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Techno-economic study of the storage of fluctuating renewable energy in liquid hydrocarbons

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HIGHLIGHTS

- Process of the production of liquid hydrocarbons from H_2 and CO_2 modeled.
- Power-to-Liquid efficiency is determined to 44.6%.
- Investment cost estimation carried out.
- Net production costs range from 12.41 \$/GGE to 21.35 \$/GGE.

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ABSTRACT

Liquid hydrocarbons are considered as an option to store renewable energy while decoupling the supply and demand of renewable resources. They can also be used as transportation fuel or as feedstock for the chemical industry and are characterized by a high energy density. A process concept using renewable energy from fluctuating wind power and CO_2 to produce liquid hydrocarbons was modeled by a flowsheet simulation in Aspen Plus®. The capacity of the plant was set to 1 GW_{LHV} of hydrogen input, using water electrolysis, reverse water–gas shift reaction (RWGS) and Fischer–Tropsch (FT) synthesis. A feed of 30 t/h of H_2 generated 56.3 t/h (12,856 bbl/d) of liquid hydrocarbons. A Power-to-Liquid efficiency of 44.6% was calculated for the base case scenario. Net production cost ranged from 12.41 \$/GGE to 21.35 \$/GGE for a system powered by a wind power plant with a full load fraction of about 47%, depending on the assumed electricity feedstock price and electrolyzer capital cost. For systems with full load fractions between 70% and 90%, the production cost was in the range of 5.48 \$/GGE to 8.03 \$/GGE.

1. Introduction

In 2012, a total of 1133 TW h of renewable power was generated worldwide, corresponding to 5.0% of the total electricity generated [1]. Depleting, finite fossil fuel reserves and the goal to reduce CO_2 emissions led to a transition to alternative power generation technologies. Therefore, an increasing number of renewable energy installations is now being observed. It is predicted that from 2014 to 2035, the renewable generation capacity will double to about 3930 GW of installed capacity [2]. Over the past decade, conventional power plants accounted for about 68% of the investment in the power sector. By 2035, however, about 62% of the investment is predicted to be in renewable technologies [2].

In conventional energy systems, power generation follows the energy demand [3]. In contrast, wind and solar power generation follows natural conditions, with hourly, daily, weekly or seasonal fluctuations [4]. Hence, long-term seasonal storage applications with a high capacity, low storage losses, well-established and safe storage tanks and low space requirements are required. Liquid hydrocarbons are considered an option to store renewable energy while decoupling supply and demand. They are characterized by a high energy density, are used in the transportation sector and exhibit little to no loss during long-term storage. Additionally, liquid hydrocarbons have an existing infrastructure, can be easily transported and also be used as transportation fuel or as feedstock for the chemical industry.

The generation of liquid hydrocarbons was investigated by several studies [5–9]. Current research focuses on the optimization of the generation of fuels and olefins from biomass and natural gas [10]. On the other hand, the use of CO_2 for the production of synthetic fuels demonstrates a real greenhouse gas sink. This technology combines CO_2/steam-mixed reforming and CO_2-active iron catalysts in Fischer–Tropsch synthesis in Gas-to-Liquid processes [11].

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Nomenclature

AC	alternate current
ACC	annualized capital cost
ASF	Anderson–Schulz–Flory distribution
α	chain growth probability
CEPCI	Chemical Engineering Plant Cost Index
COP	coefficient of performance
CSF	carbon safety factor
DC	direct current
EL	electrolysis
η_C	carbon conversion
η_{CCE}	chemical conversion efficiency
η_{Plant}	chemical plant efficiency
η_{PtL}	Power-to-Liquid efficiency
f_{H_2+CO}	molar fraction of H_2 and CO
FCI	fixed capital investment
FLF	full load fraction
FT	Fischer–Tropsch
FTS	Fischer–Tropsch synthesis reactor
GGE	gasoline gallon equivalent
ΔH_R^0	standard enthalpy of reaction (kJ/mol)
LH	liquid hydrocarbons
LHV	lower heating value
LP	low pressure steam
$\dot{m}$	mass flow (t/h)
MP	medium pressure steam
n	carbon number
NPC	net production cost
p	pressure (MPa)
P	power (MW)
PC	purchased cost
PEM	proton exchange membrane
PtL	Power-to-Liquid
R	recycle ratio
$R_{H_2/CO}$	H_2-to-CO ratio
RWGS	high temperature reformer, reverse water–gas shift reaction
T	temperature (°C)
TAC	total annualized cost
TCI	total capital investment
TOC	total operation cost
TPC	total purchased cost
w	mass fraction

The generation of liquid transportation fuels by combining a solid oxide electrolyzer cell and Fischer–Tropsch (FT) synthesis was investigated by [6] and [7]. Mignard et al. investigated the generation of alcohols from marine energy and CO_2 [5]. Jess et al. suggest generating liquid fuels from solar energy and CO_2 [8]. A rating of several Power-to-Liquid (PtL) technologies was proposed by Tremel et al. [9]. The aforementioned references assume a continuous supply of energy and reactant to the fuel production plant.

The present work investigates the techno-economic effect of an option to couple continuous fuel production with fluctuating energy sources, considering present realistic assumptions and future technological developments.

The economic potential of storing fluctuating renewable energy in liquid hydrocarbons is of special interest for renewable power station operators and for the prediction of future energy scenarios. Renewable liquid hydrocarbons may contribute to the fuel supply for aviation as well [12]. A techno-economic study was carried out, starting with a detailed process model of the generation of liquid hydrocarbons by FT synthesis. The model was analyzed by pinch-point analysis and the economic performance was estimated on the basis of capital and operation cost estimations.

2. Scope of evaluation and process description

The evaluation focuses on the production of liquid hydrocarbons from renewable excess power and CO_2. The system boundary and the block flow diagram of the process concept are shown in Fig. 1.

The focus on fluctuating renewable energy requires a highly flexible electrolyzer unit. A proton exchange membrane (PEM) electrolyzer can be operated at high current densities (above 2 A/cm^2) and cover a nominal power density range from 10% to 100% [13]. A storage cavern acts as the link between the highly fluctuating source, the electrolyzer unit and the continuous chemical synthesis. Hydrogen is stored if excess power is available and used when the hydrogen demand exceeds its generation. The liquid product is stored in tanks for later use. The economic analysis comprises the cost estimation for the electrolyzer unit, the hydrogen storage cavern and the chemical plant, including auxiliary units and utilities.

Fig. 2 illustrates a more detailed flowsheet of the process concept. The PEM electrolysis and the cavern are not modeled in the flowsheet. The capacity of the plant is set to 1 GW of hydrogen input based on its lower heating value (LHV). H_2 from electrolysis and CO_2, which is delivered by a pipeline, are fed to the plant. CO_2 and H_2 are converted in the reverse water–gas shift (RWGS) reactor to syngas, which is composed of H_2 and CO. The syngas is then further converted to hydrocarbons in the FT synthesis. The hydrocarbon syncrude is upgraded and separated from unreacted feed and gaseous hydrocarbons to make the final product.

3. Simulation model

A flowsheet simulation model was developed in Aspen Plus®. Heat losses of reactors, heat exchangers and piping were neglected. Furthermore, the electrolyzer and the storage cavern are not included in the flowsheet model. The pressure losses in the process are lumped in the recycle stream and are assumed to be 0.2 MPa [14].

3.1. Components and thermodynamic model

The model is based on the pure components H_2, CO_2, CO, and H_2O and the n-alkanes CH_4 through to $C_{30}H_{62}$, which were selected from the Aspen database. Coke is represented by solid carbon. Hydrocarbon products are represented only by n-alkanes, since the main products of cobalt based low temperature FT synthesis are n-alkanes [15]. CH_4 through to C_4H_{10} are gases, C_5H_{12} through to $C_{20}H_{42}$ are liquids and hydrocarbons with a chain length longer than C_{20} are waxes. In this work, the Peng–Robinson equation of state in combination with the Boston–Mathias alpha function is used to describe the phase behavior in the process [16,17]. The Peng–Robinson equation of state is widely applied in gas processes, refining and FT modeling studies [14,18,19].

3.2. Reverse water–gas shift reactor

The reverse water–gas shift (RWGS) reaction (1) is the endothermic hydrogenation of CO_2 to CO [20].