HySelect

Efficient water splitting via a flexible solar-powered Hybrid thermochemical-Sulphur dioxide depolarized Electrolysis Cycle

Energy demand analysis of a practical solar hybrid sulfur cycle: the HySelect project

Yasuki Kadohiro (DLR, Institute of Future Fuels)
19.06.2024 – Rhodes International Conference 2024, Session III

Clean Hydrogen Partnership

Co-funded by the European Union

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

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Background

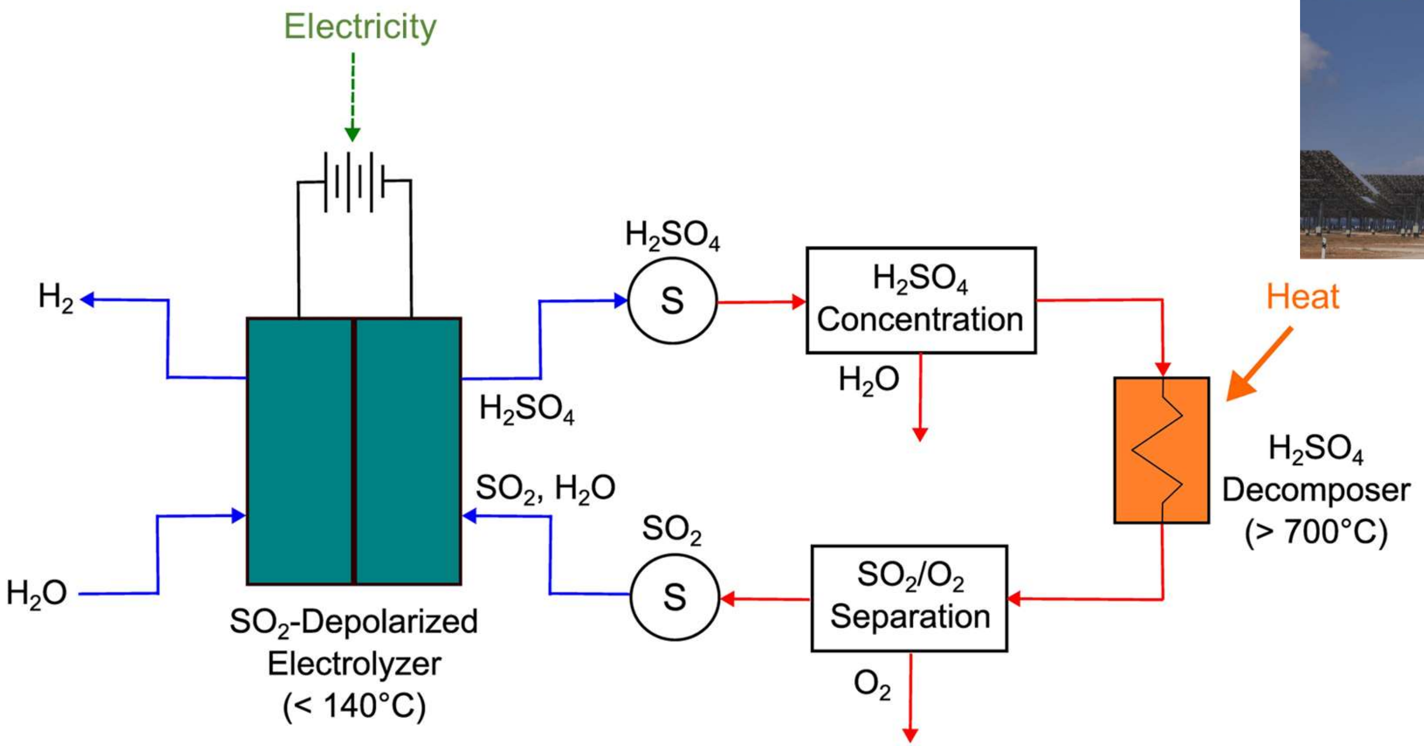

Image source: [Clifford (2017)]

$SO_2\ (aq) + 2H_2O\ (l) \rightarrow H_2SO_4\ (aq) + 2H^+\ (aq) + 2e^-$ [Anode]

$2H^+\ (aq) + 2e^- \rightarrow H_2\ (g)$ [Cathode]

$H_2SO_4 \leftrightarrow SO_3 + H_2O$ [350-400 °C]

$SO_3 \leftrightarrow SO_2 + 1/2O_2$ [700-1000 °C]

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*Thermochemical process efficiency is based on the hydrogen lower heating value (LHV)

Background

(1) Gorensek et al. [1]: Thermochemical process efficiency of 35...%

Hybrid Sulfur Cycle ← Heat — Nu...

(2) Niehoff et al. [2]: Th...

Hybrid Sulfur...

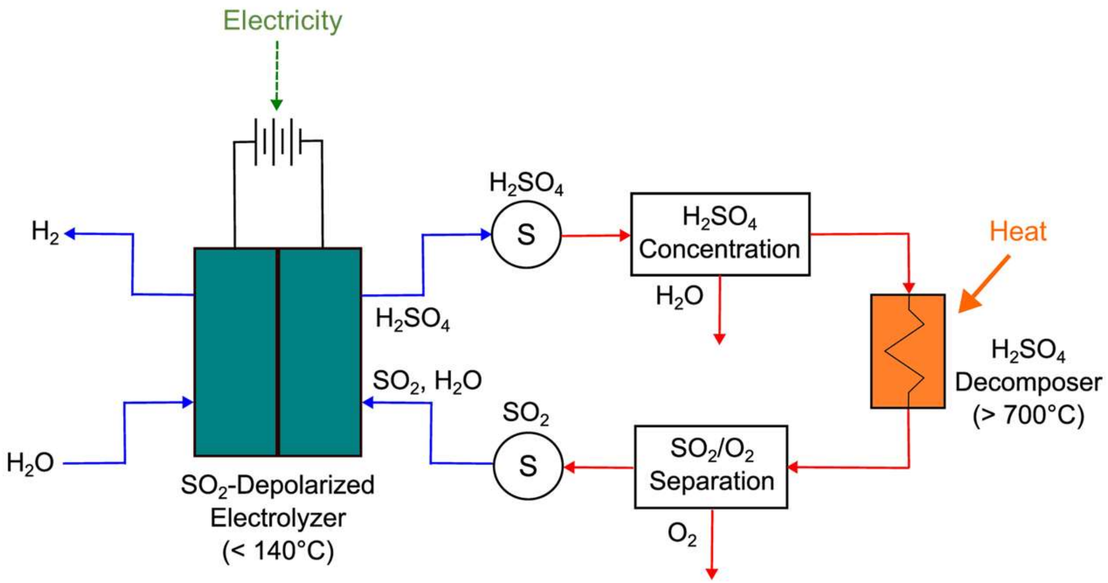
No pilot and demonstration plant yet!!

(3) Gorensek et al. [3]: Thern...mical process efficiency of 35%

Hybrid Sulfur Cycle ← Heat / Electricity — Falling particle concentrated solar receiver

Objective

- Energy demand analysis of a Solar Hybrid Sulfur Cycle from **practical point of view for the implementation of a demonstration plant.**
- Example of the practical point: Operating pressure of sulfuric acid decomposition section and SO_2-depolarized electrolyzer section is slightly under ambient pressure.



SO_2 (aq) + $2H_2O$ (l) → H_2SO_4 (aq) + $2H^+$ (aq) + $2e^-$ [Anode]

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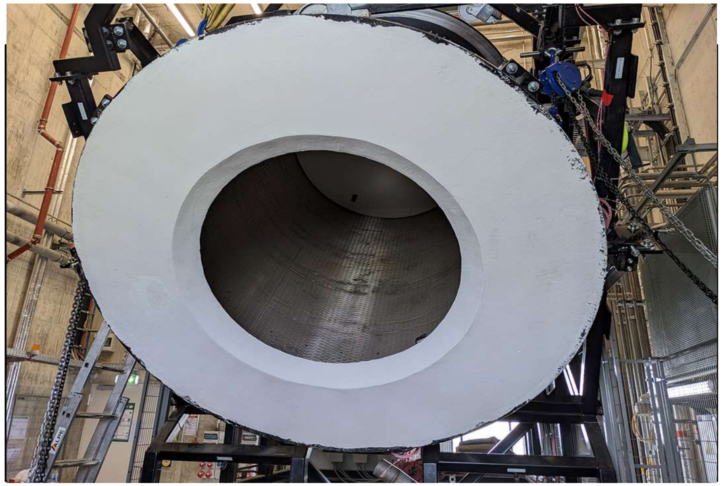
SO_3 ↔ SO_2 + $1/2O_2$ [700-1000 °C]



Centrifugal particle receiver

Image source: Ebert et al. (2019)

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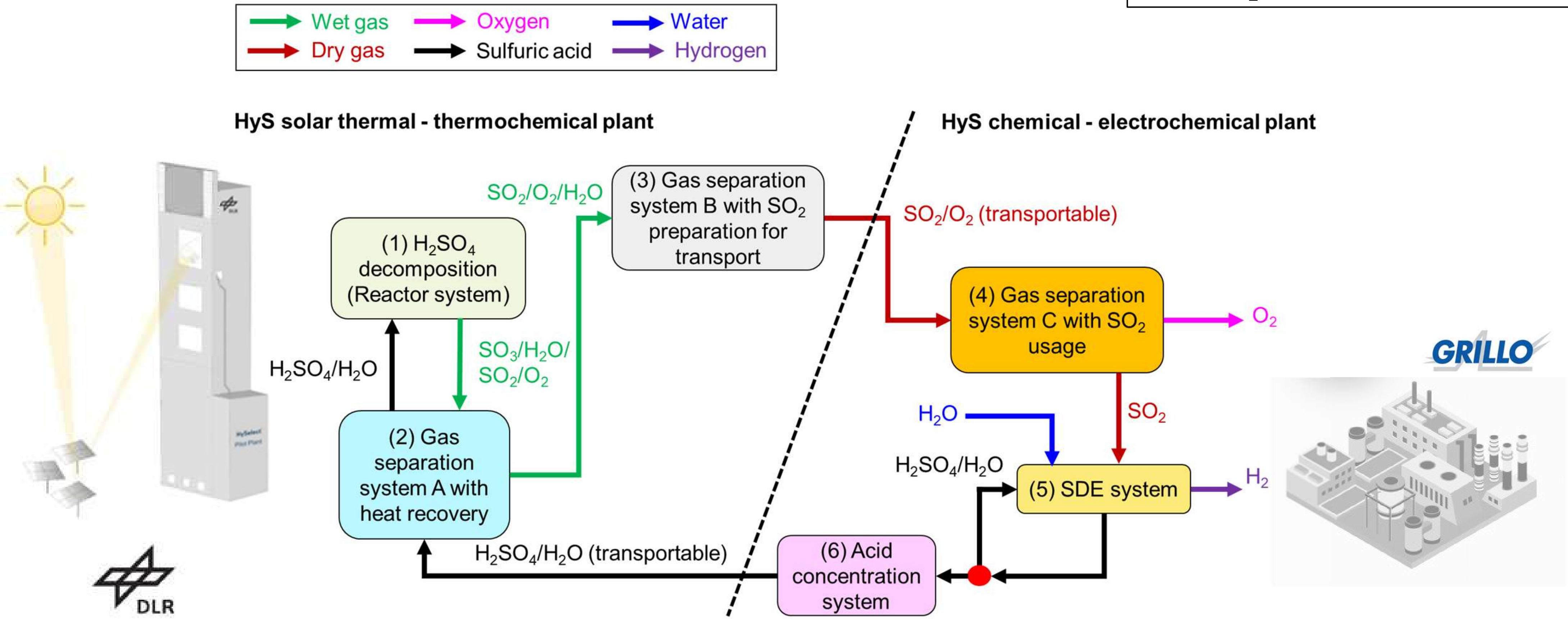
Method

HyS: Hybrid Sulfur Cycle
SDE: SO_2-Depolarized Electrolyzer



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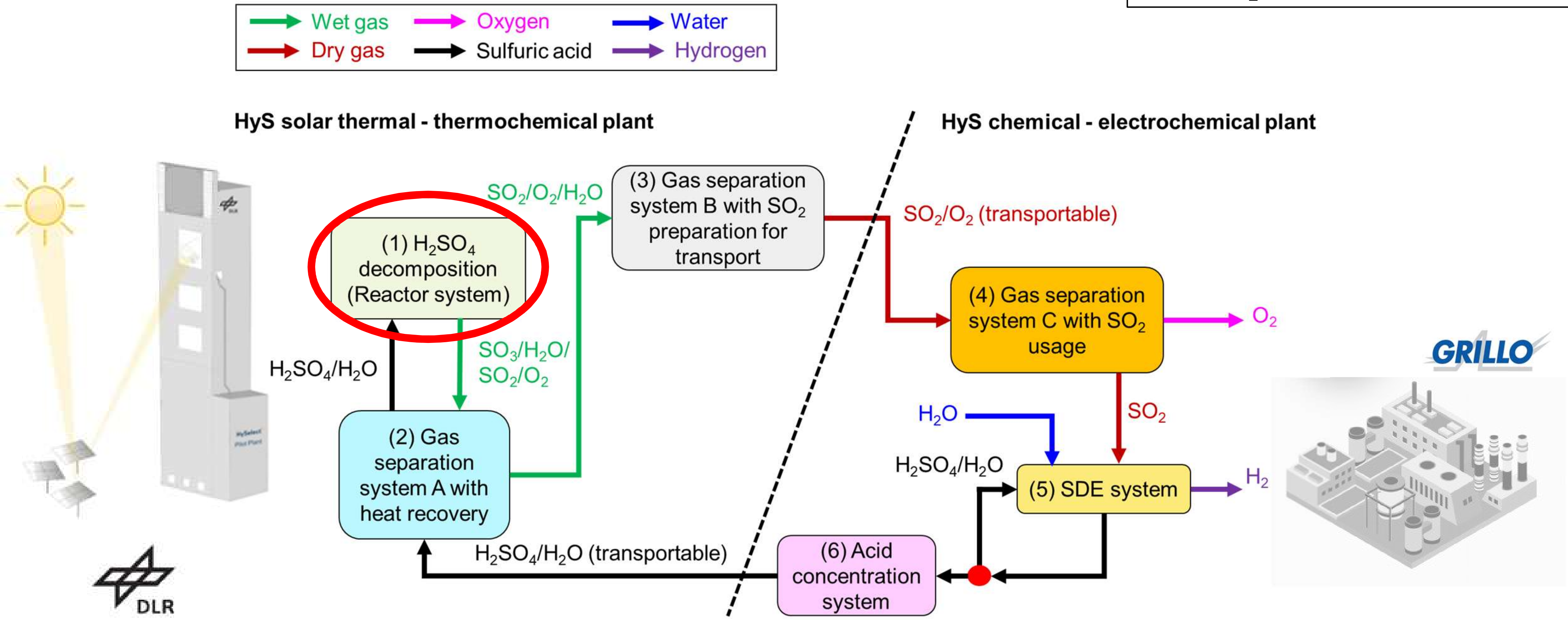
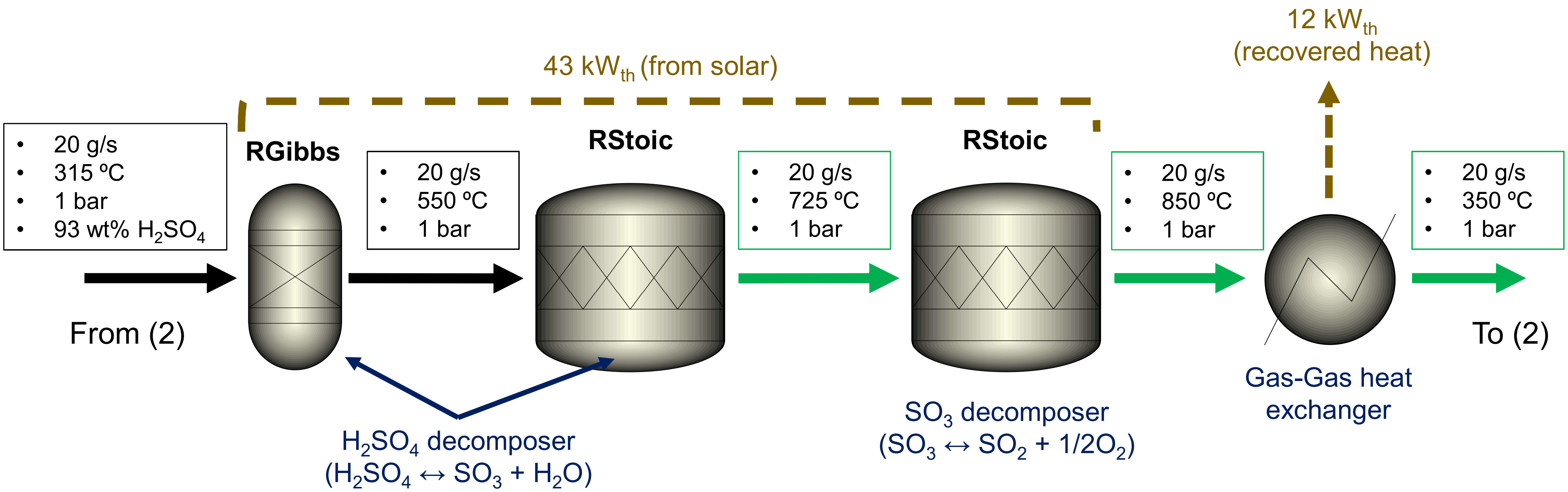
Method

HyS: Hybrid Sulfur Cycle
SDE: SO_2-Depolarized Electrolyzer



Aspen plus model – (1) H_2SO_4 decomposition

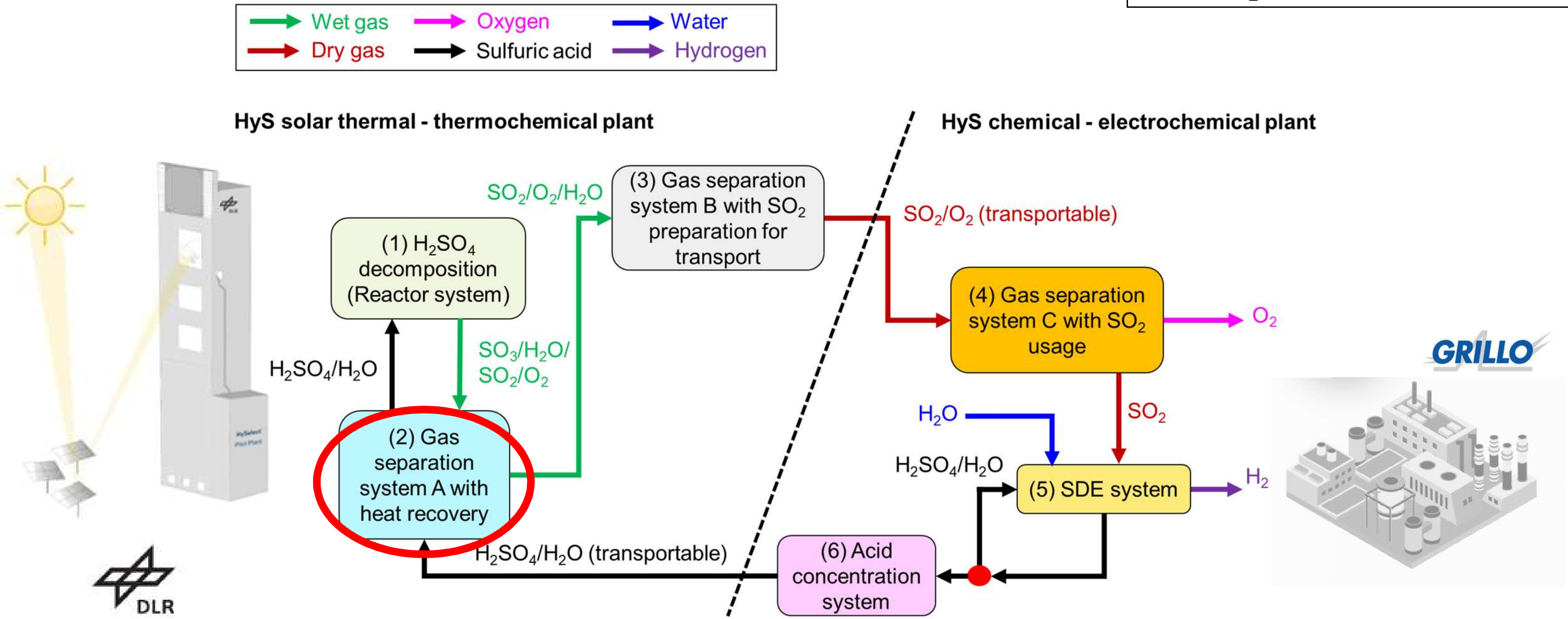
Method



- Molar flow rate of SO_2 after the SO_3 decomposer is fixed to 0.12 mol/s
- Conversion rate of the SO_3 decomposer is set to 63% (consider catalytic degradation)

Method

HyS: Hybrid Sulfur Cycle
SDE: SO_2-Depolarized Electrolyzer



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Method

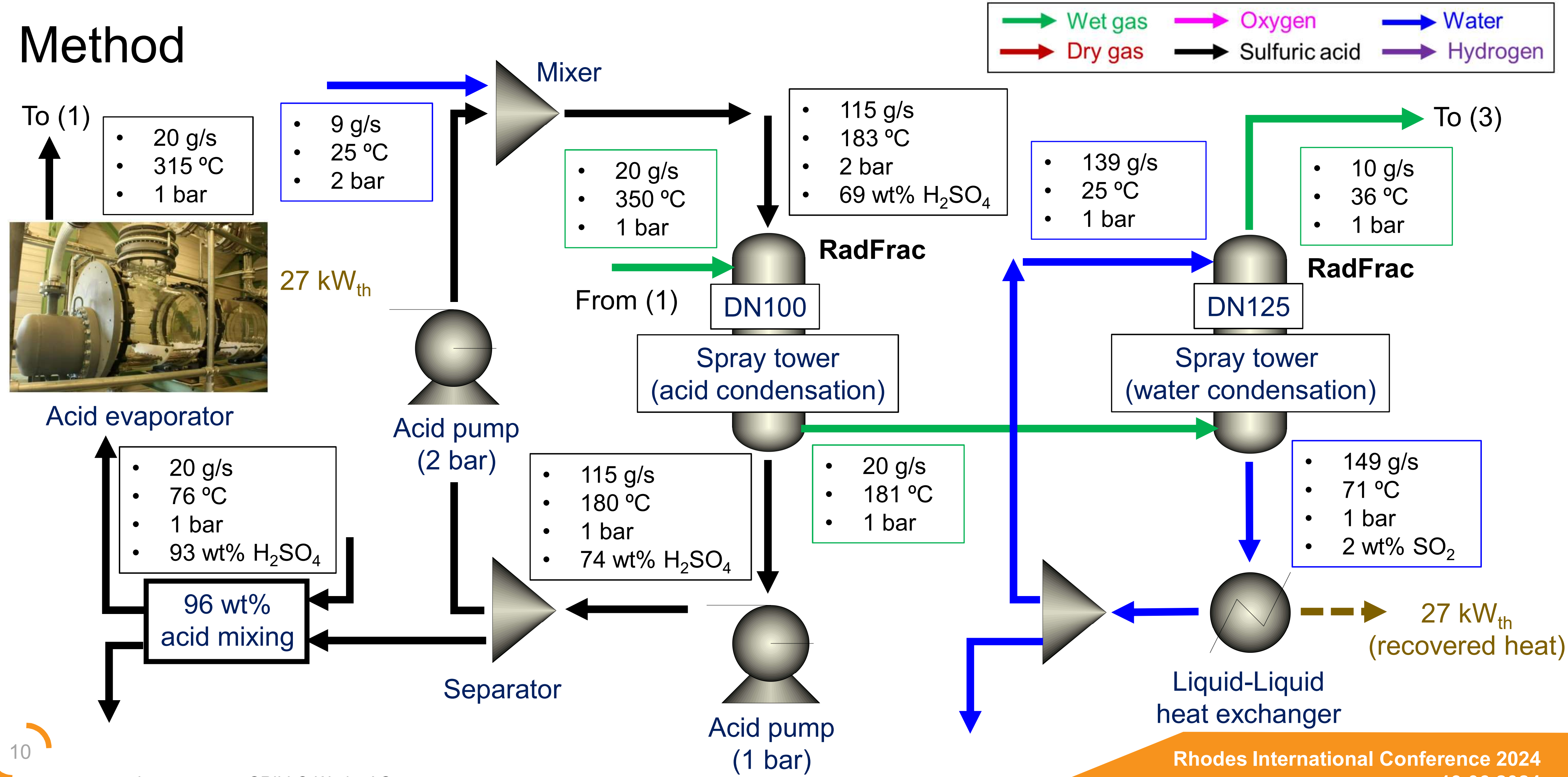
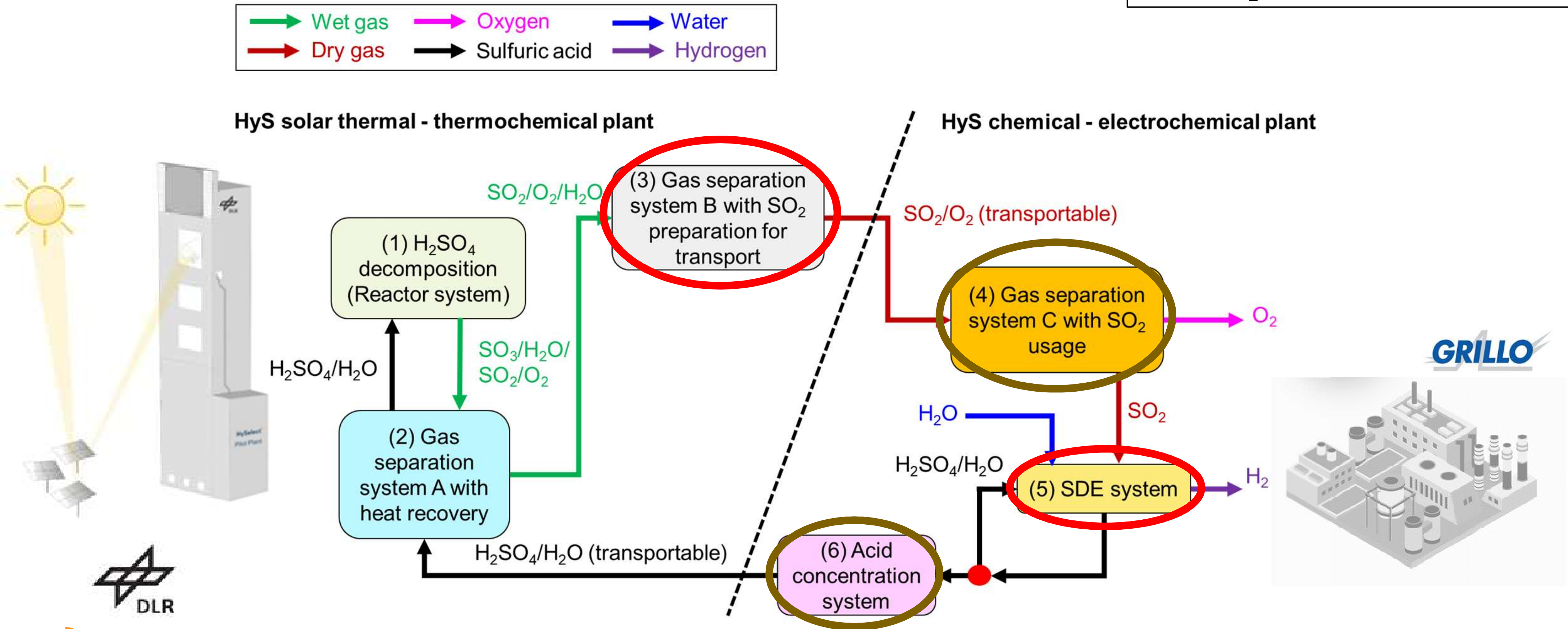


Image source: GRILLO-Werke AG

Concept of the demonstration plant

Method

HyS: Hybrid Sulfur Cycle
SDE: SO_2-Depolarized Electrolyzer



Energy efficiency for hydrogen production

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Results and discussions

* SO_2 conversion rate in SDE is fixed at 50%

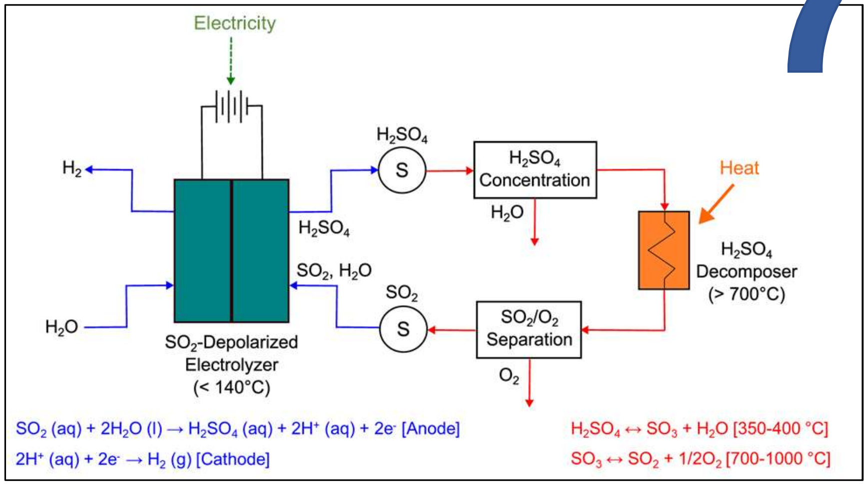
Parameter	Our study	Niehoff et al. [2]	Gorensek et al. [3]
Target H_2 production rate	0.06 mol/s	0.13 kmol/s	1 kmol/s
Applied thermal energy to H_2SO_4 decomposition process	43 kW_{th}	86 MW_{th}	353 MW_{th}
Operating pressure in H_2SO_4 decomposition process	1 bar(a)	1 bar(a)	14.1 bar(a)
Maximum temperature in H_2SO_4 decomposition process	850 ºC	1300 ºC	850 ºC
Consumed electric power in SDE	8 kW_{el}	15 MW_{el}	116 MW_{el}
Operating pressure in SDE	1 bar(a)	12 bar(a)	22.7 bar(a)
Operating temperature in SDE	70 ºC	74 ºC	123 ºC
Energy efficiency for hydrogen production	**25%**	**33%**	**41%**

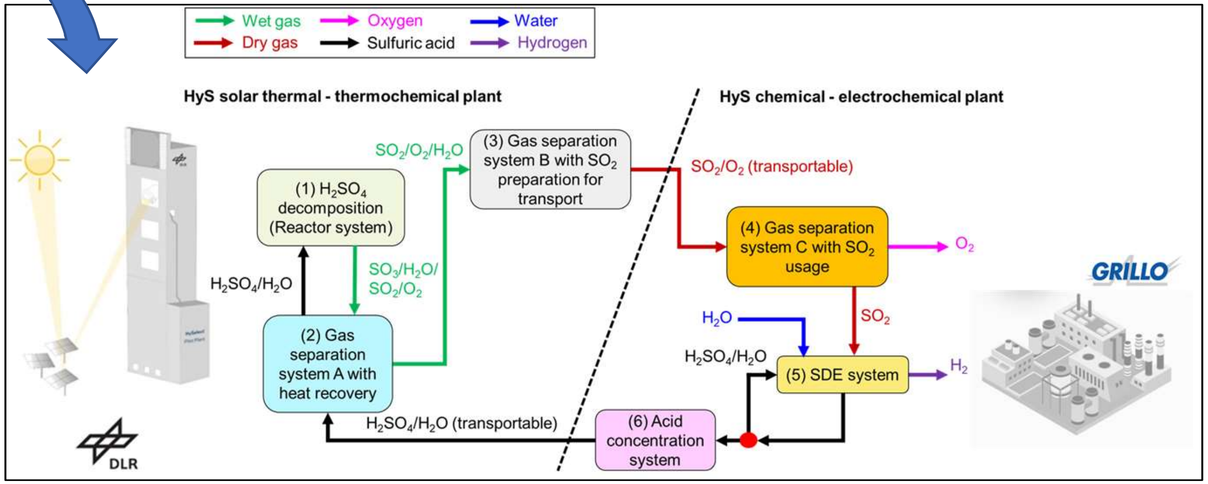
- Energy efficiency calculation

$$\eta_{en} = \frac{\dot{m}_{H2,out} \cdot LHV_{H2}}{\dot{W}_{elec} + \dot{Q}_{heat}}$$

$\dot{m}_{H2,out}$: Outlet mass flow rate of hydrogen [kg/s]
LHV_{H2}: Hydrogen lower heating value [J/kg]
W_{elec}: Total electrical energy input [W_{el}]
$\dot{Q}_{heat}$: Total thermal energy input [W_{th}]

Summary





Aspen plus model

25% of energy efficiency (provisional results)

Future study

- Complete the investigation of chemical – electrochemical plant (Block (4), (5), and (6)).
- Complete the energy demand analysis with the final plant concept.
- Integrate the solar particle receiver concept into the Aspen model.
- Complete the techno-economic study of the concept.

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References

- [1] Gorensek MB, Summers W (2009) Hybrid sulfur flowsheets using PEM electrolysis and a bayonet decomposition reactor. Int J Hydrogen Energ 34:4097–4114.
- [2] Guerra Niehoff A, Bayer Botero N, Acharya A et al. (2015) Process modelling and heat management of the solar hybrid sulfur cycle. Int J Hydrogen Energ 40:4461–4473. https://doi.org/10.1016/j.ijhydene.2015.01.168
- [3] Gorensek MB, Corgnale C, Summers WA (2017) Development of the hybrid sulfur cycle for use with concentrated solar heat. I. Conceptual design. Int J Hydrogen Energ 42:20939–20954. https://doi.org/10.1016/j.ijhydene.2017.06.241

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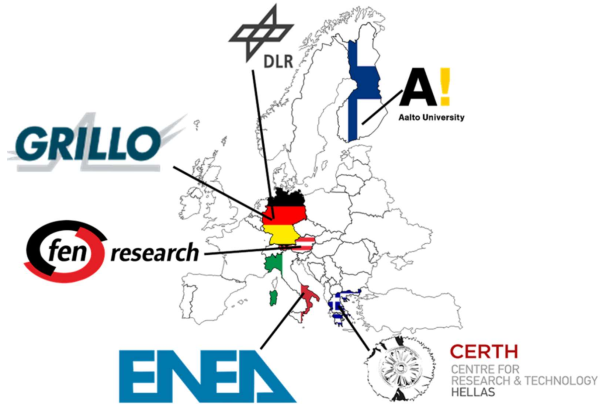

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The project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research under the Grant Agreement Nr. 101101498.

HySelect Jülich

At the HySelect Jülich site, all solar thermal & thermochemical processes are located.

HySelect Duisburg

At the HySelect Duisburg site, all chemical & electrochemical processes are located.

Concept of the demonstration plant

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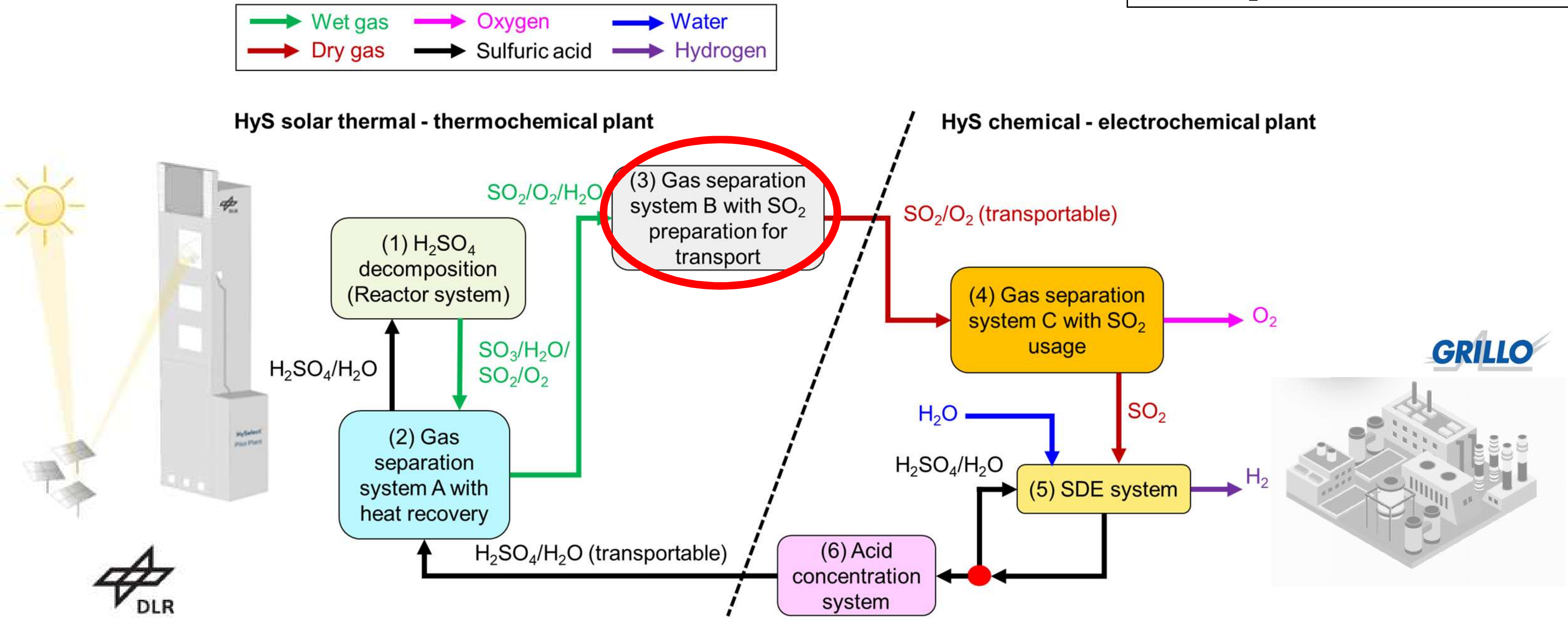
Method

HyS: Hybrid Sulfur Cycle
SDE: SO_2-Depolarized Electrolyzer



Aspen plus model – (3) Gas separation system B with SO_2 preparation for transport

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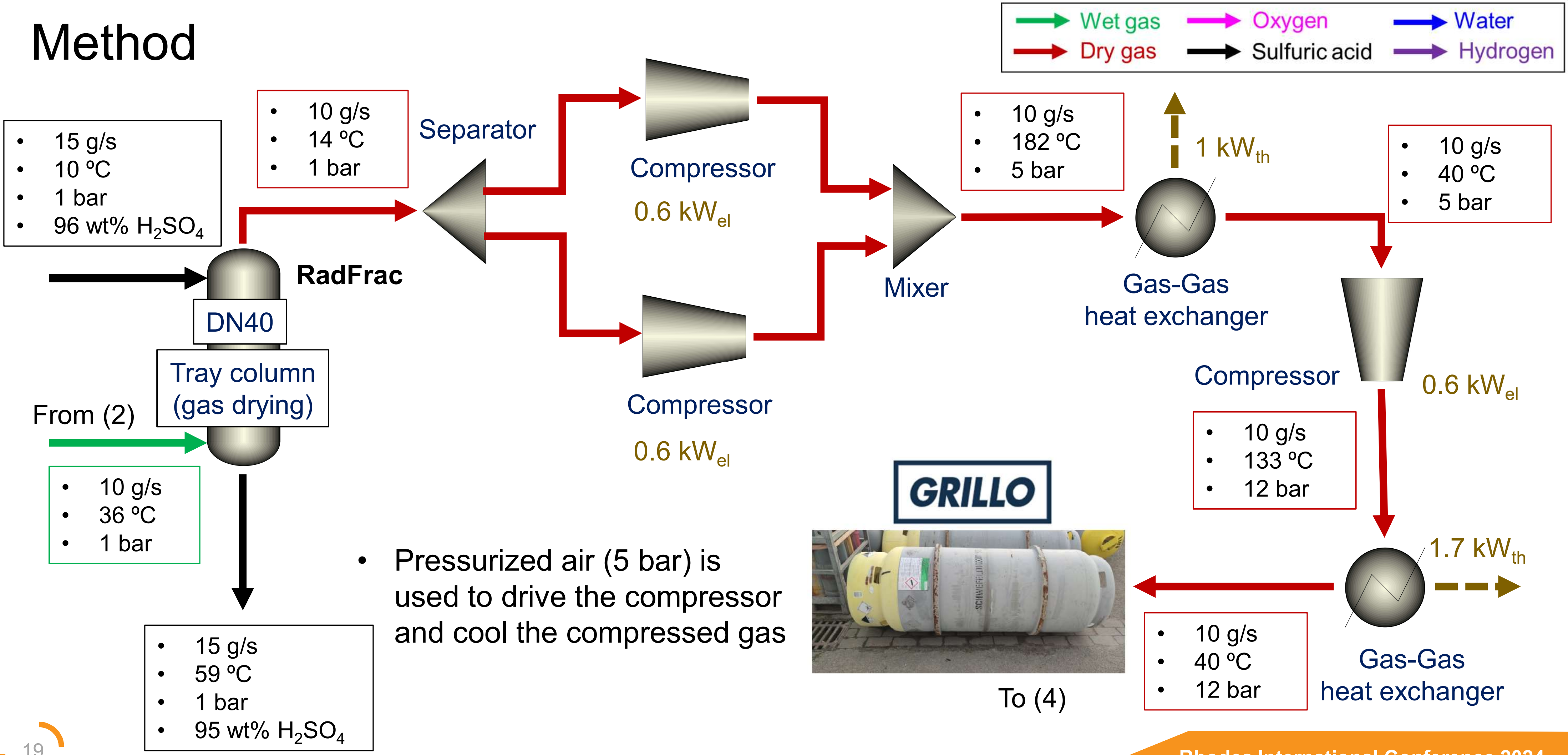
Method



- Pressurized air (5 bar) is used to drive the compressor and cool the compressed gas

Image source: GRILLO-Werke AG

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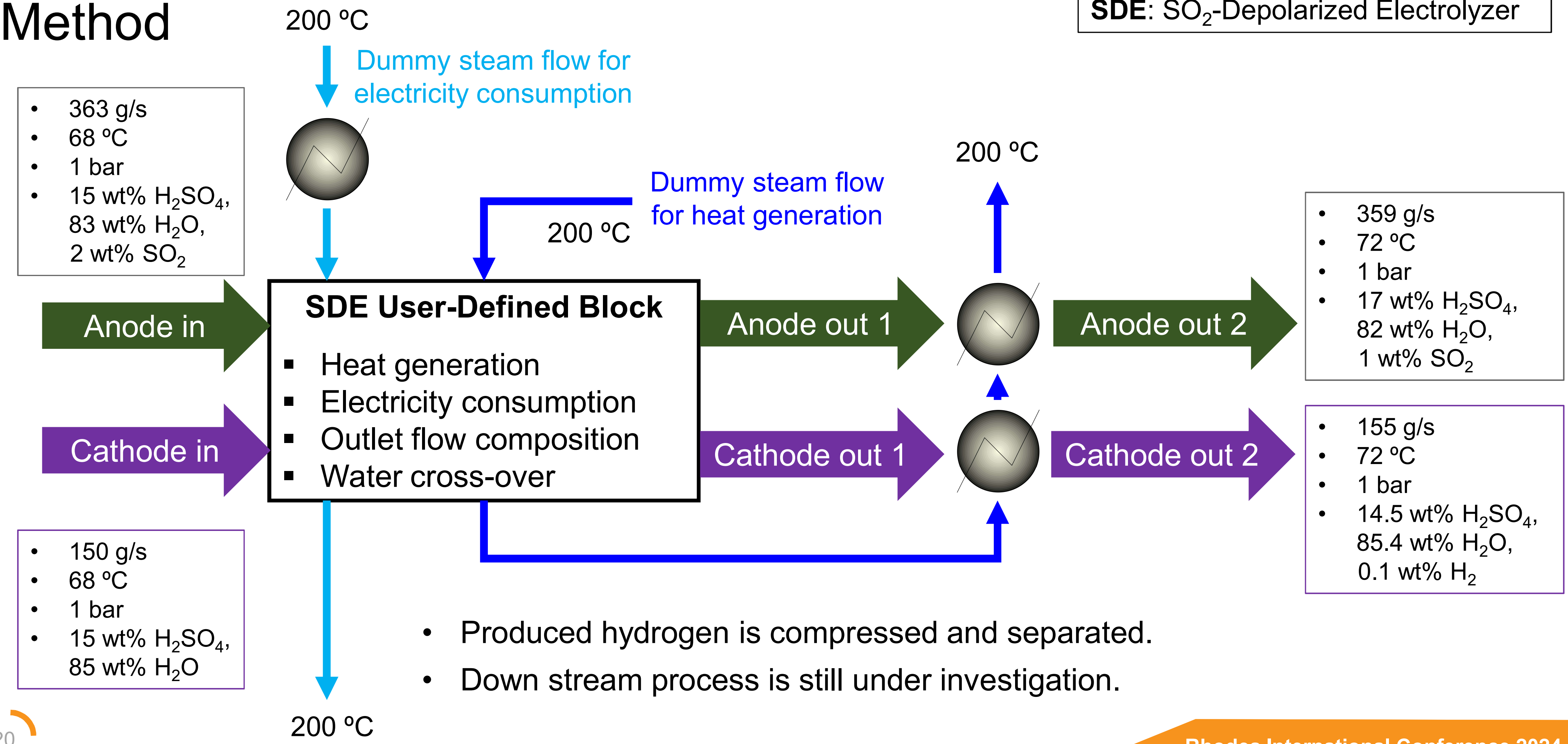
Method

SDE: SO_2-Depolarized Electrolyzer



- Produced hydrogen is compressed and separated.
- Down stream process is still under investigation.

Aspen plus model – (5) SDE system

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Method

SDE: SO_2-Depolarized Electrolyzer

- Liquid-fed catholyte and anolyte compartments are considered.
- 5-15 wt% of H_2SO_4 is considered in anolyte and catholyte to obtain reasonable high reactant solubility.
- Nafion 117 is considered as a SDE's membrane. It was reported to have the least SO_2 transfer capability from anolyte to catholyte.
- Water crossover phenomena are considered in our model. Only the water crossover due to electro-osmotic drag is considered since it has the greatest impact of all other causes.
- SO_2 crossover is not considered in our model so far.
- Current density value of 5000 A/m^2 is used.
- Total cell potential value of 0.7 V is used in our study.
- SO_2 conversion rate of 20-50% is considered.
- Cell temperature is adjusted between 20-95 ºC

Method

- 86 °C hot water (input) carries 40 kW_{th}
- 8 °C chilled water (output) carries 29 kW_{th}

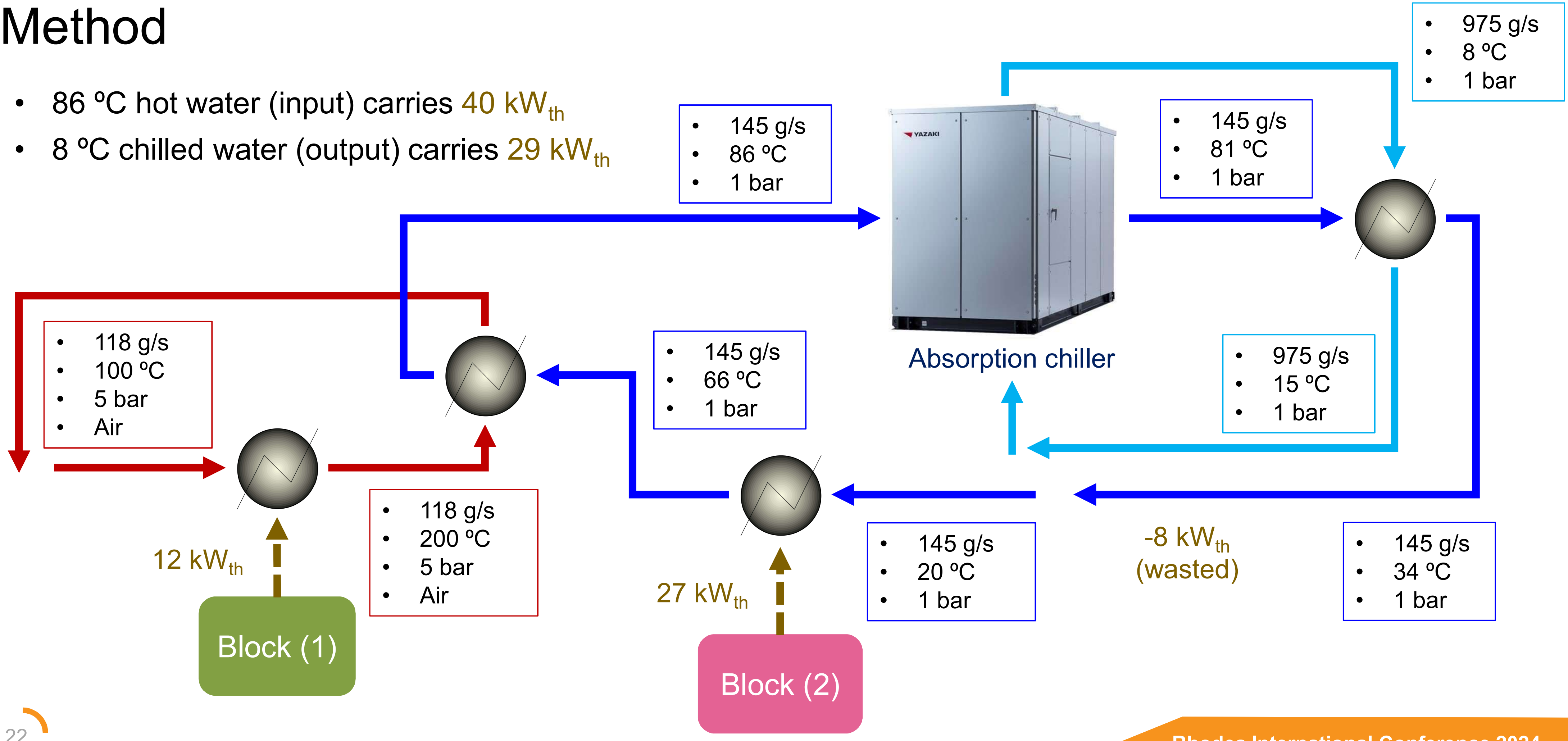
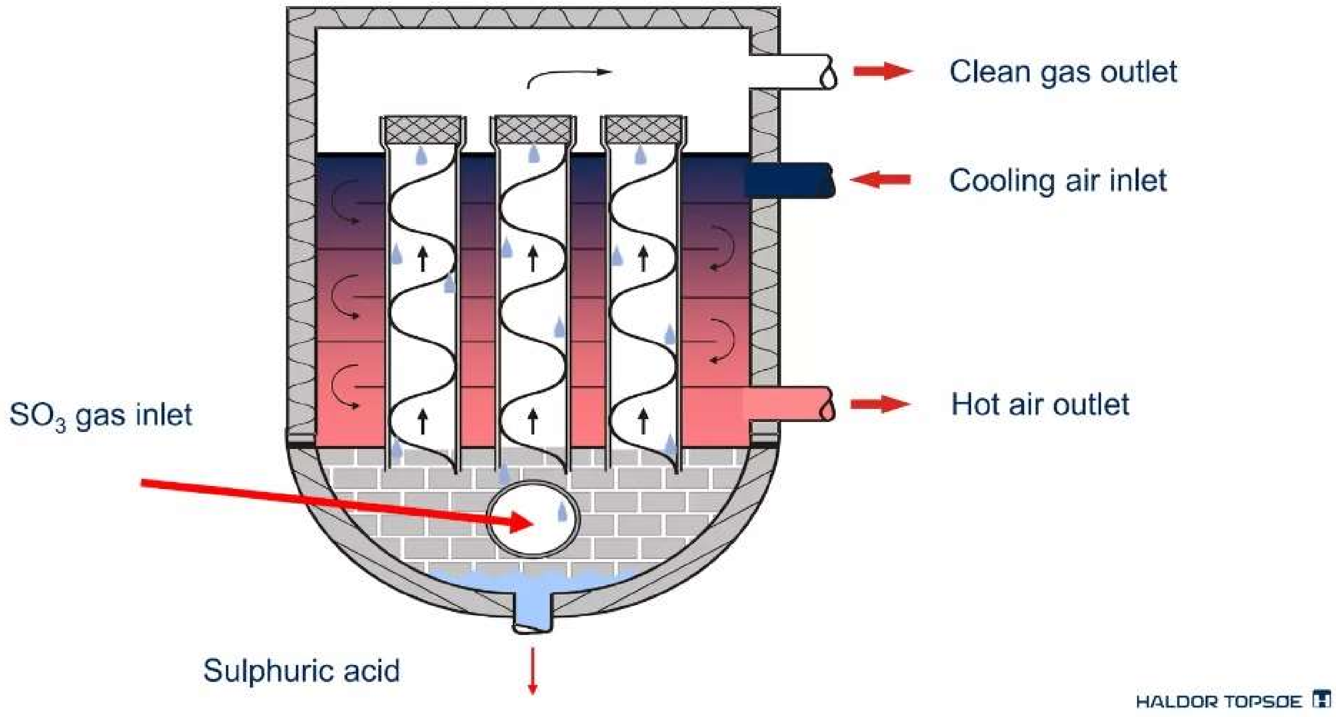


Image source: Yazaki Energy Systems, Inc.

Method



Wet gas Sulfuric Acid (WSA) unit

Image source: HALDOR TOPSUE

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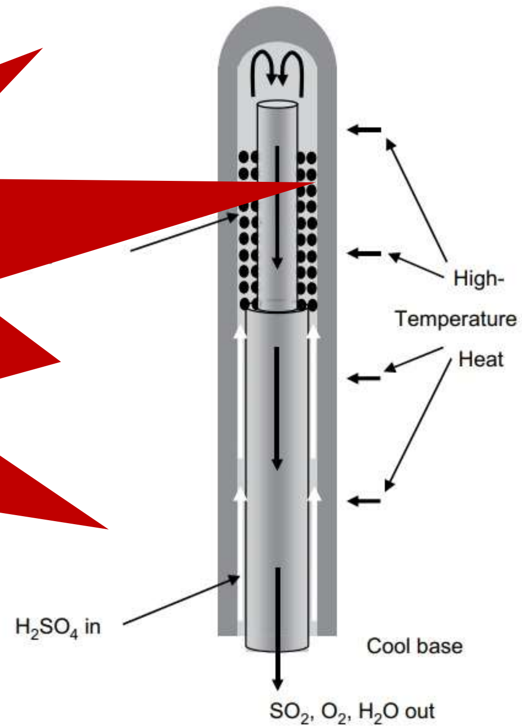
Heat

Hybrid Sulfur Cycle ← Falling particle concentrated solar receiver

Electricity



Bayonet decomposition reactor

Image source: Gorensek et.al. (2009)