Techno-Economic Assessment of Modular Water Electrolysis System Coupled with Heat-Pipe Cooled Microreactor

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Author: SeockYong Lee[a], UngJin Na[a], and HangJin Jo[a,b]

Presenter: SeockYong Lee

Research advisor: HangJin Jo

Pohang University of Science and Technology

[a]Department of Mechanical Engineering

[b]Division of Advanced Nuclear Engineering

dltjrdyd2000@postech.ac.kr

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dltjrdyd2000@postech.ac.kr

01. Introduction

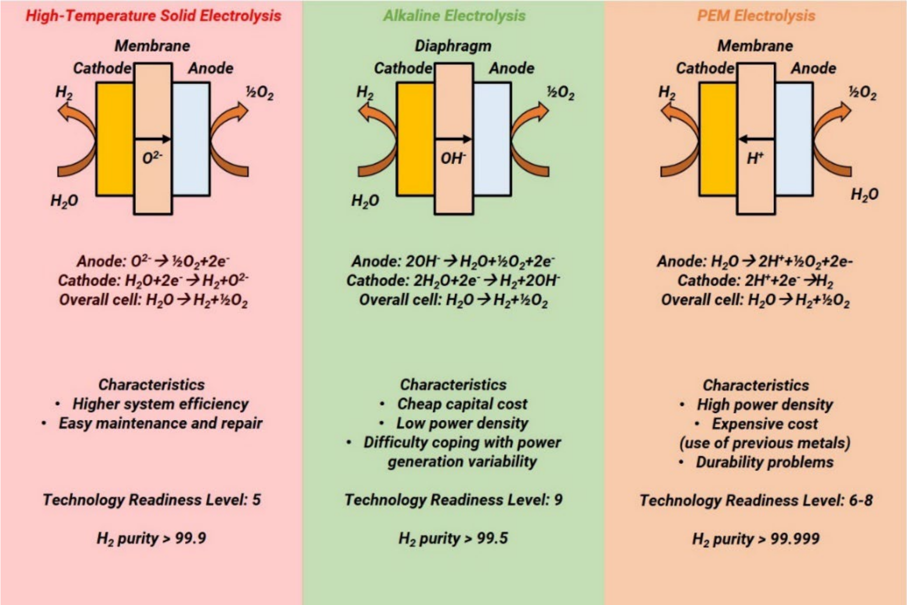
- ✓ Rapid increase of interest in clean energy without CO_2 emission
- ✓ Hydrogen gets attention as an energy carrier (Abundance, high specific energy)
- ✓ Target cost: 3,000 ₩/kg & Production rate: 5.26 Million ton/year (Korea, ~2040)
- ✓ Electrolysis was selected as the main hydrogen production method in Korea
  Due to high system efficiency, high TRL (Technology readiness level)
- ✓ Electrolysis depends on the reaction in the cell (HTSE, AE, PEM, AEM[2] etc.)

type	Specific energy [MJ/kg]
Hydrogen	141.86
Natural gas	53.6
Gasoline	46.4
Coal	24-35

수소경제 활성화 주요 로드맵 자료 : 산업통상자원부

구분		2018년	2022년	2040년
수소차(대)		1만8000	8만1000	620만
수소충전소(개소)		14	310	1200
연료전지	발전용	307MW	1.5GW	15GW
	가정·건물용	7MW	50MW	2.1GW
수소 공급(연간, t)		13만	47만	526만
수소 가격(1kg당 원)		8000	6000	3000

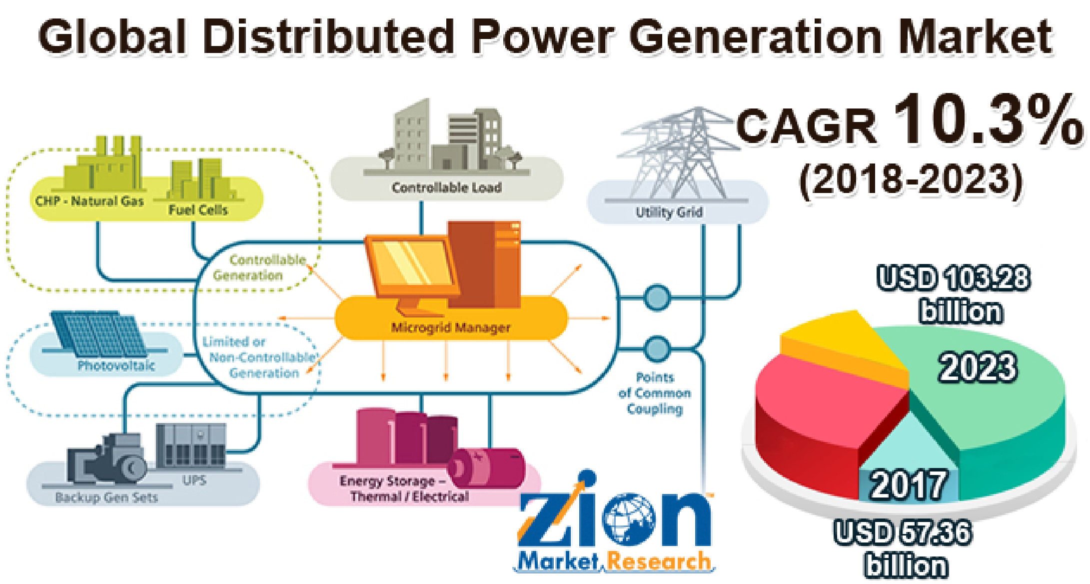
Hydrogen Roadmap in Korea[1]



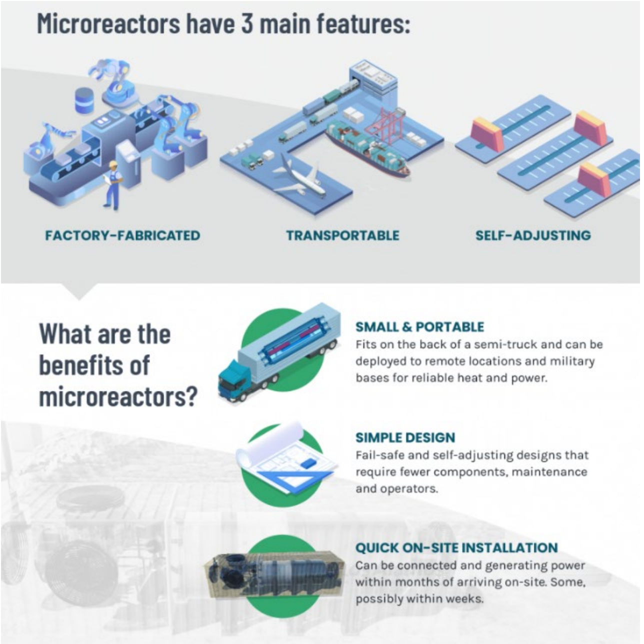
Characteristics of various electrolysis methods

01. Introduction

- ✓ Nuclear Power plant is a stable and economical heat source without CO_2 emission
  → appropriate for the baseline heat source
- ✓ NPP can be classified by size (Microreactor < 20 MW_e, SMR < 300 MW_e)
- ✓ De-centralized systems got attention due to affordability, reliability, flexibility, energy security, etc.
- ✓ Microreactors got attention due to their simple design and quick on-site installation, portability



Forecast for distributed power market size[3]



Common features of microreactors[4]

02. Research objective

Main objective

- To propose and evaluate a modular hydrogen production system coupling water electrolysis with heat-pipe-cooled microreactors

STEP 01

- **System establishment and operating condition selection**
- **Code development (MATLAB)**

STEP 02

- **Parametric study (PR, ε, discount rate, plant size, etc.)**
- **Compare the results for the current state and future state**

STEP 03

- **Calculate cost required for hydrogen storage and transport**
- **Compare proposed modular system with centralized system**

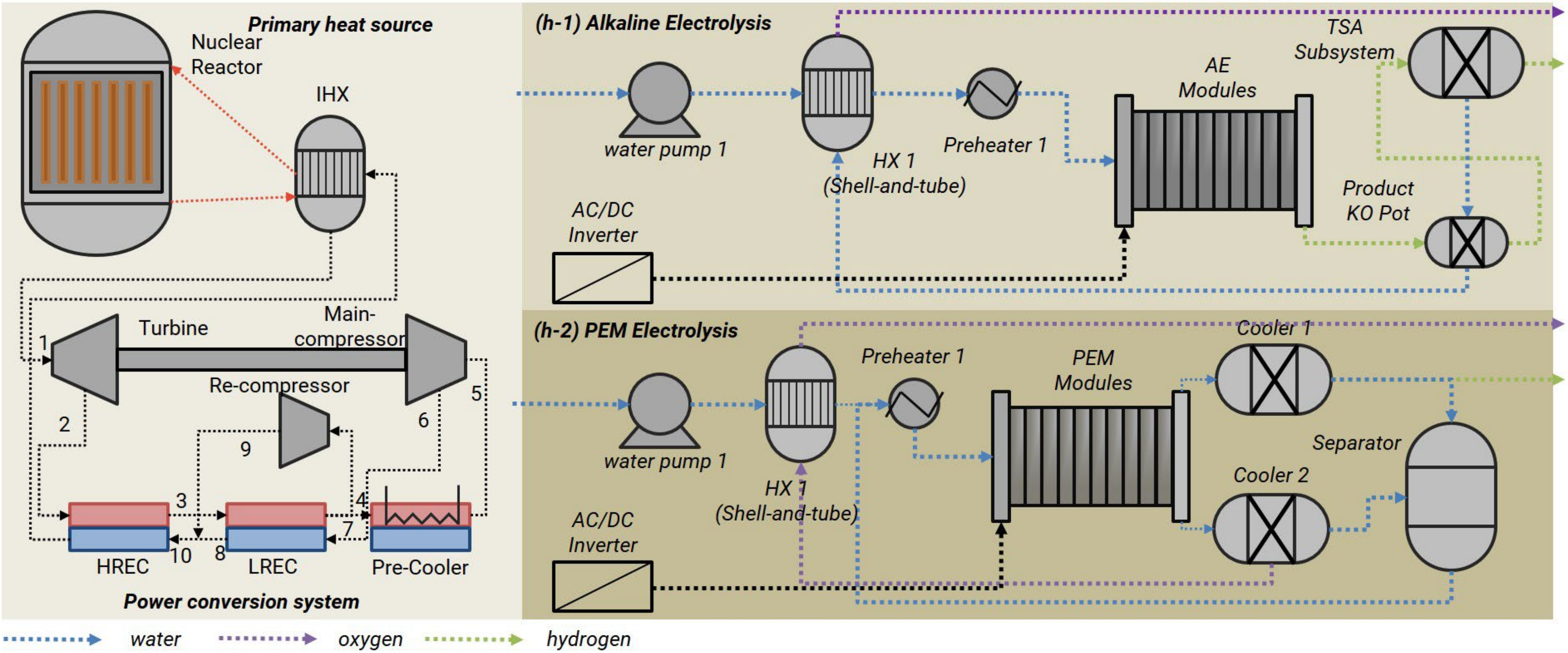
Evaluation index

- LCOH (Levelized cost of hydrogen)

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX} + \sum_{t_{cons}}^{t_{oper}} \frac{\mathrm{OPEX}}{(1+r)^n}}{\sum_{t_{cons}}^{t_{oper}} \frac{H_t}{(1+r)^n}}$$

CAPEX-Capital Expenditure [M$]
OPEX-Operating Expenditure [M$]
H-Annual hydrogen production rate [kg]
r-discount rate [-]

03. System description



Schematic of the proposed water electrolysis system coupled with microreactor

	Type	Ref
Heat source	Heat-pipe-cooled microreactor	LANL [5]
Power conversion system	SCO_2 recompression cycle	-
Electrolysis	AE, PEM	IRENA [6]

- ✓ Selected Design A of Los Alamos National Lab's special-purpose reactor for the primary heat source
- ✓ SCO_2 recompression cycle was selected in consideration of its portability (small volume) and high efficiency
- ✓ Alkaline and PEM electrolysis were selected as hydrogen production methods

03. System description

- ✓ Operating conditions and corresponding cell performances were selected considering the state-of-the-art and expected future level
- ✓ Costs for electrolysis systems including stacks and BOP are calculated considering the learning rate, operating year, plant size, etc.
- ✓ Additional cost for stack degradation (stack recycle, KOH^- solutions) were considered

	Alkaline water electrolysis		PEM electrolysis	
	Current (2020)	Future (2050)	Current (2020)	Future (2050)
Current density [A/cm^2]	0.5	2	2	3
Voltage [V]	1.9	1.7	1.9	1.8
Total electrical usage [kWh/kgH_2]	50	45	55.8	51.4
Stack electrical usage [kWh/kgH_2]	47	42	50.4	47.8
BOP electrical usage [kWh/kgH_2]	3	3	5.4	3.6
Operating temperature [̊C]	70	90	50	80
Cell pressure [bar]	30	70	30	70

Operating conditions and energy usage of each electrolysis system in current (2020) and future (2050) state[6] (IRENA, 2020)

$$C = \left(k_0 + \frac{k}{Q} Q^{\alpha}\right)\left(\frac{V}{V_0}\right)^{\beta}$$

C-specific cost
V-operating year
Q-plant size

	AE	PEM
α Scaling factor	0.649	0.622
β Learning factor	-27.33	-158.9
k_0	301	586
k	11603	9458.2
V_0 Reference year	2020	2020

IRENA-International Renewable Energy Agency, 국제재생에너지기구

03. System description

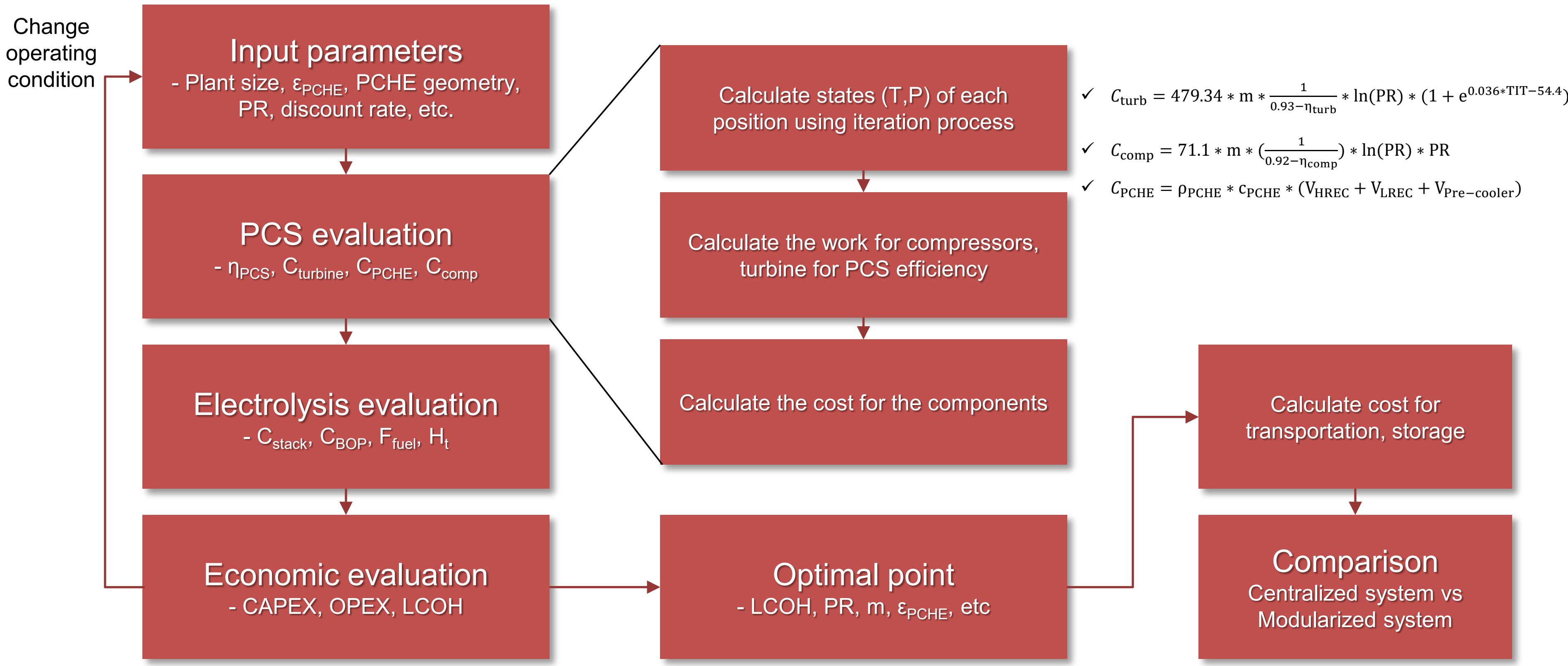
- ✓ Considered three hydrogen storage methods and transport methods
- ✓ Selected Pohang as the hydrogen production point and LA as the hydrogen consumption point

Storage method	Specific cost [$/kgH$_2$]	Energy required [kWh/kg H$_2$]
Compression (30-35 bar)	0.335	0.5
Liquefaction (1 bar)	2.855	11.5
Liquid ammonia (1 bar)	1.39	10.5 (including recover from ammonia)
Transport method	**Storage method**	**Specific cost [$/km*tH$_2$]**
Truck	Compression	2.33
	Liquefaction	0.92
	Ammonia	0.33
Rail	Compression	0.55
	Liquefaction	0.28
	Ammonia	0.04
Ship	Compression	0.52
	Liquefaction	0.09
	Ammonia	0.03

The cost required for hydrogen storage and transportation according to each methods[7]

03. System description

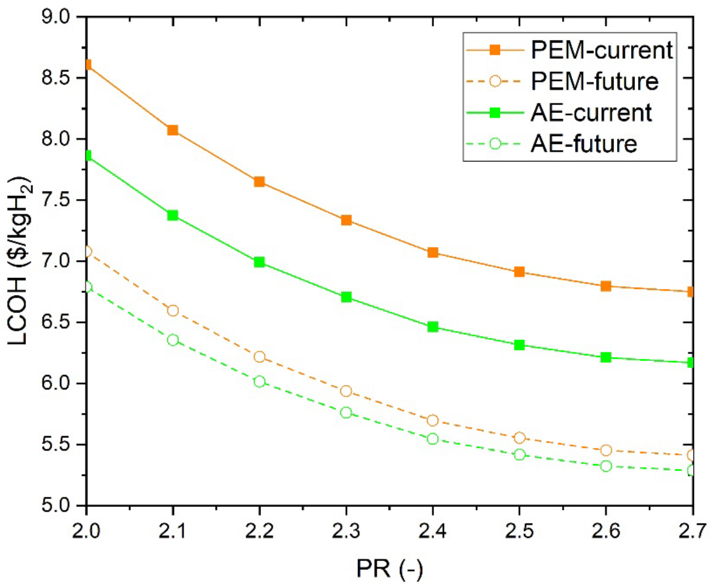
- ✓ Developed our own in-house code using MATLAB to evaluate the proposed system
- ✓ Conduct a parametric study for the effect of design parameters on LCOH
- ✓ Based on optimal point, LCOH was compared with centralized system

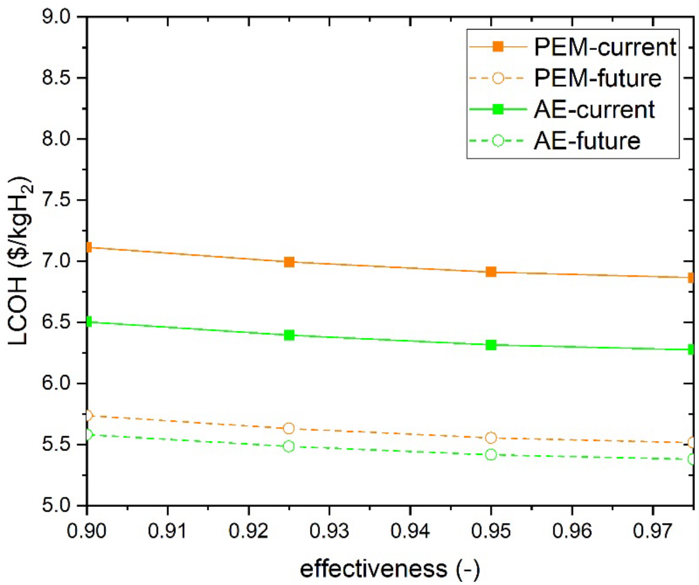


Code flowchart

04. Results & Discussion

- ✓ LCOH decrease as PR increased due to increased thermal-to-electricity efficiency
  thermal-to-hydrogen: 15.3 % (PR-2.0) → 21.1 % (PR-2.7)
- ✓ Effectiveness showed an optimal point around 0.98, which is determined by the balance between increased efficiency and additional cost due to increased volume
- ✓ At the optimal point, AE showed 6.08 \$/kgH_2 and PEM showed 6.65 \$/kgH_2 for current state whereas AE showed 5.20 \$/kgH_2 and PEM showed 5.32 \$/kgH_2 for future





LCOH according to PR, effectiveness

04. Results & Discussion

$$r = \left(\frac{future\ value}{present\ value}\right)^{1/n} - 1$$

n: number of period X frequency

- ✓ The discount rate varies greatly depending on the time and market environment

  OMB[1] discount rate differs from -0.3 %(2020) to 7.9 % (1982) & 4~10 % are used in various pervious studies

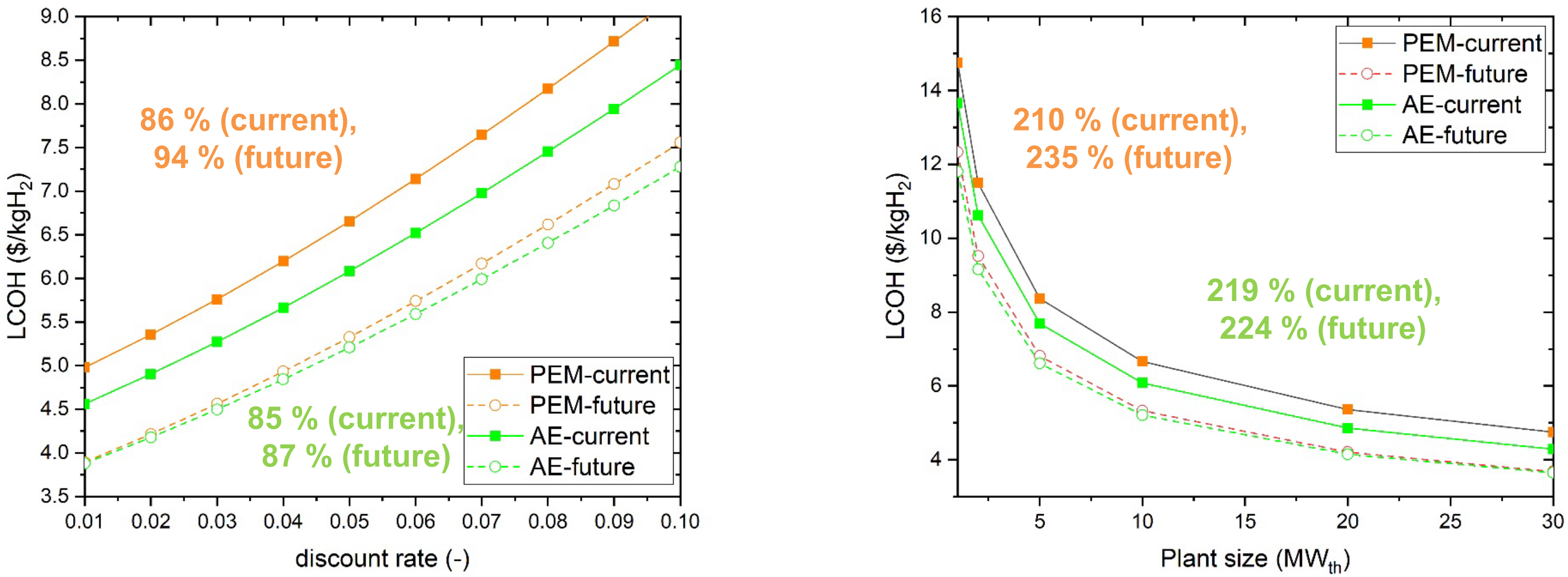
- ✓ The target plant size is different depending on the electricity requirement of the installation location

  Electricity usage per capita in the bottom 20: 52 kWh/year & the top 20: 14,337 kWh/year

- ✓ The six-tenth rule was used to investigate the effect of plant size on LCOH

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2}\right)^{0.6}$$

  → optimization procedure considering system parameters (plant size, discount rate) should be performed

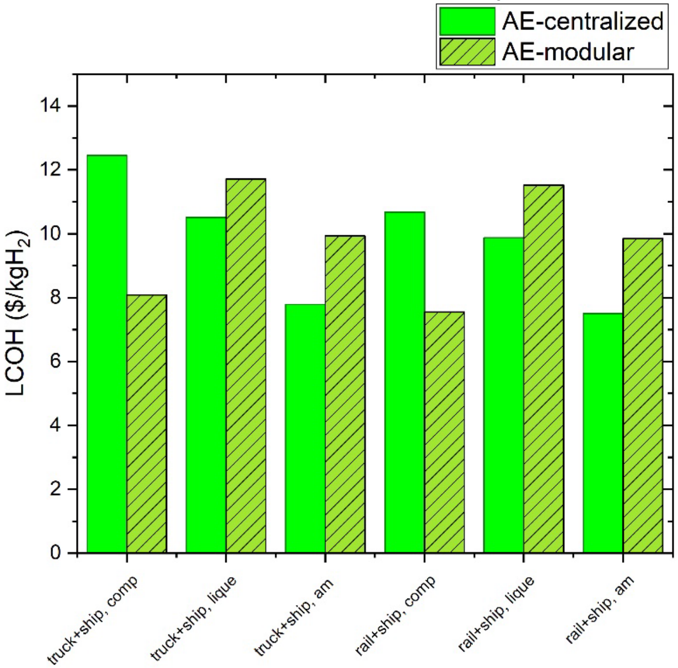


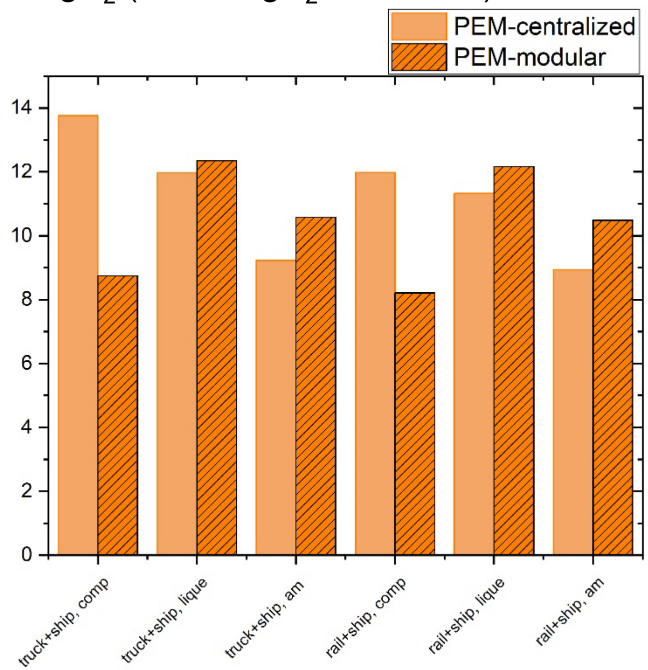
Effect of discount rate and plant size on the proposed system

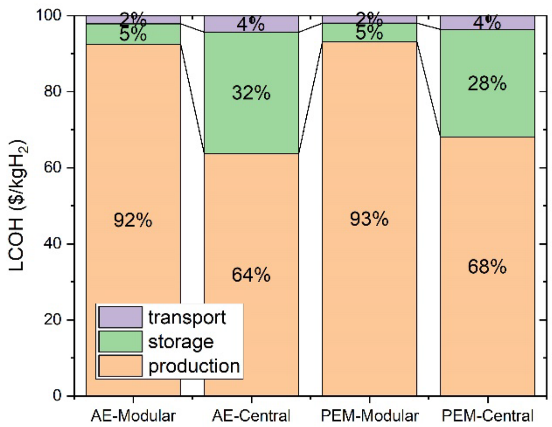
OMB-United State Office of Management and Budget, 미국관리예산실

04. Results & Discussion

- ✓ Total cost including storage and transport differs depending on the methods
  difference between max and min cost is 4.16 $/kgH$_2$ for AE and 4.13 $/kgH$_2$ for PEM (centralized system)
- ✓ For centralized systems, storage using ammonia with rail shows the optimal LCOH
- ✓ For modular systems, compression with a truck shows the optimal LCOH
- ✓ Total cost for a modular system is 7.55 $/kgH$_2$ (7.50 $/kgH$_2$ for central) for AE, 8.21 $/kgH$_2$ (8.93 $/kgH$_2$) for PEM





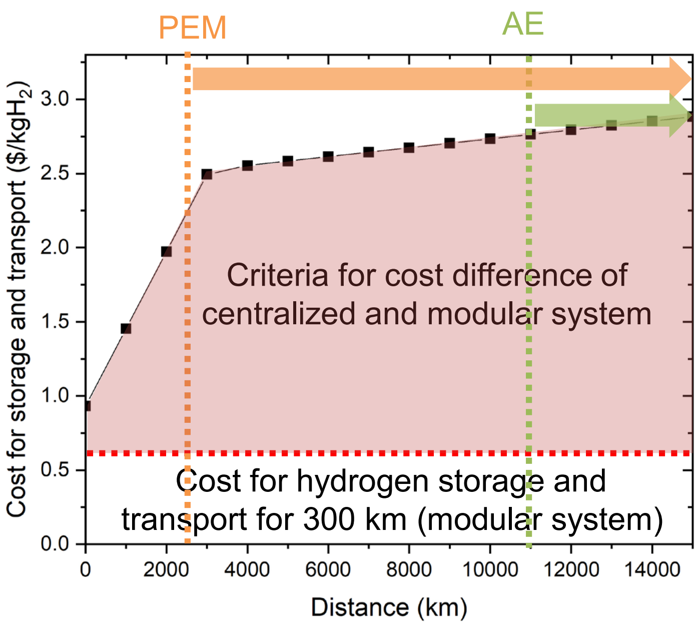


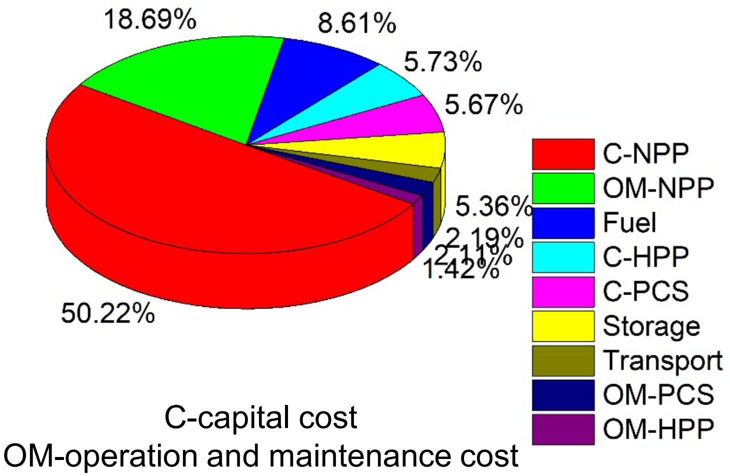
Production cost for centralized system
AE: 4.78 $/kgH$_2$
PEM:6.08 $/kgH$_2$

Total cost for AE, PEM according to storage and transport methods for current state

04. Results & Discussion

- ✓ The minimum cost of hydrogen storage and transport for the modular system is 0.57 $/kgH_2$
- ✓ For the range where the cost difference between central, modular systems is less than 0.93 ~ 2.88 $/kgH_2$
  → the modular system is cheaper
- ✓ CAPEX takes over 66% whereas OPEX takes only 34% (Fuel-9.3 %, O&M cost-24 %)
  Due to the high specific cost of nuclear power plants induced by low TRL





cost for hydrogen storage and transport according to distance and cost portion analysis

05. Summary & Conclusion

- ✓ A modular hydrogen production system using a heat-pipe-cooled microreactor was proposed
- ✓ Developed in-house code to calculate the economic indicator (LCOH) of the system
- ✓ Optimal operating conditions for the proposed system were suggested

  At the current state, the modular system with AE shows 6.08 \$/kgH_2, PEM shows 6.65 \$/kgH_2

  In future, the LCOH is expected to decrease 5.20 \$/kgH_2 for AE, 5.32 \$/kgH_2 for PEM
- ✓ The modular system is more economical with transport distance over 11000 km for AE, 2500 km for PEM
- ✓ With the advancement of microreactors, LCOH of the modular system would much decrease which eventually lower the distance criteria for modular system

Thank you

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Pohang University of Science and Technology

[a]Department of Mechanical Engineering

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