

TECHNO-ECONOMIC EVALUATION OF POWER-TO-AMMONIA SYSTEM

Hanfei Zhang, Umberto Desideri *

Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, Largo L. Lazzarino, 56122 Pisa, Italy

ABSTRACT

At present, the source of hydrogen for commercial ammonia synthesis process are mainly obtained through methane reforming and coal gasification. To reduce fossil fuels consumption and CO₂ emission, hydrogen production is a critical process in ammonia synthesis. Power-to-ammonia with solid-oxide electrolysis process can not only store renewable power (wind or solar), but also solve the problem of green hydrogen source. This research focuses on the techno-economic evaluation of the power-to-ammonia with solid-oxide electrolysis process. The results show that, the annual yield of ammonia is 50 kt with a purity of 99.8 mol%, with the storage capacity for renewable power being 360 GWh/year. SOEC case can achieve higher energy efficiency, the energetic efficiencies and production cost of the power-to-ammonia were 65% and 558 \$/ton, respectively.

Keywords: Power-to-ammonia, Hydrogen storage, Solid-oxide electrolyzer, heat integration, multi-objective optimization;

not have any CO₂ emission problem [5]. At present, large-scale industrial production of ammonia is done through the synthesis of nitrogen and hydrogen in the Haber-Bosch process [6]. The hydrogen mainly comes from natural gas, coal and other fossil fuels [7]. To reduce fossil fuel consumption and CO₂ emission, the power-to-ammonia (PtA) technology might contribute to solving this issue, and it could also serve as a means of energy storage for excess renewable power generated. The core technology of power-to-ammonia is the electrolyzer, which uses electrochemical methods to electrolyze water into hydrogen and oxygen. At present, three different electrolysis technologies are of interest for PtA process chains: alkaline electrolysis (AE), polymer electrolyte membranes (PEM), and solid oxide electrolysis (SOE) [8]. High-temperature solid oxide electrolysis (SOE) is more advantageous than AEL and PEM because SOE can produce hydrogen at a higher chemical reaction rate with a lower electrical energy consumption [9].

In this paper, ASPEN Plus software was used to simulate solid-oxide electrolysis integrated ammonia synthesis system. This paper is organized as follows: the power-to-ammonia plant is described in Section 2 with corresponding models developed. In section 3, the methodology is briefed with definition of the performance indicators. Afterward, details of the case study and results are discussed in section 4; and the conclusions are summed up in section 5.

NONMENCLATURE

Abbreviations

U_f	Reactant utilization
E_{cell}	Voltage of stack
J_{cell}	Current density of stack
$\Delta \dot{E}^+$	Net electric power input
$\Delta \dot{E}^-$	Net electric power output
PtA	Power to ammonia
SOE	Solid-oxide electrolyzer

1. INTRODUCTION

Ammonia is one of the most important chemicals produced in the world [1-4], which is considered a promising alternative to carbon-free fuel because it does

2. PROCESS DESCRIPTION AND MODEL DEVELOPMENT

In this section, the steady-state simulation models were developed using ASPEN PLUS, which is illustrated in Figure 1. For the hydrogen generation, demineralized water is heated and sent to the cathode of SOE to produce H₂. Along with H₂ production, the produced O₂ transports across the membrane and flows out of the

anode. The generated oxygen is cooled and used as a by-product. The H₂ mixed with N₂ which supplied by an ASU, to ensure the 3:1 of H₂/N₂ ratio. The mixed syngas compressed is fed to the 3 beds ammonia synthesis

reactor. The product gas from third bed passes through refrigeration station, two-stage flash, and finally a pure ammonia is obtained. The purge gas and flash gas are burned by a recovery boiler for energy recovery.

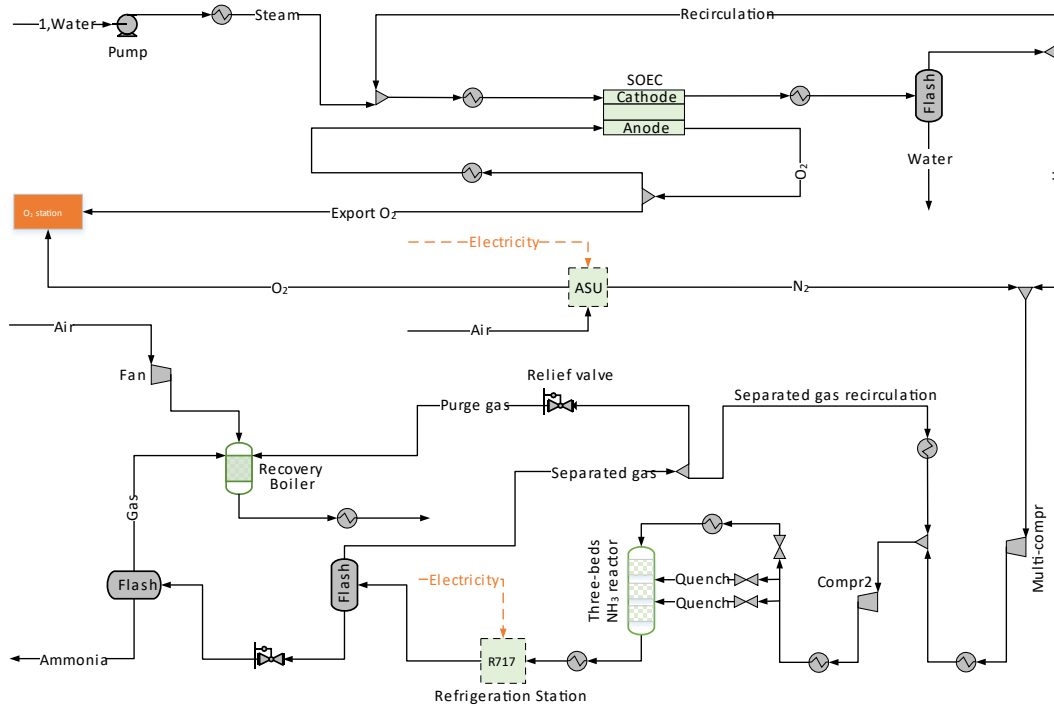


Figure 1. Schematic of power-to-ammonia with SOE without explicit heat exchanger network, whose performance is estimated with heat cascade calculation.

2.1 Solid-oxide electrolyzer

A quasi-2D SOE model is employed in this study which has been developed and detail described in [11] by considers electrochemistry, mass diffusion, heat transfer, reaction kinetics and chemical equilibrium, and has been calibrated with the multiple test data for both cell and stack. The model can accurately predict the SOE performances under various operating conditions and has been successfully applied by [12,13]. The SOE adiabatic operates with an inlet temperature of 750 °C and a maximum temperature gradient of 120 °C. The key parameters of the SOEC's operating point employed in this paper are listed in Table 1.

Table 1 The operating parameters of the SOE stack.

Parameter	Units	Value	Parameter	Units	Value
Temperature	°C	750	U _f	-	0.8
Pressure	bar	1.1	Pe	kW	7.75
E _{cell}	V	1.4	H ₂ O inlet	mol/s	0.035
J _{cell}	A/cm ²	1.07	H ₂ outlet	mol/s	0.028

2.2 Ammonia synthesis

The three-beds adiabatic quench cooling converter was modeled using Rplug model and reaction kinetics are from [14].

Refrigeration unit is modeled using Heater model as a simple black-box, ammonia temperature after freezing is -5 °C, through cooling load and COP considering only the electricity requirement. The cryogenic ASU is modeled as a black-box by considering only the total electricity requirement, around 160 kWh/t.

3. METHODOLOGY

To assess the process performance, thermodynamic and economic indicators be defined in this section. The process integration, the techno-economic evaluation is carried using a flexible computing platform based on mathematical programming continuously developed and improved by the group of Industrial Process and Energy Systems Engineering in École Polytechnique Fédérale de Lausanne, named OSMOSE, is employed in this study.

3.1 Process performance indicators

The thermodynamic performance of PtA plant is evaluated by energy efficiency (η):

$$\eta = \frac{\dot{M}_{NH_3} \cdot LHV_{NH_3} + \Delta \dot{E}^-}{\Delta \dot{E}^+} \cdot 100 \quad (4)$$

where \dot{M} is the mass flowrate. The superscripts – and + refer, respectively, to the net produced (output to the power grid) and consumed (input from power grid) services, and $\Delta \dot{E} = |\dot{E}^- - \dot{E}^+|$ [15].

3.2 Economic performance indicators

One main purpose of the economic analysis was to evaluate the proposed cases processes in terms of investment cost and methanol production costs in this study. The investment estimated cost is based on Turton et al. [16] and literature data. The uncertainty range of such estimates is up to $\pm 30\%$ [15,16]. The ammonia production cost (\$/ton) can be calculated by literature [17].

4. RESULTS

In this study, the PtA plant capacity with a fixed scale of 50 kiloton of ammonia per year. The results are summarized in Table 2. As shown in Table 2, the PtA has high energy efficiency that reaches up to 65%. The imported electricity of the system is 55.2 MW, including 48.7 MW of SOE consumption and 6.5 MW of other processes. The ammonia production cost is 558 \$/ton, the corresponding payback time is 7.7 years.

Table 2 Summary of results for the PtA plant.

Parameter	Unit	Value
Ammonia capacity	kton/year	50
η	%	65
SOE electricity consumption	MW	48.7
Electrical heater consumption	MW	0
Import electricity	MW	55.2
Ammonia production cost	\$/ton	558
Payback time	years	7.7

System-level heat integration of the BtA plant is illustrated in Figure 2 by Grand composite curves, which show that (1) SOE operates under the exothermic model with the outlet temperature of 842°C. The outlet of SOE partially heat steam generator and feed streams of SOE to 750°C; (2) the steam generator of SOE and feed streams are also heated by the heat released from the waste boiler and outlets of ammonia reactor.

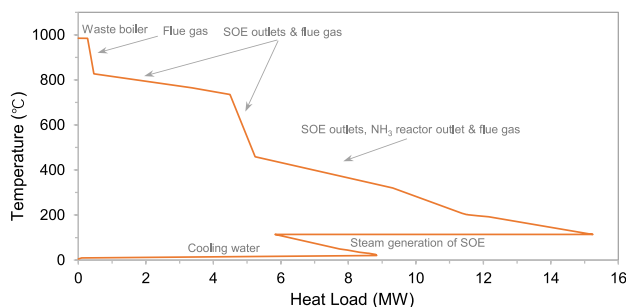
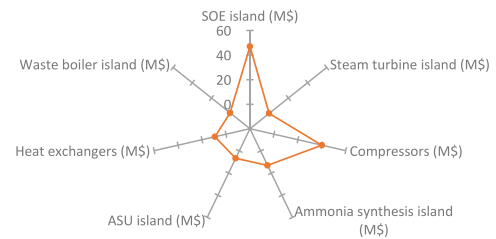


Figure 2 Grand composite curve of PtA plant.

The distribution of investment for the PtA plant is shown in Figure 2, and the total investment is 116 M\$. The SOE island (47 M\$) accounts for 40% of total investment, ranking the highest among others in the BtA plant. Figure 3 shows the distribution of operation cost and revenue of the PtA plant, where positive and negative values represent operation cost and revenue, respectively. The operation cost is about 30 M\$/year and the proportion of imported electricity is the highest (29 M\$/year). The revenue is about 45 M\$/year, including the export of ammonia, and oxygen as by-product, registering as 30 M\$/year, and 15 M\$/year respectively.

(a)



(b)

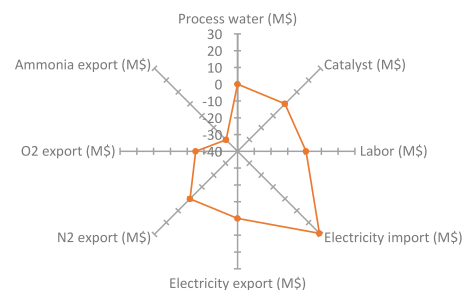


Figure 3 Cost distribution: (a) investment distribution, (b) Operation cost and revenue distribution.

5. CONCLUSIONS

In this study, the power-to-ammonia system with SOE was proposed and evaluated competitiveness systematically with regard to the efficiency of energy integration and economic performances. The main conclusions are: (1) the system can achieve a higher efficiency (65%) with the corresponding ammonia production cost and payback time being 558 \$/ton and 7.7 years respectively; (2) SOE is the main factor affecting the investment, which accounts for up to 60% of total investment; (3) The system has a high energy storage capacity (390 GWh/year). There is a significant amount of heat available from the whole system, which requires the integration of various heat recovery technologies to further increase the overall-system efficiency. Next step will carry out the research on the techno-economic optimization of power-to-ammonia, and integrating the Rankine cycle for heat recovery.

ACKNOWLEDGEMENT

The financial support by China Scholarship Council and the University of Pisa is gratefully acknowledged. Hanfei Zhang, who also thanks the Group of Industrial Process and Energy Systems Engineering at EPFL.

REFERENCE

- [1] Khademi MH, Sabbaghi RS. Comparison between three types of ammonia synthesis reactor configurations in terms of cooling methods. *Chemical Engineering Research and Design* 2017; 128: 306–317.
- [2] Maryam A, Adentoyese O, Amit K. Ammonia production from black liquor gasification and co-gasification with pulp and waste sludges: A techno-economic assessment. *Energy* 2018; 151:133–143.
- [3] Muhammad A, Takuya O, Atsushi M, Takao K. Combined nitrogen production, ammonia synthesis, and power generation for efficient hydrogen storage. *Energy procedia* 2017; 143: 674-679.
- [4] Fuerte A, Valenzuela R, Escudero M, Daza L. Ammonia as efficient fuel for SOFC. *Journal of Power Sources* 2009; 192: 170-174.
- [5] Yapicioglu A, Dincer I. A review on clean ammonia as a potential fuel for power generators. *Renewable and sustainable energy reviews* 2019; 109: 96-108.
- [6] Yusuf B, Ibrahim D, Calin Z, Greg V, Frank R. Comparative life cycle assessment of various ammonia production methods. *Journal of Cleaner Production* 2016; 135: 1379-1395.
- [7] Jeffrey R. A feasibility study of implementing an ammonia economy. Ph.D. thesis, Iowa state university; 2008.
- [8] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *Hydrogen Energy* 2013; 38: 2039-2061.
- [9] Ni M, Leung M, Leung D. Technological development of hydrogen production by solid oxide electrolyzer cell (SOEC). *Hydrogen Energy* 2008; 33: 2337-2354.
- [10] Leonzio G. Design and feasibility analysis of a Power-to-Gas plant in Germany. *Journal of Cleaner Production* 2017; 162: 609-623.
- [11] Wang L, Pérez-Fortes M, Madi H, et al. Optimal design of solid-oxide electrolyzer based power-to-methane systems: A comprehensive comparison between steam electrolysis and co-electrolysis. *Applied Energy* 2018; 211: 1060-1079.
- [12] Ligang W, Megha R, Stefan D, Tzu-En L, Hanfei Z, et al. Power-to-methane via co-electrolysis of H₂O and CO₂:

Process modeling, pressurized operation and internal methanation. *Applied Energy* 2019; under review.

- [13] Ligang W, Johannes D, Francois M, Jan V. Trade-off designs and comparative exergy evaluation of solid-oxide electrolyzer based power-to-methane plants. *International Journal of Hydrogen Energy* 2018; 44: 9529-9543.
- [14] Morud J, Skogestad S. Analysis of instability in an industrial ammonia reactor. *AIChE Journal* 1998, 44: 888–895.
- [15] Peduzzi E, Boissonnet G, Haartemmer G, Marechal F. Thermo-economic analysis and multi-objective optimisation of lignocellulosic biomass conversion to Fischer–Tropsch fuels. *Sustainable Energy Fuels* 2018; 2: 1069-1084.
- [16] Turton R, Richard C.B, Wallace B.W, Joseph S. A. *Analysis, Synthesis, and Design of Chemical Processes*, Prentice Hall, 2nd edn, 2002.
- [17] Albarelli J.Q, Onorati S, Caliandro P, et al. Multi-objective optimization of a sugarcane biorefinery for integrated ethanol and methanol production. *Energy* 2017; 138: 1281-1290.