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Thomas Steffen,
Grace Zhou

2024-09-09
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Reversible Solid Oxide Fuel Cells (rSOC) for Building Energy Storage

School of Aeronautical, Automotive, Chemical and Materials Engineering

Funded by UKRI Research England

Lead academic partners ERA Energy Research Accelerator, Keele University, Midlands Innovation

About myself

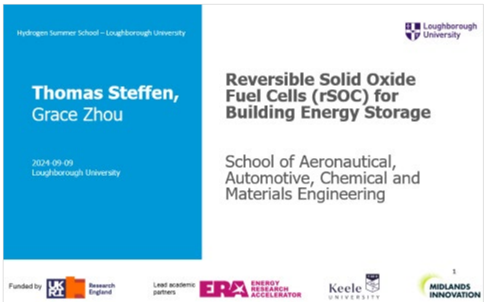
Thomas Steffen

- At LU since 2007
- Reader since 2023
- PhD in Fault Tolerant Control
- “MEng” in ElecEng
- Research in Control of Energy Systems
- Long-term EV driver

Grace Zhou

- Doctoral researcher
- Experimental analysis of rSOC
- Simulation and interpretation of mode switching

Overview


Hydrogen Summer School – Loughborough University
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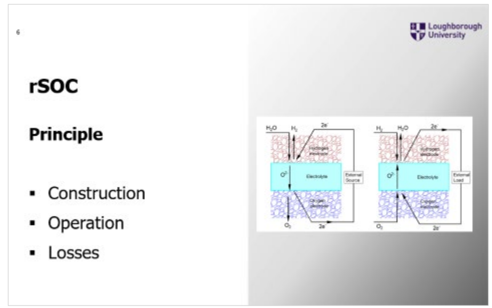
ERA ENERGY RESEARCH ACCELERATOR
Keele UNIVERSITY
MIDLANDS INNOVATION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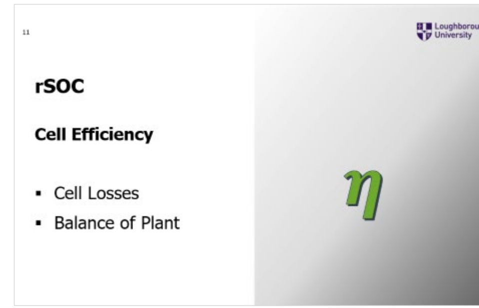
rSOC
Principle
▪ Construction
▪ Operation
▪ Losses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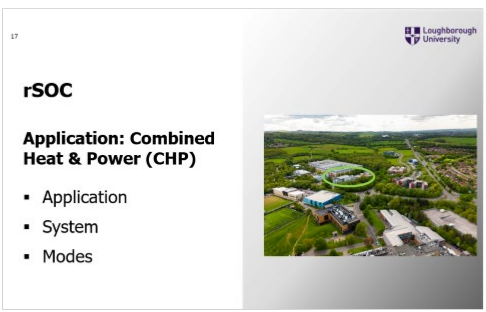
Cell Efficiency
▪ Cell Losses
▪ Balance of Plant
η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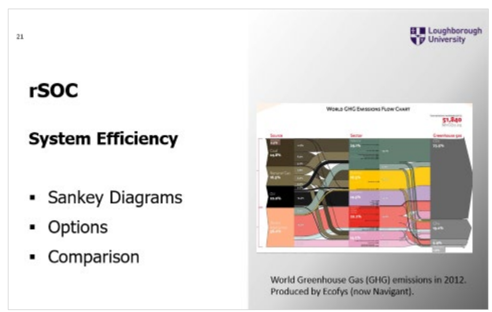
rSOC
Application: Combined Heat & Power (CHP)
▪ Application
▪ System
▪ Modes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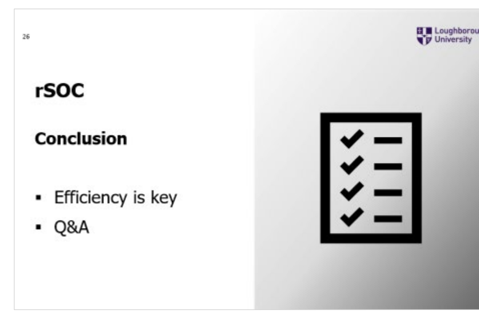
System Efficiency
▪ Sankey Diagrams
▪ Options
▪ Comparison
World Greenhouse Gas (GHG) emissions in 2012.
Produced by Ecofys (now Navigant).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Conclusion
▪ Efficiency is key
▪ Q&A

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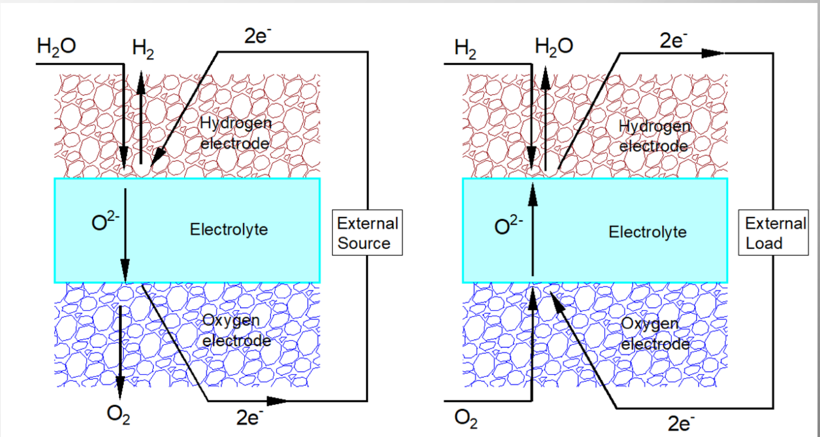
rSOC

Principle

- Construction
- Operation
- Losses



Proton Exchange Membrane (PEM) Fuel Cell

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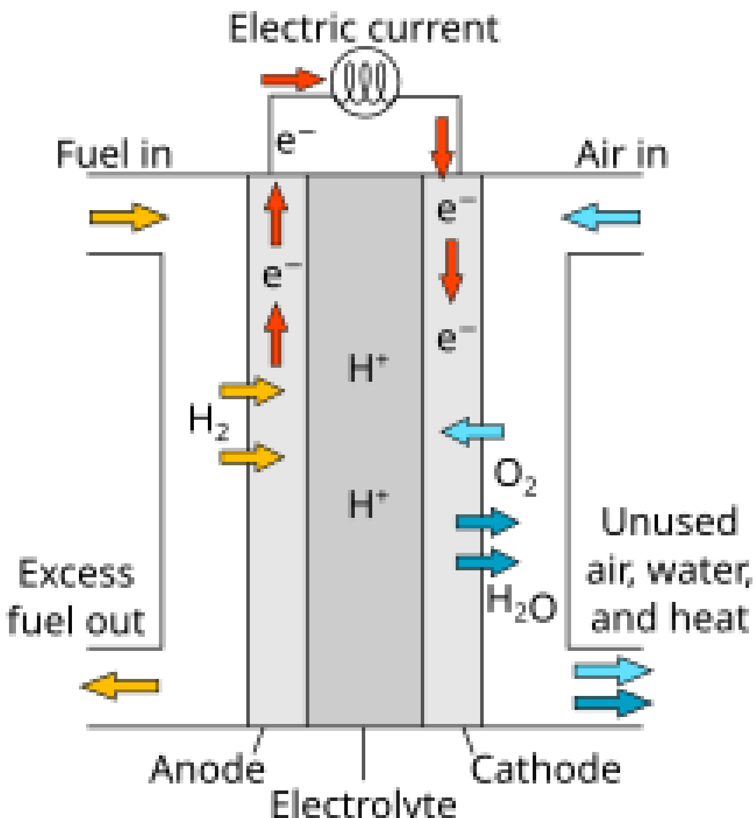

Wikipedia

- Polymer membrane
  - Proton conductor
  - At ca 90C or 120C
- Platinum Group Metal (PGM) catalyst
- Needs pure hydrogen
- Theoretically reversible
- Water management is a challenge

Solid Oxide Fuel Cell (SOFC)

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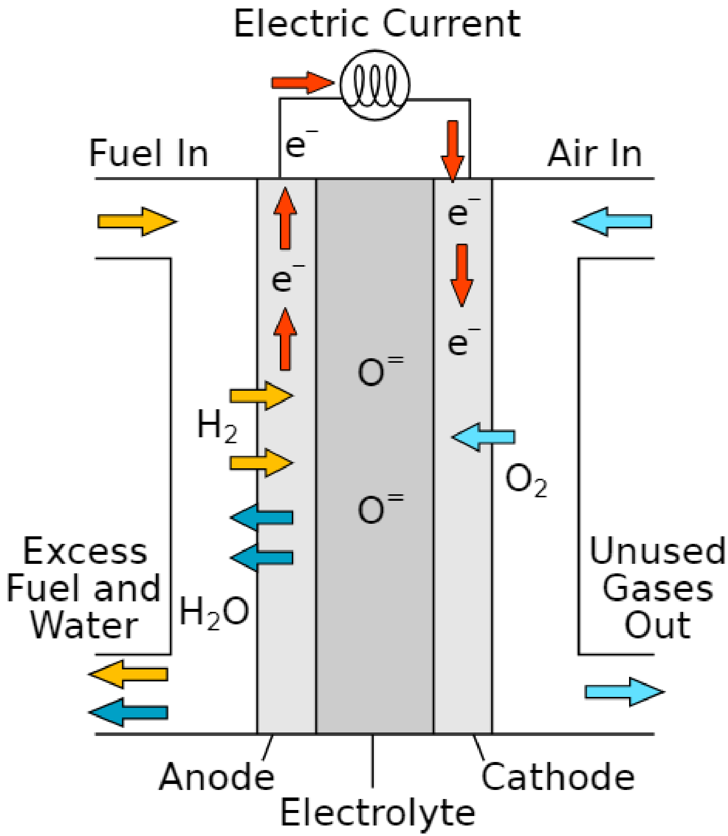

Solid oxide fuel cell. (2024, June 8). In Wikipedia. https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell

- Ceramic separator: gadolinium-doped ceria (GdC)
  - Oxygen ion conductor
  - At ca 800 C
- Nickel catalyst (no PGM)
- Multi-fuel capable
- Reversible
- (Very fragile)

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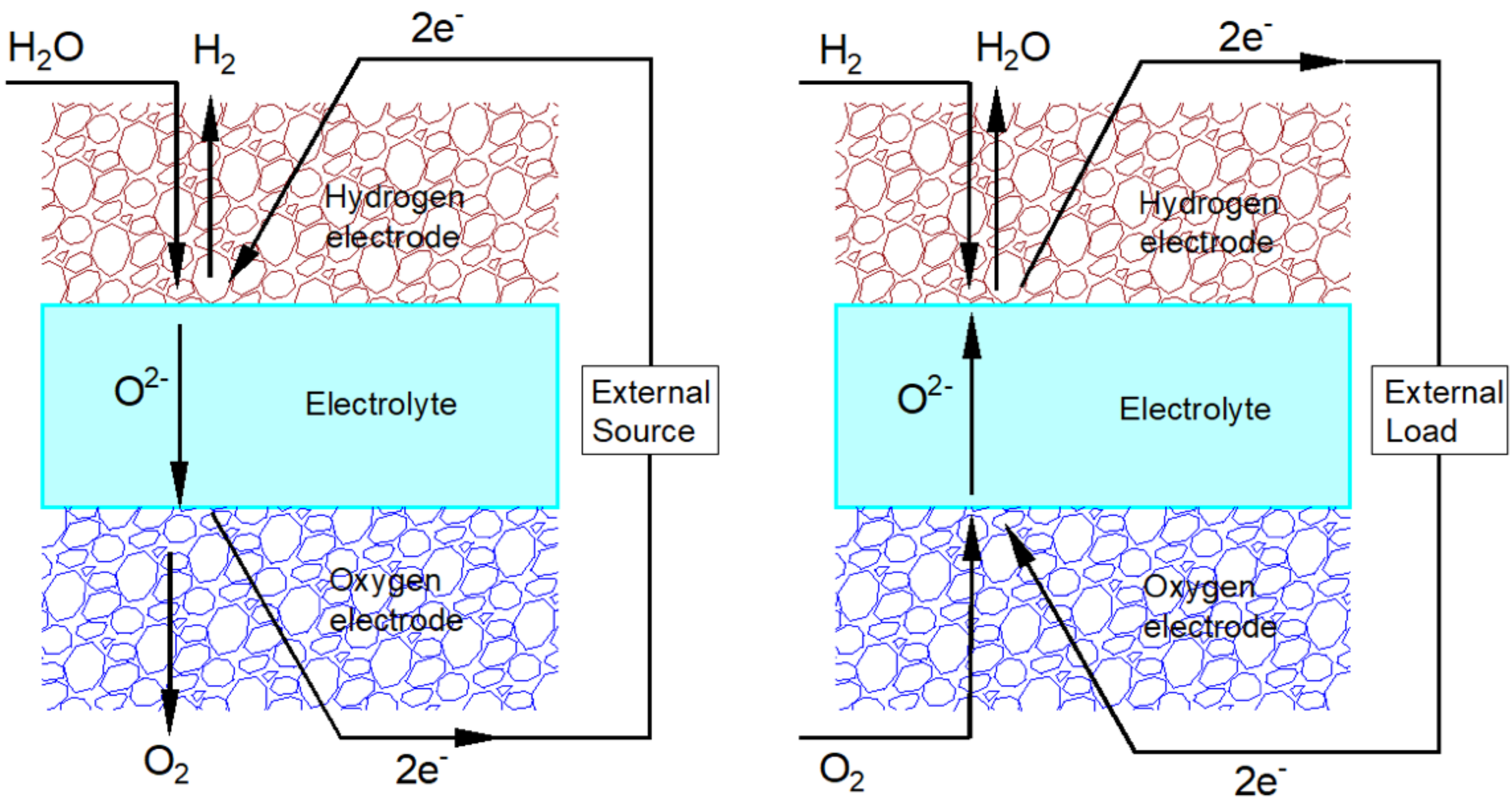

H_2O
H_2
$2e^-$
Hydrogen electrode
O^{2-}
Electrolyte
External Source
Oxygen electrode
O_2
$2e^-$
H_2
H_2O
$2e^-$
Hydrogen electrode
O^{2-}
Electrolyte
External Load
Oxygen electrode
O_2
$2e^-$

Modes

$$H_2 + \frac{1}{2}O_2 \underset{EC\ mode}{\overset{FC\ mode}{\rightleftarrows}} H_2O + electric\ energy + some\ heat$$

(theoretically reversible)

Fuel Cell Mode

- Hydrogen & air → Water
- Generates electricity & heat

Electrolyser Mode

- Water → Hydrogen & Oxygen
- Uses electricity, generates heat

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Cell Efficiency

- Cell Losses
- Balance of Plant

η

Laboratory Setup

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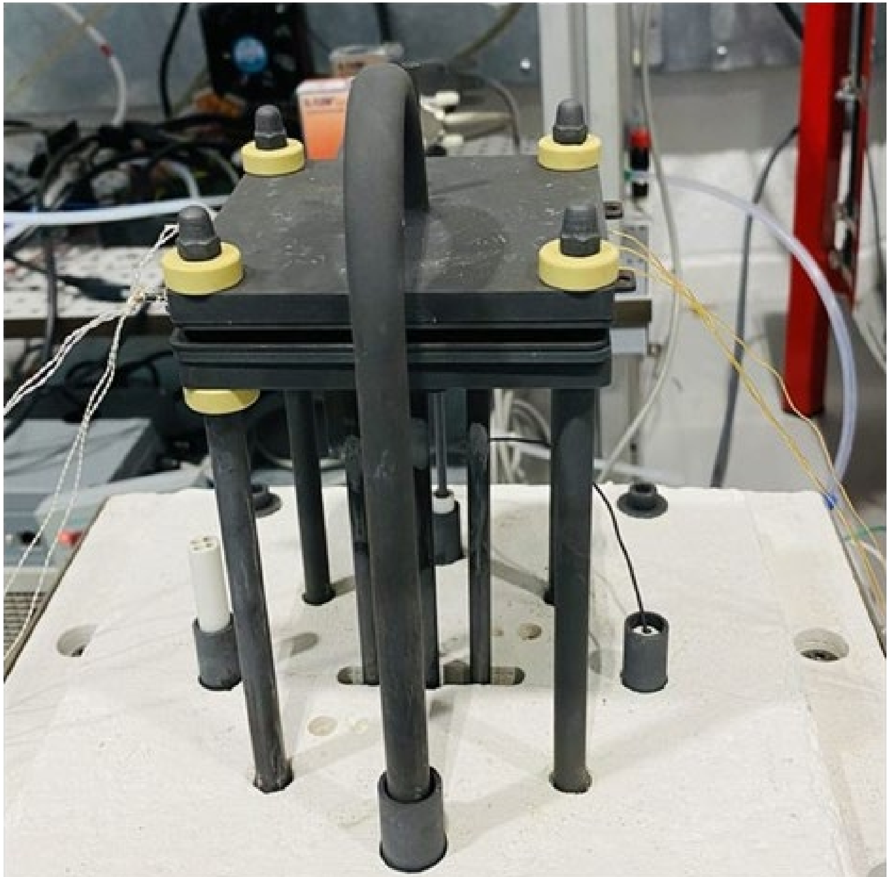
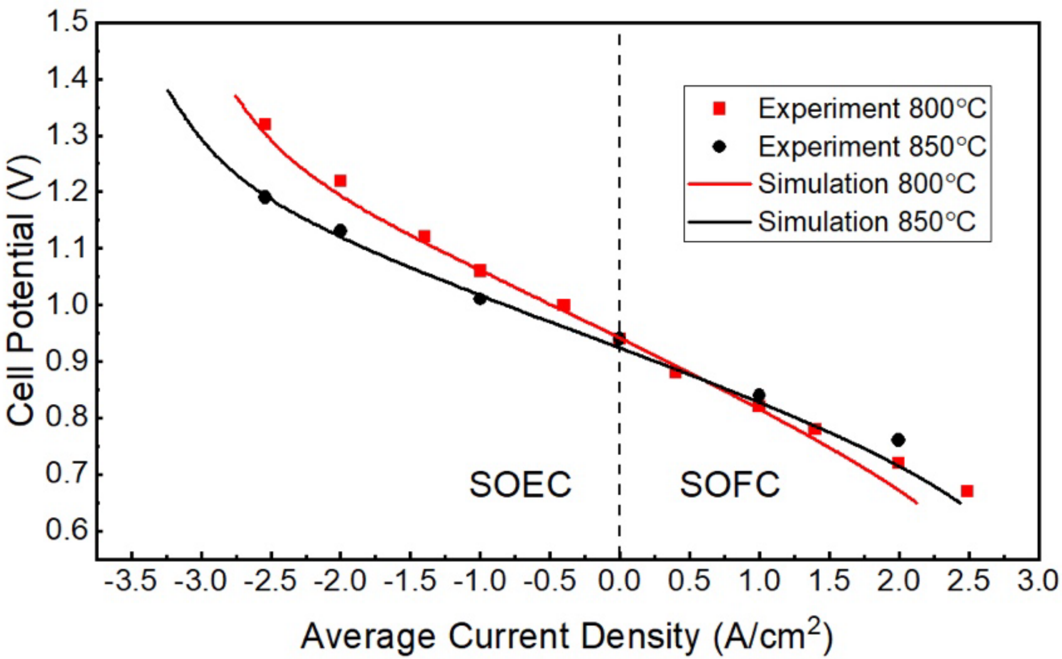


Cell Losses



Z. Zhou et al: Novel porous electrode designs for reversible solid oxide hydrogen planar cell through multi-physics modelling, Fuel Cells, Nov 2022, https://doi.org/10.1002/fuce.202200151

- Resistive losses (I^2R)
  - Conduction
  - Diffusion
- Activation energy
- Saturation effects

Fuel Cell Balance of Plant

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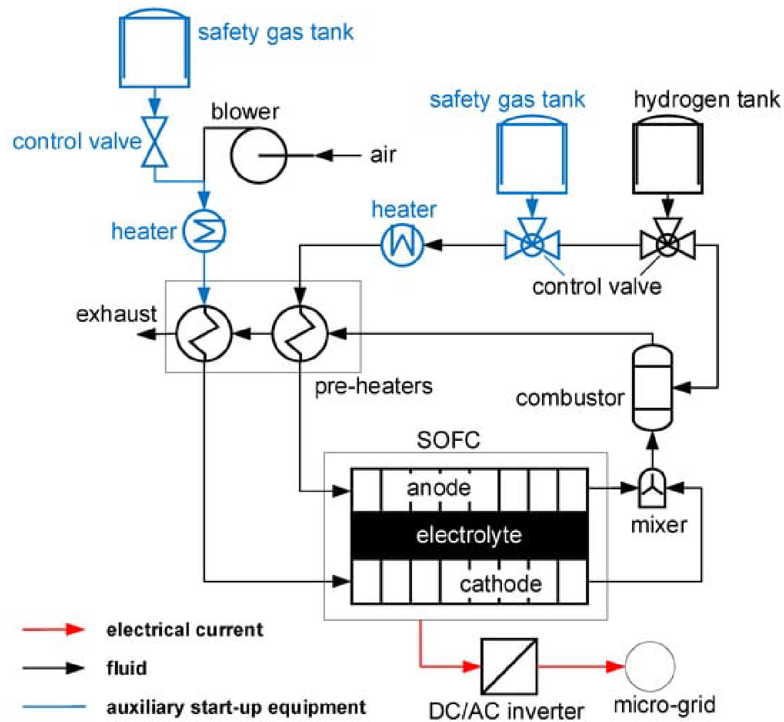

- Hydrogen Storage
- Heating
- Pressurisation
- Humidification
- Recirculation
- Exhaust Treatment

K. Colombo etc al: Start-Up of a Solid Oxide Fuel Cell System with a View to Materials Science-Related Aspects, Control and Thermo-Mechanical Stresses, Crystals 2021, 11(7), 732; https://doi.org/10.3390/cryst11070732

Electrolyser Balance of Plant

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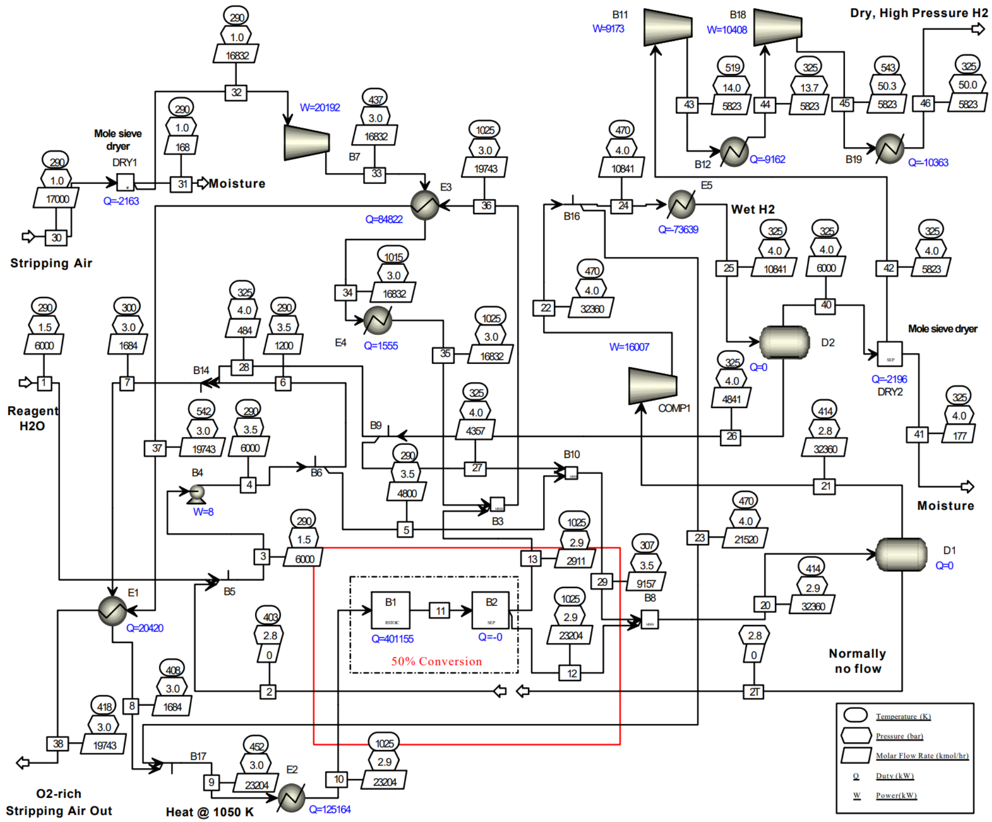

Aspen Plus 12.1 Run:Electrolysis 2004-10-29a 50%H2O-50% Conversion 10/29/2004 11:29:04 AM

US DoE

- Humidification
- Heating
- Cooling
- Pressurisation
- Recirculation
- Hydrogen Separation
- Hydrogen Drying
- Hydrogen Compression

Plant Losses

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- Theoretically, the air compression is the main loss, and it is partially recoverable in the exhaust.
- Practically, we do not have a good model for plant losses/efficiency yet.
- But we know that the losses are significant, and using waste heat will be essential for a good energy balance.

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Application: Combined Heat & Power (CHP)

- Application
- System
- Modes

CHP Principle

https://www.energy.gov/eere/iedo/combined-heat-and-power-basics

Utilise

- Power conversion, e.g. gas to electric
- Use waste heat for heating

Classic Approach

- Heat and energy distribution (we have 3 CHP plants on campus)
- High complexity

Modern Proposal

- Decentralised CHP
- Connect to electricity network (maybe hydrogen)
- More flexibility, less complexity
-

Building Energy Management Systems (BEMS)

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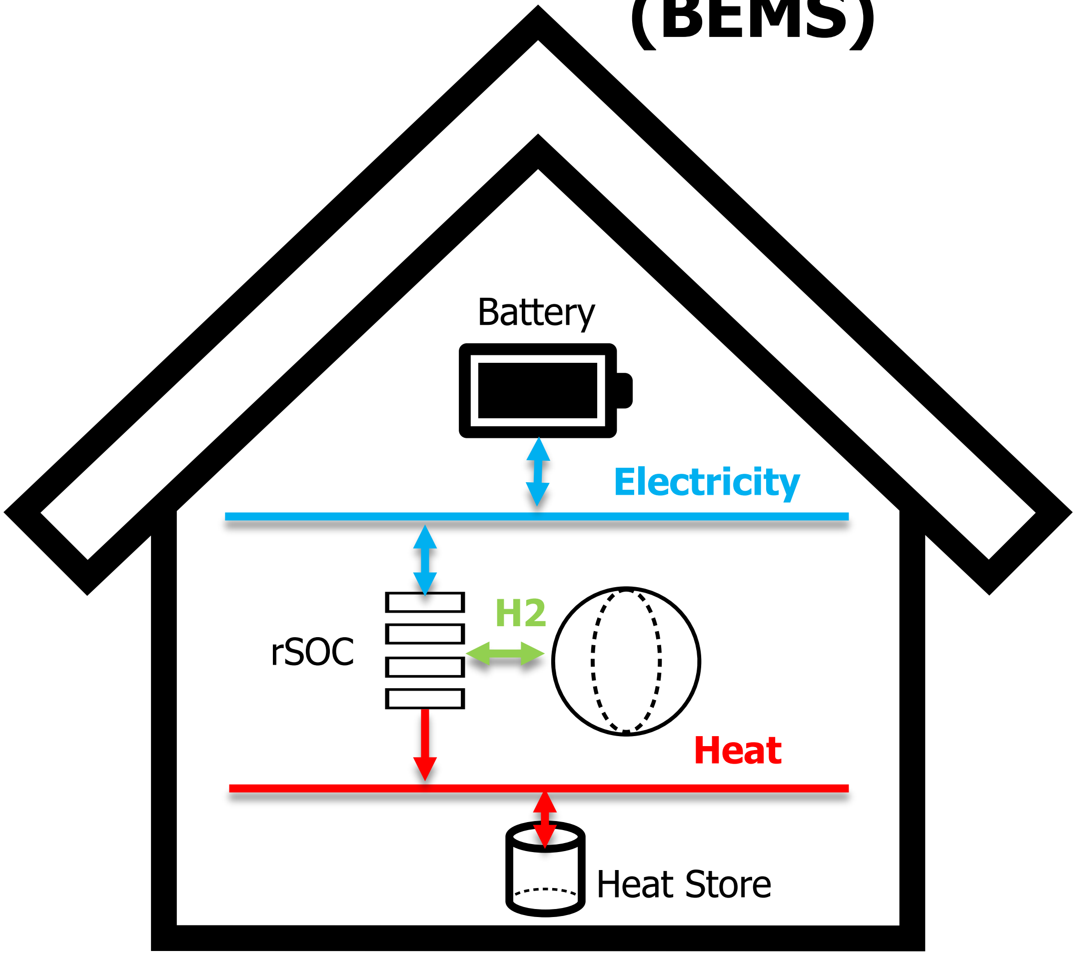
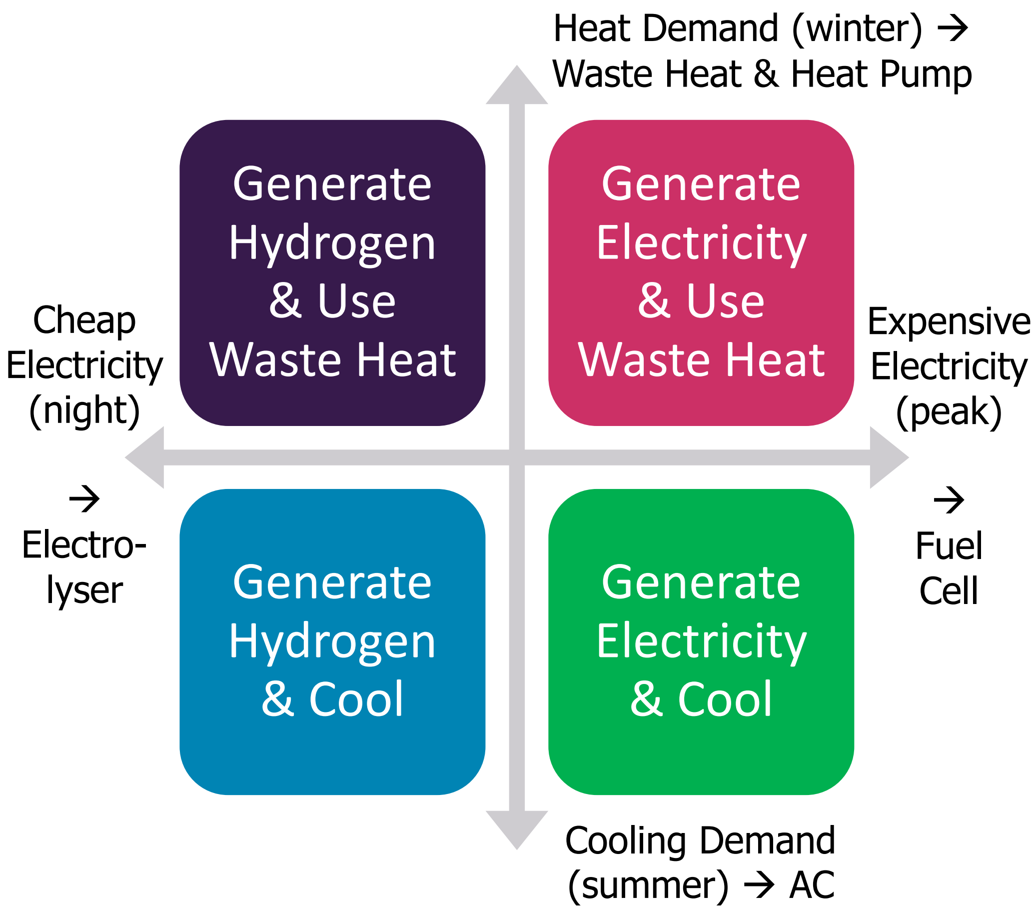


Needs to coordinate three stores:

- Battery
- Hydrogen
- Heat

while satisfying demand & minimising waste.

Operation



Operation depends on

- electricity price
- heat demand
- (hydrogen storage)

This helps with seasonal electricity shortage, especially in winter.

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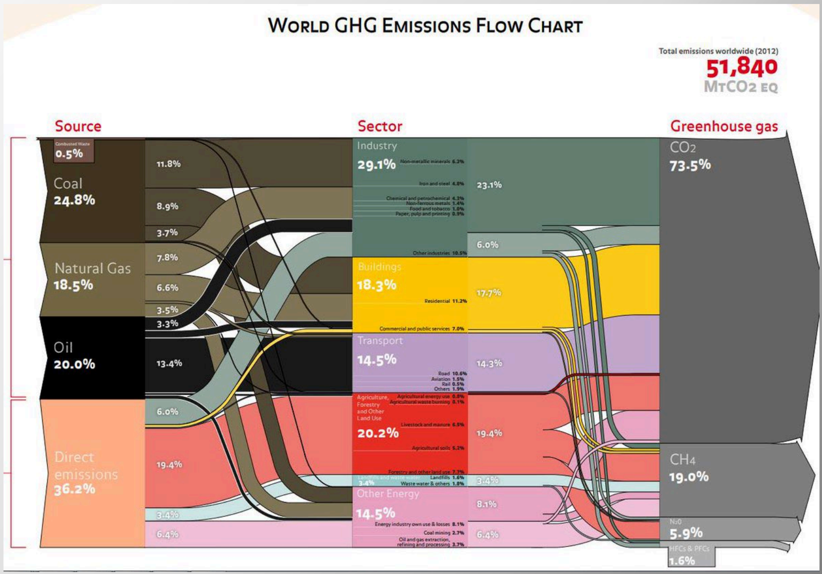
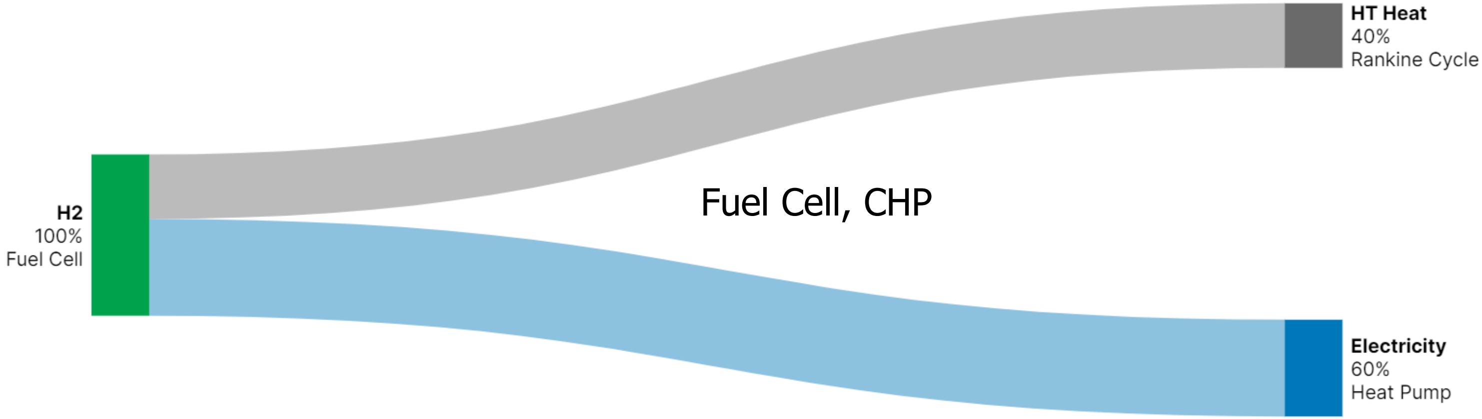
System Efficiency

- Sankey Diagrams
- Options
- Comparison

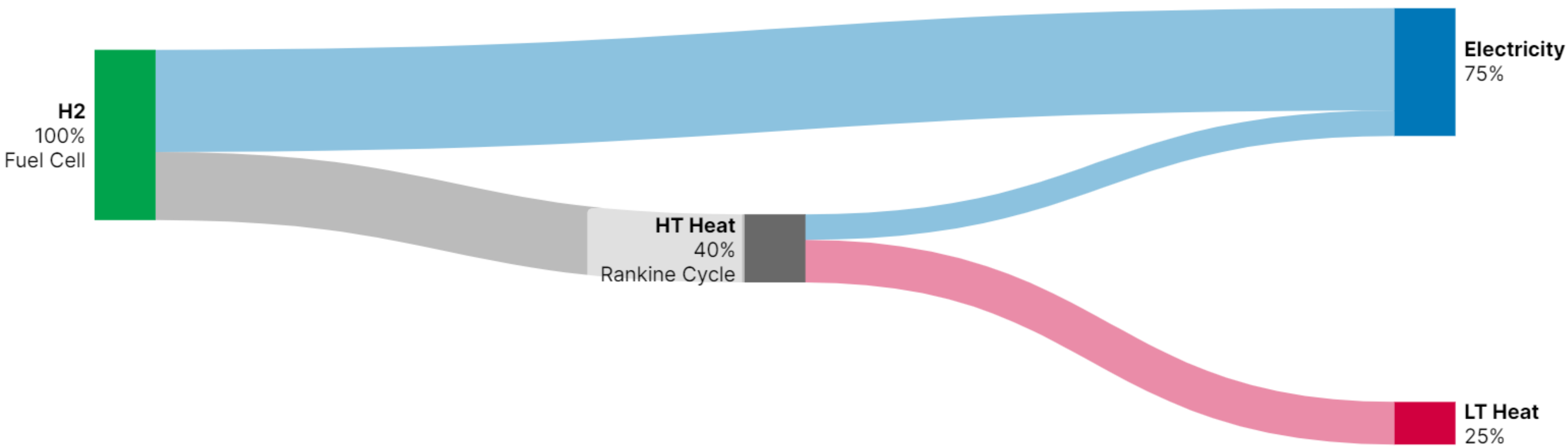


World Greenhouse Gas (GHG) emissions in 2012. Produced by Ecofys (now Navigant).

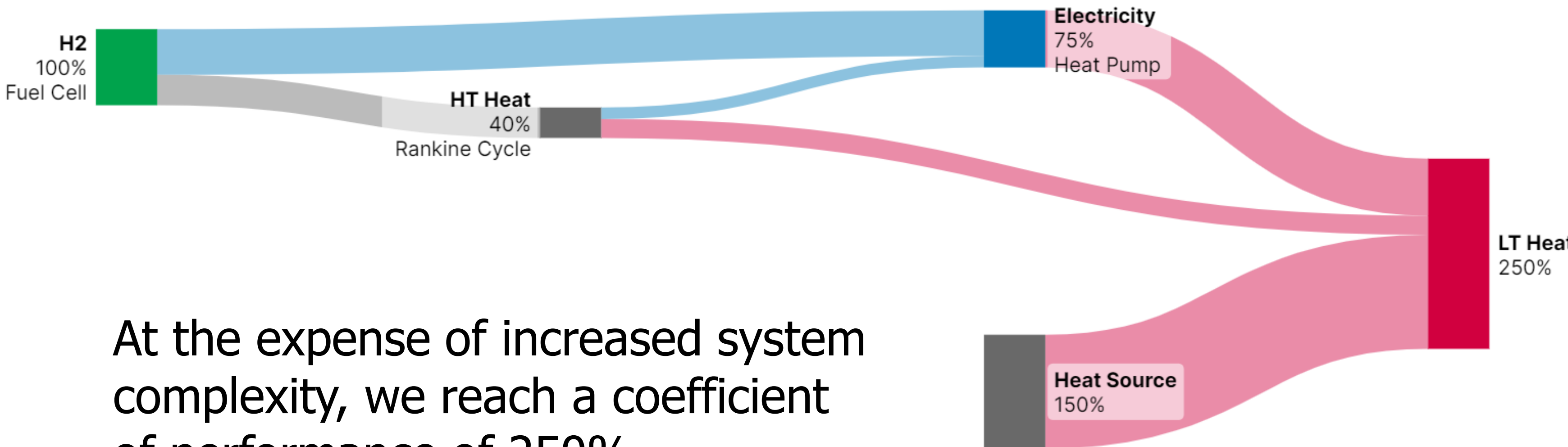
Basic Efficiencies



Waste Heat Recovery



Maximum Heating



At the expense of increased system complexity, we reach a coefficient of performance of 250%.

(Not far from an electric heat pump at 300%.)

Pareto Curve

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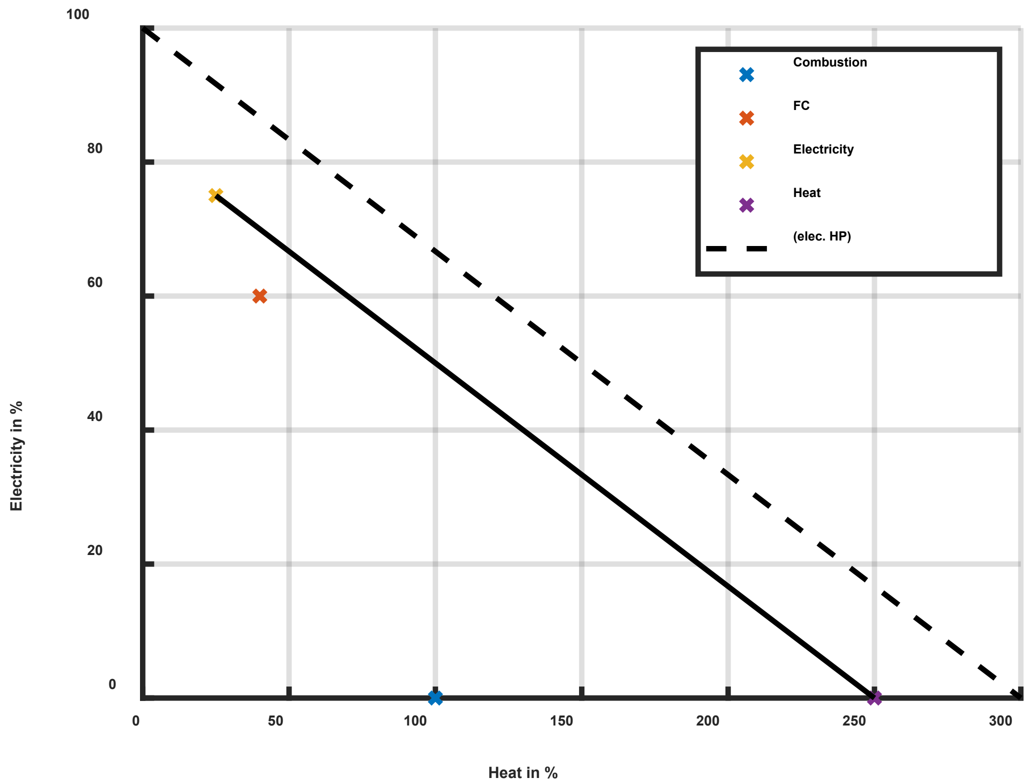

Fuel Cells provide high efficiency use of H2,

in combination with WHR and HP.

(Similar for electrolyser mode)

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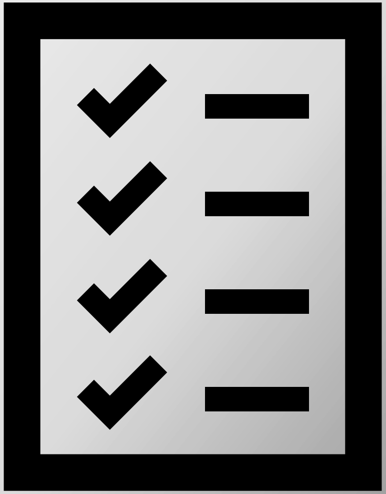
Conclusion

- Efficiency is key
- Q&A



Efficiency of rSOC

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Advantages

- Reversible
- High Temperature

→ high thermodynamic value of waste heat

→ to be used locally

Challenges

- System complexity
- Safety
- Cost
- Durability
- Control

Any Questions?

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