Chemical Engineering Research and Design 134 (2018) 90–103

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

An outlook towards hydrogen supply chain networks in 2050 — Design of novel fuel infrastructures in Germany

*Anton Ochoa Bique**, *Edwin Zondervan*

Laboratory of Process Systems Engineering, Department of Production Engineering, Universität Bremen, Leobener Str. 6, 28359 Bremen, Germany

ARTICLE INFO

Article history:
Received 30 August 2017
Received in revised form 20 March 2018
Accepted 23 March 2018
Available online 3 April 2018

Keywords:
Hydrogen supply chain design
Fuel infrastructures
Mixed integer linear programming
Germany
AIMMS

ABSTRACT

This work provides a comprehensive investigation of the feasibility of hydrogen as transportation fuel from a supply chain point of view. It introduces an approach for the identification the best hydrogen infrastructure pathways making decision of primary energy source, production, storage and distribution networks to aid the target of greenhouse gas emissions reduction in Germany. The minimization of the total hydrogen supply chain (HSC) network cost for Germany in 2030 and 2050 years is the objective of this study. The model presented in this paper is expanded to take into account water electrolysis technology driven by solar and wind energy. Two scenarios are evaluated, including a full range of technologies and "green" technologies using only renewable resources. The resulting model is a mixed integer linear program (MILP) that is solved with the Advanced Integrated Multidimensional Modeling System (AIMMS). The results show that renewable energy as a power source has the potential to replace common used fossil fuel in the near future even though currently coal gasification technology is the still the dominant technology.

1. Introduction

Up till now, fossil fuels, which include natural gas, oil, and coal are the primary energy sources for transportation, electricity, and residential services. Based on a report by the International Energy Agency (IEA) and the U.S. EIA, the global energy demand will grow with 30% in 2040 (International Energy Agency (IEA), 2016; U.S. Energy Information Administration, 2017). This means a progressively growing fuel consumption in the near future i.e. greenhouse gas emissions such as carbon dioxide also increase. Fossil fuel is a nonrenewable energy source. The depletion time for fossil fuel is estimated to be around 100 years, where oil and gas will be exhausted earlier than coal (Shafiee and Topal, 2009). Moreover, due to increasing fuel consumption, cause of concern is the fast rise of CO_2 level, now already exceeding 400 ppm level and, left unmitigated, can possibly double in 100 years to 800 ppm (CO2.earth, n.d.).

Due to the increasing demand of electric energy and a decreasing amount of fossil fuel sources, the development of solar-, wind- and biomass based production of energy and chemicals is strongly supported by governments (Schill, 2014). For example, the German government decided to completely phase out nuclear energy by 2022 (Pregger et al., 2013) and replace it with renewable energy production. The largest part of renewable power will come from solar and wind as shown in Fig. 1. Electric power from wind mills increases its contribution by 225 TWh in 2050, which is 39% of the final produced energy; solar contributes 17%, at 100 TWh per year, while biomass reaches 60 TWh per year.

While biomass as a raw material might be stored for a long period of time, wind and solar are more difficult to handle. As battery systems do currently not have enough capacity and storage of electricity is very expensive, the developments in new long-term storage technology is one of the main challenges. Industrial key players, like Siemens currently work on a new type of energy storage system based on hydrogen production (Siemens, n.d.). The main idea is that excess energy from renewable energy sources can be converted into hydrogen from water by electrolysis, which is a non-toxic source of energy to con-

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* *Corresponding author.*
E-mail address: antochoa@uni-bremen.de (A. Ochoa Bique).

https://doi.org/10.1016/j.cherd.2018.03.037
0263-8762/

Nomenclature

Indices

e	Type of energy source
f	Type of hydrogen physical form
g	Grid points, each grid point represents German state
p	Type of hydrogen production facility
s	Type of storage facility
t	Type of transportation mode

Abbreviation

CH	Compressed-gaseous hydrogen
FCEV	Fuel cell electric vehicle
HSC	Hydrogen supply chain
IEA	International Energy Agency
LH	Liquid hydrogen
USEIA	U.S. Energy Information Administration

Continuous variable

$EESAv_{e,g}$	Amount of available energy source e in the grid point g, which is used to satisfy energy demand in grid point g $[\mathrm{kWh\,d^{-1}}]$
$EESN_{e,g'',g}$	The flowrate of the supplied energy source e from neighboring grid point g'' to grid point g, which is used to satisfy energy demand in grid point g $[\mathrm{kWh\,d^{-1}}]$
$ESAv_{e,g}$	Amount of available energy source e in the grid point g $[\mathrm{unit\,e\,d^{-1}}]$
ESC	Total cost for the energy source consumed for hydrogen production $[\$\,\mathrm{d^{-1}}]$
ESD_g	Daily energy source demand $[\mathrm{kWh\,d^{-1}}]$
HD_g	Hydrogen demand by grid point $[\mathrm{kg\,d^{-1}}]$
$HF_{g,g',t,f}$	Hydrogen flowrate in the form f from grid point g to g' via transportation mode t $[\mathrm{kg\,d^{-1}}]$
$HHED_g$	Total energy demand in the grid point g $[\mathrm{kWh\,d^{-1}}]$
$HP_{g,f}$	Hydrogen generation in the form f at grid point g $[\mathrm{kg\,d^{-1}}]$
$HP_{p,g,f}$	Amount of produced hydrogen in the production facility p in the form f at grid point g $[\mathrm{kg\,d^{-1}}]$
PC	Daily production costs $[\$\,\mathrm{d^{-1}}]$
PCC	Production capital cost $[\$\,\mathrm{d^{-1}}]$
$PESAv_{e,g}$	Amount of available energy source e in the grid point g, which is used to satisfy energy source demand for hydrogen production $[\mathrm{unit\,e\,d^{-1}}]$
$PESIm_{e,g'',g}$	Flowrate of imported energy source e from neighboring grid point g'' to grid point g, which is used to satisfy energy source demand for hydrogen production $[\mathrm{unit\,e\,d^{-1}}]$
$PESN_{e,g'',g}$	Flowrate supplying energy source e from neighboring grid point g'' to grid point g $[\mathrm{unit\,e\,d^{-1}}]$
POC	Production operating cost $[\$\,\mathrm{d^{-1}}]$
$PCC_{p,f}$	Capital cost of facility p, producing hydrogen in form f $[\$]$
$POC_{p,f}$	Hydrogen production operating cost in form f at facility p $[\$\,\mathrm{kg^{-1}}]$
SC	The total hydrogen storage cost $[\$]$
$SCC_{p,f}$	Capital cost for storage facility s holding hydrogen in the form f $[\$]$
$SOC_{p,f}$	Operating cost to store 1 kg of hydrogen in the from f inside of storage facility s $[\$\,\mathrm{kg^{-1}\,d^{-1}}]$
TC	Daily distribution cost $[\$\,\mathrm{d^{-1}}]$
$TCC_{f,t}$	Capital cost of transport mode t for distribution hydrogen in the form f $[\$]$
Total	Total cost of HSC network $[\$]$

Integer variables

$NPF_{p,f,g}$	Number of production facility p generating hydrogen in from f at grid point g
$NSF_{s,f,g}$	Number of storage facility s holding hydrogen in the form f at grid point g
$NTF_{g,g',f,t}$	The number of transport mode t used for hydrogen distribution in the form f from g to g'
PN_g	Population at the grid point g

Parameters

AvCon	Average of household energy consumption $[\mathrm{kWh\,d^{1}}]$
AvD	The average distance travelled by personal car $[\mathrm{km\,y^{1}}]$
AvT	The average amount of personal car per 1000 people
AF_p	Annual factor for the facility p [%]
AF_s	Annual factor for the s storage facility s [%]
AF_t	Annual factor for the transport mode t [%]
$Dis_{g'',g}$	Distance between grid points [km]
$Dis_{g,g',t}$	Distance between grid points depending of type of transport [km]
$ESCost_e$	Energy source e price in year y, generated locally $[\$\,\mathrm{unit^{-1}\,e}]$
$ESDis_e$	Delivery price for energy source e $[\$\,\mathrm{unit^{-1}\,km^{-1}}]$
$ESICost_e$	Energy source e import price $[\$\,\mathrm{unit^{-1}}]$
FE	The fuel economy $[\mathrm{kg\,H_2\,km^{-1}}]$
FP_t	Fuel price for transport mode t $[\$\,\mathrm{l^{-1}}]$
$MaxPCap_p/MinPCap_p$	Max/min production capacity for hydrogen production facility p $[\mathrm{kg\,d^{-1}}]$
OP	Operating period $[\mathrm{d\,y^{-1}}]$
$SCap_{s,f}$	Capacity of storage facility s for holding hydrogen in the from f [kg]

Greek letters

$\alpha_{e,p}$	The ratio between energy sources e consumption to produce 1 kg $[\mathrm{unit\,e\,kg^{1}\,H_2}]$
γ	FCEVs penetration rate [%]
τ	Is total product storage period [d]

sumers allowing a greater energy security and flexibility. As soon as there is energy shortage, hydrogen might be used in different applications such as power generation, domestic and industrial services, navigation and space (Hake et al., 2006). However, hydrogen is not a naturally occurring fuel of mineral origin; it can be produced from both renewable and non-renewable resources: from coal and biomass gasification, the reforming of natural gas, from water electrolysis, photo-electrolysis, water-splitting thermochemical cycle, photobiological production, and high temperature decomposition. Moreover, hydrogen generation is only a part of the hydrogen production network, which can be defined as a supply chain consisting of several components (such as production, storage and distribution). For each of these stages a wide range of potential technological options exist. Due to increasing demand for energy, the development of sustainable and environmental friendly concepts such as the HSC should be developed to replace non-sustainable alternatives to meet the global need for