Solar Hydrogen – Status and Trends

Dr. Martin Roeb

International Conference: The renewable hydrogen, new opportunities for Chile, Santiago de Chile, 10th May 2017

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Outline

- International Goals for Decarbonisation of Energy Economy
- Hydrogen Production and Applications
- Potential of Solar Resources
- Solar Hydrogen Production Routes
- Technology and Project Examples
- Summary

Political Drivers: Examples – EU Sustainable Energy Technology Plan (SET-Plan 2007) G7 Goals (2015)

- **Goals of the EU until 2020 (20/20/20)**
  - **20%** higher energy efficiency
  - **20%** less GHG emission
  - **20%** renewable energy
- **Goal of the EU until 2050:**
  - **80%** less CO_2 emissions than in 1990
- **G7 Goals, Elmau, Germany**
  - **100%** Decarbonisation until 2100
  - **100 bln $/year** for climate actions in developing countries, large share by industrial investment

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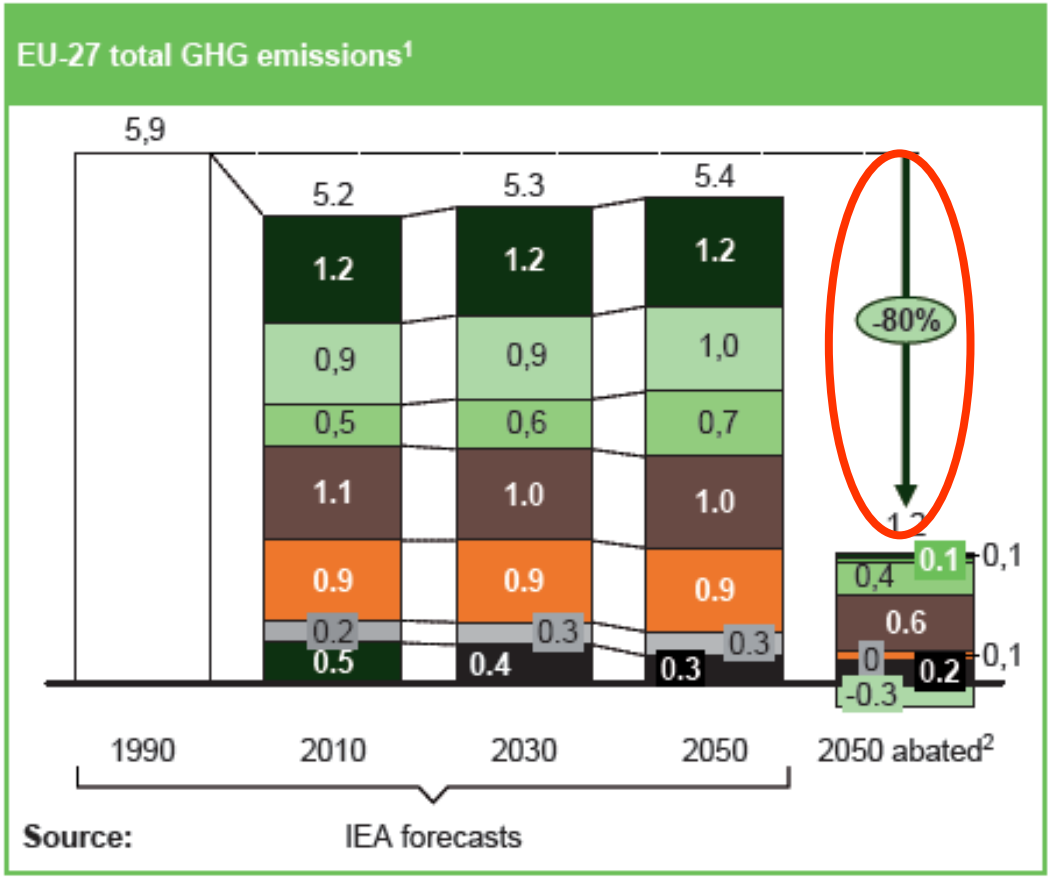
Development of EU GHG emissions [Gt CO_2e]



Sector	Total abatement
Power	95-100%
Road transport	95%
Air & sea transport	50%
Industry[3]	40%
Buildings	95%
Waste	100%
Agriculture	20%
Forestry	-0.25 Gt CO_2e

1 Large efficiency improvements are already included in the baseline based on the International Energy Agency, World Energy Outlook 2009, especially for industry
2 Abatement estimates within sector based on Global GHG Cost Curve
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

SOURCE: www.roadmap2050.eu

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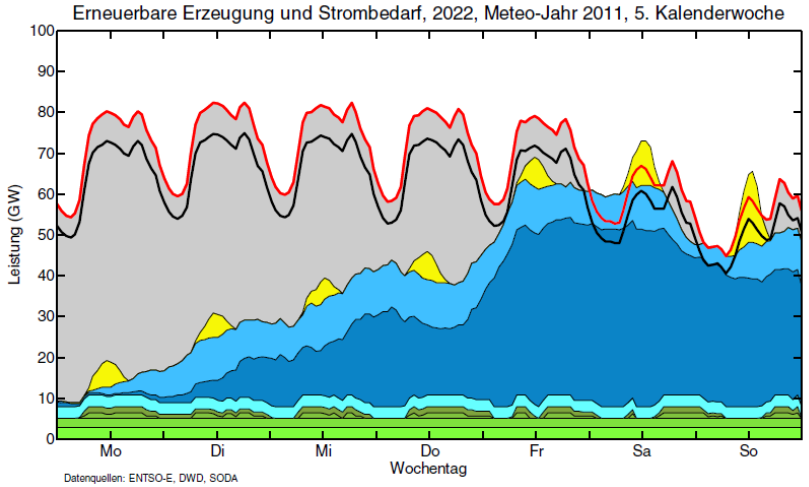
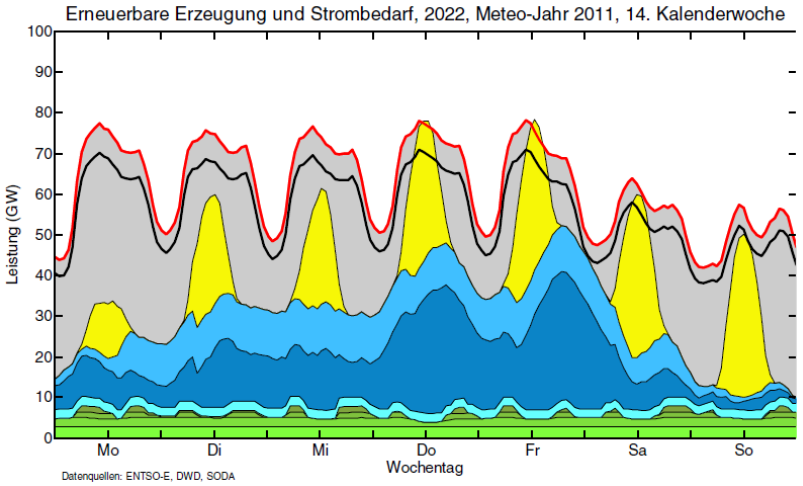
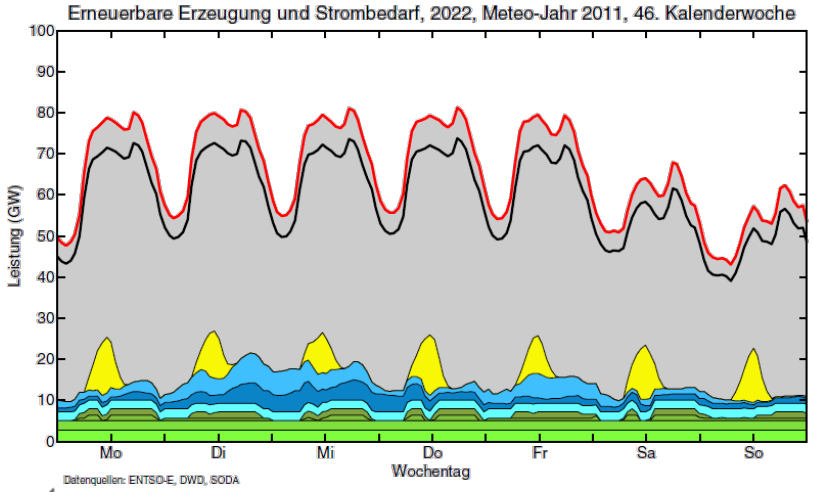
Ambitious goals of IATA

Importance of Storage for Renewable Energy

Forecast: Renewable Energy and Electricity Demand







- Biomasse Grundlast
- Biomasse wärmegeführt
- Biogas flexibel
- Biomethan flexibel
- Wasserkraft
- Onshore-Wind
- Offshore-Wind
- Photovoltaik
- konv. Kraftwerke
- Strombedarf
- ohne Bahnstrom und Arealnetze

Fraunhofer IWES

Agora Energiewende

- **Demand ≠ Production**
  ⇒ Storage needed

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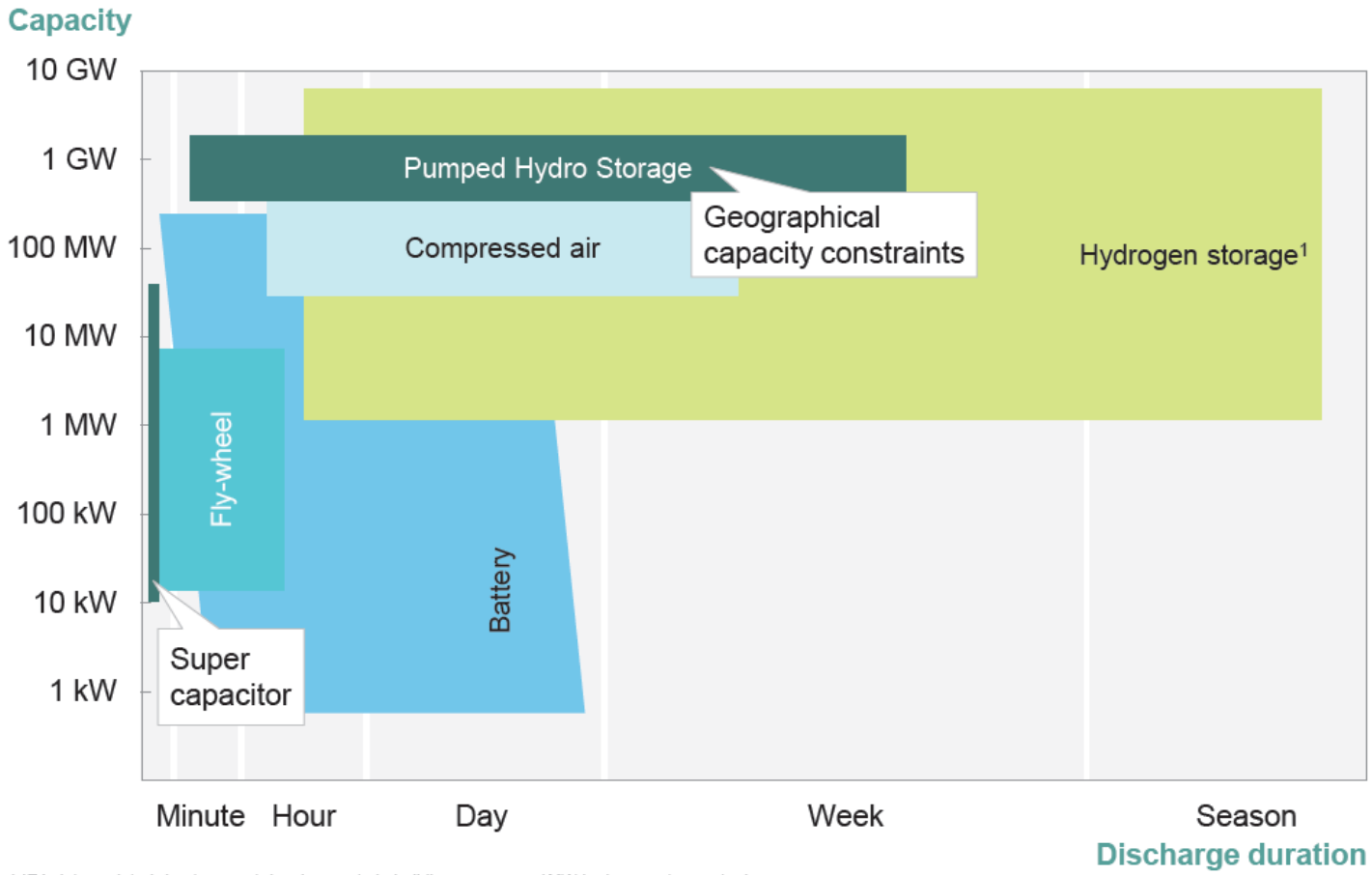
Available Energy Storage Technologies

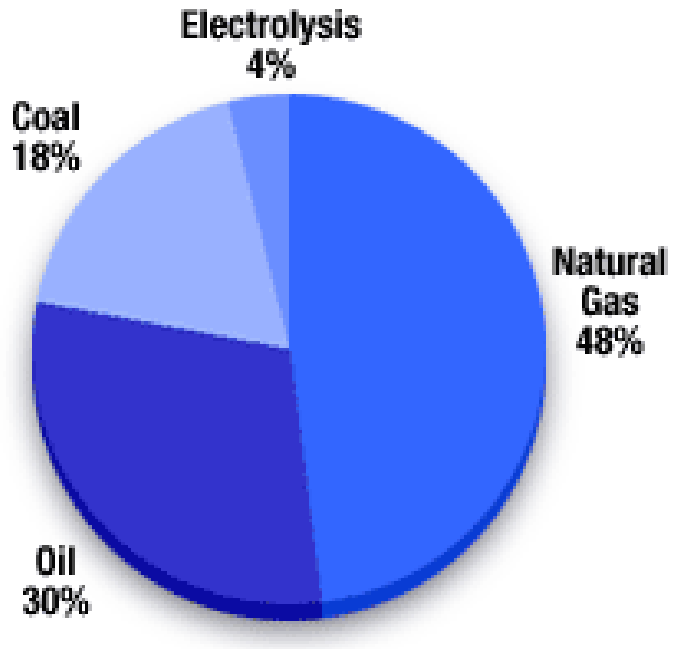


1 IEA data updated due to recent developments in building numerous 1MW hydrogen storage tanks

Source: IEA Energy Technology Roadmap Hydrogen and Fuel Cells, JRC Scientific and Policy Report 2013

Options and Boundary Conditions for a Hydrogen Economy

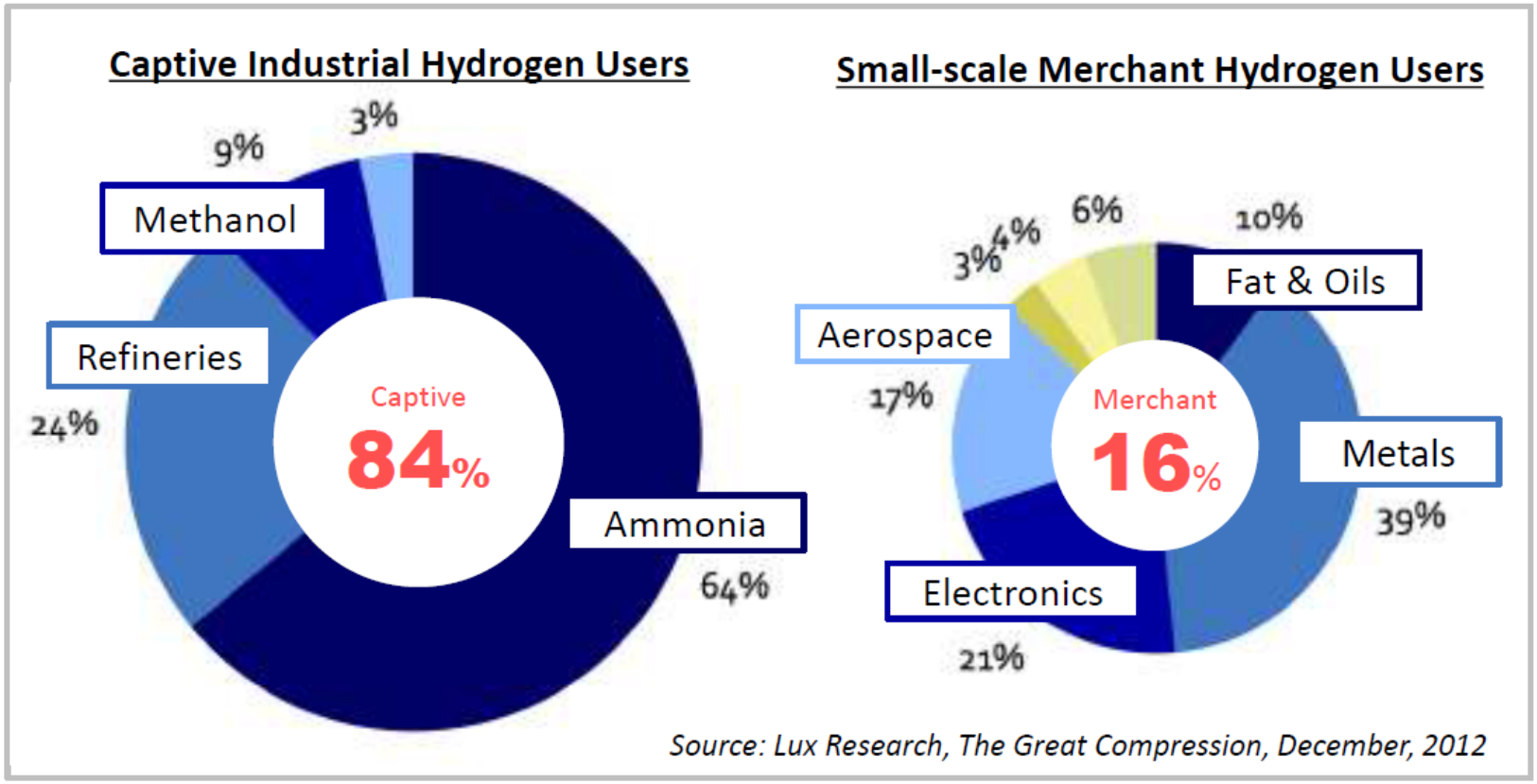
Origin of Hydrogen Today



Production Methods

- Steam and mixed reforming
- Partial oxidation
- Gasification

Applications of Hydrogen



Applications of Hydrogen today and tomorrow

- Raw material of chemical industry
  - e.g. fertiliser production, mineral oil refineries

- Fuels for mobile and stationary applications

Hydrogen vehicles

RVK-Hydrogen Bus

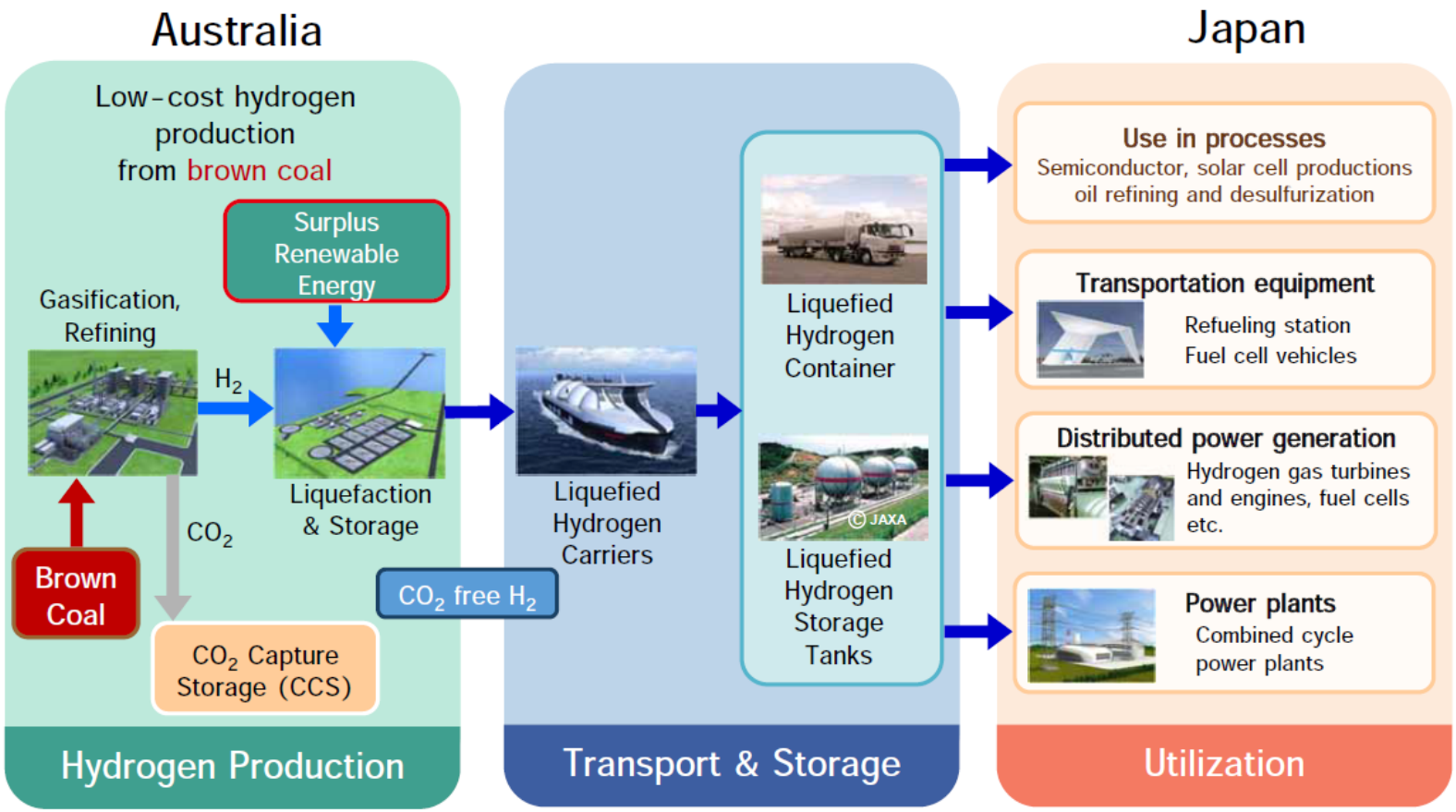
Hydrogen Cars

Fuels cell power plants

4,8 MW-Plant by UTC Power

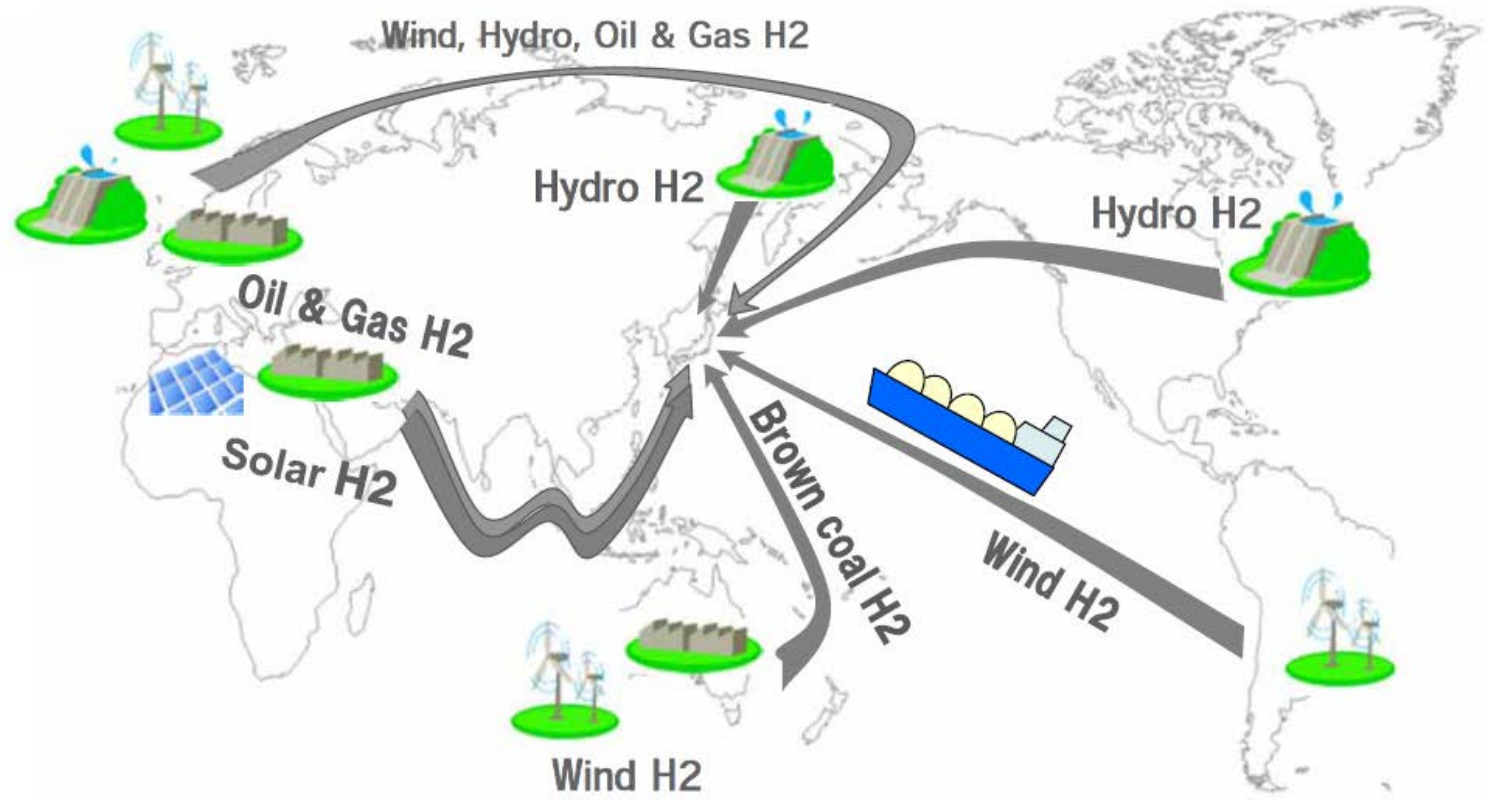
- Generation of liquid hydrocarbons (e.g. **Kerosene**) from hydrogen and CO via **Fischer-Tropsch-Synthesis**

Concept of a CO2-free Hydrogen Supply for Japan



Source: Kawasaki Heavy Ind.

Japan‘s Vision of Future Energy Import



Source: Japan Ministry of Economics (METI)

European visions and objectives

Vision 2020

- To develop by 2020 to the point of market readiness a portfolio of clean, efficient and affordable solutions that fully demonstrate the potential of H2 as an energy carrier and fuel cell as energy convertor, as part of an energy system that integrates sustainable solutions and energy supplies with low carbon stationary and transport technologies.

Objectives:

- to demonstrate by 2020 fuel cell and hydrogen technologies as one of the pillars of future European energy and transport systems, making a valued contribution to the transformation to a low carbon economy by 2050.
- reduce the production cost of fuel cell systems to be used in transport applications, while increasing their lifetime to levels competitive with conventional technologies,
- increase the energy efficiency of production of hydrogen demonstrate on a large scale the feasibility of using hydrogen to support integration of renewable energy

Europe‘s vision on the future hydrogen economy
(source FCH-JU)

Hydrogen R&D in Europe

Fuel Cells & Hydrogen Joint Undertaking

Industry Grouping
Hydrogen Europe
105 members

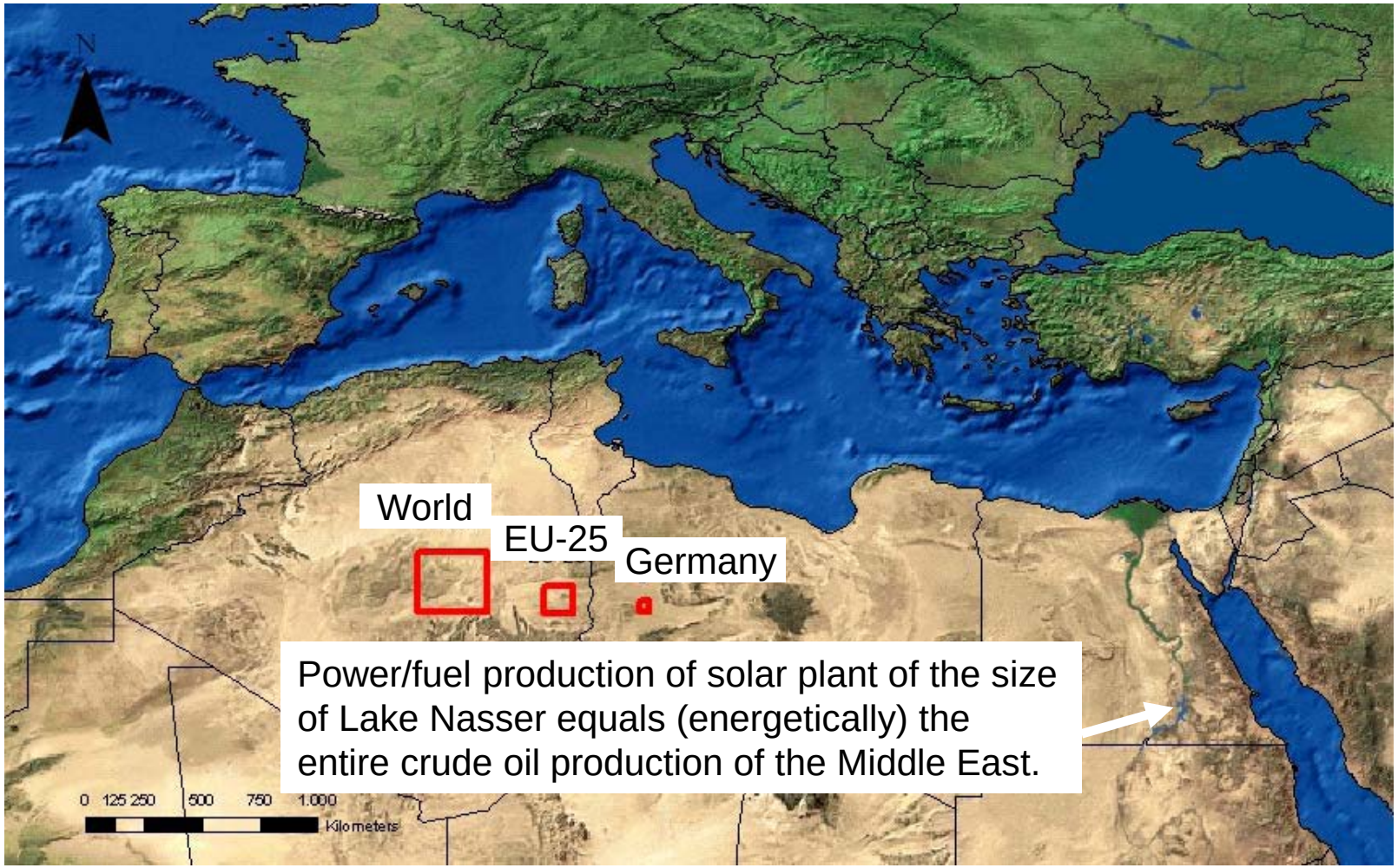
European Union
represented by the
European Commission

Research Grouping
N.ERGHY
65 members

The Joint Undertaking is managed by a Governing Board composed of representatives of all three partners and lead by the Industry.

A portfolio of clean, efficient and competitive solutions *based on fuel cells and hydrogen technologies in energy and transport*

Potential of Solar Energy



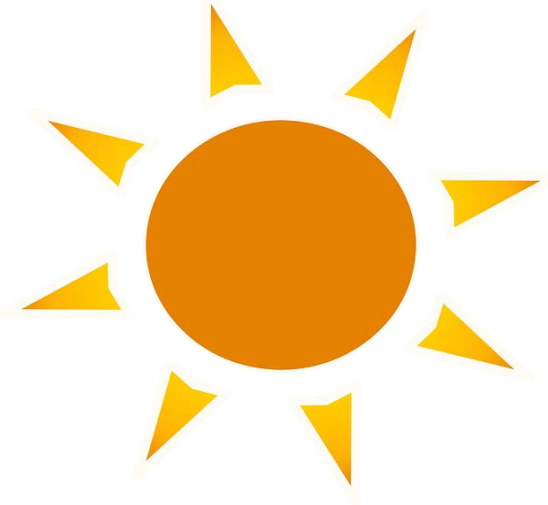
M. Schmitz, TSK Flagsol

Solar Hydrogen Production

Principle of Solar Fuel Production from Water and CO_2

Carbon dioxide (CO_2)

Water (H_2O)

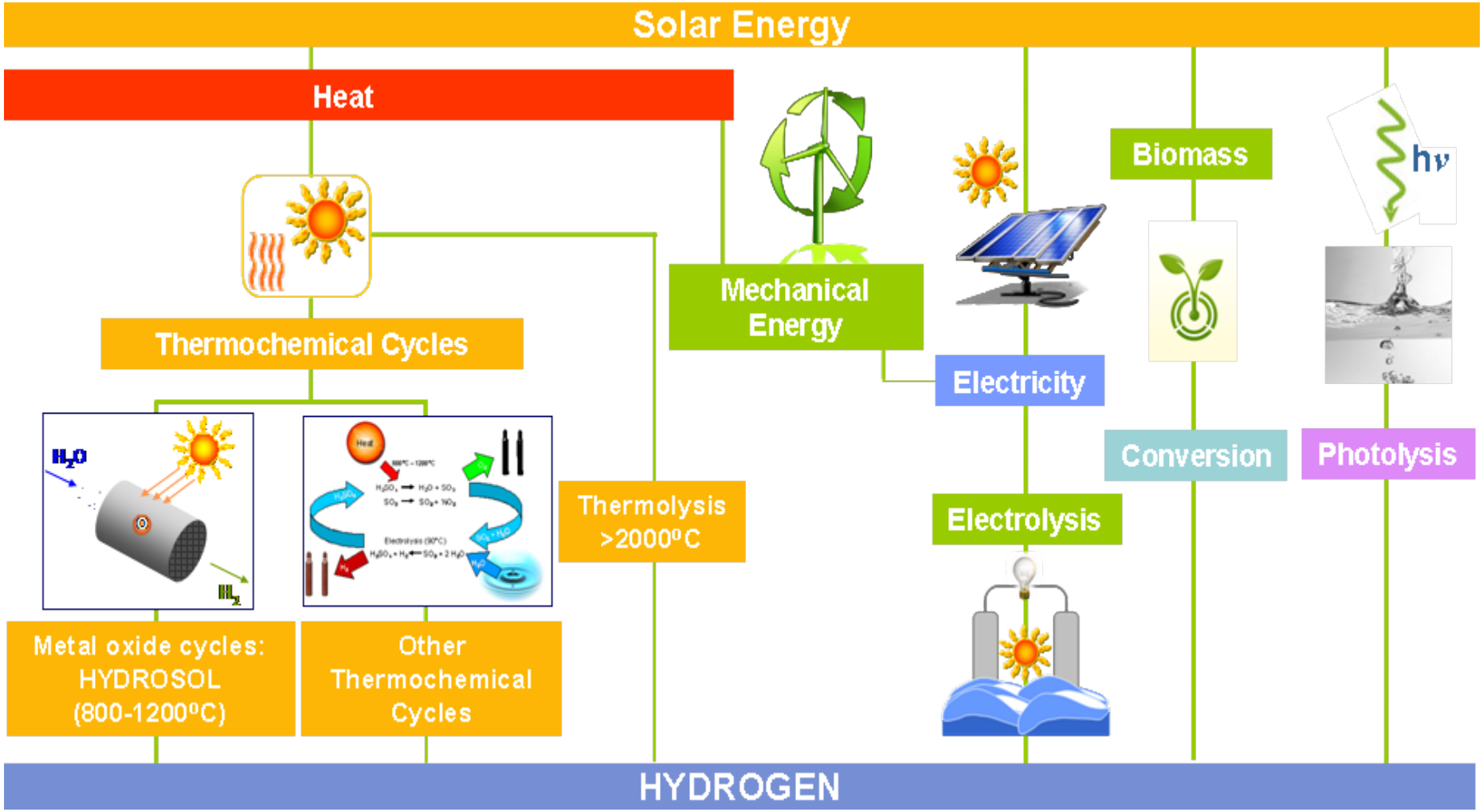


Synthesis gas (H_2 + CO)

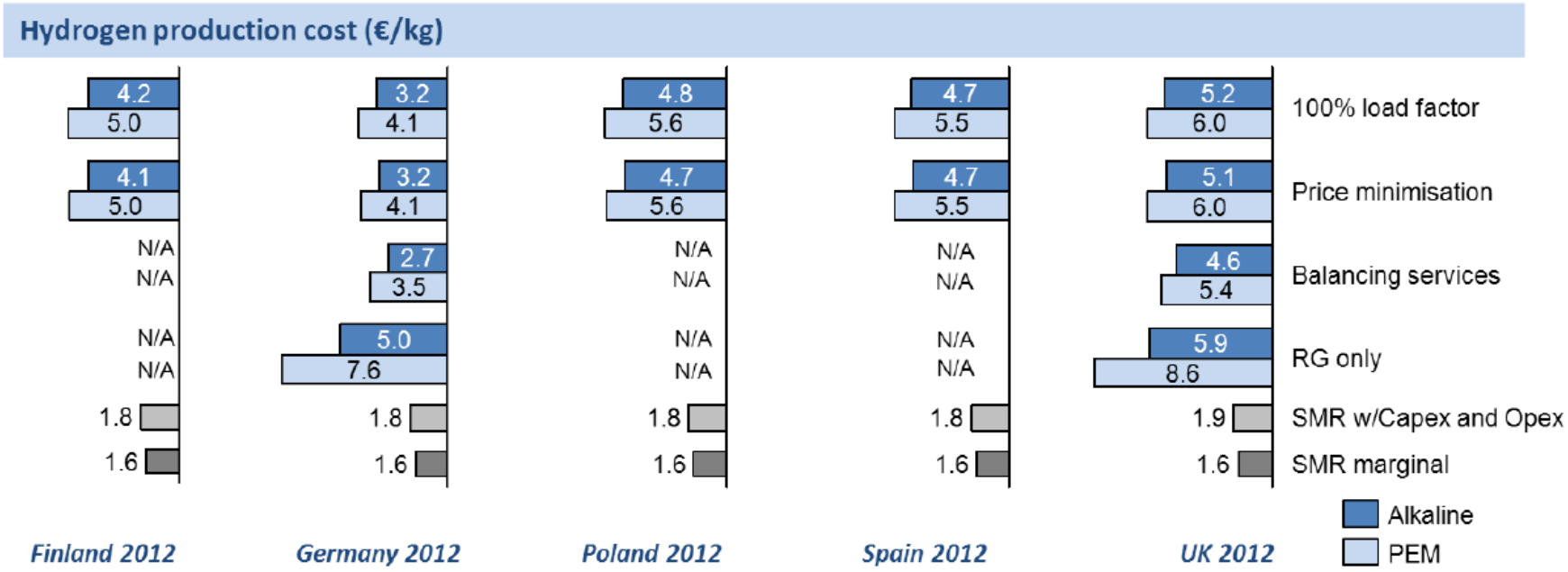
e.g. Fischer-Tropsch-Plant

Sustainable synthetic petrol,
diesel, kerosene
hydrogen, methanol,
(fertilisers, polymers)…

Solar Pathways from Water to Hydrogen Fuel



Hydrogen via Electrolyser: Production Cost
Source: FCH JU



Comparison of Efficiencies of Solar Hydrogen Production from Hydrogen

Process	T [°C]	Solar plant	Solar-receiver + power [MW_{th}]	η T/C (HHV)	η Optical	η Receiver	η Annual Efficiency Solar – H_2
Electrolysis (+CSP or PV)	NA	Actual Solar tower	Molten Salt 700	30%	57%	83%	13%
High temperature steam electrolysis	850	Future Solar tower	Particle 700	45%	57%	76,2%	20%
Hybrid Sulfur-process	850	Future Solar tower	Particle 700	50%	57%	76%	22%
Hybrid Copper Chlorine-process	600	Future Solar tower	Molten Salt 700	44%	57%	83%	21%
Metaloxide two step Cycle	1800	Future Solar dish	Particle Reactor	52%	77%	62%	25%

Siegel, et al. (2013) *Ind Eng Chem Res*

Crescent Dunes, Nevada, USA
110 MW, 10 h Storage, 2015

Khi Solar One, South Africa
50 MW, 2h Storage, 2016

Gemasolar
Sevilla, Spain (2011)
20 MW, 15 h Storage

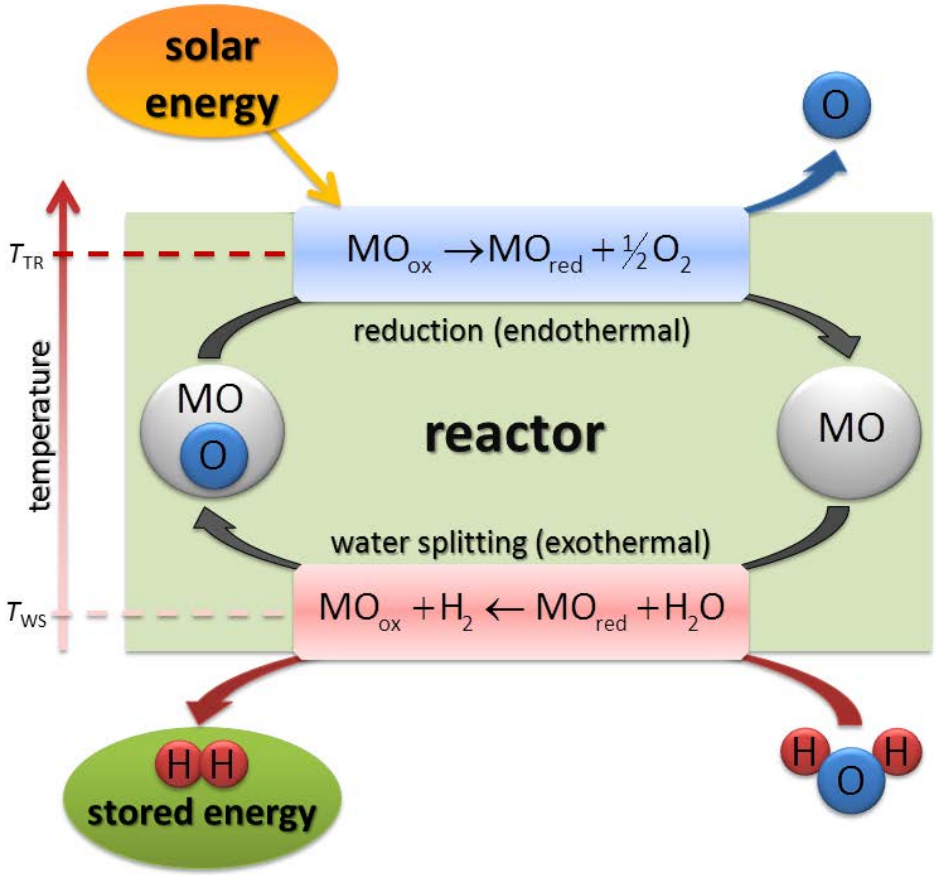
PS10
11 MW, 2007

PS20
20 MW, 2009

Sevilla, Spain

Ivanpah, California, USA (2014)
377 MW, supplies 140.000 households

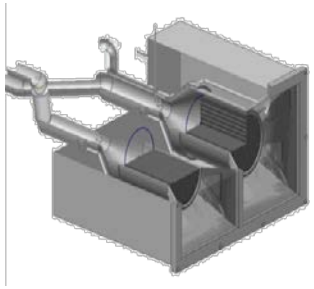
Principle of solar thermal Water Splitting



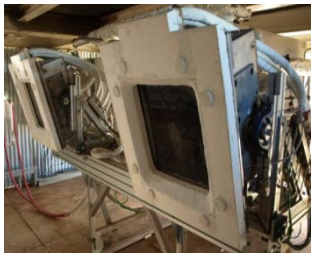
MO = ferrites, ceria, perovskites…

Development of HYDROSOL-Technology

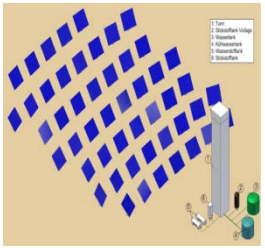
Hydrosol I
2002 – 2005
< 10 kW

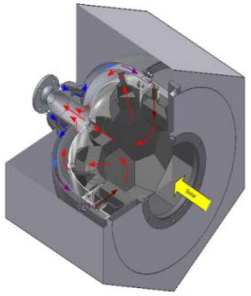


Hydrosol II
2006 – 2009
100 kW

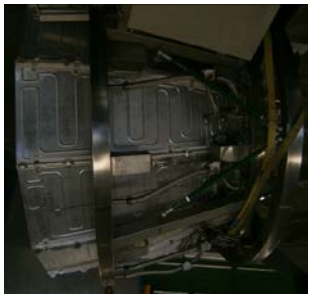


Hydrosol 3D
2010 – 2013
design



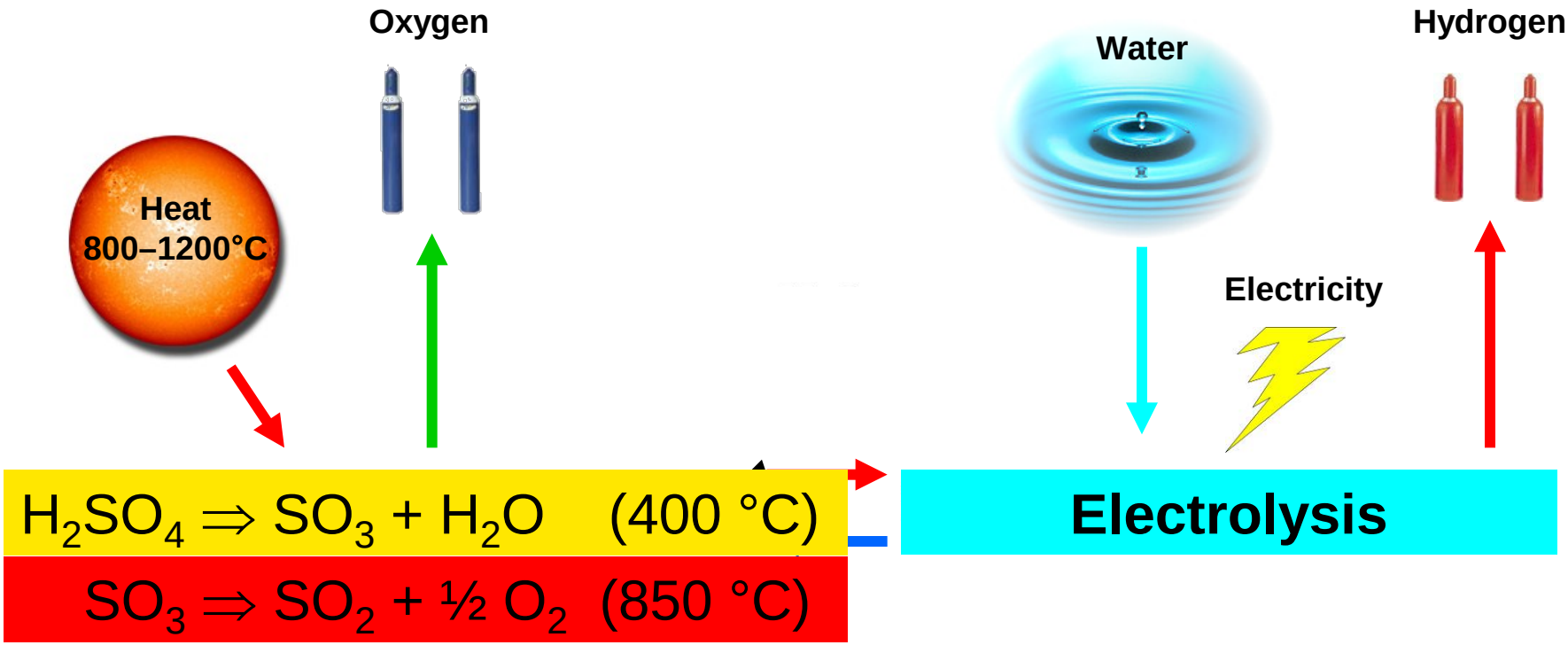


Hydrosol Plant
2013 – 2017
750 kW



Hydrogen Production through solar HyS-Process

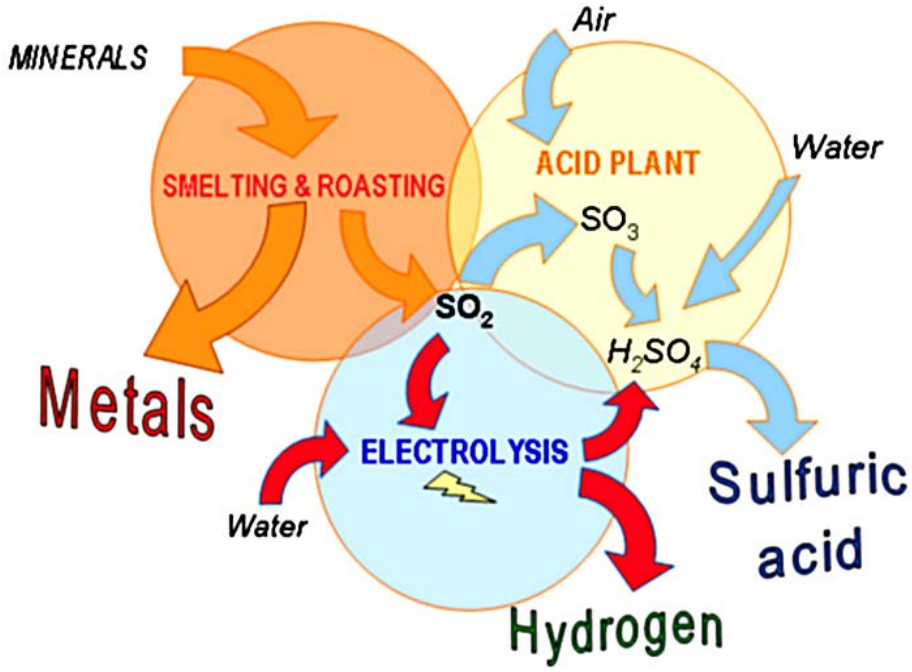
FCH-JU Projekt SOL2HY2



SOL2HY2 – Solar To Hydrogen Hybrid Cycles

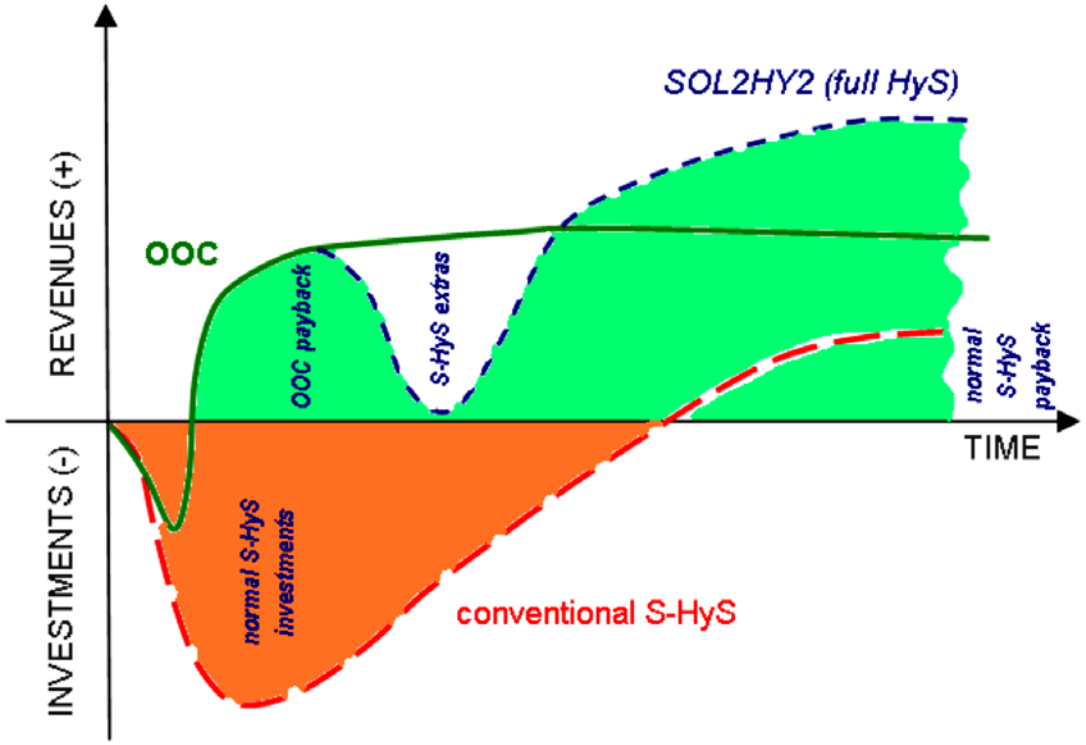
- FCH JU project on the solar driven Utilization of waste SO_2 from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners:
  - **Industry: EngineSoft (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)**
  - Research: Aalto University (FI), DLR (DE), ENEA (IT),

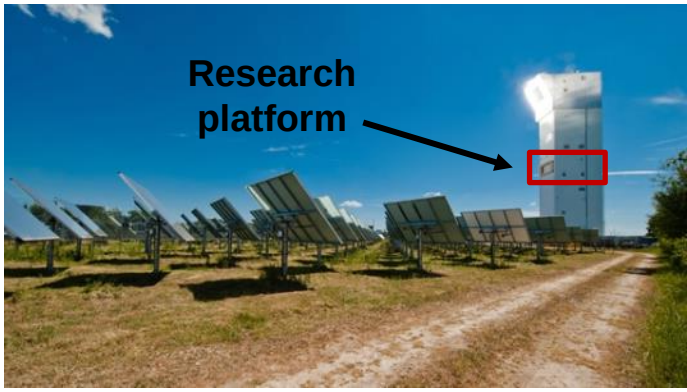
Outotec™ Open Cycle (OOC)



- Utilization of waste SO_2 from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis

Investments vs. revenues





Demonstration on the Solar Tower Jülich
~100 kW total thermal power

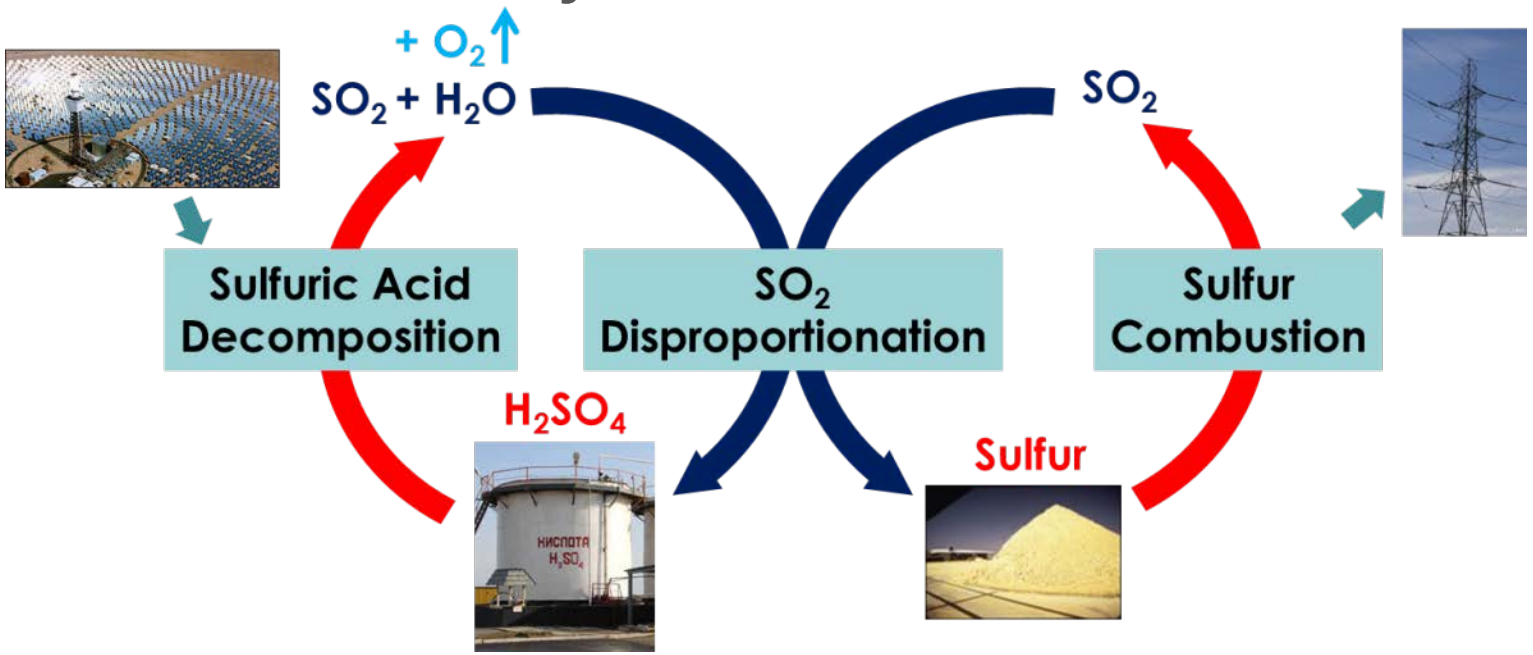
- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues

Thermochemical heat storage can provide very high energy storage densities

Technology	Energy Density (kJ/kg)
Gasoline	45000
Sulfur	12500
Cobalt Oxide	850
Molten Salt (Phase Change)	230
Molten Salt (Sensible)	155
Lithium Ion Battery	580
Elevated water Dam (100m)	1

- **High energy densities with low storage cost**
- **Ambient and long term storage**
- **Transportability**

Solar energy can be stored in elemental sulfur via a three step thermochemical cycle



	Reaction	Temp (°C)
H_2SO_4 Decomposition	$2H_2SO_4 \rightarrow 2H_2O(g) + O_2(g) + 2SO_2(g)$	800
SO_2 Disproportionation	$2H_2O(l) + 3SO_2(g) \rightarrow 2H_2SO_4(aq) + S(l)$	150
Sulfur Combustion	$S(s,l) + O_2(g) \rightarrow SO_2(g)$	1200

Projects carried out by DLR: Solar Process Heat for Industry and Ore Processing

- Solar oxygen and nitrogen production
- Solar fertilizer production
- Solar process heat provision (steam, air, particles…)
- Solar calcination
- Solar cement production
- Solar reduction of metal oxides
- Solar smelting and recycling of metals
- …

Summary

- World energy and fuel demand can be covered by solar energy – driver is the trend to decarbonise the energy economy
- Visions and scenarios for (renewable) hydrogen based energy economy are already there (Japan and EU)
- Several pathways to produce hydrogen without emissions are available
- Solar thermochemical routes are able to split water thermally and highly efficient
- Huge potential to use solar high temperature heat in several industries and mining