Future CCUS system driven by Allam cycle for simultaneous production of electricity and green fuels

Haoshui Yu

Department of Chemistry and Bioscience

Aalborg University, Denmark

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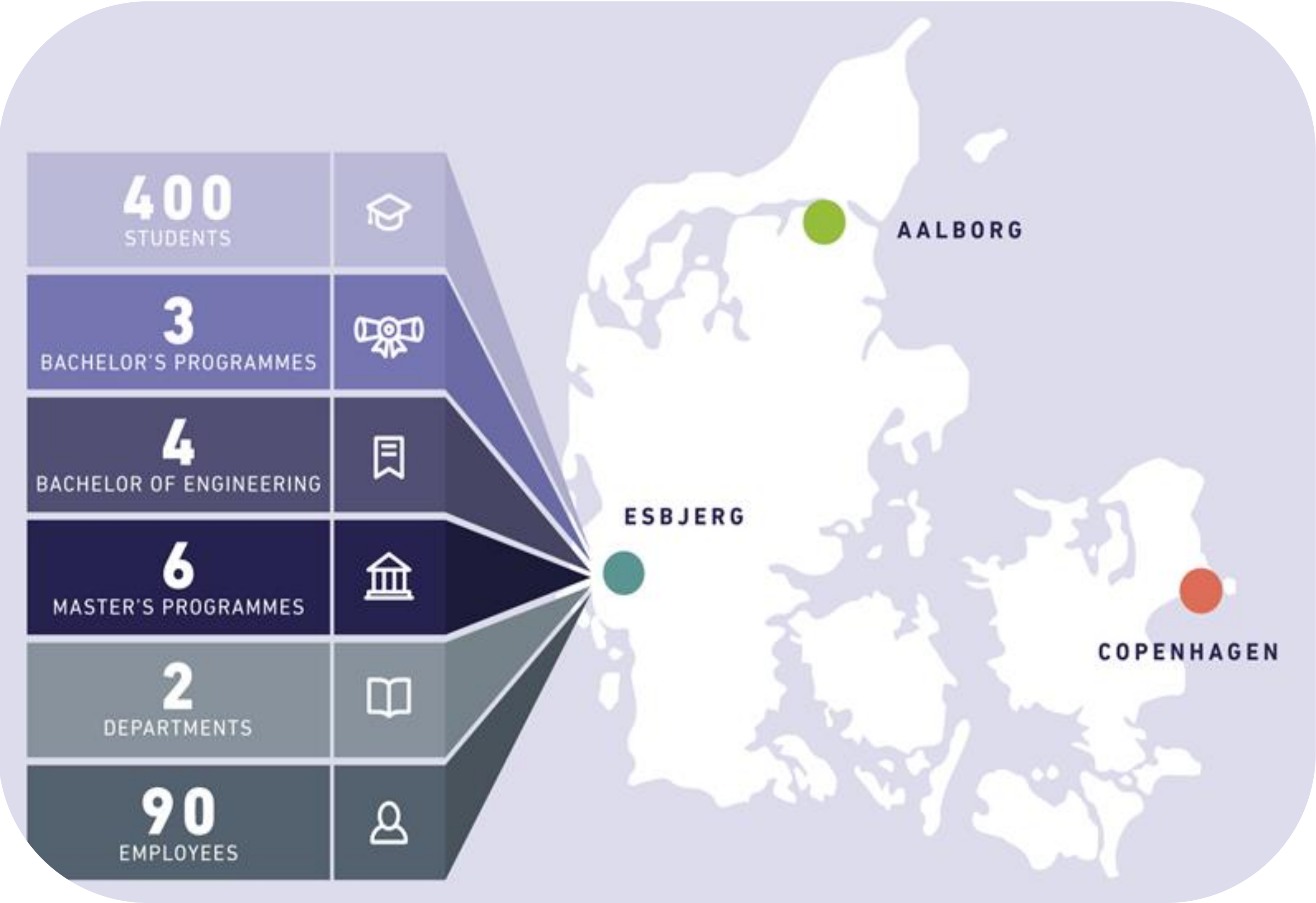
Agenda

- **Introduction**
    - Aalborg University in Esbjerg
    - Research Background
- **System description and methodology**
    - System description
    - System modeling
- **Results and discussion**
    - Steady state
    - Transient behavior
- **Conclusions**

Introduction

Where is Aalborg University?


400 STUDENTS

3 BACHELOR'S PROGRAMMES

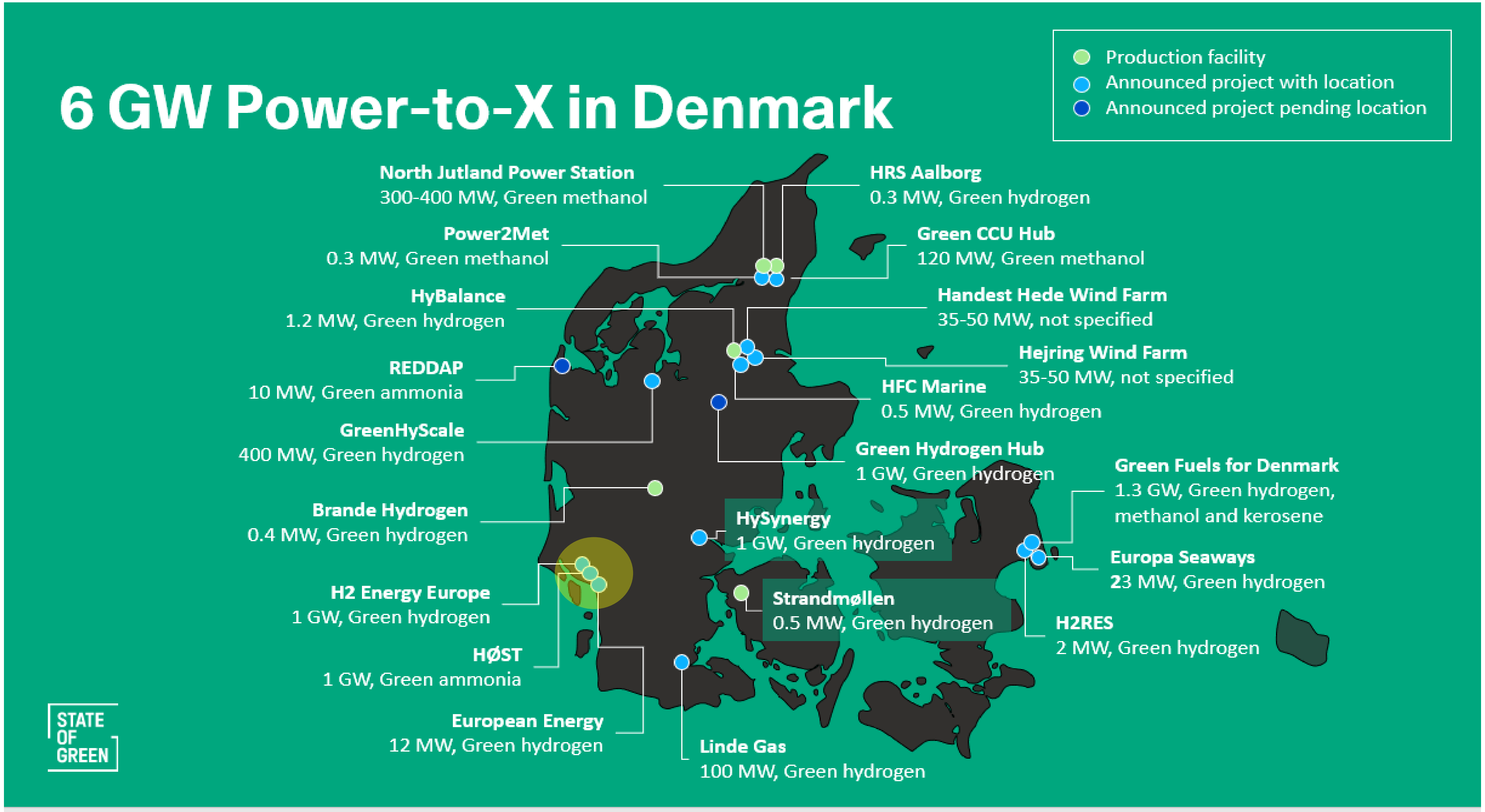
4 BACHELOR OF ENGINEERING

6 MASTER'S PROGRAMMES

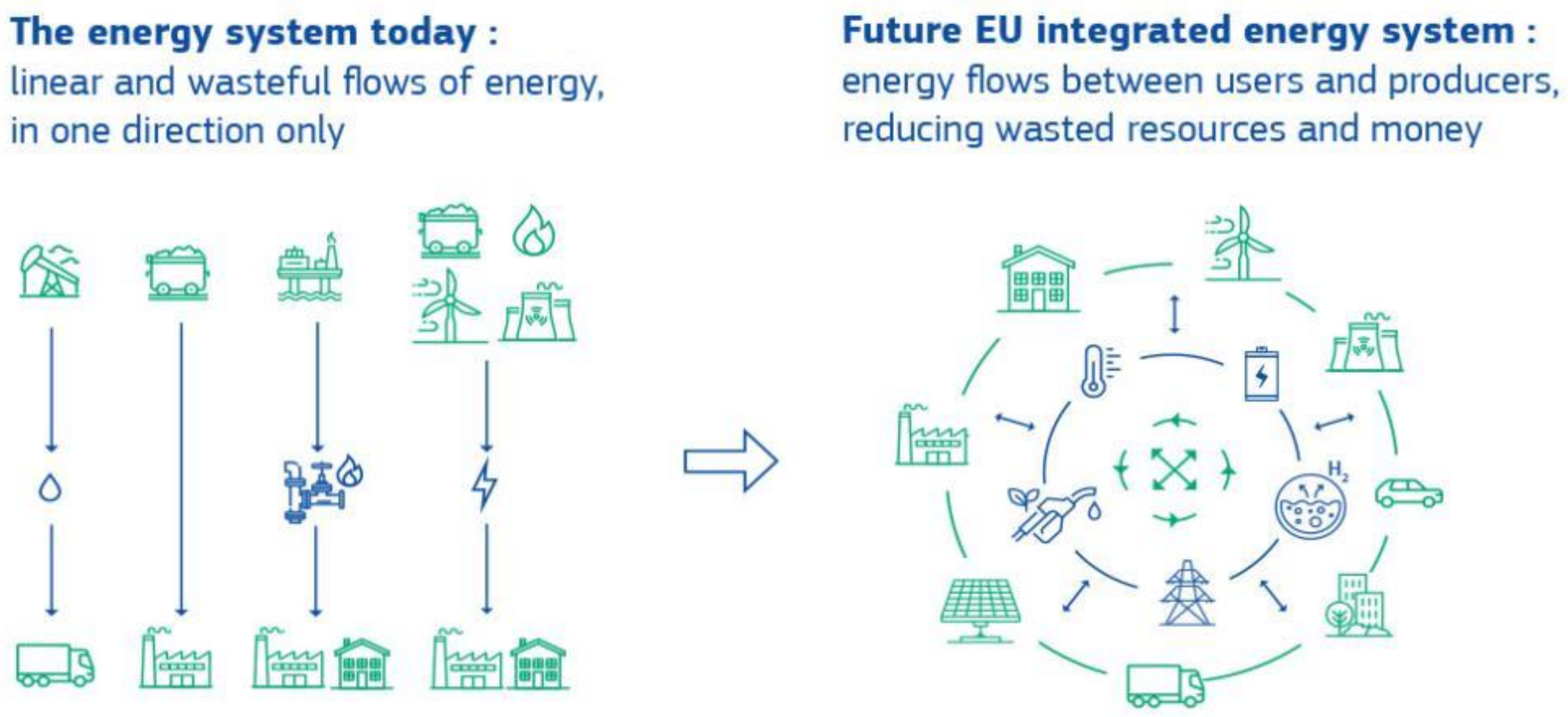
2 DEPARTMENTS

90 EMPLOYEES

Europe's largest Power-to-X plant in Esbjerg



Energy System Integration

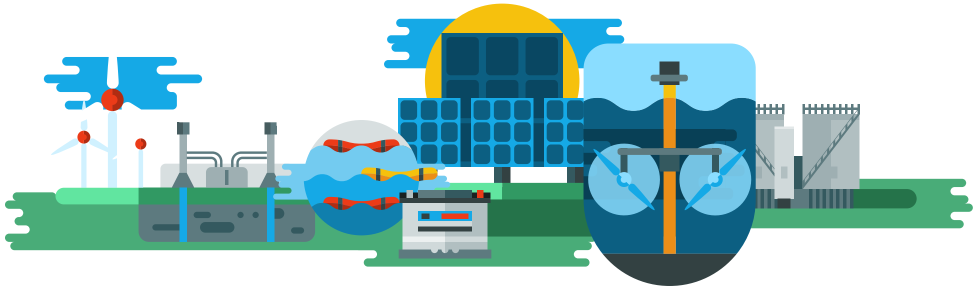


The energy system today :
linear and wasteful flows of energy,
in one direction only

Future EU integrated energy system :
energy flows between users and producers,
reducing wasted resources and money

Reference: EU strategy on energy system integration
https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en

Energy Generation



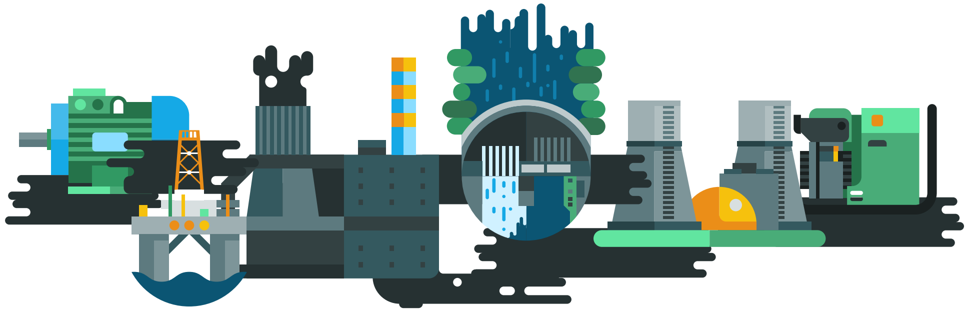
Renewable sources

Advantages

- Environmentally sustainable
- Infinite resource availability

Disadvantages

- Intermittent power supply
- Geographic limitations



Fossil fuels

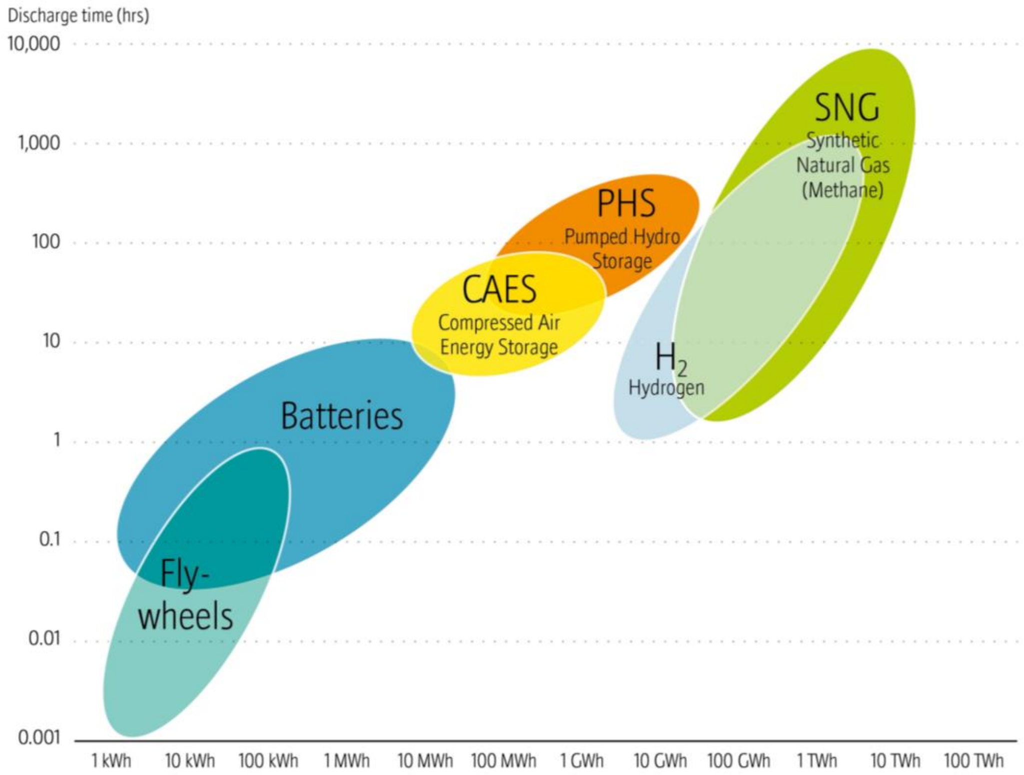
Advantages

- Mature, widely adopted technology
- Cost-effective and reliable

Disadvantages

- Greenhouse gas emissions
- Finite resource with eventual depletion

Energy Storage



Overview storage capacity of different energy storage systems

Renewables Global Futures Report Great debates towards 100 % renewable energy

REN21 Renewable Energy Policy Network for the 21st Century

Source: Fraunhofer Institute, Germany, 2014

Power-to-Gas (PtG) / SNG

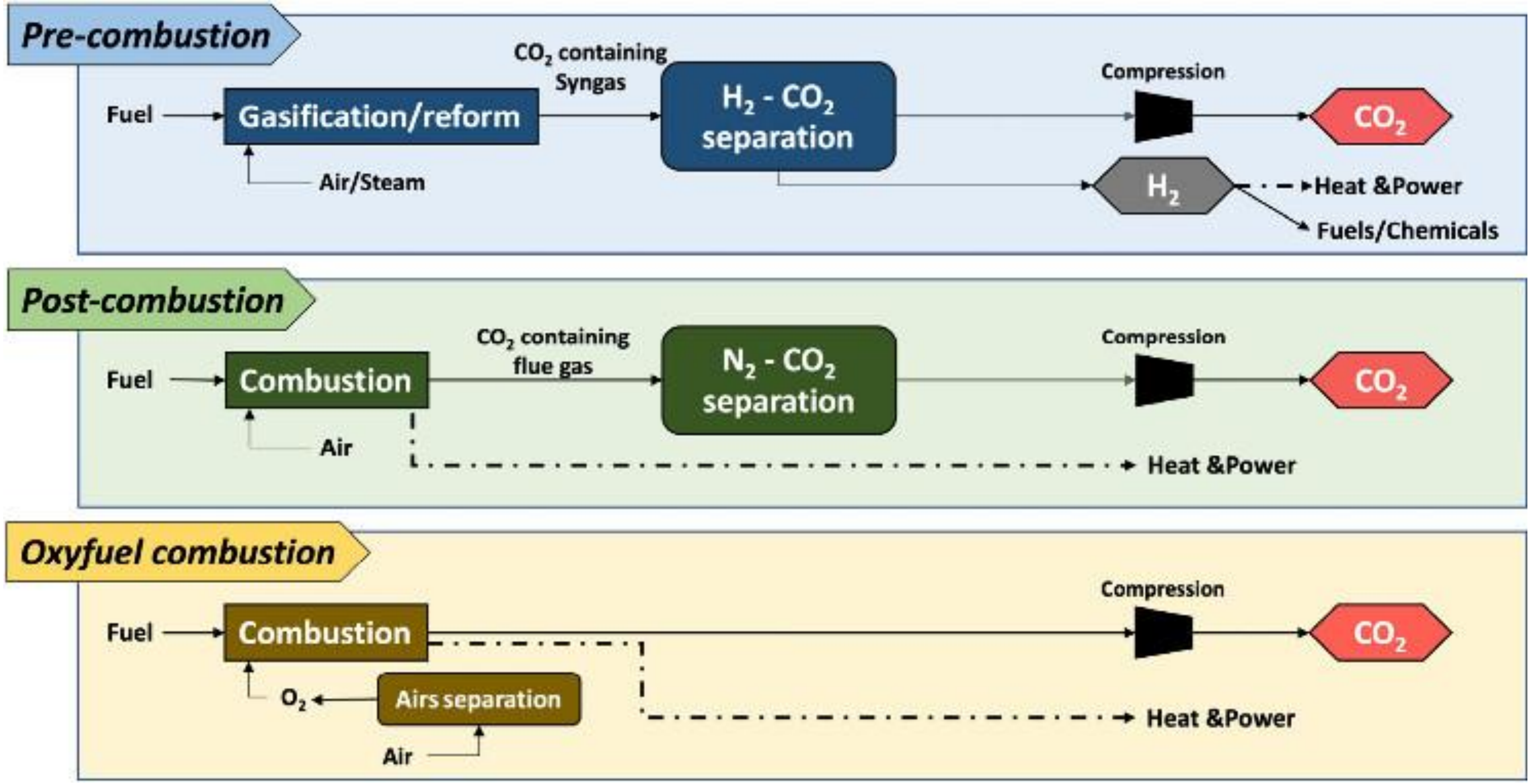
Advantages

- Long-duration storage for renewable energy
  Producing O_2 as a by-product

Disadvantages

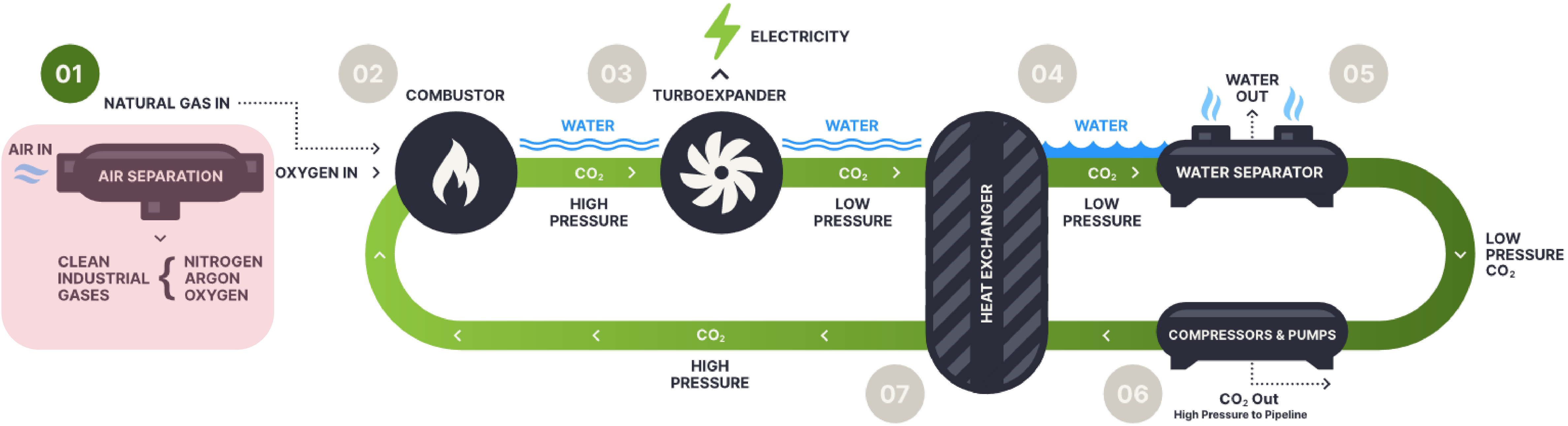
- Usually requires additional supply of material, such as CO_2 or N_2
- Expected to remain more expensive than fossil fuels in the near future

Gas-to-Power Considering Carbon Capture



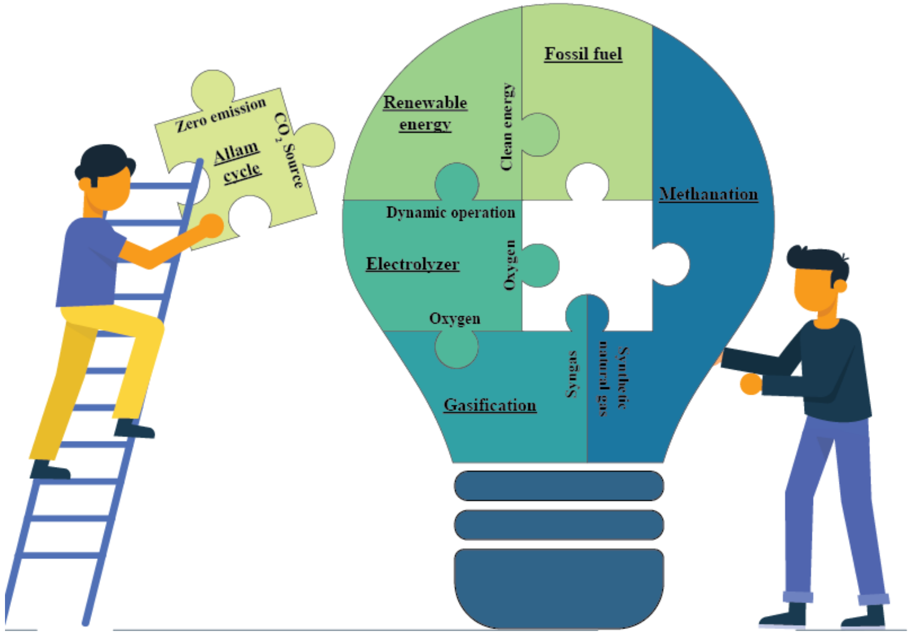
Reference: F. Raganati; P. Ammendola. CO_2 Post-combustion Capture: A Critical Review of Current Technologies and Future Directions. Energy &Fuels. 2021. 13858. https://doi.org/10.1021/acs.energyfuels.4c02513

Allam Cycle- an Oxyfuel Combustion Cycle



*https://netpower.com/technology/

Allam Cycle for Cross-sector Integration



		Advantages	Disadvantages
Generation	Renewable sources	Environmentally friendly	Intermittent energy production (1) Geographic limitations
	Fossil fuels	Globally developed technology Cheap and reliable (2)	Emit greenhouse gases (3)
Storage	Power-to-X	Long-duration storage for renewable energy (1) Producing O_2 as a by-product (4)	Usually requires an additional supply of material, such as CO_2 or N_2 (5) Expected to be remain more expensive than fossil fuels in the near future (2)
Reconversion	Oxy-fuel cycles	Higher efficiency compared to conventional plant An efficient carbon capture technology (3) The flue gas is primarily pure CO_2 (5)	Need pure O_2 for combustion (4)

(1) Power-to-X storage offers long-duration storage for renewable energy, which directly addresses the intermittent issues of renewable sources.

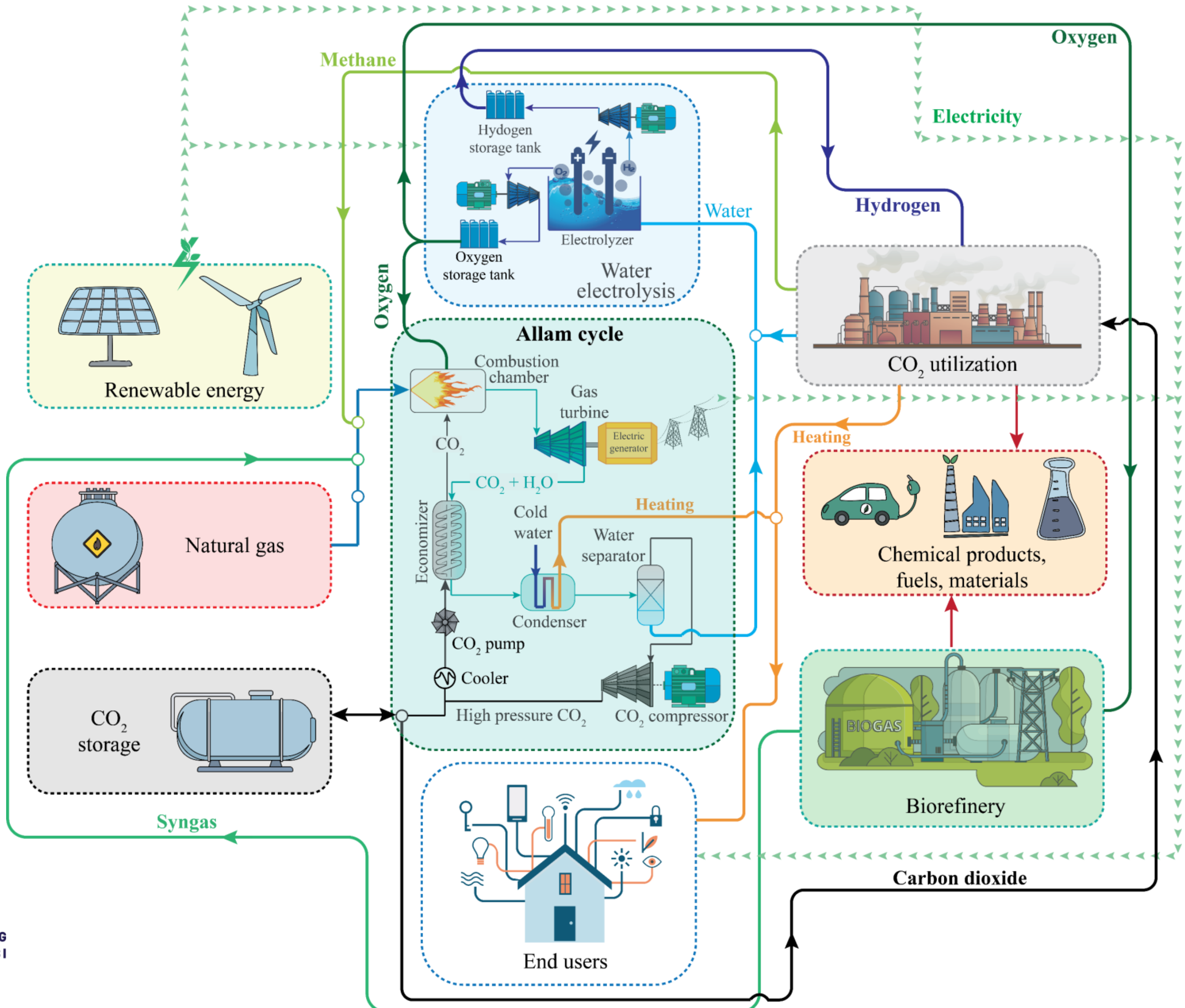
(2) Fossil fuels can serve as a backup for PtX and renewable energy, providing a bridge as PtX develops and becomes more cost-effective.

(3) Oxy-fuel cycles provide an energy-efficient carbon capture technology, which can mitigate the greenhouse gas emissions from fossil fuels.

(4) Power-to-X storage produces O_2 as a by-product, which could potentially be used in oxy-fuel cycles that need pure O_2 for combustion.

(5) Oxy-fuel cycles produce flue gas that is primarily pure CO_2. This could potentially address the disadvantage of Power-to-X storage, which usually requires an additional supply of material such as CO_2.

System description and methodology



Inputs:
Renewable energy
Natural gas
Biomass

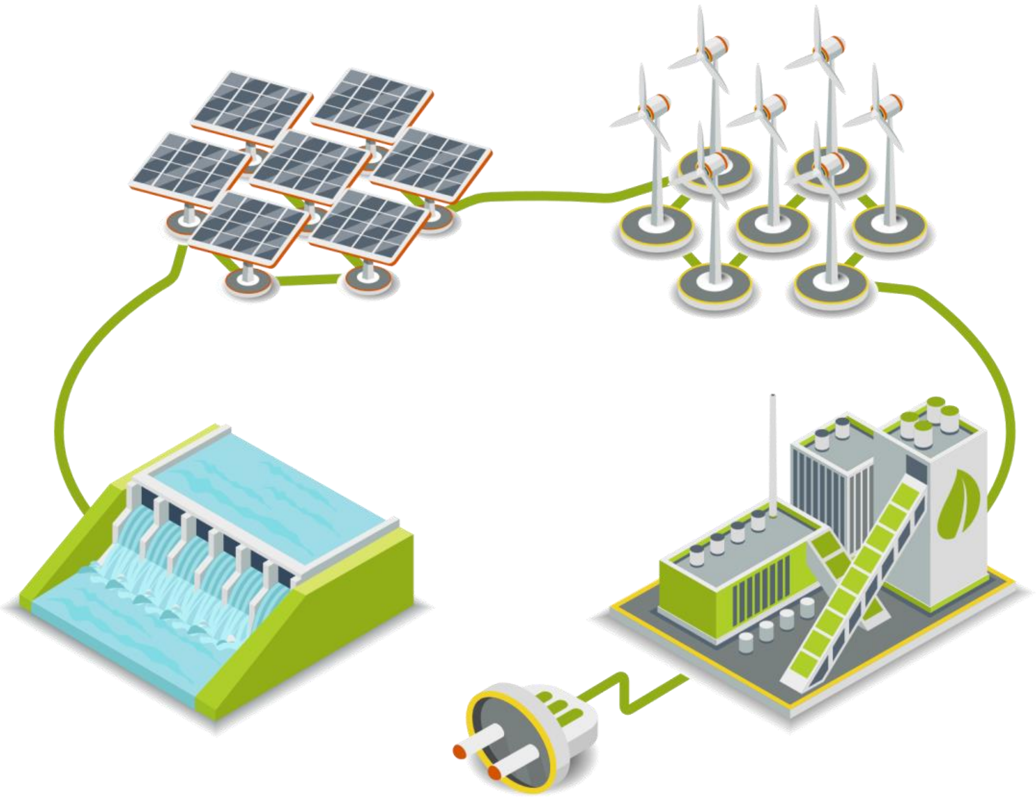
Subsystem:
Electrolysis
Allam cycle
CO_2 utilization
Biorefinery
End users

Subsystem operation:
Short-term
Medium-term
Long-term

Renewable Energy

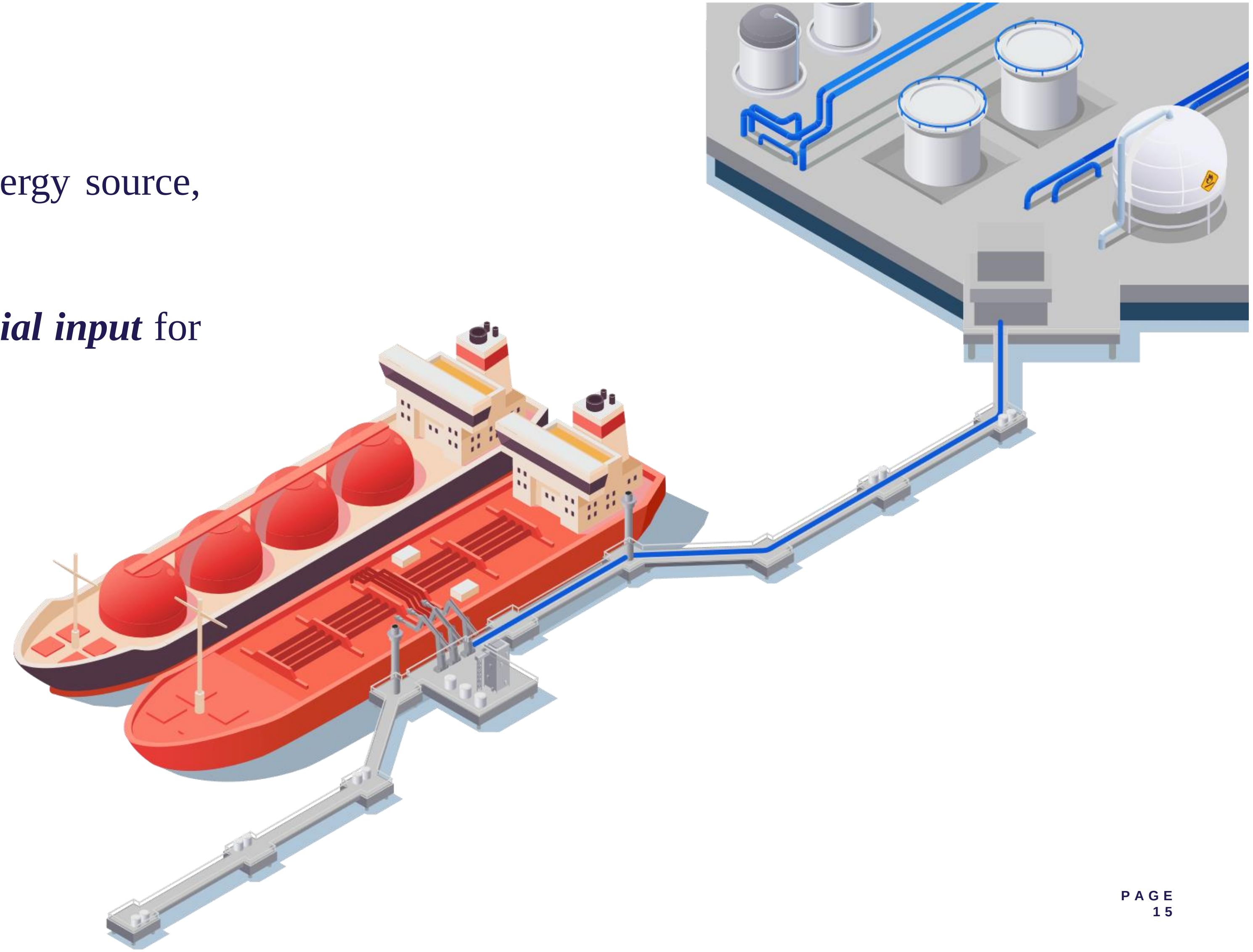
- The proposed Integrated Energy System (IES) exhibits exceptional flexibility for seamless integration with renewable energy sources, such as wind and solar.

- These renewable sources provide the primary ***energy input*** to the IES.



Natural Gas

- Natural gas continues to serve as a key energy source, ensuring reliable power generation.
- Natural gas provide both ***energy and material input*** for the integrated system



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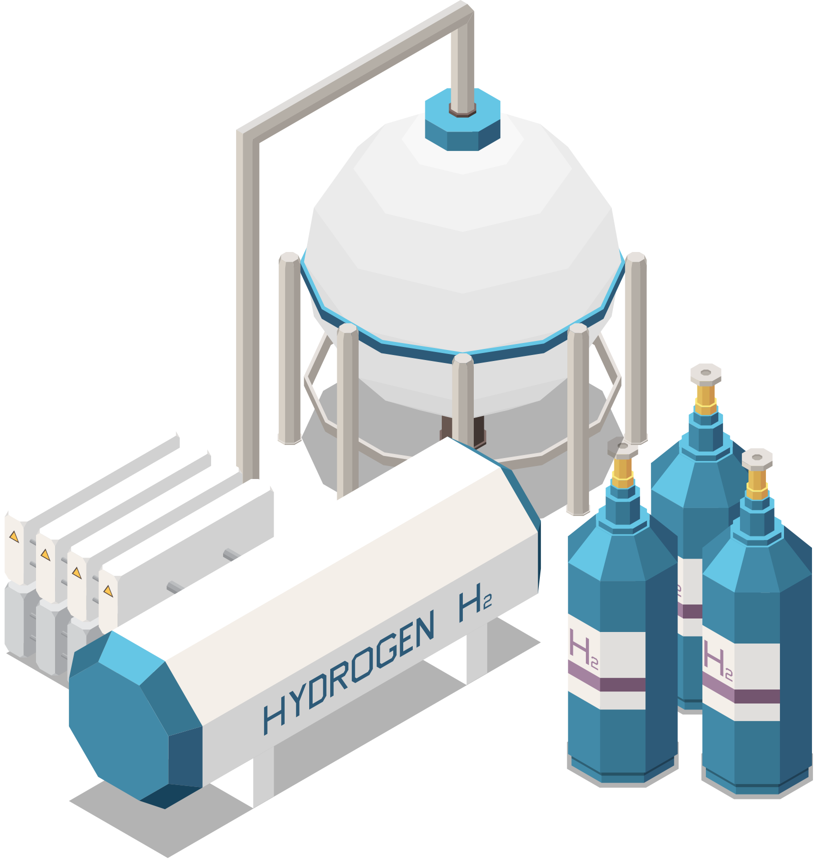
Electrolysis

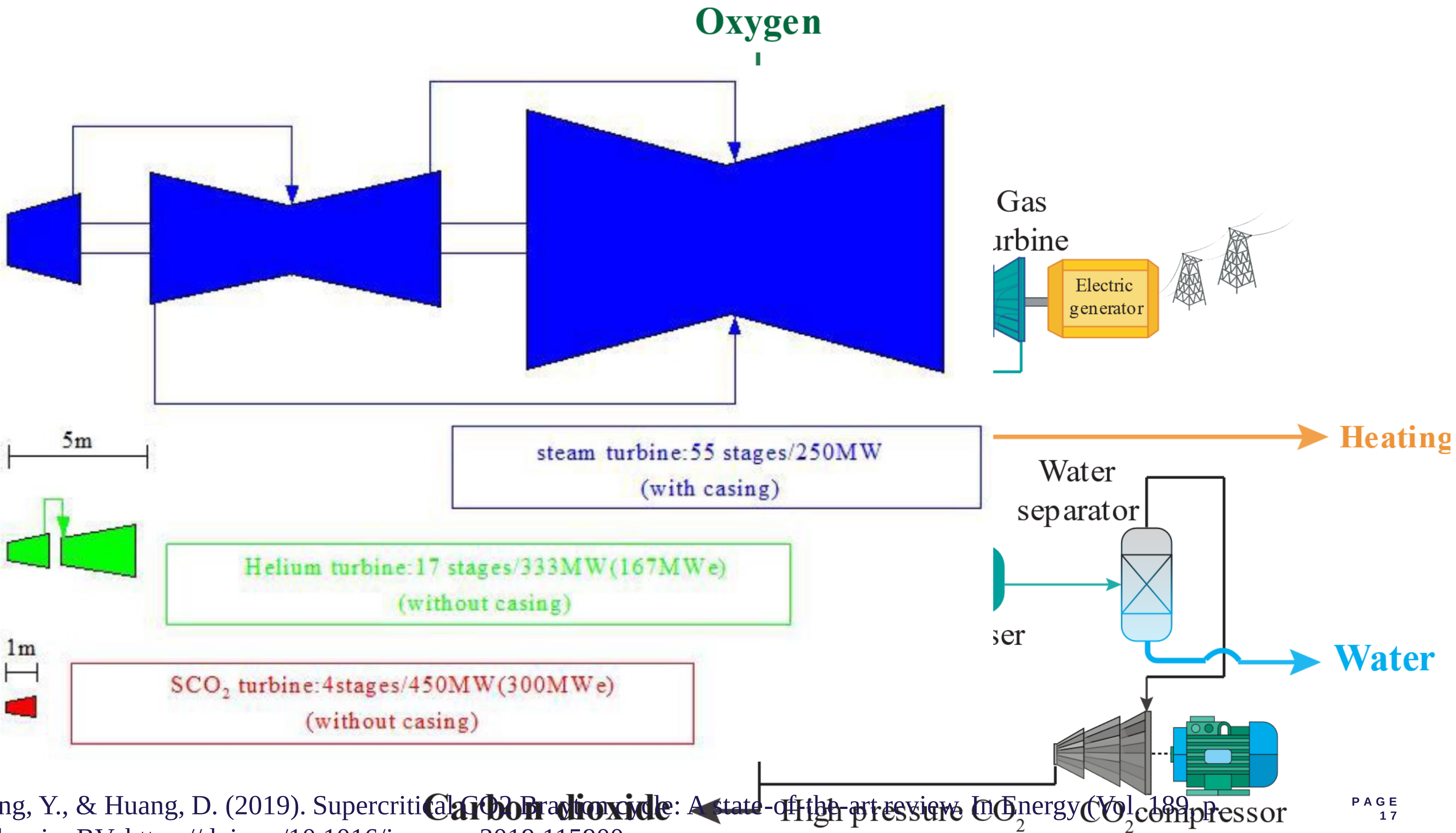
- Electrolysis is foundational step in Power-to-X process
- Various technologies are available, with rapid advancements continuously enhancing their performance.
- PEM electrolyzers are investigated in this study.



Allam Cycle

Allam cycle plays a
energy system, pr
simultaneously captur
other processes.

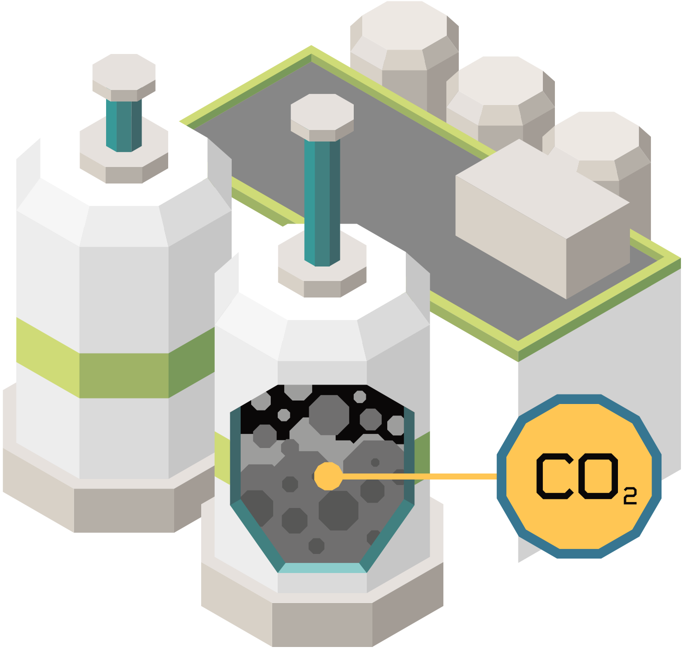
The excess CO_2 fr
subsequently utilized i
loop carbon utilization



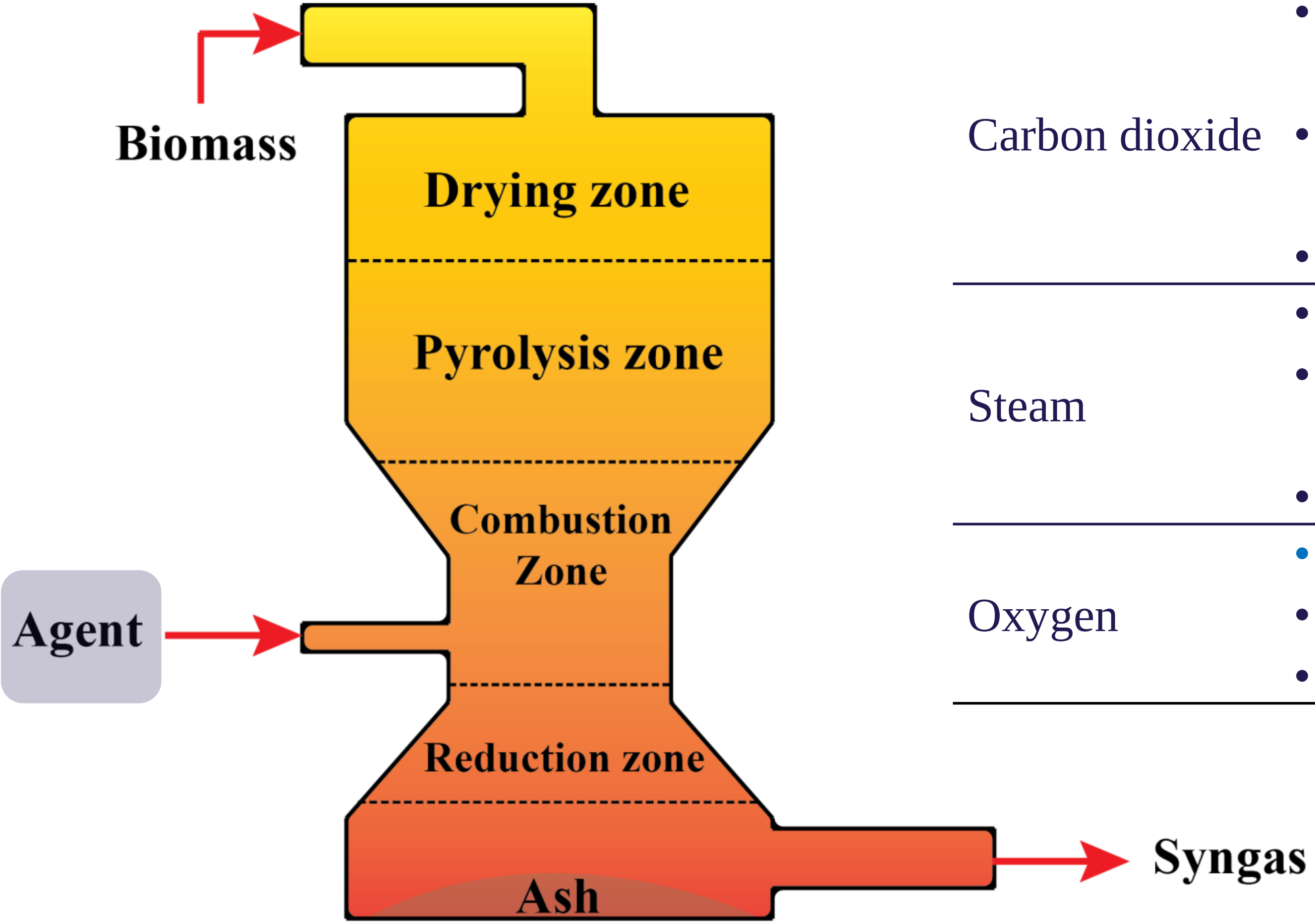
Liu, Y., Wang, Y., & Huang, D. (2019). Supercritical CO2 Brayton cycle: A state-of-the-art review. In Energy (Vol. 189, p. 115900). Elsevier BV. https://doi.org/10.1016/j.energy.2019.115900

CO_2 Utilization

- The proposed system has the flexibility to produce methanol, methane, and other products, **methane** has been chosen in this study as an example of one possibility.
- The methanation reactor combines captured CO_2 from Allam cycle with H_2 from the electrolyzer using the Sabatier reaction to produce synthetic natural gas (SNG).



Biorefinery - Gasification



Agent	Advantage	Disadvantages
Air	• Simplicity • Low cost	• Low efficiency • **High nitrogen content**
Carbon dioxide	• Reduce the greenhouse gas emission • High heating value producer • N_2 free product	• **External heat source** • Char content can be relatively high
Steam	• High hydrogen content • High heating value producer • N_2 free product	• **External heat source** • Water and vaporization are needed
Oxygen	• **High efficiency** • N_2 free product • Very low tar and char	• **Very expensive**

End Users

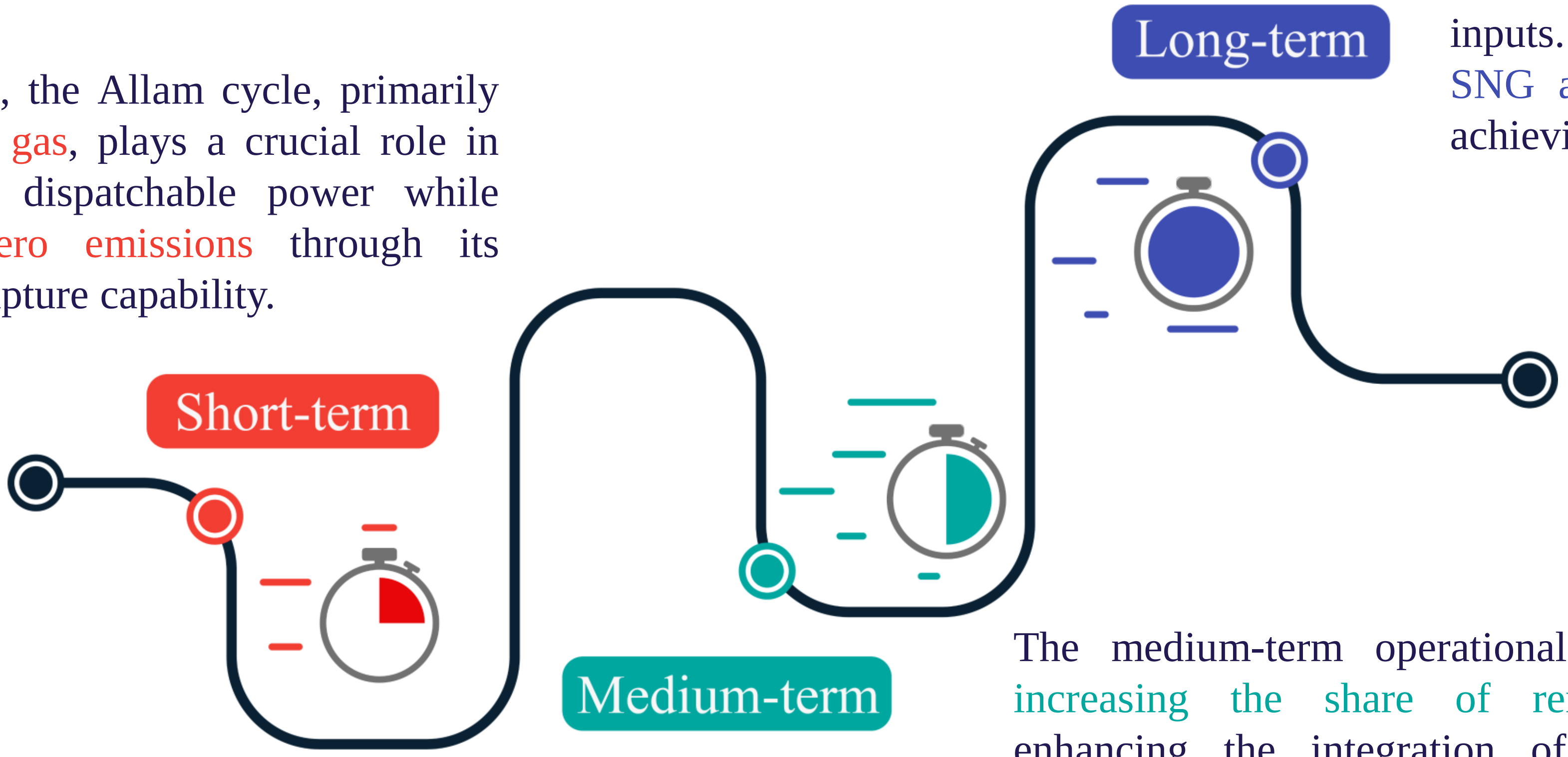
The system is designed to address the diverse energy requirements of both ***residential and industrial users*** through the simultaneous production of electricity, heat, and fuel.

Residential needs: Electricity for appliances, space and water heating system

Industrial needs: Large-scale electricity and heat for manufacturing, plus raw materials for production processes

Transportation needs: Fuels for cars, ships etc.

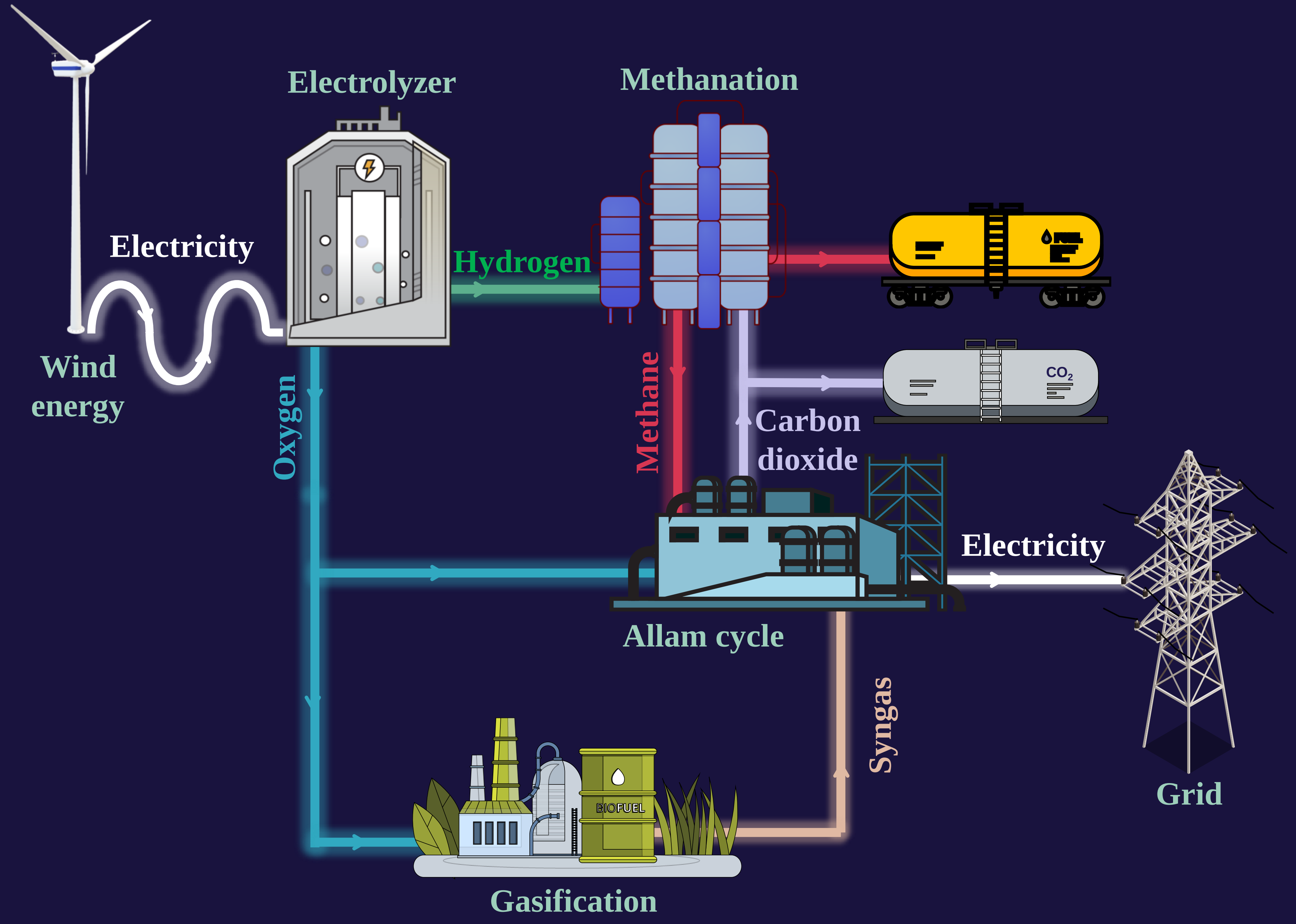
Short-, Medium-, and Long-Term Operation



During this phase, the Allam cycle, primarily fueled by natural gas, plays a crucial role in providing stable, dispatchable power while achieving near-zero emissions through its inherent carbon capture capability.

The medium-term operational strategy focuses on increasing the share of renewable energy and enhancing the integration of Power-to-Gas (PtG) technologies. To support this, electrolyzer capacity will be expanded to manage the higher penetration of renewable energy effectively.

The system exclusively utilizes renewable power and biomass as inputs. The Allam cycle operates on SNG and biomass-derived syngas, achieving a negative emission goal.


Electrolyzer
Methanation
Electricity
Hydrogen
Wind energy
Oxygen
Methane
CO2
Carbon dioxide
Electricity
Allam cycle
Syngas
Grid
BIOFUEL
Gasification

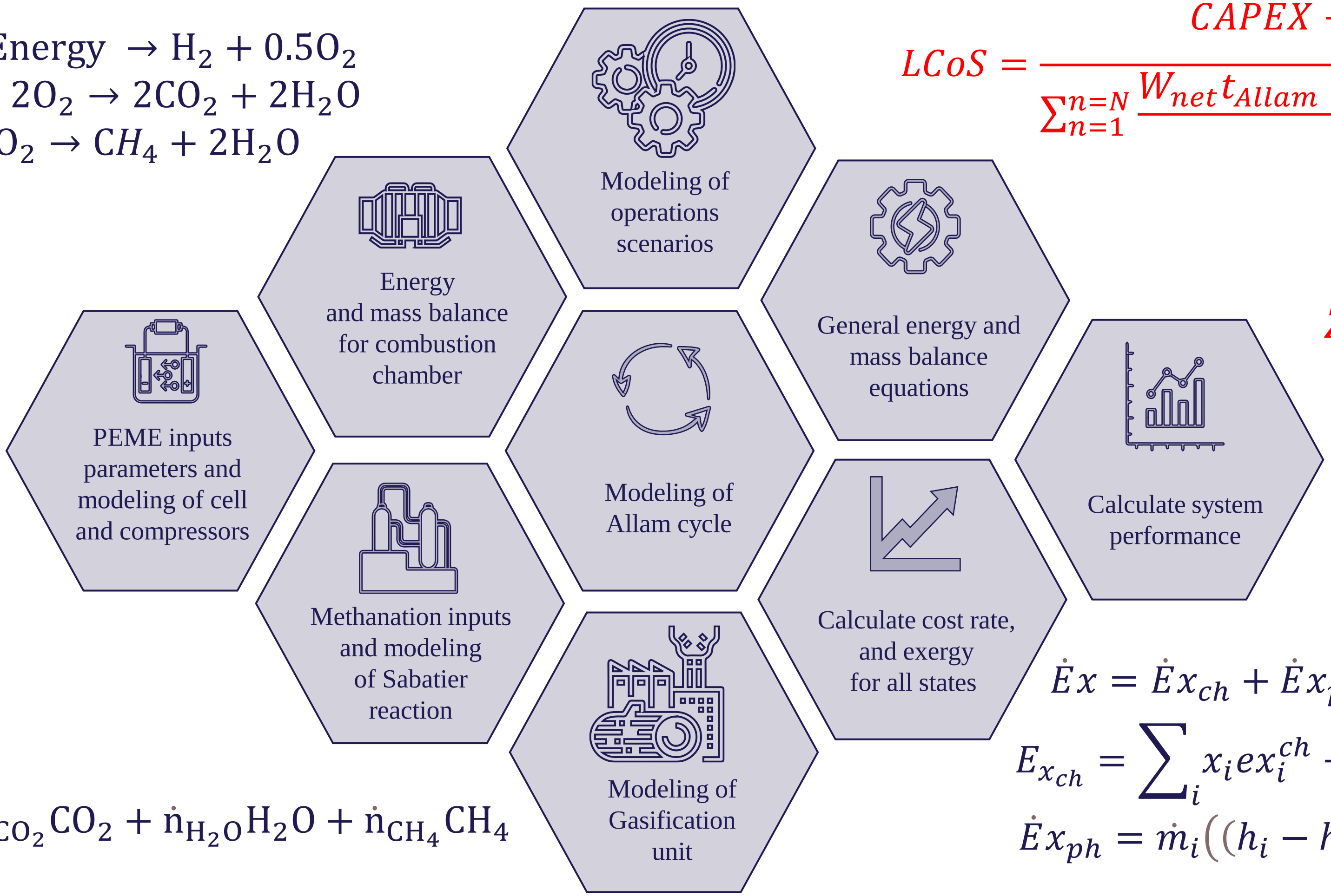
Process Modeling

PEM electrolyzer: $H_2O + \text{Energy} \rightarrow H_2 + 0.5O_2$

Allam cycle: $CH_4 + CO_2 + 2O_2 \rightarrow 2CO_2 + 2H_2O$

Sabatier reaction: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

$$LCoS = \frac{CAPEX + \sum_{n=1}^{n=N} \frac{A_n}{(1+i)^n}}{\sum_{n=1}^{n=N} \frac{W_{net} t_{Allam} + \dot{m}_{Fuel} LHV_{Fuel} t_{SNG,Grid}}{(1+i)^n}}$$



Modeling of operations scenarios

Energy and mass balance for combustion chamber

General energy and mass balance equations

PEME inputs parameters and modeling of cell and compressors

Modeling of Allam cycle

Calculate system performance

Methanation inputs and modeling of Sabatier reaction

Calculate cost rate, and exergy for all states

Modeling of Gasification unit

$$\dot{Z}_k = \left(\frac{\mathrm{CRF}}{\tau}\right).\left(Z_{PEC}^{k} + Z_{O\&M}^{k}\right)$$

$$\dot{E}x = \dot{E}x_{ch} + \dot{E}x_{ph}$$

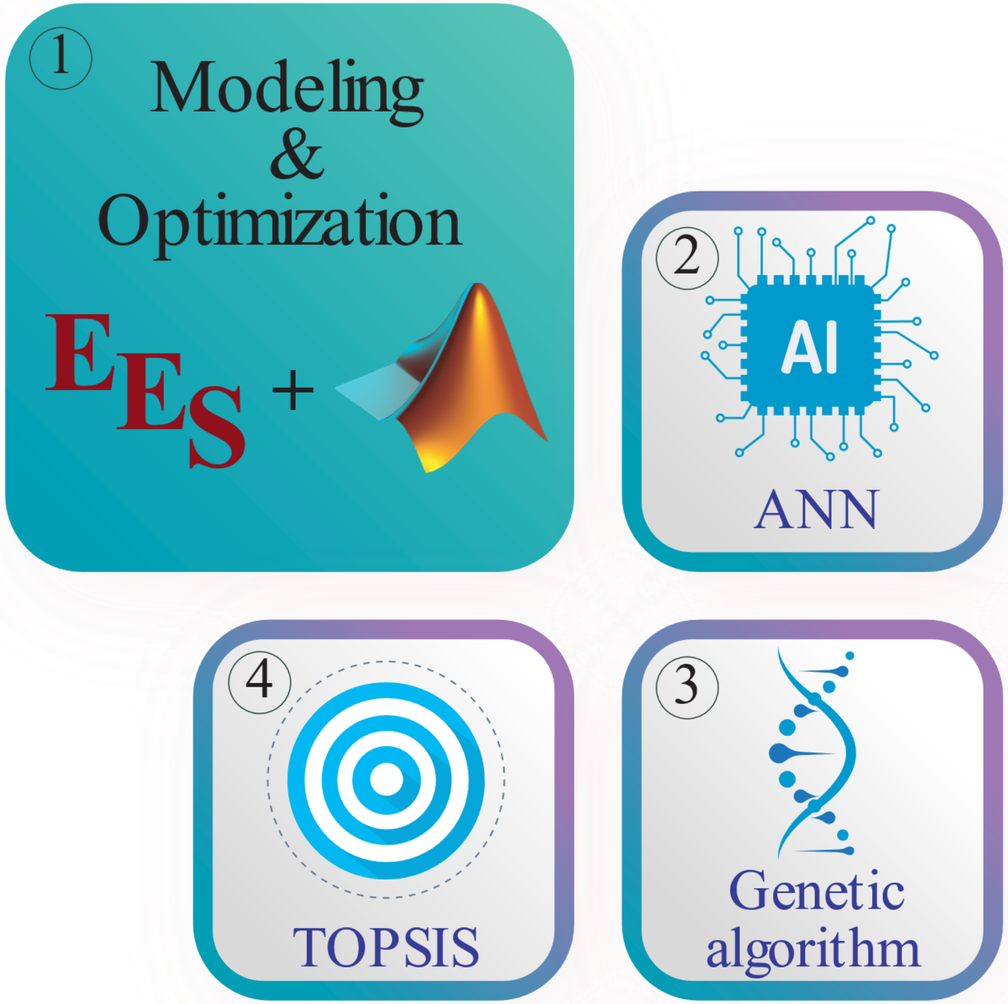
$$E_{x_{ch}} = \sum_i x_i ex_i^{ch} + RT_0 \sum_i x_i \ln x_i$$

$$\dot{E}x_{ph} = \dot{m}_i\left((h_i - h_0) - T_0(s_i - s_0)\right)$$

$$\dot{n}_{Feed} CH_a O_b + \dot{n}_{O_2} O_2$$
$$\rightarrow \dot{n}_{H_2} H_2 + \dot{n}_{CO} CO + \dot{n}_{CO_2} CO_2 + \dot{n}_{H_2O} H_2O + \dot{n}_{CH_4} CH_4$$

$$\mathrm{ERTE} = \frac{\dot{W}_{net} t_{Allam} + \dot{E}x_{Heating,Allam} t_{Allam} + \dot{E}x_{SNG} t_{SNG,Grid} + \dot{E}x_{Heating,MU} t_{MU} + \dot{E}x_{Syngas} t_{Syngas,Grid}}{\dot{W}_{Renewable} t_{PEM} + \dot{E}x_{Biomass} t_{Gasifier} + \dot{E}x_{NG} t_{NG}}$$

Optimization



① Modeling & Optimization

EES +

② ANN

③ Genetic algorithm

④ TOPSIS

Results and Discussion

Steady-state

Assumptions

Design parameters of the proposed system

Parameter (unit)	Value
Ambient temperature (K)	298
Ambient pressure (bar)	1
Combustion chamber pressure drop (%)	2
Generator efficiency (%)	95
Compressor isentropic efficiency (%)	85
Gas turbine isentropic efficiency (%)	90
Pump isentropic efficiency (%)	80
Energy to power ratio (hour)	700
Yearly cycle (-)	6
Biomass price ($/GJ)	8

Biomass Composition

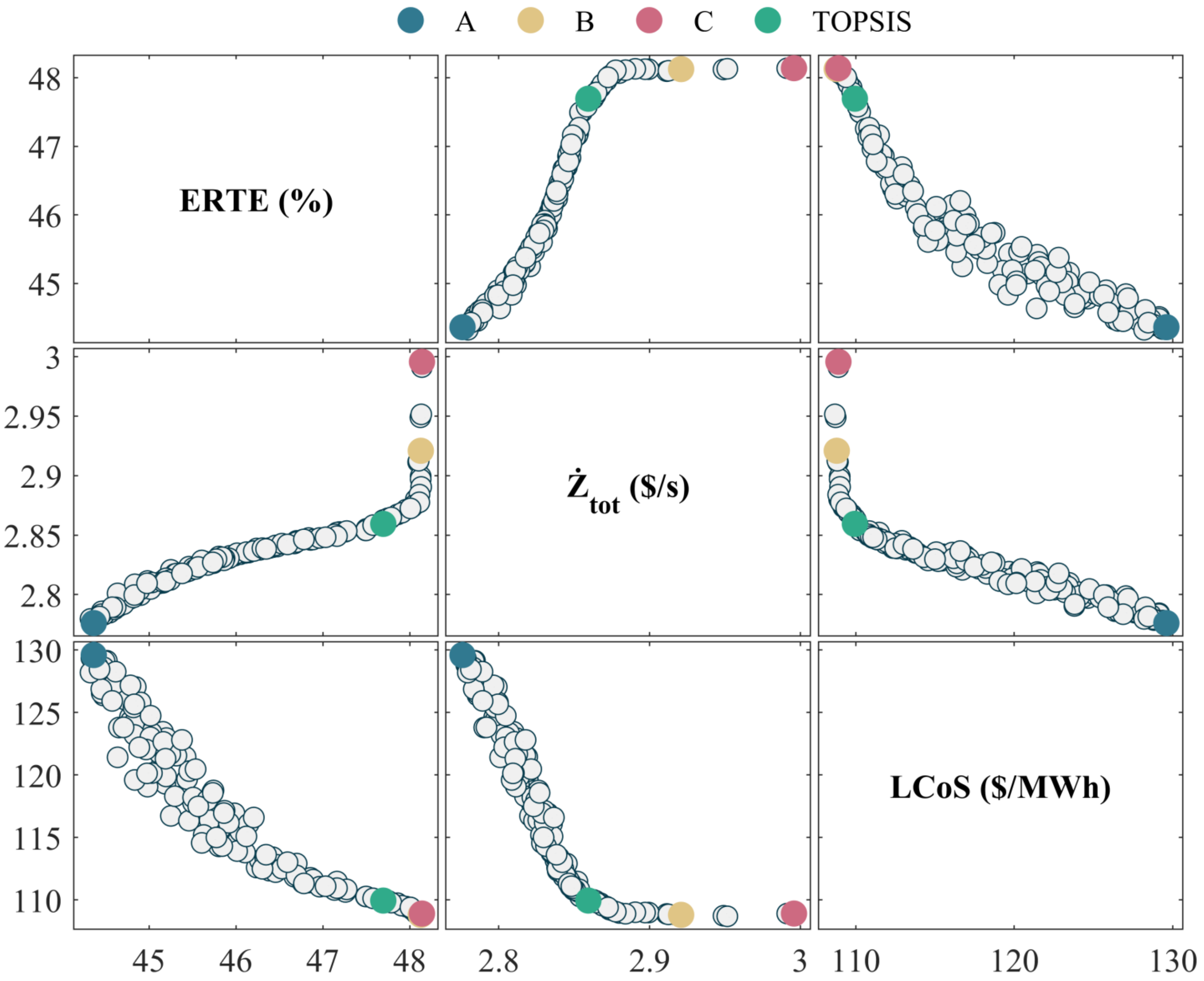
Elements	Value (%)
Carbon	50
Hydrogen	6
Nitrogen	0
Oxygen	44

Decision Variables

	Parameter (unit)	Lower bound	Upper bound
Decision variables	FS_{ratio} (%)	20	80
	J_{PEM} (A/m^2)	500	5000
	P_{MU} (bar)	5	10
	P_{high} (bar)	250	400
	P_{low} (bar)	25	45
	T_{MU} (K)	523	873
	T_{PEM} (K)	338	358
	T_{syngas} (K)	1123	1273
	$T_{turbine}$ (K)	973	1523
	$\dot{W}_{net}$ (MW)	150	300
Objective functions	η_{ex} (%)	**Should be maximized**	
	LCoS (\$/MWh)	**Should be minimized**	
	$\dot{Z}_{tot}$ (\$/h)	**Should be minimized**	

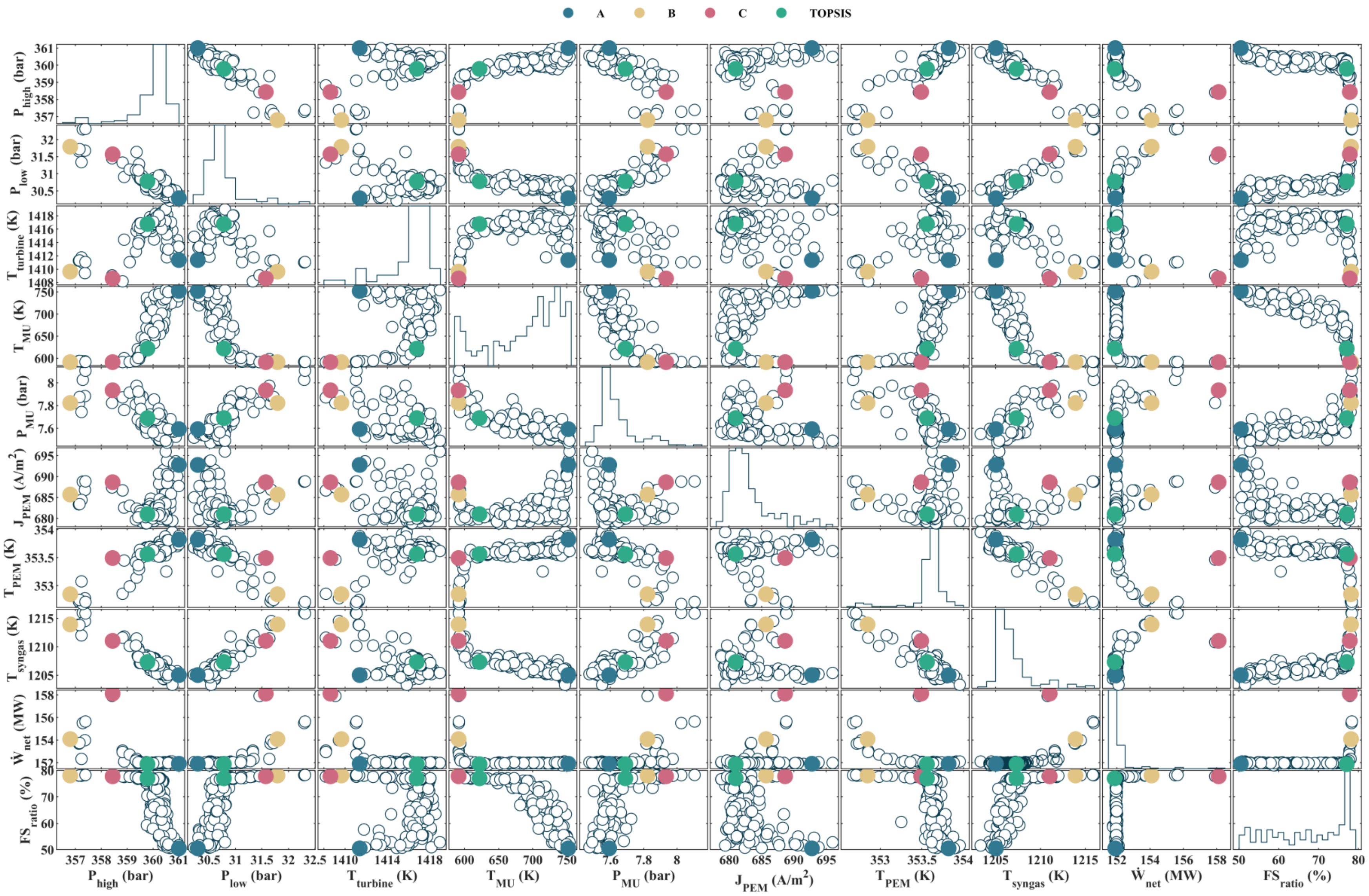
Optimization

Distribution of three objective Pareto front based on NSGA-II

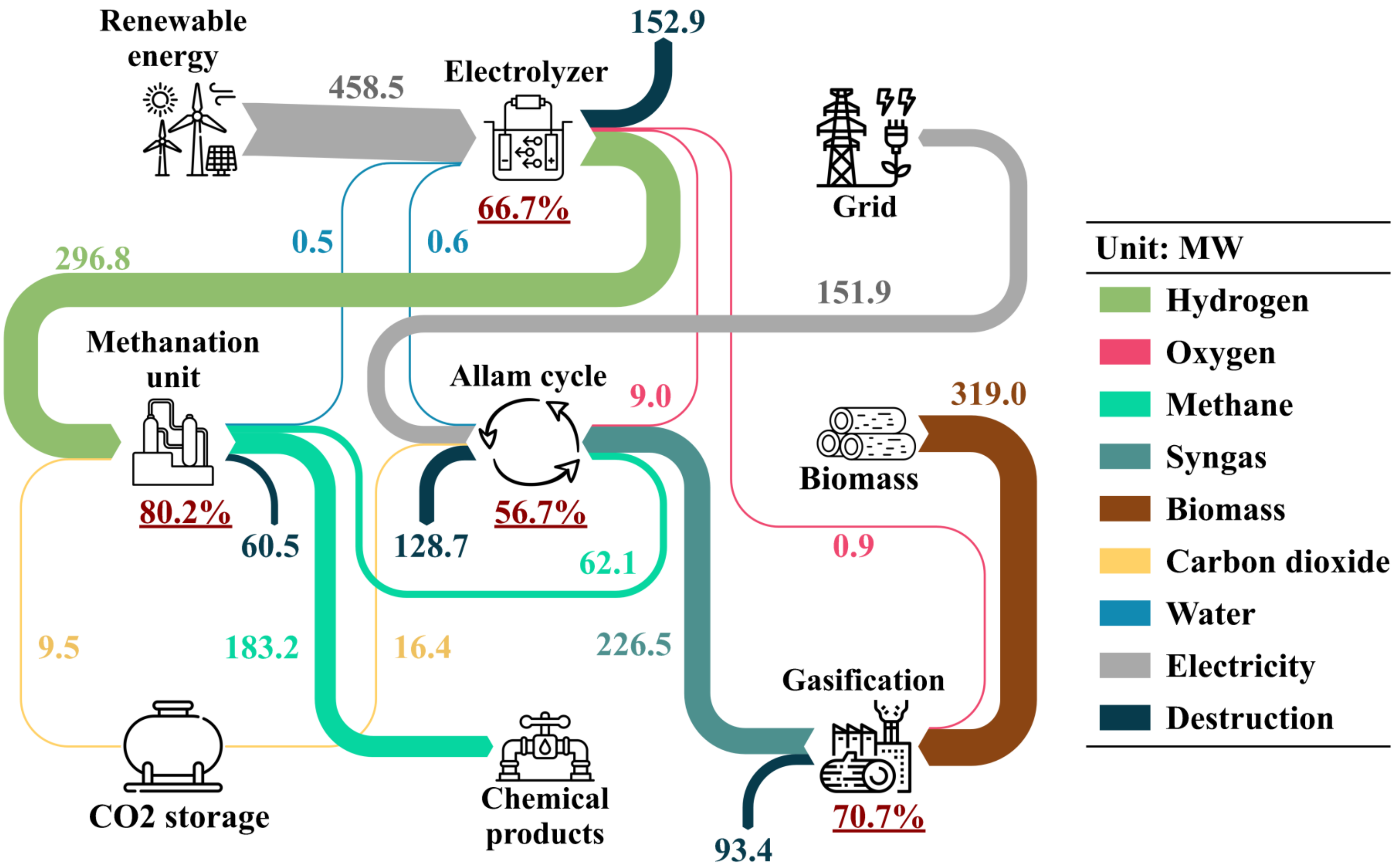


Optimization

Scattered distribution of decision variables

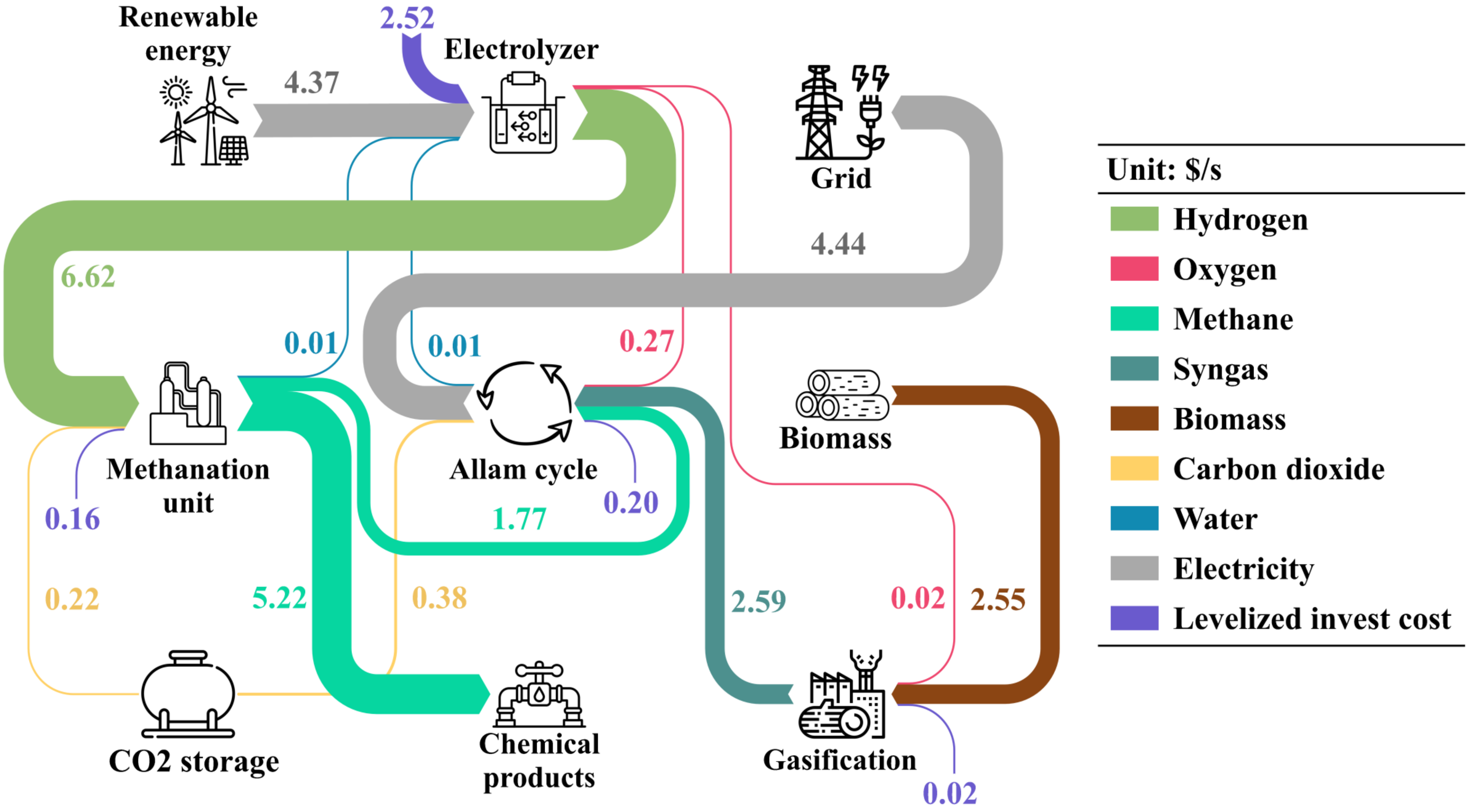


Optimization



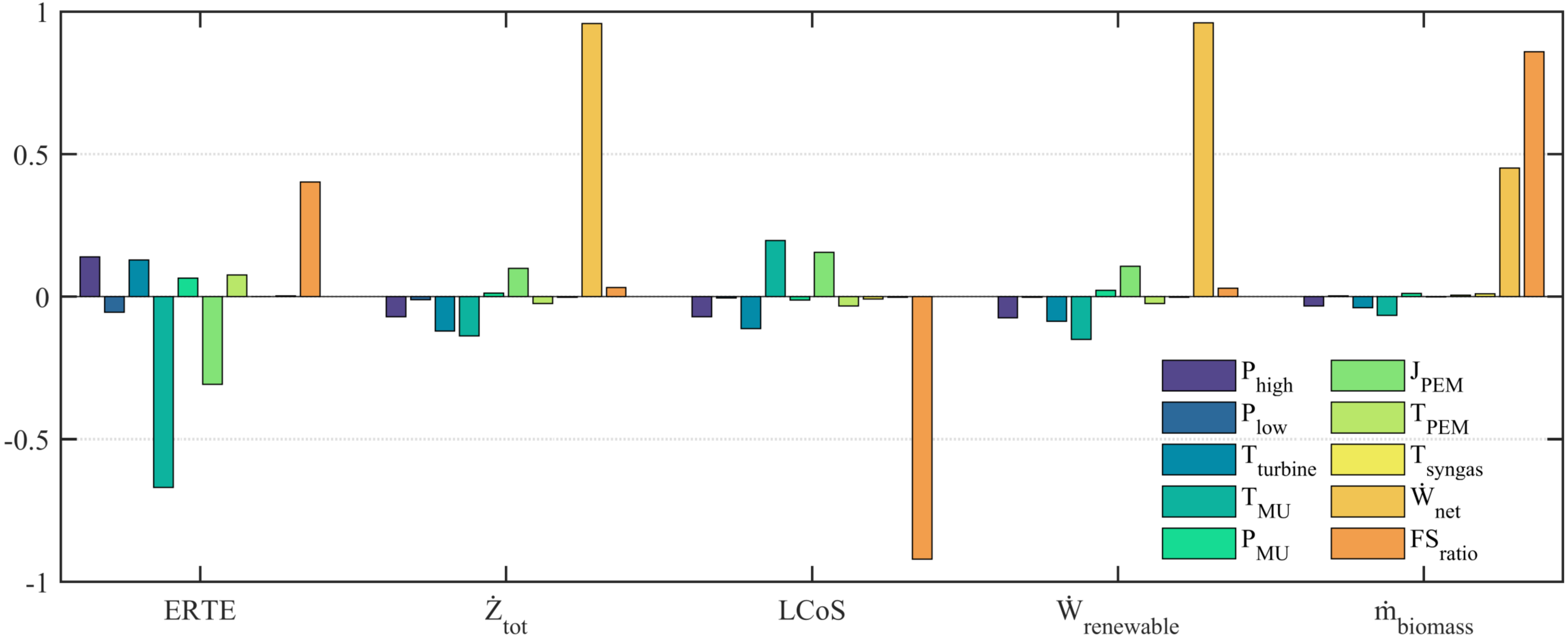
Grassman exergy diagram of the proposed storage system of long-term scenario

Optimization



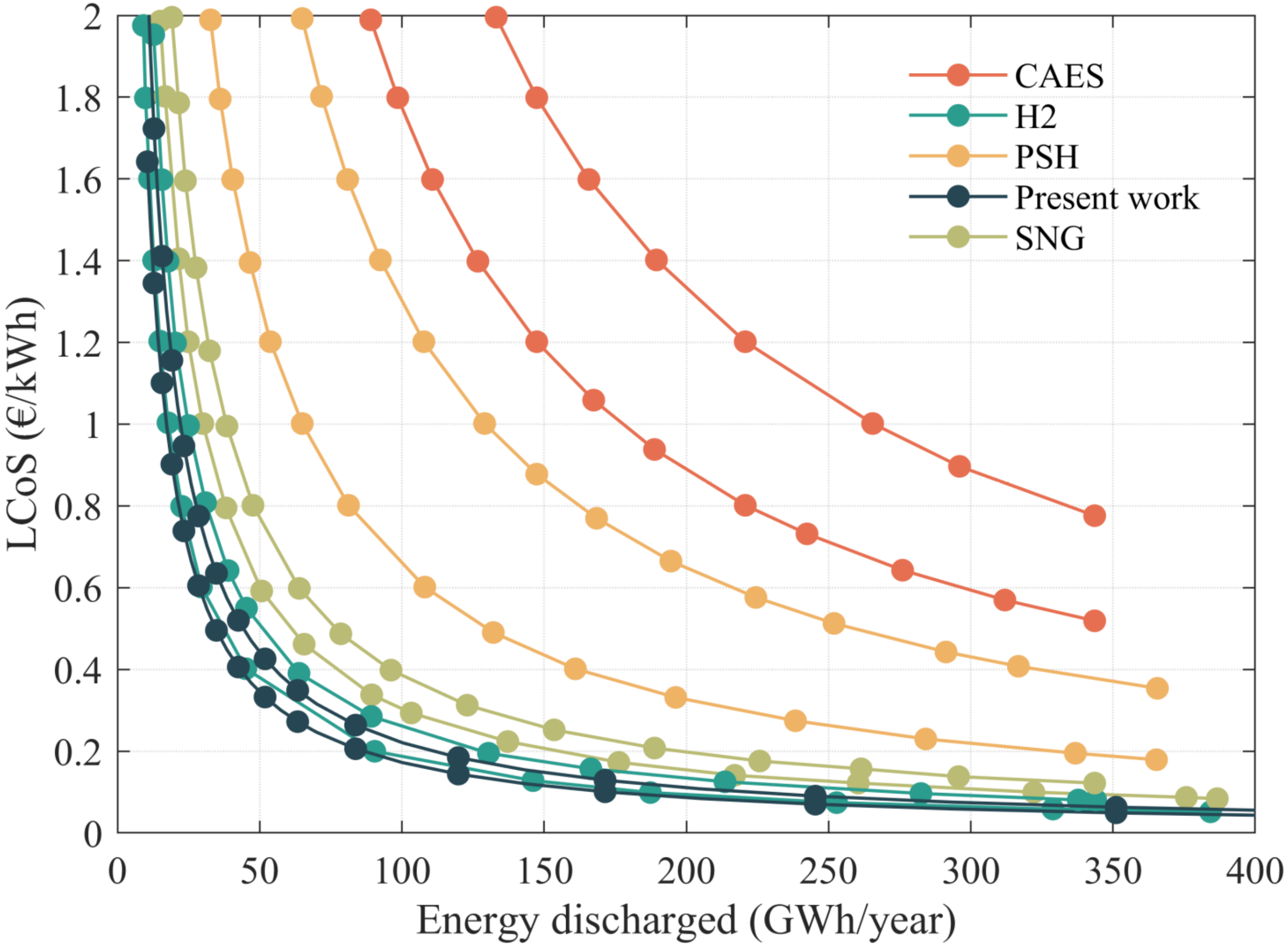
Cost rate diagram of the proposed storage system of long-term scenario

Sensitivity Analysis



Sensitivity analysis of decision variables with easyGSA

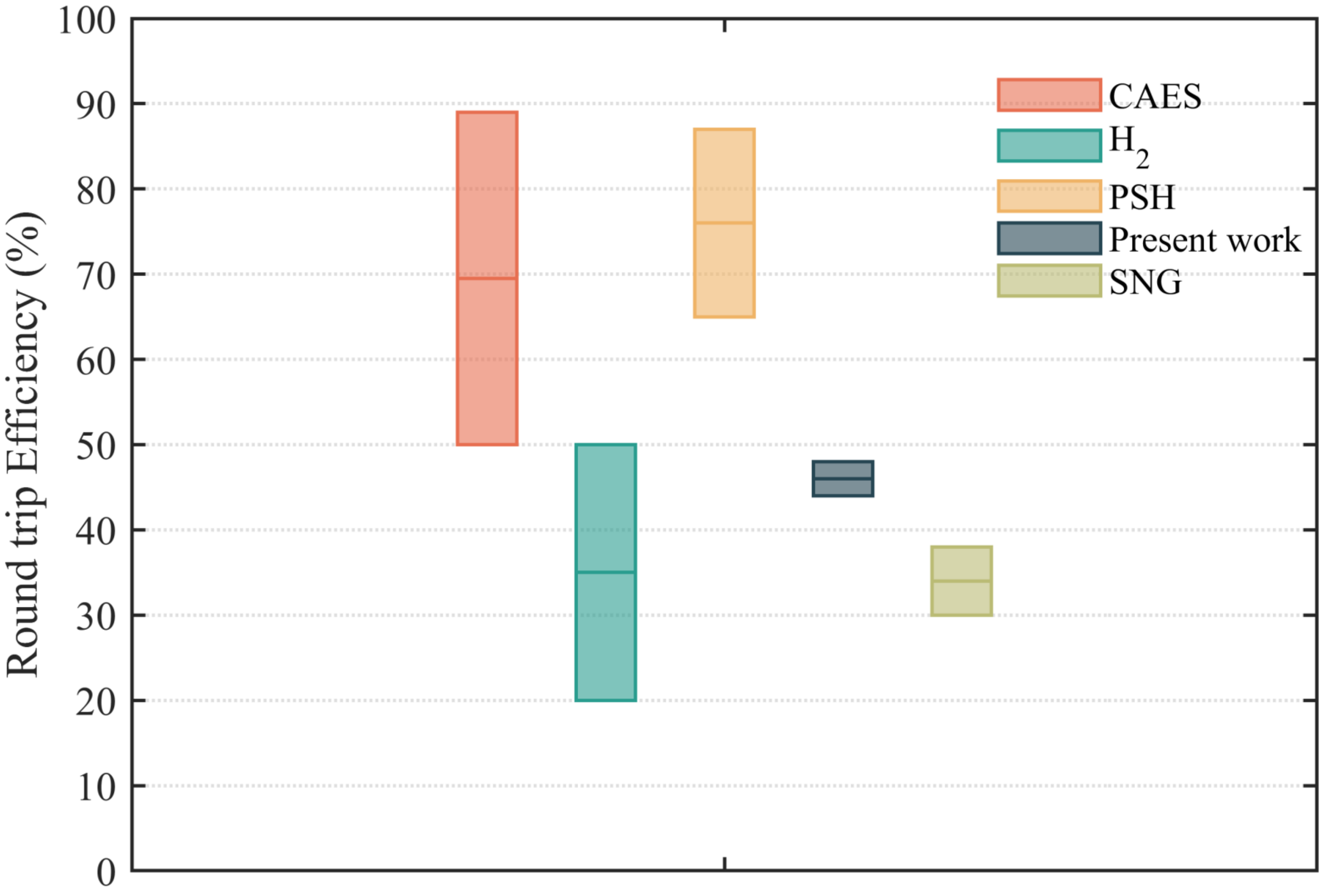
Comparative Analysis



Levelized Cost of Storage (LCoS) as a function of yearly energy discharge for long-duration ES systems (not including the cost of electricity) *

* Jülch, V. (2016). Comparison of electricity storage options using levelized cost of storage (LCOS) method. Applied Energy (Vol. 183, pp. 1594–1606). Elsevier BV. https://doi.org/10.1016/j.apenergy.2016.08.165

Comparative Analysis



Round-trip efficiency for long-duration energy storage system *

* Rohit, A. K., Devi, Ksh. P., & Rangnekar, S. (2017). An overview of energy storage and its importance in Indian renewable energy sector. Journal of Energy Storage (Vol. 13, pp. 10–23). Elsevier BV. https://doi.org/10.1016/j.est.2017.06.005

Transient Performance

Case Study

This study analyzes three key renewable energy technologies in Europe's energy transition: **offshore wind, onshore wind, and solar photovoltaic (PV)**. Each technology has unique capacity factors, intermittency, and geographical suitability that affect its integration into a large-scale energy storage system.

To ensure consistency in the analysis, the study assumed a **profile load of 1000 GWh per year** to evaluate the feasibility of integrating these renewable sources with the proposed system.

Capacity factors for each technology are calculated using **historical data** (based on https://energy-charts.info/) from each country, ensuring the model reflects realistic operation.

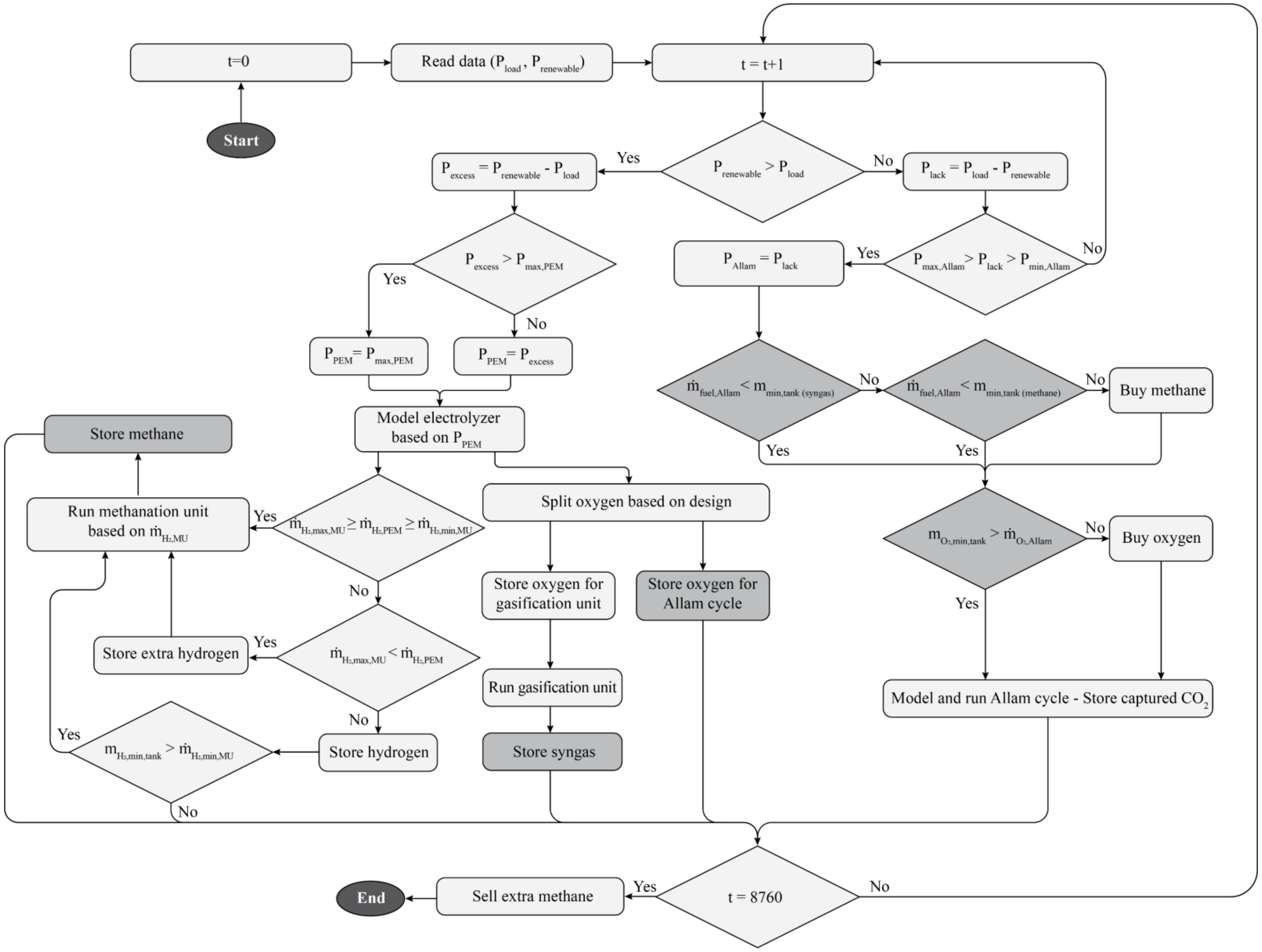
2023 and 2050 Scenarios

	LCOE (USD/MWh) [1]	
	2023	2050
Solar PV	50	25
Wind onshore	60	50
Wind offshore	70	35

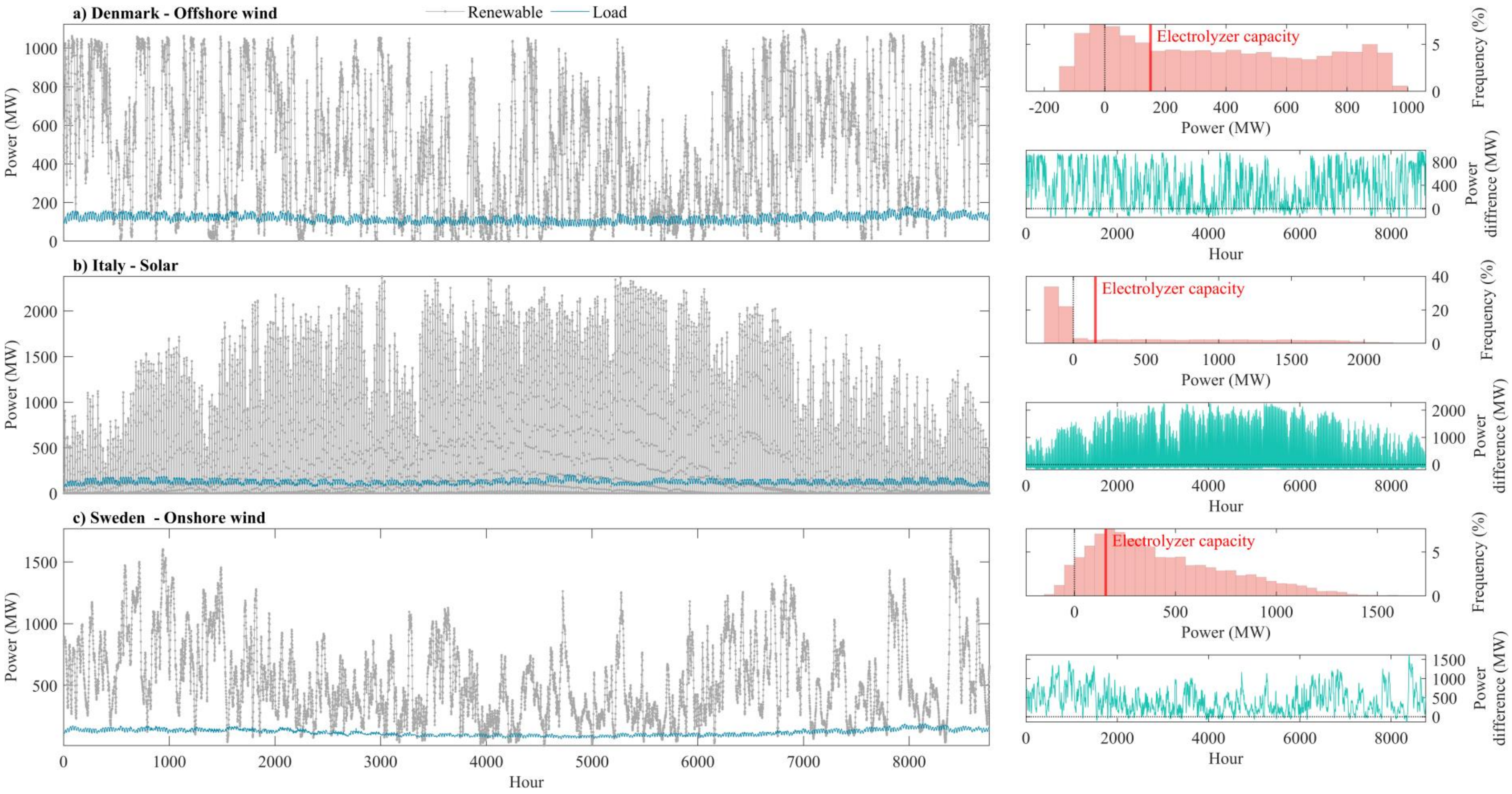
In the short term, the cost of PEM electrolyzers is $1000 per kW. In the long term, it is expected that the cost of electrolyzers will be less than $200 per kW [2].

[1] IEA (2024), ***World Energy Outlook 2024***, The International Energy Agency
[2] IRENA (2021), ***Making the breakthrough: Green hydrogen policies and technology costs***, International Renewable Energy Agency.

Modeling Framework



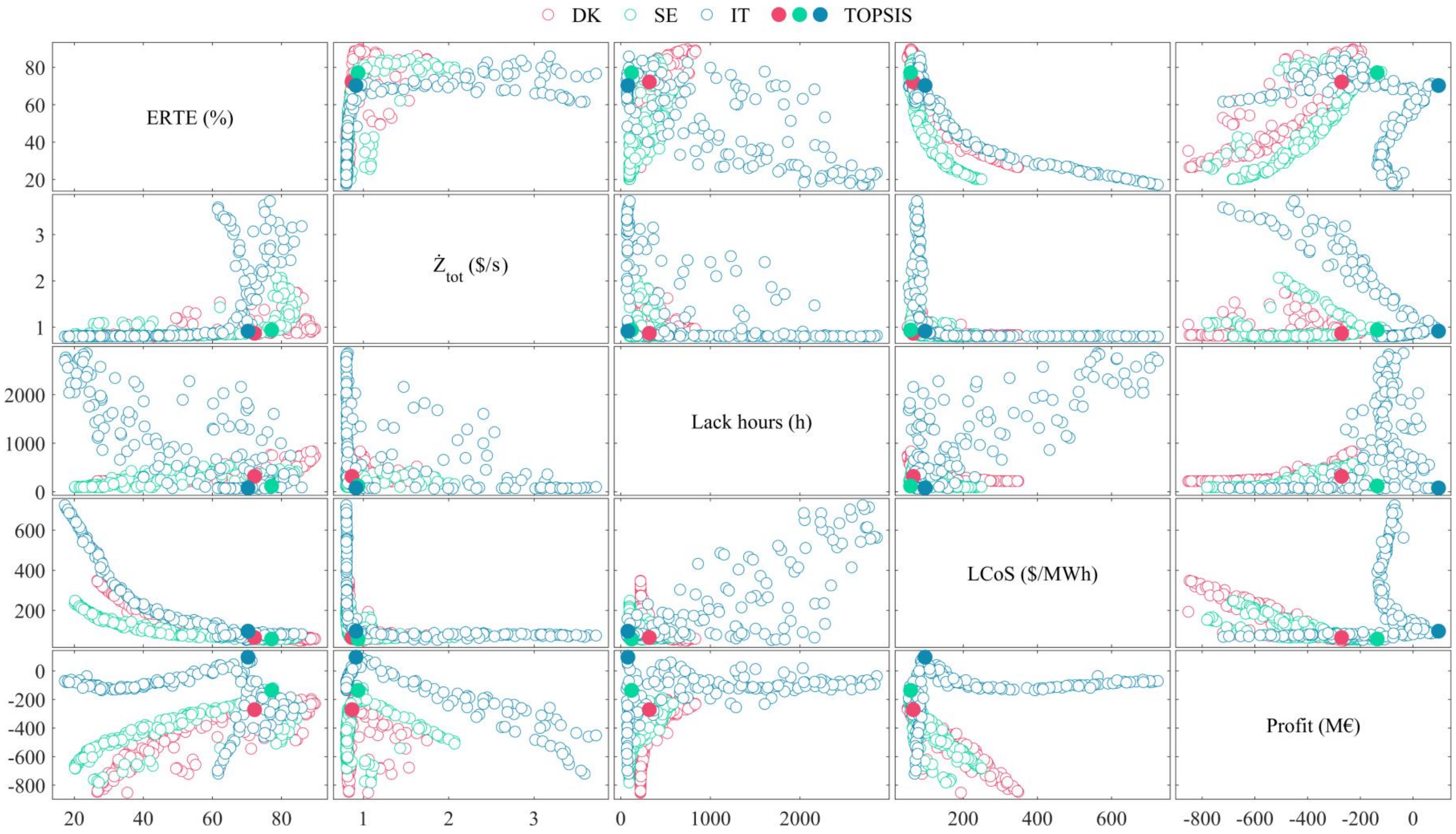
Renewable Power Generation and Load Profile



Temporal patterns of renewable power generation and load profiles over 8760 hours (one year) for three different countries: a) Denmark's offshore wind, b) Italy's solar generation, and c) Sweden's onshore wind.

Optimization – 2023 Scenario

Distribution of five objective Pareto frontier based on NSGA-II for three countries with different renewable sources



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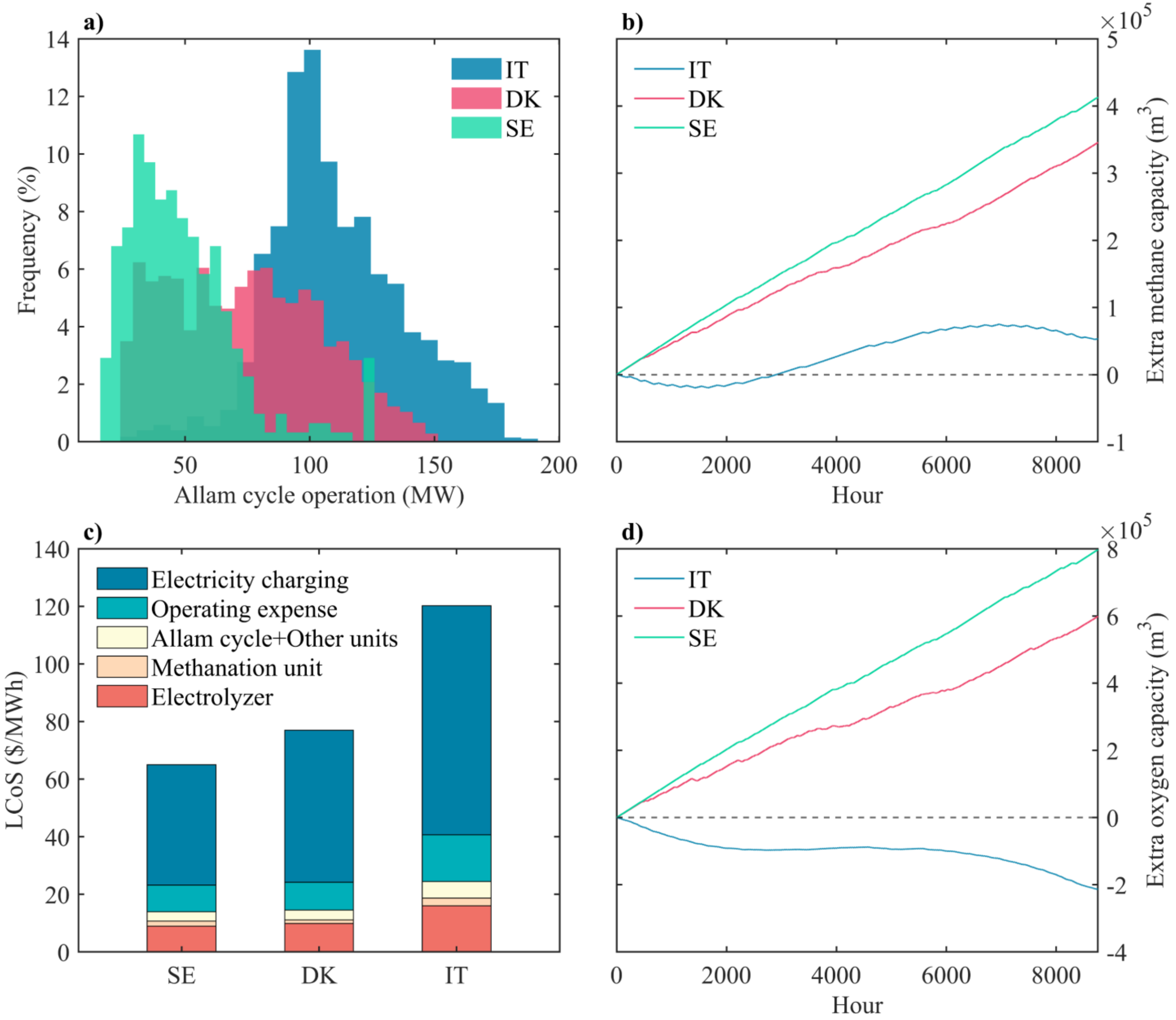
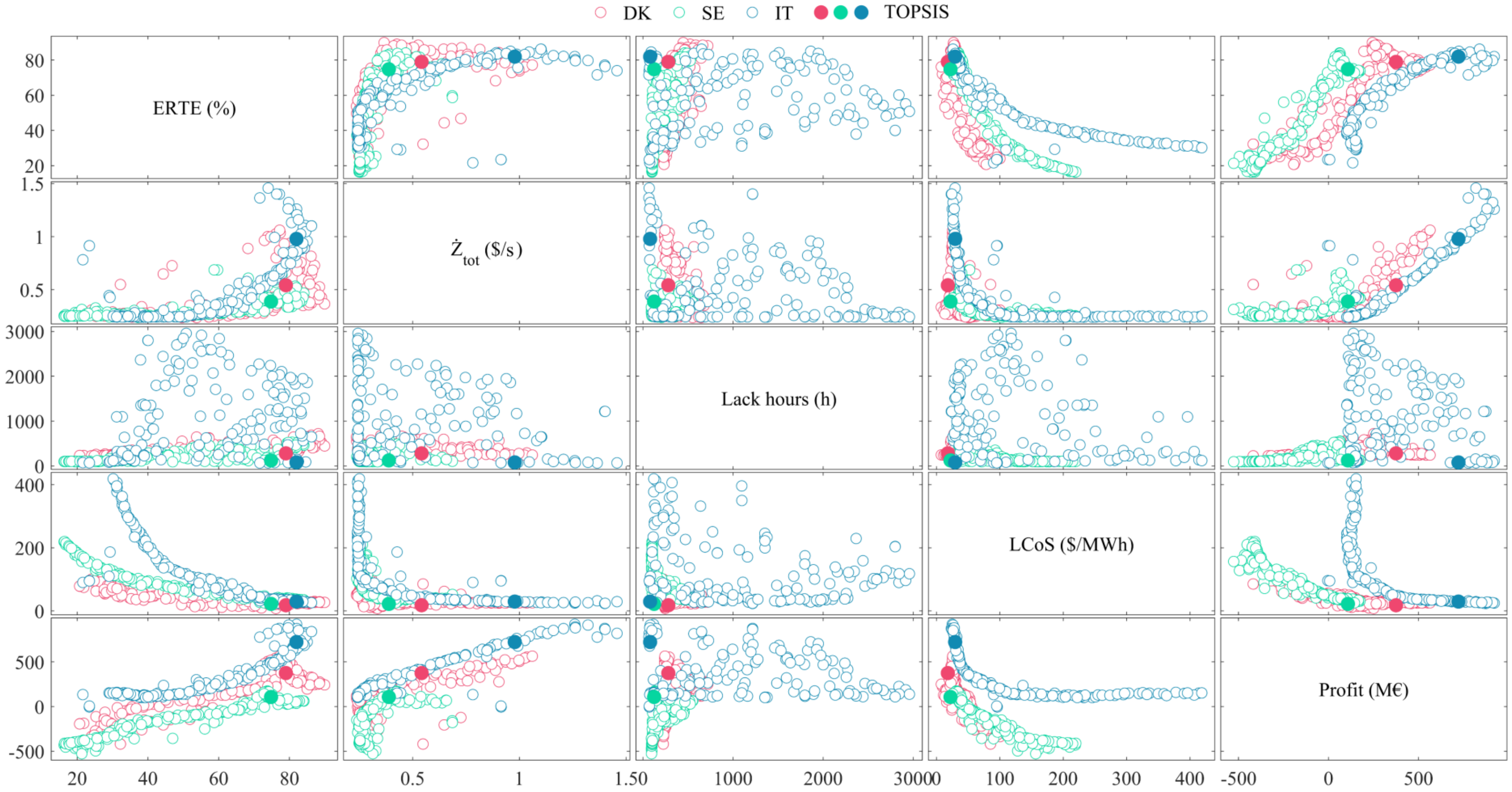
Operation Results - 2023 Scenario

a) Operation of the Allam cycle
b) Extra methane capacity
c) Share of each parameter in LCoS
d) Extra oxygen capacity



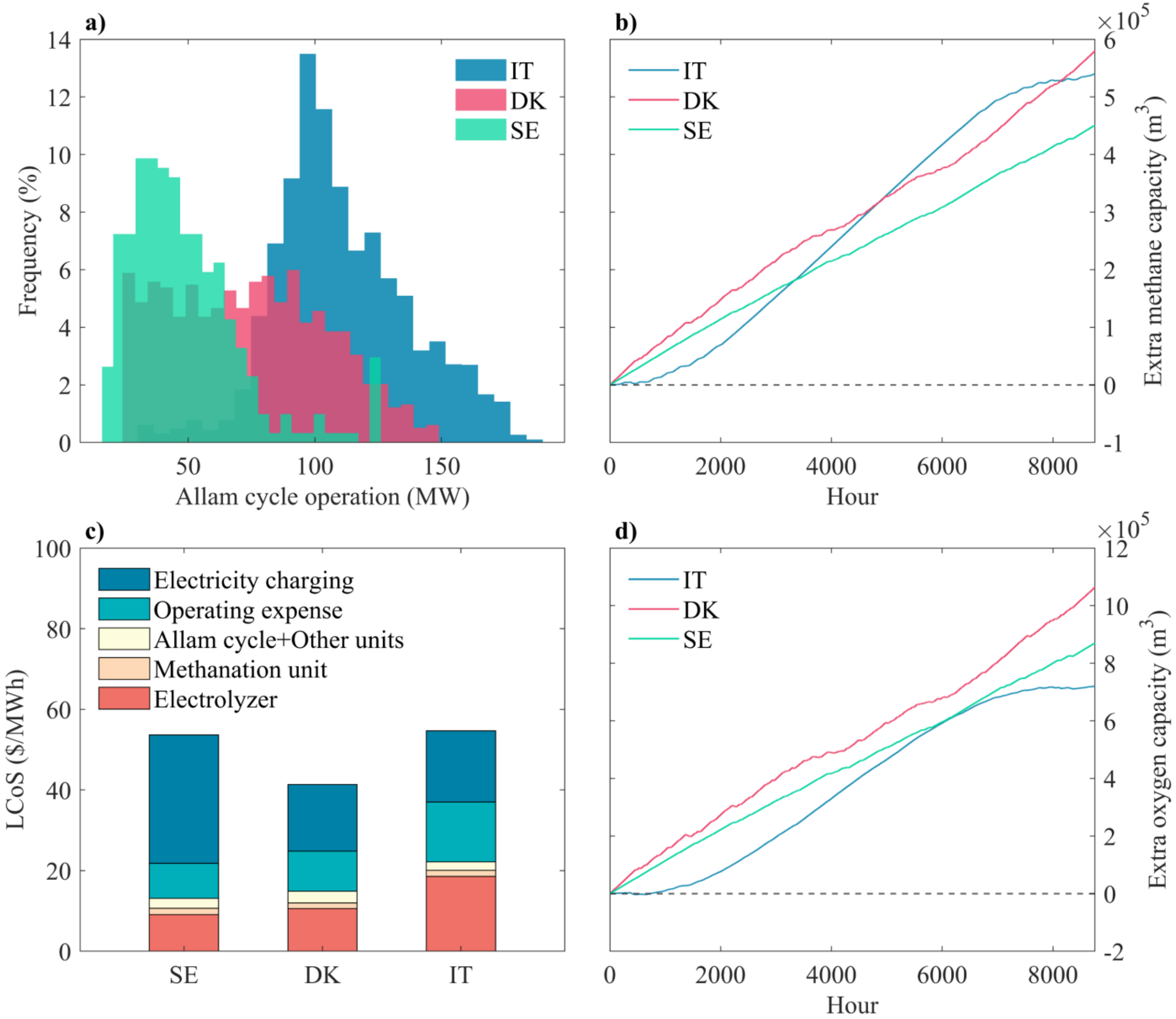
Optimization – 2050 Scenario

Distribution of five objective Pareto frontier based on NSGA-II for three countries with different renewable sources



Operation Results - 2050 Scenario

a) Operation of the Allam cycle
b) Extra methane capacity
c) Share of each parameter in LCoS
d) Extra oxygen capacity



Conclusions

Conclusions

- ❑ A future CCUS system powered by Allam cycle for simultaneous production of electricity and green fuels is proposed in this project.
- ❑ The integrated system's performance has been analyzed under both steady-state and transient conditions.
- ❑ The ERTE and LCoS demonstrate competitiveness with other existing processes, particularly within the 2050 scenario.
- ❑ The integrated system can be emission free or negative emission.
- ❑ The proposed system is versatile and adaptable to various applications.

Thank you for your attention!

Haoshui Yu
hayu@bio.aau.dk

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Ph.D. Candidate Seyed Mojtaba Alirahmi