Solar Fuels and Electricity by using Sunlight concentrating Systems

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Our Future Visions

- CO₂
- Ammonia
- Water
- Rocket propellant
- Plastics
- H₂ + CO
- Syngas
- Liquid Fuels
- Kerosene
- Polymers
Global Challenges

- Climat change
- Urbanization
- Ressources
- Markets


Note: Designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.
Development of EU GHG emissions [Gt CO$_2$e]

<table>
<thead>
<tr>
<th>EU-27 total GHG emissions$^1$</th>
<th>Sector</th>
<th>Total abatement</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Power</td>
<td>95-100%</td>
</tr>
<tr>
<td>5.2</td>
<td>Road transport</td>
<td>95%</td>
</tr>
<tr>
<td>5.3</td>
<td>Air &amp; sea transport</td>
<td>50%</td>
</tr>
<tr>
<td>5.4</td>
<td>Industry$^3$</td>
<td>40%</td>
</tr>
<tr>
<td>1.2</td>
<td>Buildings</td>
<td>95%</td>
</tr>
<tr>
<td>1.2</td>
<td>Waste</td>
<td>100%</td>
</tr>
<tr>
<td>1.2</td>
<td>Agriculture</td>
<td>20%</td>
</tr>
<tr>
<td>1.2</td>
<td>Forestry</td>
<td>-0.25 Gt CO$_2$e</td>
</tr>
</tbody>
</table>

$^1$ 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
Potential of Solar Energy

WORLD MAP OF GLOBAL HORIZONTAL IRRADIATION

Long-term average of:

Annual sum:
< 700  900  1100  1300  1500  1700  1900  2100  2300  2500  2700>
kWh/m²

Daily sum:
< 2.0  2.5  3.0  3.5  4.0  4.5  5.0  5.5  6.0  6.5  7.0  7.5>

SolarGIS © 2013 GeoModel Solar
Potential of Solar Energy

Power/fuel production of solar plant of the size of Lake Assuan equals (energetically) the entire crude oil production of the Middle East.

Quelle: M. Schmitz, TSK Flagsol
CSP in Canada

- **1 MW$_e$ Demonstration Plant**
  Medicine Hat, Alberta
- Integrated Solar Combined Cycle
  Demonstration plant 1 MW$_e$
- Combined with a local power plant 203 MW$_e$
- Location: 50.04° N; 110.72° W
  Frankfurt: 50.06° N; 8.40° O
- 2544 Sonnenstunden im Jahr
- DNI annual average 1833 kWh/m²
- Annual production 4100 MWh$_{th}$ = 1380 MWh$_e$

DNI annual average

- 700 - 900
- 901 - 1100
- 1101 - 1300
- 1301 - 1500
- 1501 - 1700
- 1701 - 1900
- > 1900

Source: NRCAN/CANMET

Global CSP Market

CANADA - 1 MW
USA - 1745 MW
MEXICO - 14 MW
SPAIN - 2304 MW
MOROCCO - 530 MW
MENA - 700 MW
INDIA - 500 MW
THAILAND - 5 MW
CHINA - 1360 MW
AUSTRALIA - 30 MW

WORLDWIDE - 8784 MW

http://www.nrel.gov/csp/solarpaces/

OPERATIONAL    UNDER CONSTRUCTION    DEVELOPMENT

Last updated December 2016
Japan’s Strategic Roadmap towards a hydrogen society
(Agency for Natural Resources and Energy, METI, 2014, revised March 2016)

**Phase 1**
- 2009: ENE-FARM DFC Program
- 2015: 120,000 DFC
- Summer Olympic Games Tokyo 2020: 40,000 FCV
- 2030: 800,000 FCV
- 2040: 5,300,000 DFC

**Phase 2**
- Full-fledged introduction of hydrogen power generation
- Establishment of a large-scale system for supplying hydrogen

- Accelerating development and demonstration
- Establishing a strategic partnership with hydrogen-suppliers overseas
- Realizing inexpensive hydrogen, anticipating growth in demand

**Phase 3**
- Establishment of a zero-carbon emission hydrogen supply system throughout the manufacturing process

- Late 2020’s:
  - H₂ price (CIF): $3.25/kg
  - 30 JPY/Nm³ = 30ct/Nm³

Japan sets the target to procure “CO₂-free” hydrogen in 2040 and looks for clean and cost competitive hydrogen globally.

DFC: Domestic Fuel Cell
FCV: Fuel Cell Vehicle
CIF: Cost, Insurance, Freight
Japanese energy mix 2013: 303 GWe,

- 44 GWe nuclear,
- 36 GWe coal,
- 41 GWe oil,
- 51 GWe autoproducers’ ‘combustible fuels’
- 13 GWe solar
- 2.6 GWe wind

(1GWe hydrogen power plant (100% H\textsubscript{2} fuel)
200,000\textasciitilde400,000 ton/yr
\textasciitilde2\textasciitilde4 million FCVs

(Source: IEA, 2014)
Kawasaki Vision – Hydrogen Potential from Overseas

Diagram showing various sources of hydrogen (Wind, Hydro, Oil & Gas, Solar, Brown coal) and their potential for hydrogen production and distribution around the world.
Kawasaki vision for the cryogenic liquid hydrogen market – team-up with Shell (March 15, 2016)

Technical Challenges – High temperatures and constant conditions
Promising and well researched Thermochemical Cycles

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>Steps</th>
<th>Maximum Temperature (°C)</th>
<th>LHV Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulphur Cycles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid Sulphur (Westinghouse, ISPRA Mark 11)</td>
<td>2</td>
<td>900 (1150 without catalyst)</td>
<td>43</td>
</tr>
<tr>
<td>Sulphur Iodine (General Atomics, ISPRA Mark 16)</td>
<td>3</td>
<td>900 (1150 without catalyst)</td>
<td>38</td>
</tr>
<tr>
<td><strong>Volatile Metal Oxide Cycles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc/Zinc Oxide</td>
<td>2</td>
<td>1800</td>
<td>45</td>
</tr>
<tr>
<td>Hybrid Cadmium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Non-volatile Metal Oxide Cycles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>2</td>
<td>2200</td>
<td>42</td>
</tr>
<tr>
<td>Cerium Oxide</td>
<td>2</td>
<td>2000</td>
<td>68</td>
</tr>
<tr>
<td>Ferrites</td>
<td>2</td>
<td>1100 – 1800</td>
<td>43</td>
</tr>
<tr>
<td><strong>Low-Temperature Cycles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid Copper Chlorine</td>
<td>4</td>
<td>530</td>
<td>39</td>
</tr>
</tbody>
</table>
## Solar Hydrogen by Water Splitting: Efficiency Comparison vs. Benchmark

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature of the Chemical Reaction</th>
<th>Solar Interface Receiver Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline Electrolysis</td>
<td>25°C</td>
<td>Solar PV</td>
</tr>
<tr>
<td>High temperature steam electrolysis</td>
<td>850°C</td>
<td>Future solar tower 1200°C</td>
</tr>
<tr>
<td>Thermochemical cycle with ceria</td>
<td>1500°C / 1150°C</td>
<td>Future solar dish 1500°C</td>
</tr>
</tbody>
</table>

*G.J. Kolb, R.B. Diver SAND 2008-1900 / N. Siegel et al. I&EC Research May 2013*
Temperature Levels of Solar Concentrators

- **Paraboloid „Dish“**
  - Concentration < 10,000
  - Power < 500 kW_{th}

- **Solar Tower**
  (Central Receiver System)
  - Concentration > 100
  - Power > 100 MW_{th}

- **Parabolic Trough / Linear Fresnel**
  - Concentration 10 - 100
  - Power 10 - >100 MW_{th}
Maximum Concentration of Solar Radiation on Earth

\[ C_{\text{max},3D} = \frac{A}{A'} = \frac{\sin^2 90^\circ}{\sin^2 0.267^\circ} \approx 46200 \]

\[ C_{\text{max},2D} = \frac{A}{A'} = \frac{\sin 90^\circ}{\sin 0.267^\circ} \approx \sqrt{46200} = 215 \]

\[ C_{\text{max}} = 46200 \cdot 0.5 \cdot 0.5 = 11550 \]

\[ C_{\text{max}} = 215 \cdot \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} = 107.5 \]
Heliostat

- Components

Sanlucar (120 m²), Abengoa Solar S.A.
Heliostat Facets

Heliostat with rectangular mirror facets

Metal foil heliostat with round facets

Steinmüller
150 m² Heliostat
Heliostat Cost

Cost reduction potential

Solucar PS10 heliostat 120m² or 90m²

Cost: 130 €/m²

Components:
- Mirrors 5%
- Frame 10%
- Structure 25%
- Drives 50%
- Column 5%
- Control unit 5%

Weight: 38kg/m²
By windload at 45 km/h

Minimum cost: 70 €/m²
Steel min. 2 €/kg

Maximum Cost reduction: 46%
Heliostat Control

- **Standard**
  - Control and energy supply by wire
  - Excavation necessary

- **Autonomous**
  - Radio control
  - Energy supply by PV-Module
  - Capacitor storage

http://autor.trinamic.com/heliomesh-project/
Solar Field Development

Solar fields need to fit the requirements of the process
- Availability
- Concentration
- Secondary optics
- Location


Heliostat Field Design

• **Field Design**
  - Dimensioning of the solar field
  - Choice, number, and positioning of the heliostats
  - Mirror quality and field design are decisive for the efficiency and the cost
• **Field Optimization**
  - Position of the heliostats,
  - Tower height
  - Receiver size
• Optimization tools are available (e.g. HFLCAL)
Heliostat Fields: Efficiency depends on Location

Annual efficiency [%]
Latitude [°]

- North field
- Round field
Heliostat field Layouts

North fields, Abengoa Solar, 37°N
Sanlucar la Mayor, Spain

Round field, SolarReserve, 38°N
Crescent Dunes, Tonopah, NV, USA
Solar Towers

Crescent Dunes

Khi Solar One

Atacama-1

Torresol

PS-10

On the Web:
http://www.ivanpahsolar.com/
http://www.torresolenergy.com/TORRESOL/home/en
Secondary Concentrators

Diameter of a heliostat field focus is several meters

To increase the concentration and reduce the aperture area secondary mirror optics are used

REFOS Secondary concentrator
CESA-I Tower
Plataforma Solar de Almería, Spain
Absorption losses ca. 8-12%
Efficiency 75 – 90 %
Aperture area reduction 4-5 times
Compound Parabolic Concentrator

\[ C_{3D} = \frac{A}{A'} = \frac{\sin^2 \Theta'}{\sin^2 \Theta} \]

Radiation acceptance angle

\[ \Theta = \arcsin \sqrt{\frac{A'}{A}} \]
Secondary Concentrators
Beam-down concept with tower reflector
Beam-down with tower reflector,
Weizmann Institute of Science, Rehovot, Israel
Beam-down with tower reflector,
Weizmann Institute of Science, Rehovot, Israel
Beam-down with tower reflector,
Mitaka Khoki, Nagano, Japan
Beam-down with tower reflector,
Mitaka Khoki, Nagano, Japan
CO₂ Reduction by solar heating of state of the art processes like steam methane reforming and coal gasification

$T = 650 \text{ – } 1000^\circ\text{C}$
Atlas of Annual Direct Normal Irradiance

DNI 2002 in kWh/m²/y
Atlas of Exclusion Areas
Atlas of Natural Gas Pipelines and Gas Fields
Overlay of Data Sets for Algeria

- 50 km Distance to Pipeline
- Acceptable DNI
- Available Land Area
Overlay of Data Sets for Italy

- 50 km Distance to Pipeline
- Acceptable DNI
- Available Land Area
Statistical Analysis

Available Heat at Receiver
ASTERIX: Allothermal Steam Reforming of Methane

- DLR, Steinmüller, CIEMAT
- 180 kW plant at the Plataforma Solar de Almería, Spain (1990)
- Convective heated tube cracker as reformer
- Tubular receiver for air heating
Near-term: Solar Production of Syngas (H₂ and CO)

Solar pilot plants demonstrated in the power range of 200-600 kWₜₐₜₜ

Solar steam reforming of natural gas / methane

Solar steam gasification of carbonaceous feedstock

SOLGAS (200 + 600 kWₜₐₜₜ) CSGIO, Australia

SOLREF (400 kWₜₐₜₜ) DLR, WIS, Germany, Israel

SYNPET (500 kWₜₐₜₜ) CIEMAT, Spain

SOLSYN (250 kWₜₐₜₜ) PSI, Switzerland
Scale-up of solar Natural Gas Reforming

- Australian Solar Fuels Program
- CSIRO develops industrial reformer
- 15 MW Demonstration at a natural gas well in the Western Australia Outback is planned

Robbie McNaughton, CSIRO, Australia
Thermochemical Cycles

$\text{MO}_{\text{ox}} \rightarrow \text{MO}_{\text{red}} + \text{O}_2$

reduction (endothermal)

$\text{H}_2\text{O}/\text{CO}_2$ splitting

$\text{MO}_{\text{ox}} + \text{H}_2/\text{CO} \leftrightarrow \text{MO}_{\text{red}} + \text{H}_2\text{O}/\text{CO}_2$

fuel (syngas)

concentrated solar power

storing solar energy

$T_{\text{red}}$

$T_{\text{ox}}$
HYDROSOL - An example for solar thermochemical water splitting (800 – 1200°C)

Hydrosol I
2002 – 2005
< 10 kW

Hydrosol II
2006 – 2009
100 kW

Hydrosol 3D
2010 – 2012
1 MW
HYDROSOL II
Heliostat Operation

7 additional heliostats for heating

24 heliostats

21 heliostats

Receiver plane

ca 110 kW/m²

ca 110+250 kW/m²

0 kW/m²
Hydrosol – Operation of Pilot Reactor

\[ \text{Flux}_{\text{Max, both Modules}} = 115 \text{ kW/m}^2 \]
Modelling - Interface Heliostat Simulation Tool:

Power East (23.04.2009)

- Regeneration
- Production

Chart 47

DLR.de • Chart 47  Sattler> Solar Fuels and Electricity by using Sunlight concentrating Systems > 20.06.2017
HYDROSOL Plant - CRS tower PSA, Spain

- European FCH-JU project
- Partner: APTL (GR), HELPE (GR), CIEMAT (ES), HYGGEAR (NL)
- 750 kW\textsubscript{th} demonstration of thermochemical water splitting
- Location: Plataforma Solar de Almería, Spain, 2017
- Reactor set-up on the CRS tower
- Storage tanks and PSA on the ground
**H₂O/CO₂-Splitting Thermochemical Cycles**
*(800 – 1500°C)*

Solar Production of Jet Fuel

- EU-FP7 Project SOLAR-JET (2011-2015)
- SOLAR-JET aims to ascertain the potential for producing jet fuel from concentrated sunlight, CO₂, and water.
- SOLAR-JET will optimize a two-step solar thermochemical cycle based on ceria redox reactions to produce synthesis gas (syngas) from CO₂ and water, achieving higher solar-to-fuel energy conversion efficiency over current bio and solar fuel processes.

- **First jet fuel produced in Fischer-Tropsch (FT) unit from solar-produced syngas!**


Partners: Bauhaus Luftfahrt (D), ETH (CH), DLR (D), SHELL (NL), ARTTIC (F)
Funding: EC

http://www.solar-jet.aero/
EU - Sun-to-Liquid: Heliostat field and Tower, (IMDEA) Mostoles Madrid

50kW Aperture (d=16cm); $C_{\text{mean}} = 2500$ (peak 3000); 169 concentrating heliostats;
**SOL2HY2 – Solar To Hydrogen Hybrid Cycles**

- FCH JU project on the solar driven Utilization of waste SO₂ from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners: EngineSoft (IT), Aalto University (FI), DLR (DE), ENEA (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)
- >100 kW demonstration plant on the solar tower in Jülich, Germany in 2015

https://sol2hy2.eurocoord.com

**Outotec™ Open Cycle (OOC)**

- Utilization of waste SO₂ from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis
Design of SOL2HY2 pilot plant

Solar receiver

Adiabatic catalyst reactor

SO₂, O₂, SO₃, H₂O (g)
750 °C

Electrical evaporator

H₂SO₄(aq)
1 l/min (50 w%)

Research platform

Gas analysis

Scrubber

57 kW solar

1000 °C

SO₃, H₂O (g)
400 °C
Investments vs. revenues

- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues
Thank you very much for your attention!