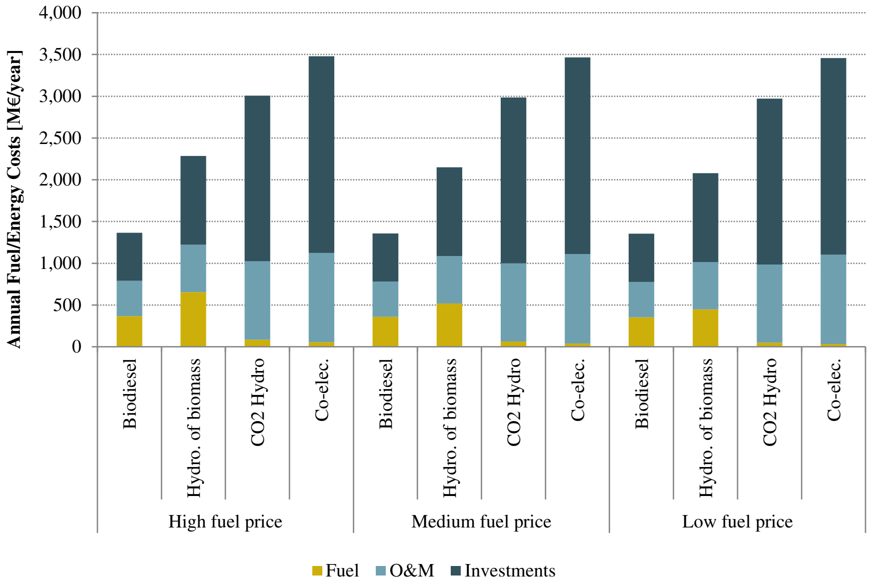

Fig. 11. Annual fuel/energy costs for all scenarios for medium price level in the transport demand.

The more wind integrated into the system, the higher the primary energy supply is. It is obvious that the technologies implemented in different scenarios are crucial for the biomass consumption. Even though the *Biodiesel* scenario overall has the lowest primary energy supply among all analysed scenarios, with 454.5 PJ compared to 526.2 PJ in the *Co-electrolysis* pathway, it has the lowest wind integration and the lowest flexibility while having the highest biomass use. In other scenarios, electricity produced with wind replaces the demand for biomass while electrolysers stabilize the grid.

Fig. 10 illustrates the annual primary energy supply excluding renewable energy sources e.g. biomass fuel consumption. The specified electricity demand for installed electrolysers cannot be met by the capacity of power plants in combination with import on the transmission line, resulting in higher primary energy supply in the *Co-electrolysis* and the *Hydrogenation of* CO_2 scenarios. After reaching a certain capacity of wind power in the system, in case of the *Biodiesel* and the *Hydrogenation of biomass*, the flexibility of their systems becomes lower than those with larger integration of electrolysers, and systems' biomass fuel consumption stays almost the same while the CEEP continues to rise.

Due to uncertainty of fuel prices in a long-term planning and the fact that fuel costs are key difference between scenarios three fuel price levels for biomass were used in the analysis [see Table 1]. The investment costs of SOEC are assumed to be 0.25 M€/MW for grid connected electrolysers with 20 year lifetime and 2% fixed O&M costs [36]. It is expected that the assumed SOEC costs will be reached in 2020 and stay the same in the period until 2050. The annual fuel/energy costs for all scenarios are shown in Fig. 11. The scenarios differ in energy system and fuel costs. Due to the implementation of new technologies, scenarios with electrolysers have higher investment costs followed by the lower fuel costs.

10. Conclusion

The production of synthetic fuels has many advantages, it connects different energy sectors making the system more flexible, it uses CO_2 recycling as a carbon source, and by implementing electrolysers it helps balancing the grid, facilitates wind power integration and represents smart energy system solutions. By combining electricity and electrolysers in the transport sector it becomes possible to relocate the electricity consumption and to replace inefficient technologies. The implementation of synthetic fuel pathways in the energy system showed the improvements of the system flexibility, which is essential for 100% renewable energy system. Moreover, a key advantage of the synthetic fuel pathways is that the production cycle finishes with chemical synthesis, meaning that a variety of different fuels can then be produced. However, as the synthetic fuel scenarios were based on the technologies that are still at the R&D level, the ultimate decision on which scenario is the best for the future transport system will depend on the technological development and demonstration of the proposed facilities on a large scale. Overall, the costs of synthetic fuel scenarios are higher, but the associated biomass savings make the additional costs worthwhile due to the limited biomass resources. Synthetic fuels could be competitive with biomass derived fuels on the market with anticipated technological developments and the mass production of SOECs, due to expected problems with biofuel production such as, land use shortage, supply related issues, and limited biomass resources. These results are also applicable for other countries that have set up the goal for high shares of renewable energy sources in their future energy systems.

Acknowledgement

The work presented in this paper is partly a result of the project Coherent Energy and Environmental Analysis (CEESA) funded by The Danish Council for Strategic Research and partly a project on development of SOEC (2011-1-10609) funded by the Danish PSO research program ForskEL. An early version of the analyses in this paper was presented at the SDEWES 2012 conference in Ohrid, July 2012. We wish to thank the audience for discussions and contributions.

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