



Integrated modeling and system analyses

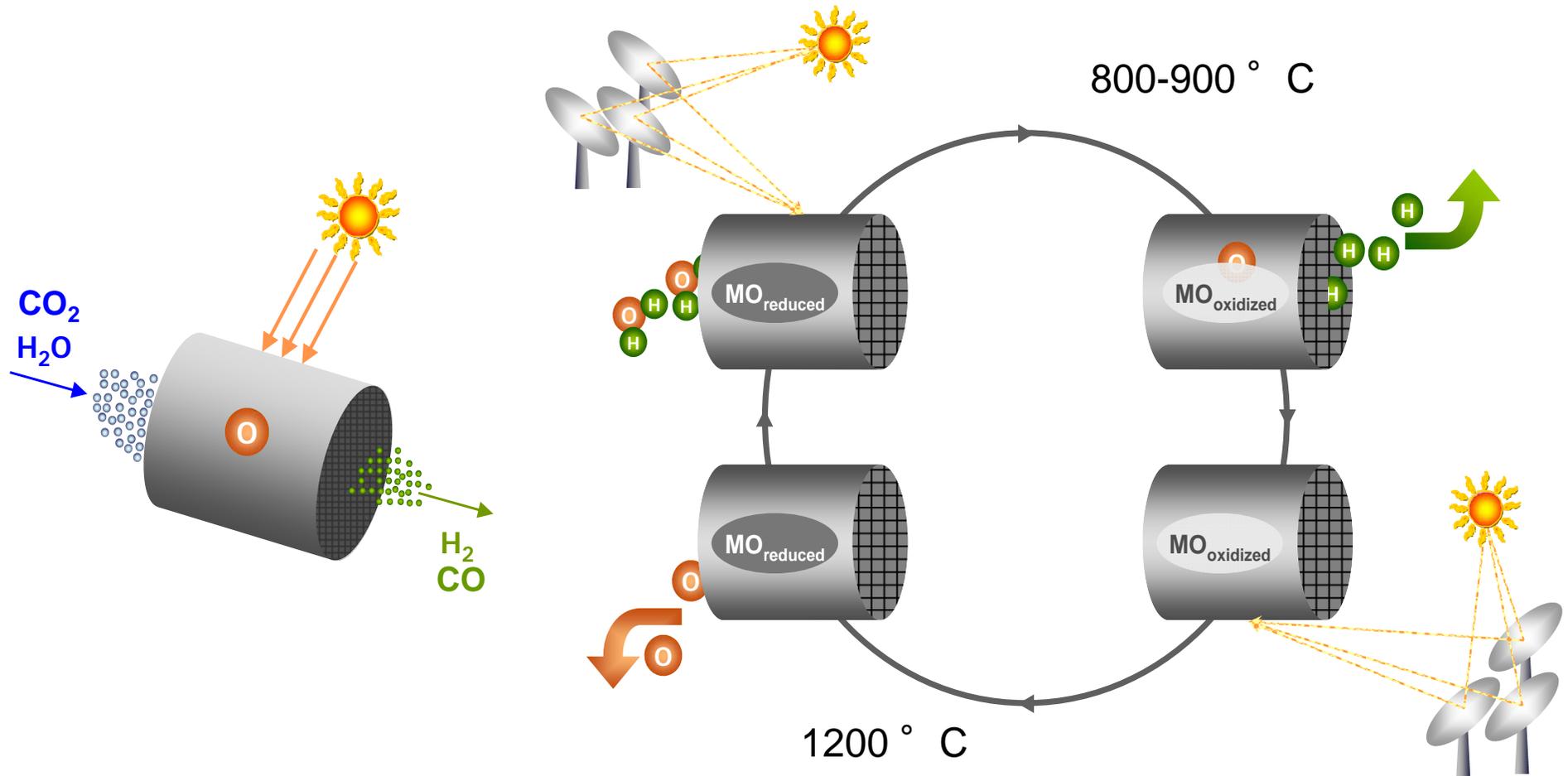
C. Sattler, F. Trieb, A. Houaijia, S. Breuer, M. Roeb



Outline

- Examples
 - Hydrosol – Metaloxide thermochemical cycle
 - Process modelling
 - Exergy analysis
 - Receiver-Reactor Optimization
 - SOLREF – Solar steam reforming of natural gas
 - Systems analysis
- Summary and Outlook

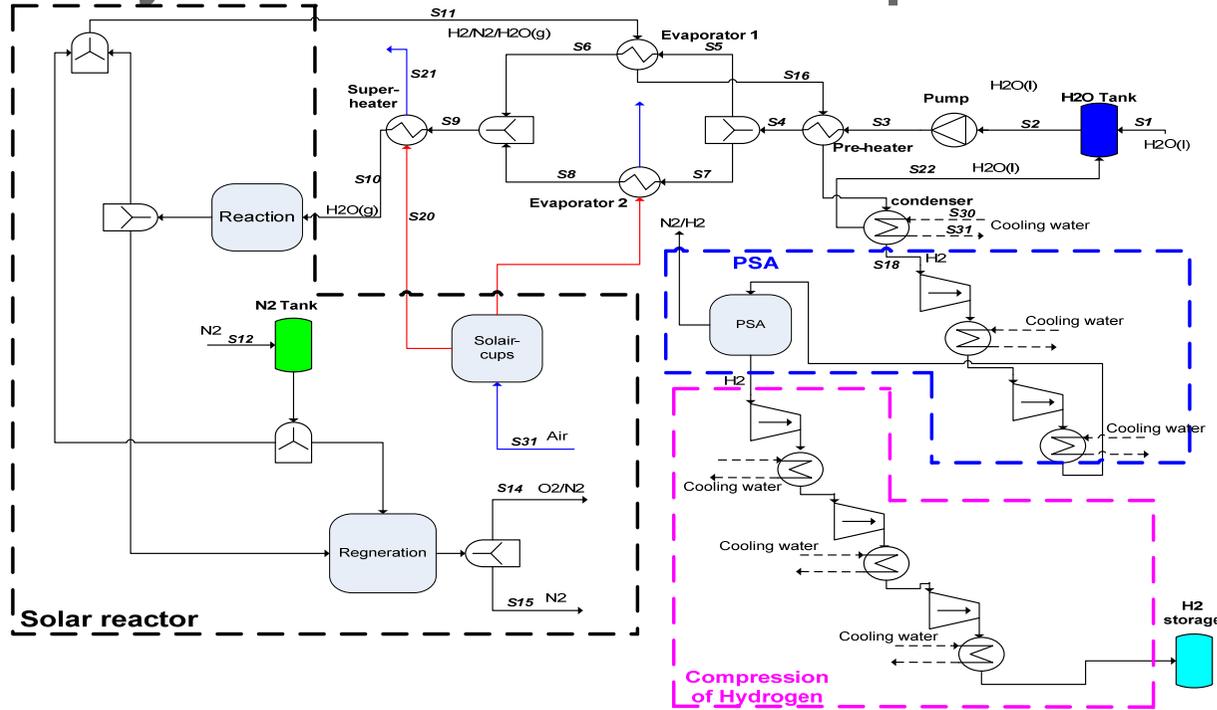
HYDROSOL - Fuel Production from H₂O and CO₂ by Solar Radiation



DLR: Roeb, Müller-Steinhagen, *Science*, Aug. 2010



Steady state simulation of the process

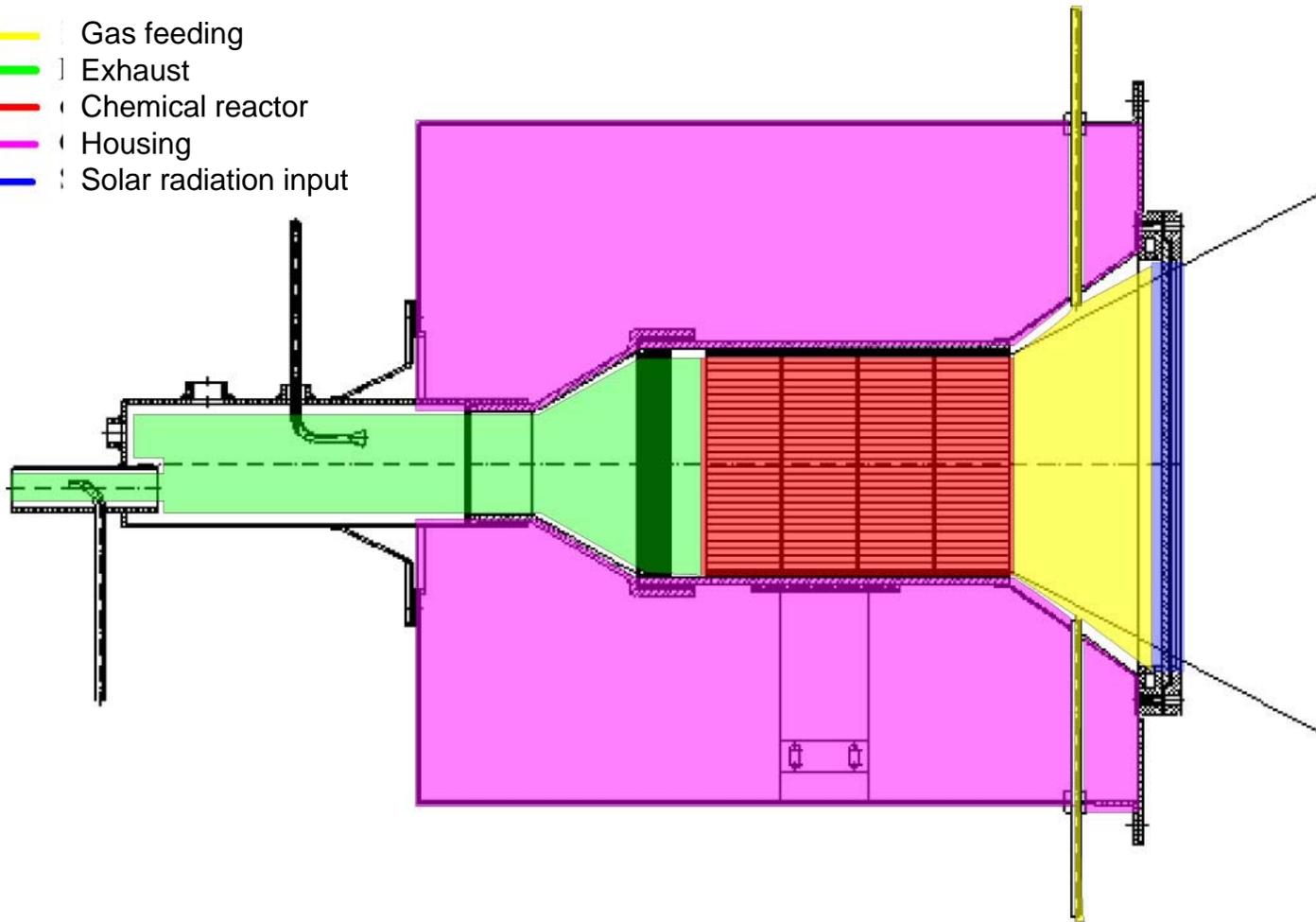


Operation	Component ID in Flow Sheet	Heat duty kW
Water preheating	Pre-heater	9.75
Water evaporation of sub-stream 1	Evaporator 1	61.78
Water evaporation of sub-stream 2	Evaporator 2	91
Water superheating	Super-heater	12.84
Reactor		
<i>Hot air generation</i>	Solar cups	131
<i>Reaction step</i>	Reaction	350
<i>Regeneration step</i>	Regeneration	500

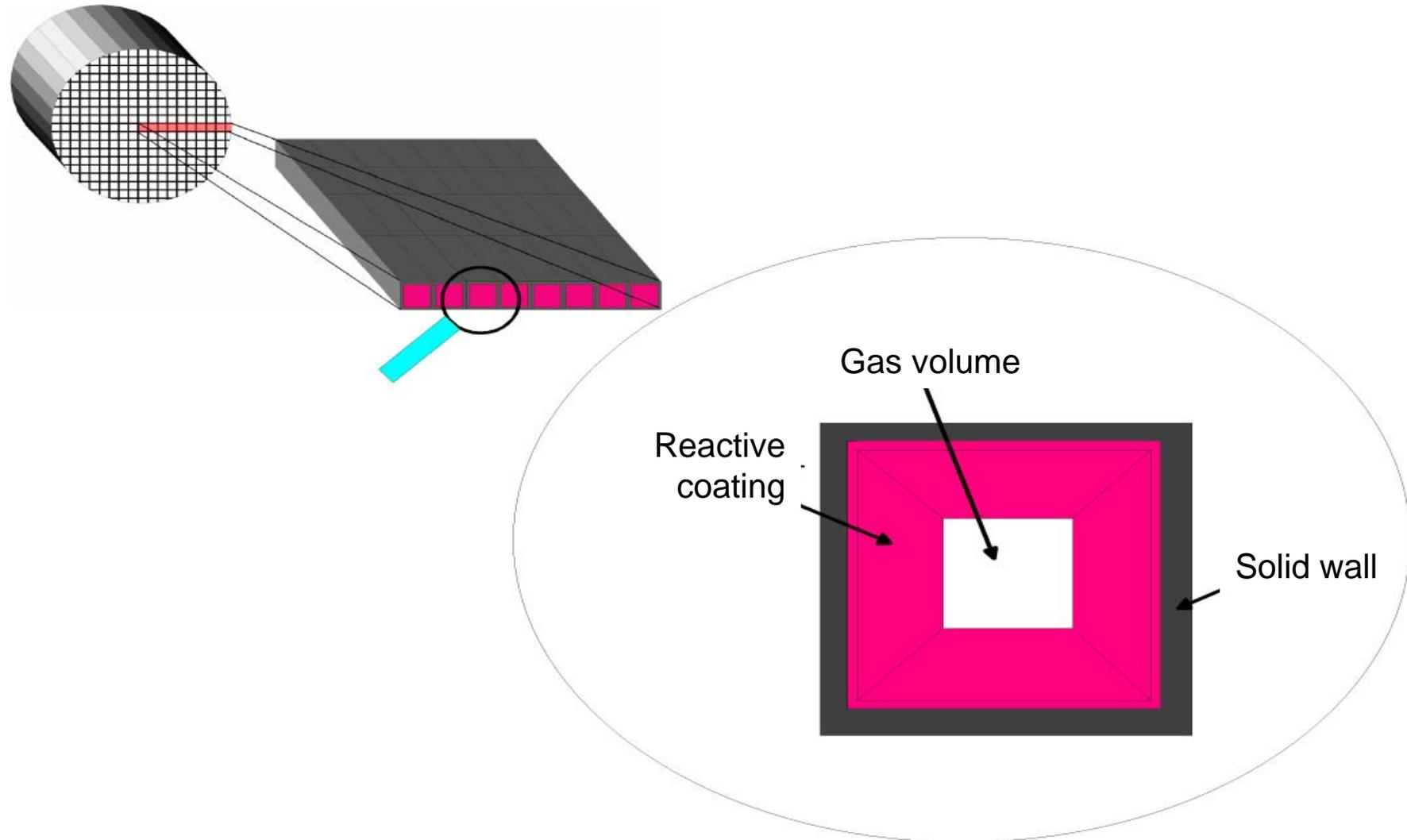


Modelling of the transient behaviour of the reactor

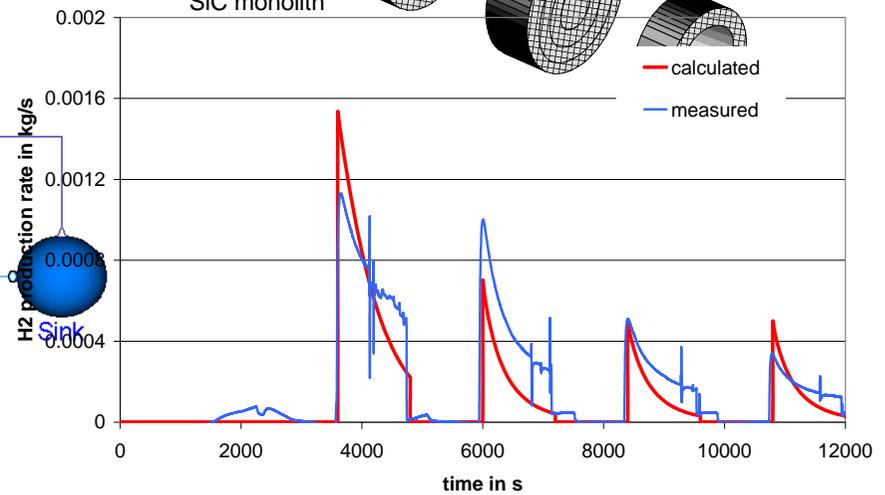
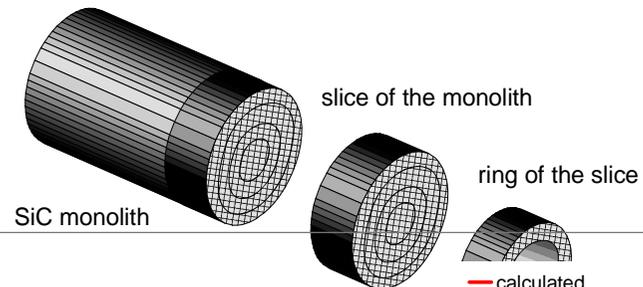
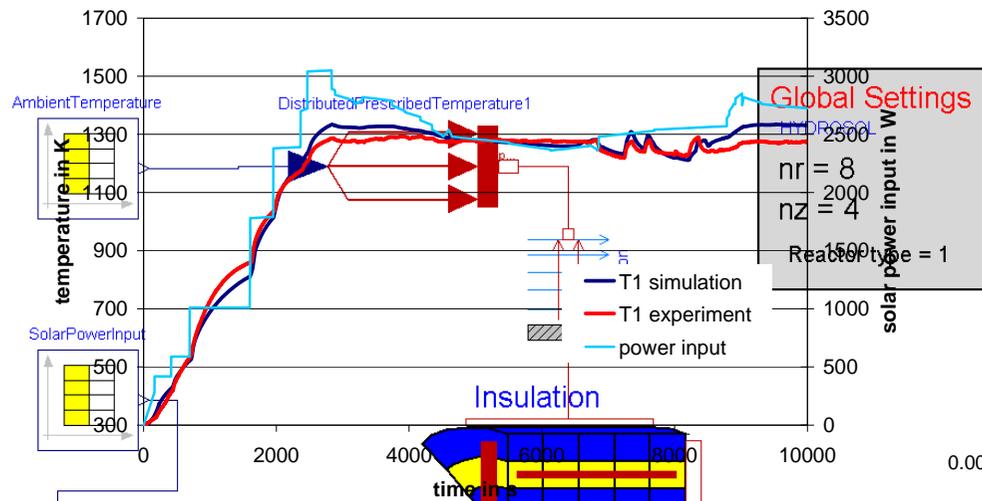
- Gas feeding
- Exhaust
- Chemical reactor
- Housing
- Solar radiation input



Submodel of the Reactor



Model for the receiver-reactor



Exergy analysis

– Exergetic efficiency of a component:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}}$$

– Exergy destruction ratio in a component:

$$\varepsilon_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

– Overall system exergetic efficiency:

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}}$$



Exergy analysis

Process unit	E_F [kW]	E_P [kW]	E_D [kW]	\mathcal{E}_K [%]	y_k [%]
Solar reactor	896	283,05	612,95	31,59	60,51
Pre-heater	3,26	1,26	2	38,65	0,19
Evaporator 1	35,89	14,02	21,87	39,06	2,15
Evaporator 2	41,03	20,59	20,44	50,18	2,01
Super-heater	4,69	3,97	0,7	84,64	0,0001
PSA	16,049	3,84	12	23,92	1,18
Hydrogen compression	16,04	7,06	8,98	44,01	0,88
Overall system	1012,95	333,79	679,16	32,95	

The optimization of the solar reactor and the evaporators is required due to the high exergy destruction ratio.



Design criteria for the receiver-reactor

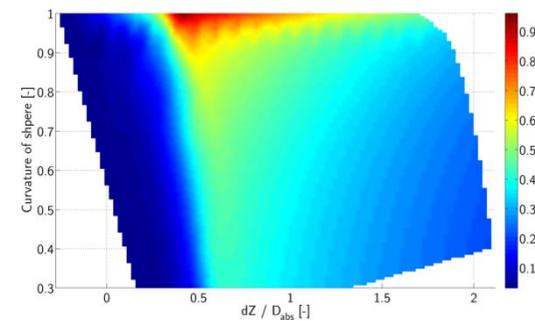
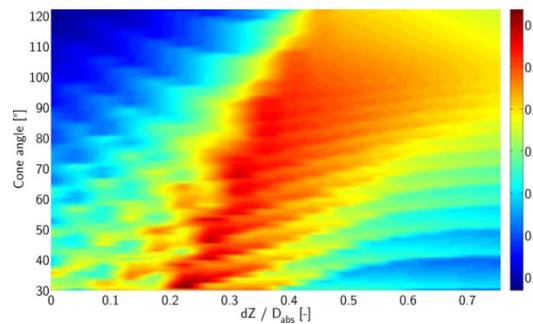
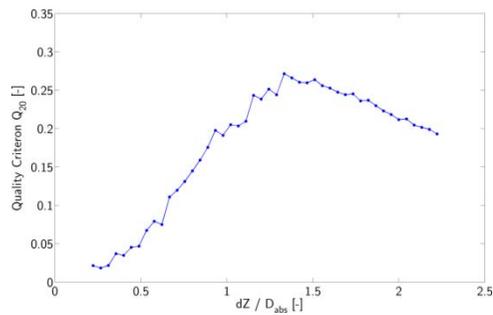
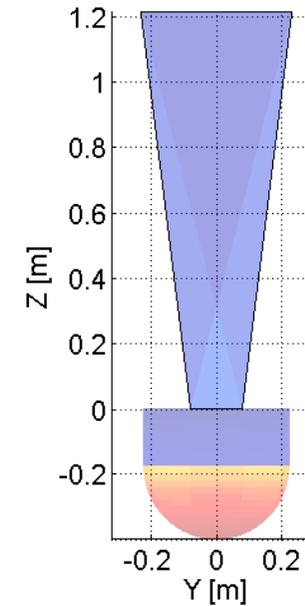
- Minimizing of aperture
- Maximizing of absorber volume
- Homogeneous flux and temperature distribution
- Easy maintainance and straightforward replacement of absorber modules

→ Cavity design with secondary concentrator

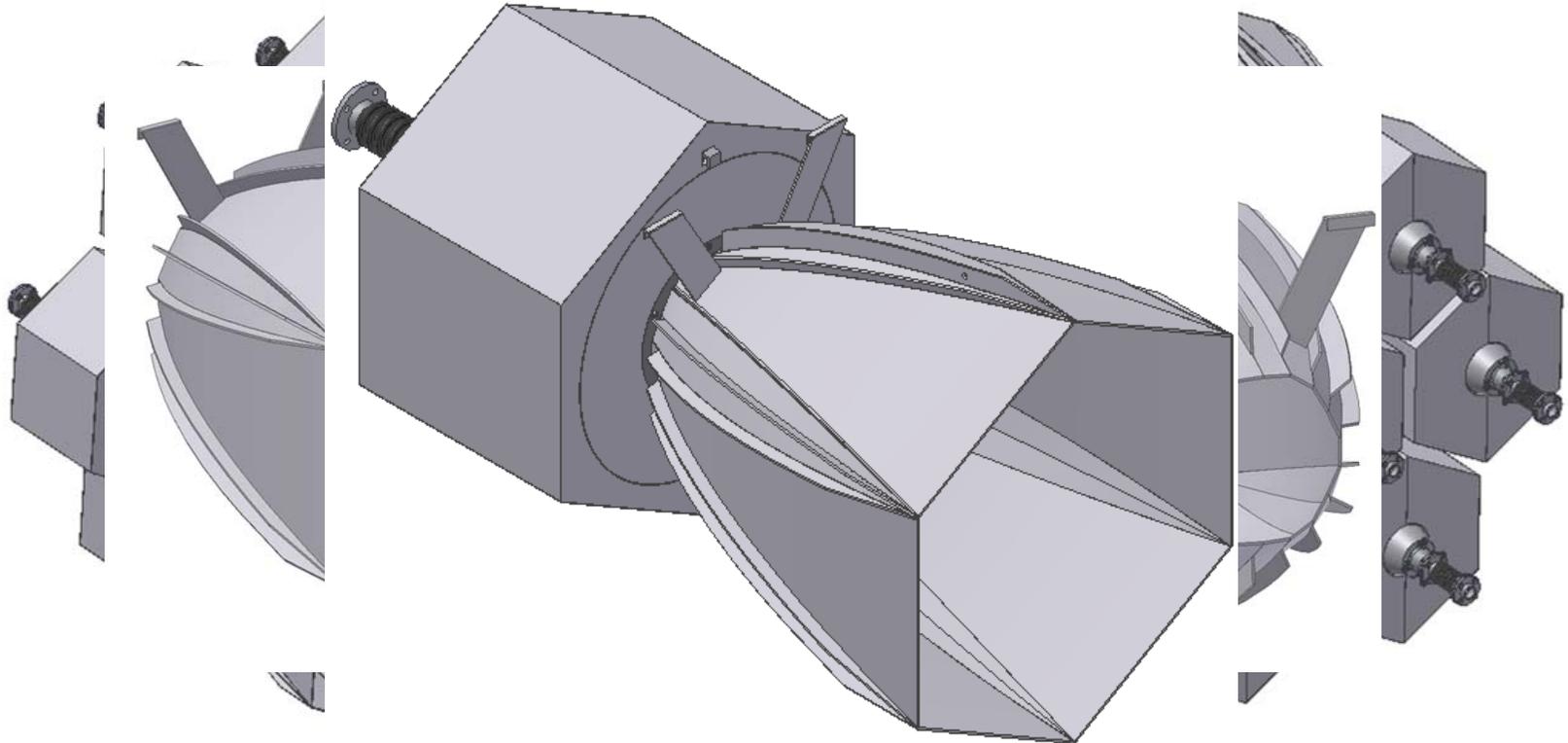


Results of Absorber Shape Variation

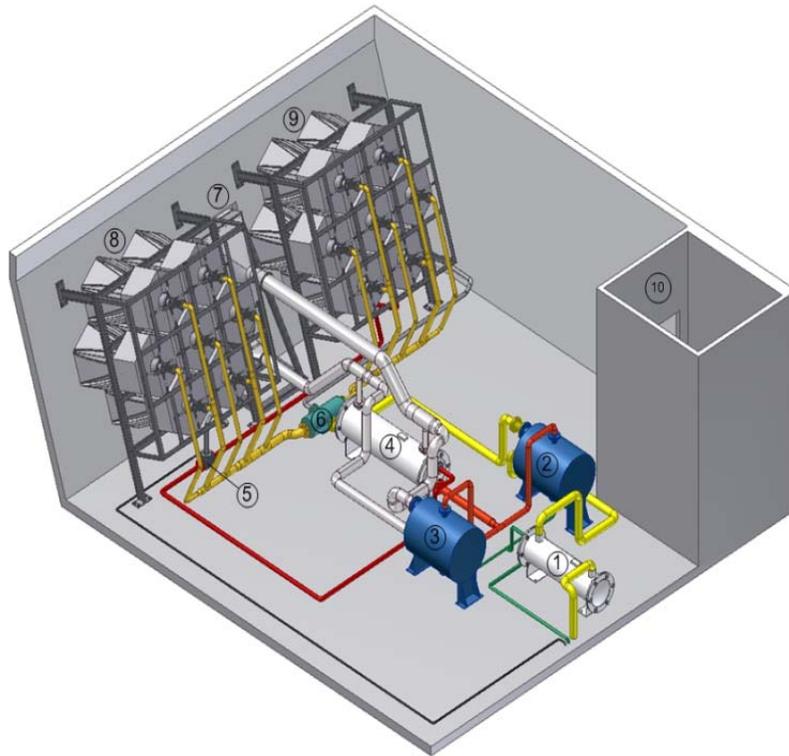
Absorber shape	Max. Quality value [-]
Flat	0,26
Conical	0,72
Spherical	0,94



Reactor Optimisation and Set-up



Integration of the HYDROSOL plant into a solar tower

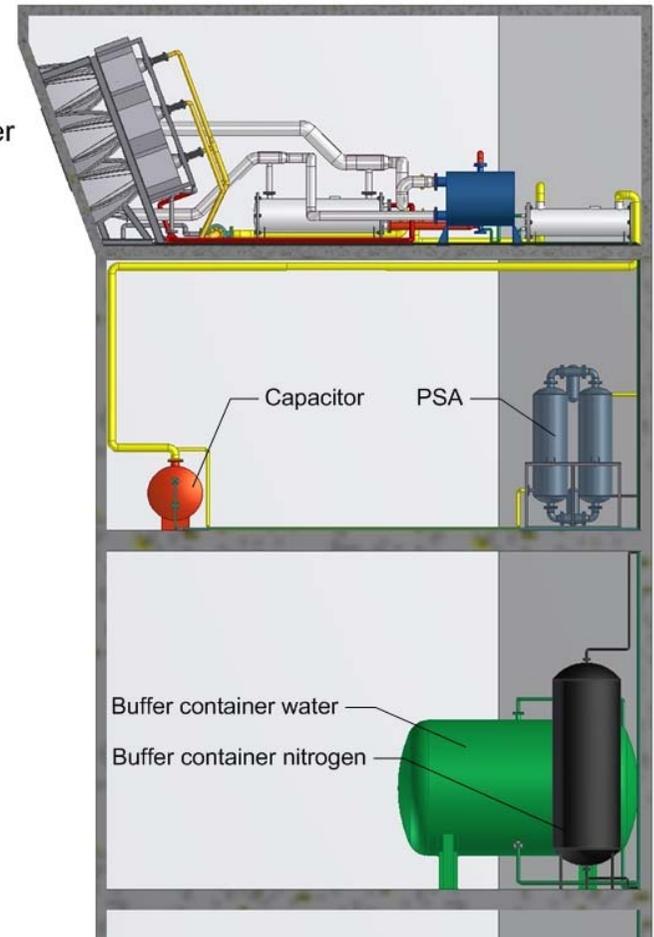


- 1: Preheater
- 2: Vaporizer 1
- 3: Vaporizer 2
- 4: Superheater
- 5: Way Valve 1
- 6: Way Valve 2
- 7: Air Receiver
- 8: Reactor Group 1
- 9: Reactor group 2
- 10: Elevator

Reactor chamber

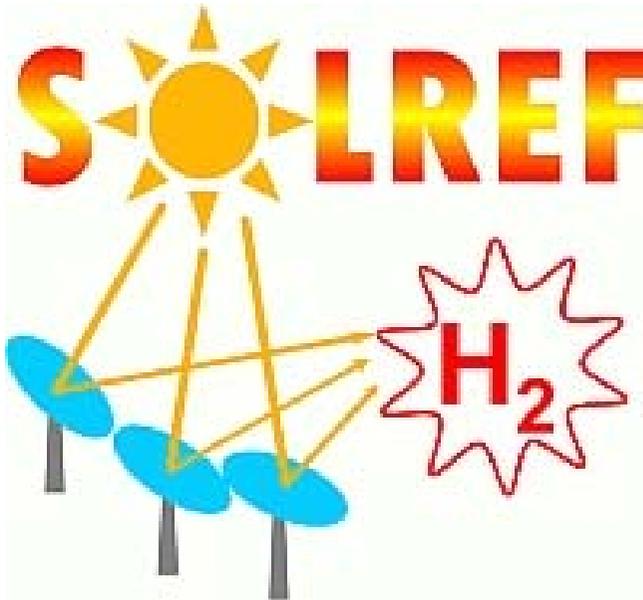
Outlet level

Buffer level





Systems Analysis – Market Study



Knowledge for Tomorrow

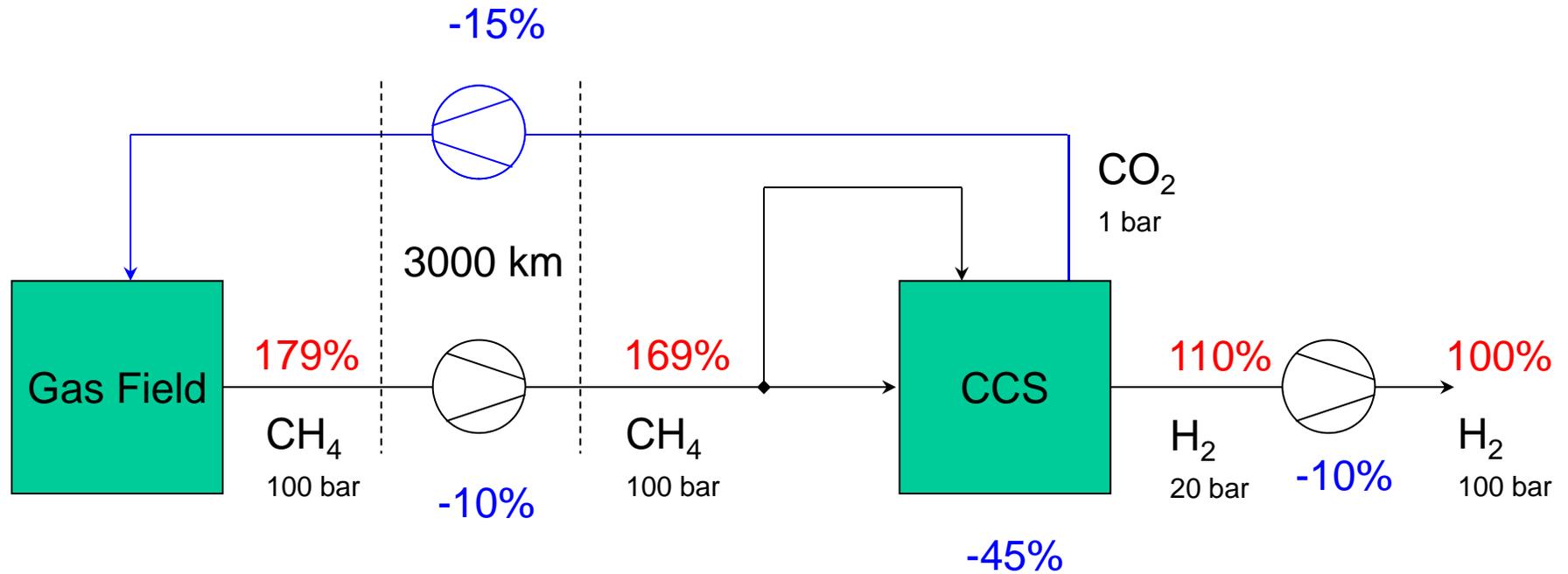


Systems Analysis - Market Study

- Market Niches
- Resource Potentials
- Market Scenarios
- Environmental Impacts
- Socio-Economic Impacts



Case 1: Conventional CCS at Consumer and Transport of CO₂ to Gas Field



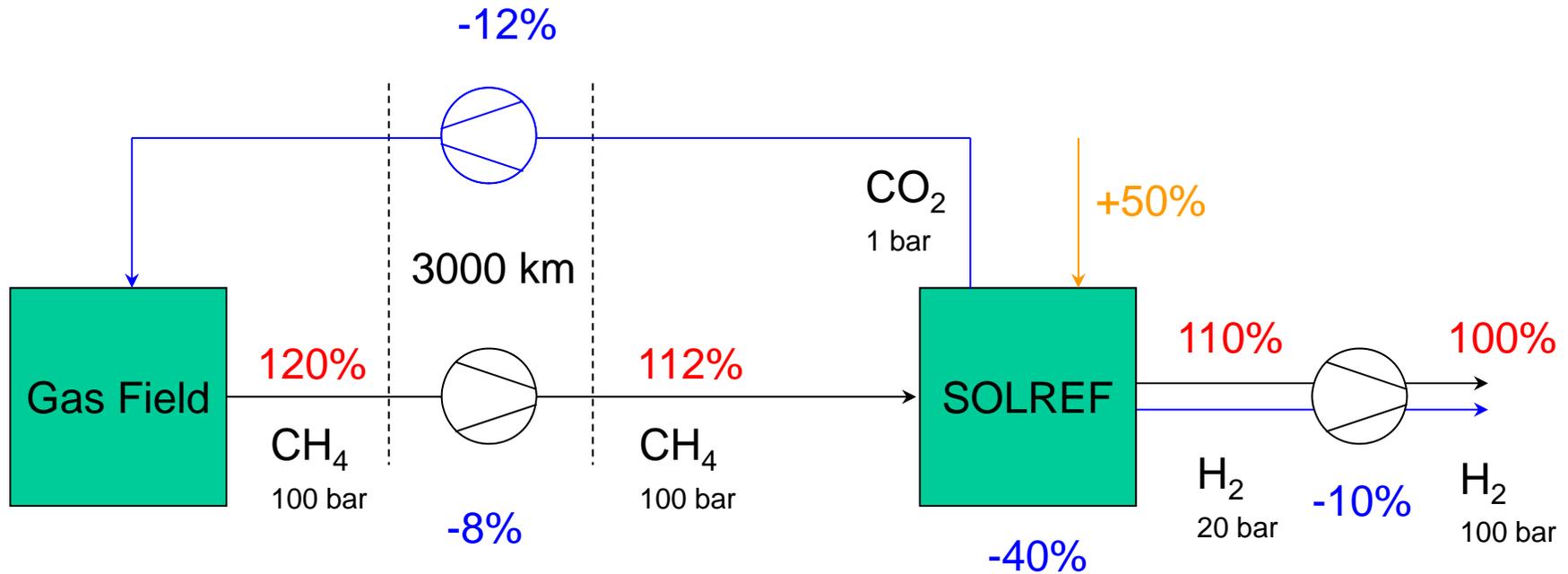
Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas



Case 2: Solar CCS at Consumer and Transport of CO₂ to Gas Field



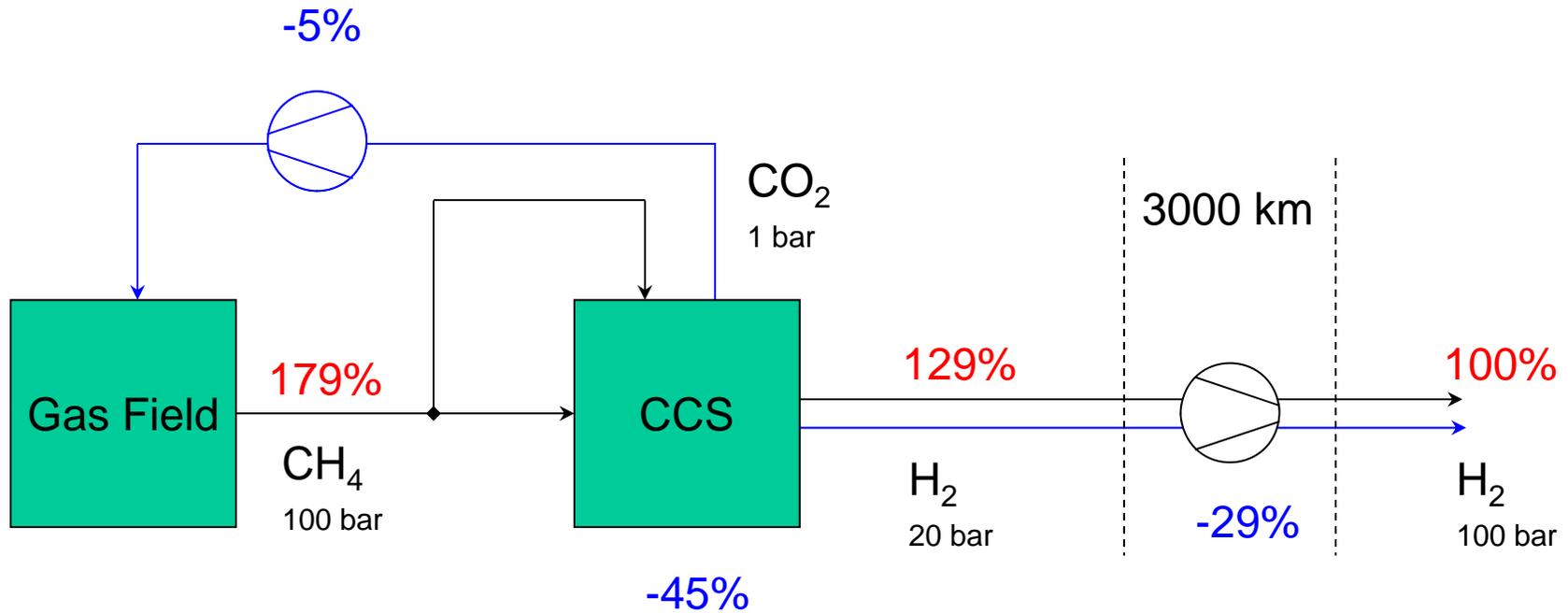
Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas



Case 3: Conventional CCS at Source and Transport of H₂ to Consumer



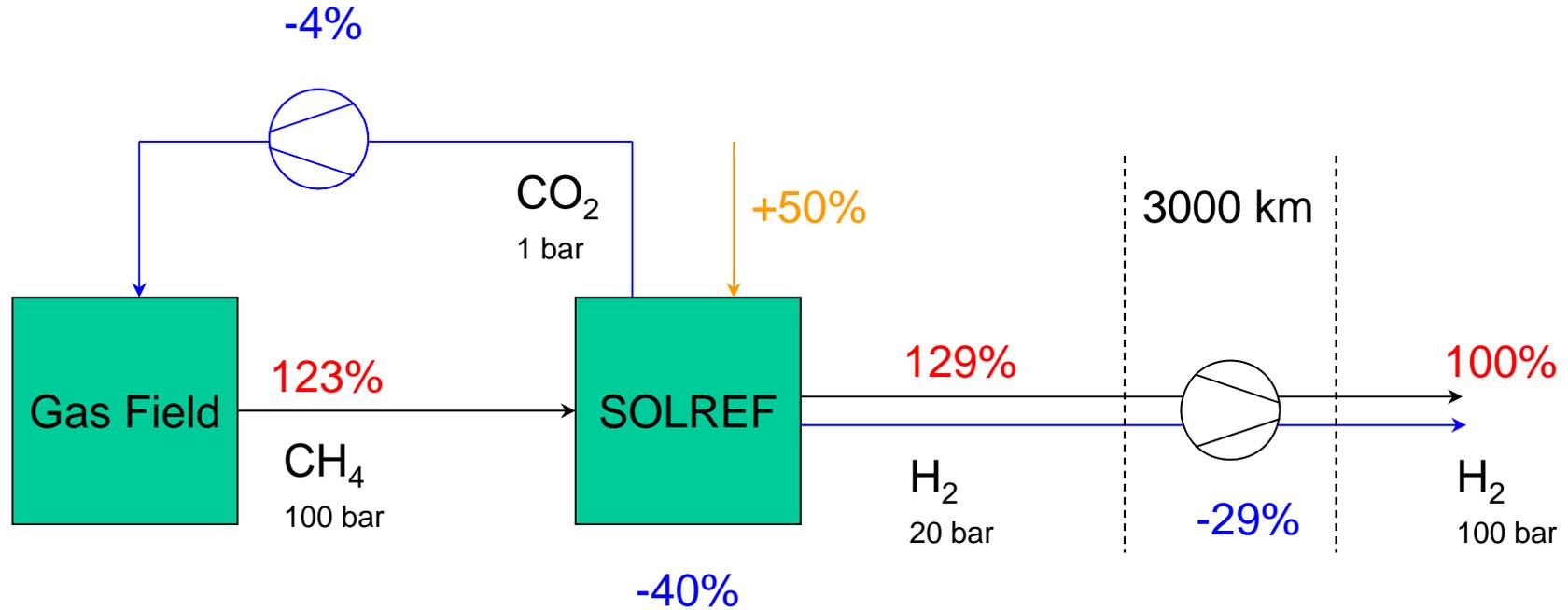
Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas



Case 4: Solar CCS at Source and Transport of H₂ to Consumer



Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas

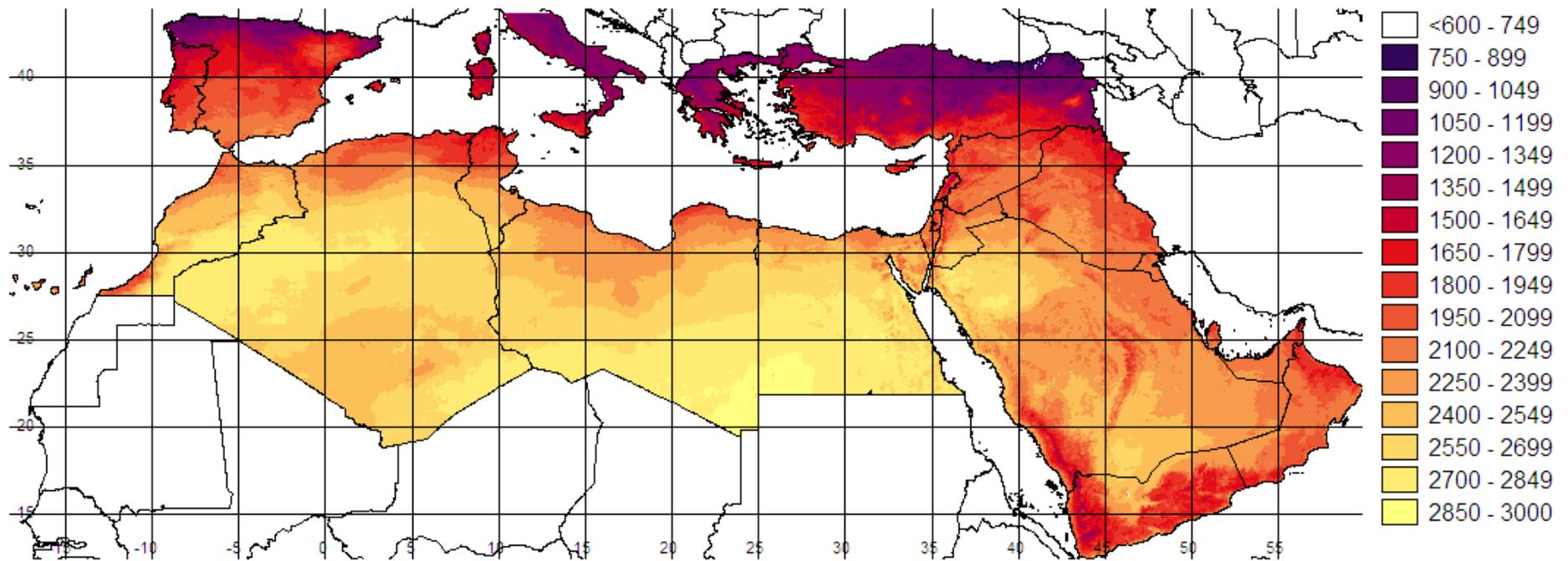


Solar Energy Resource Potentials

- Atlas of Annual Direct Normal Irradiance
- Atlas of Exclusion Areas
- Atlas of Natural Gas Pipelines
- Overlay and Statistical Analysis



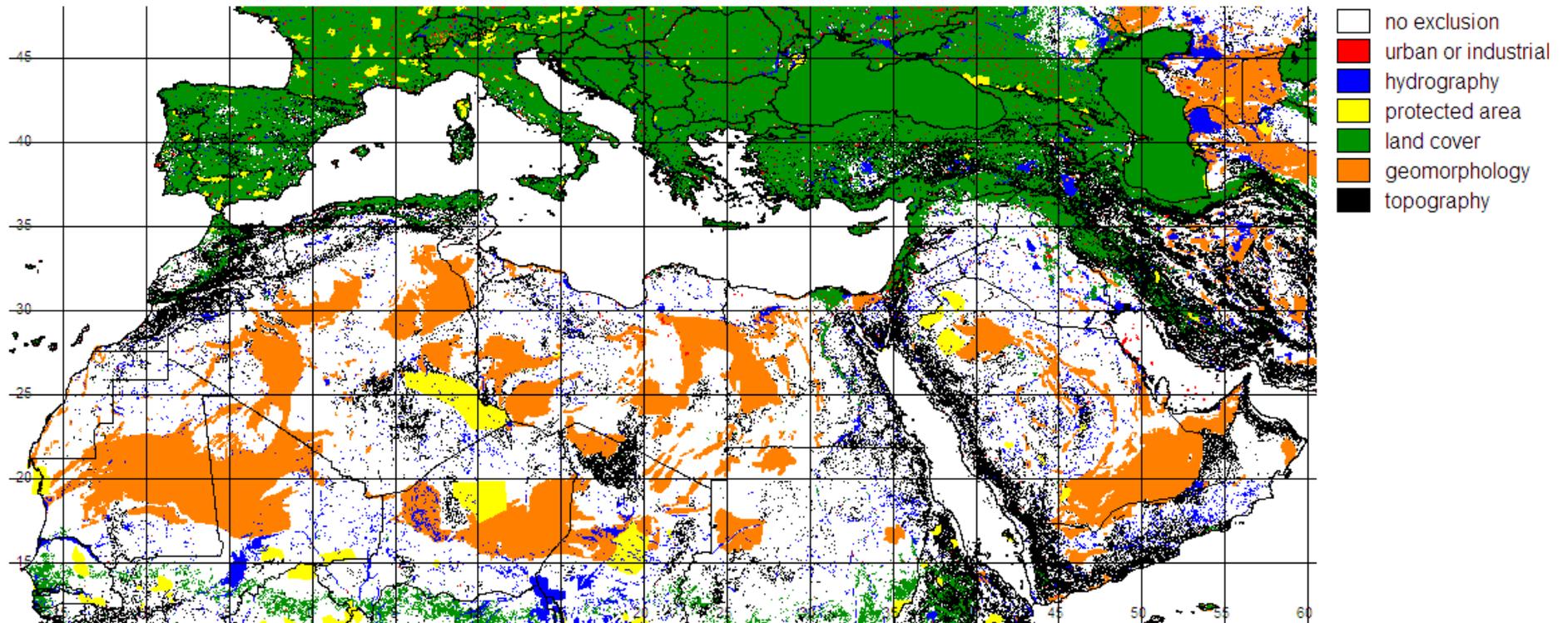
Atlas of Annual Direct Normal Irradiance



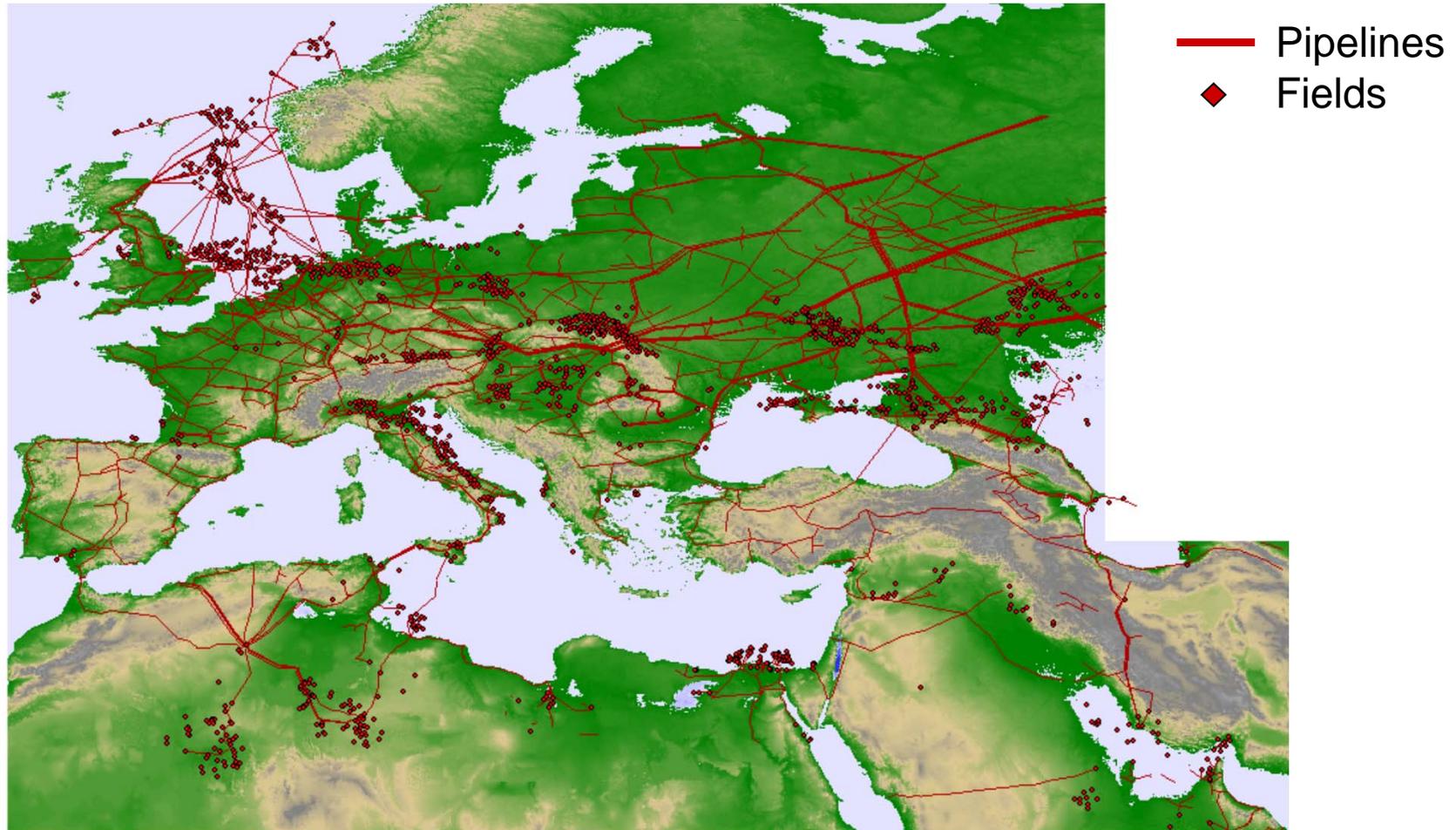
DNI 2002 in kWh/m²/y



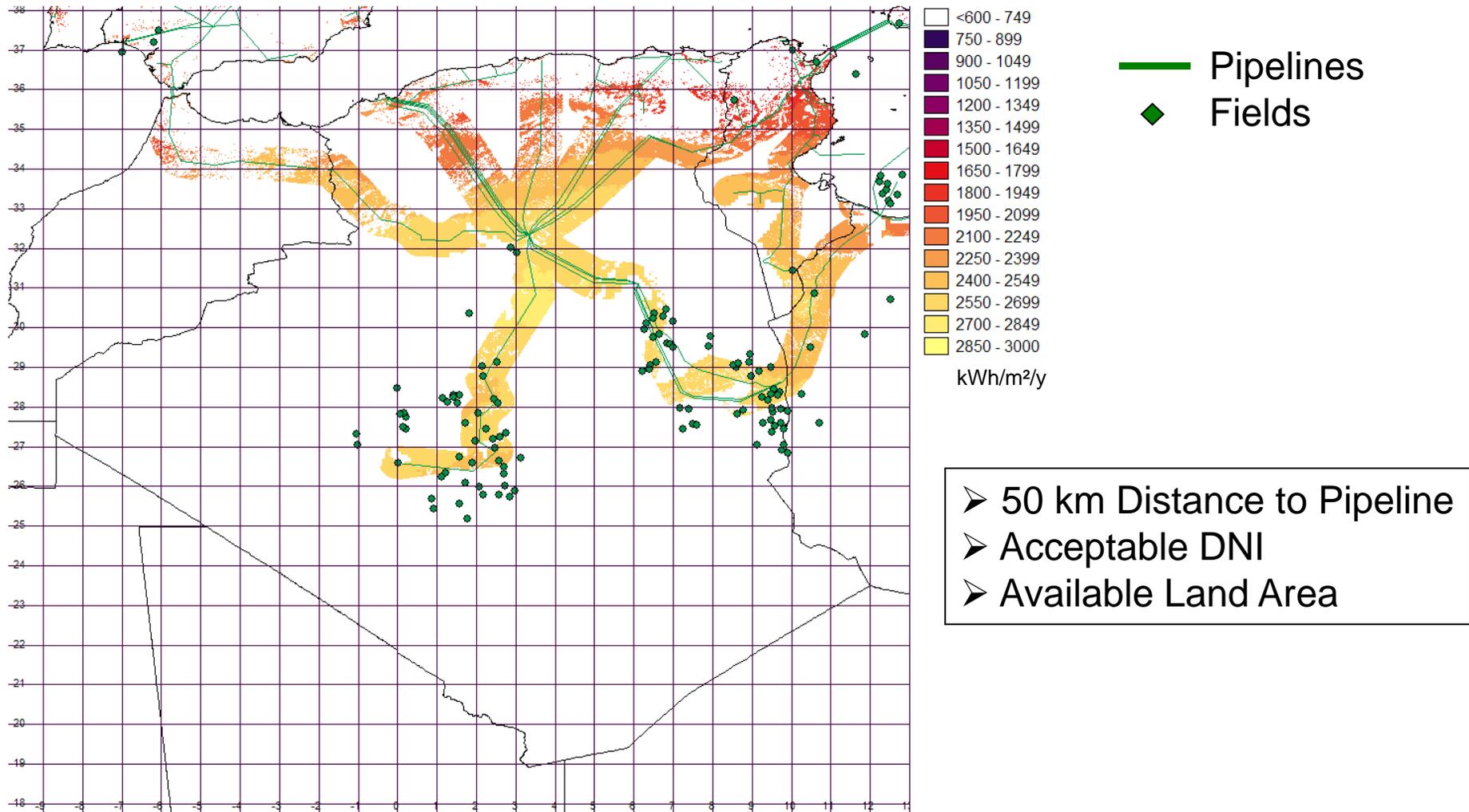
Atlas of Exclusion Areas



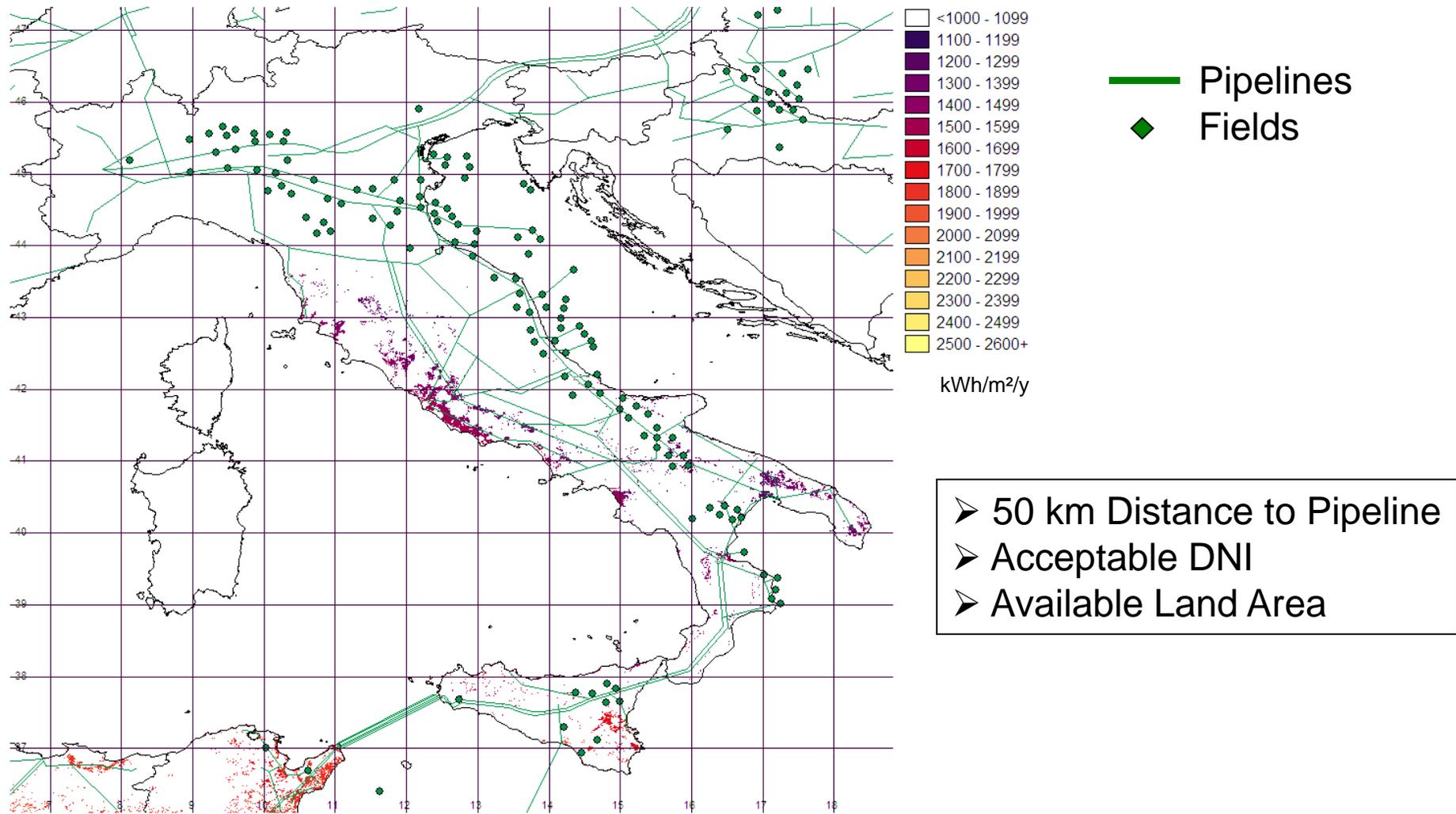
Atlas of Natural Gas Pipelines and Gas Fields



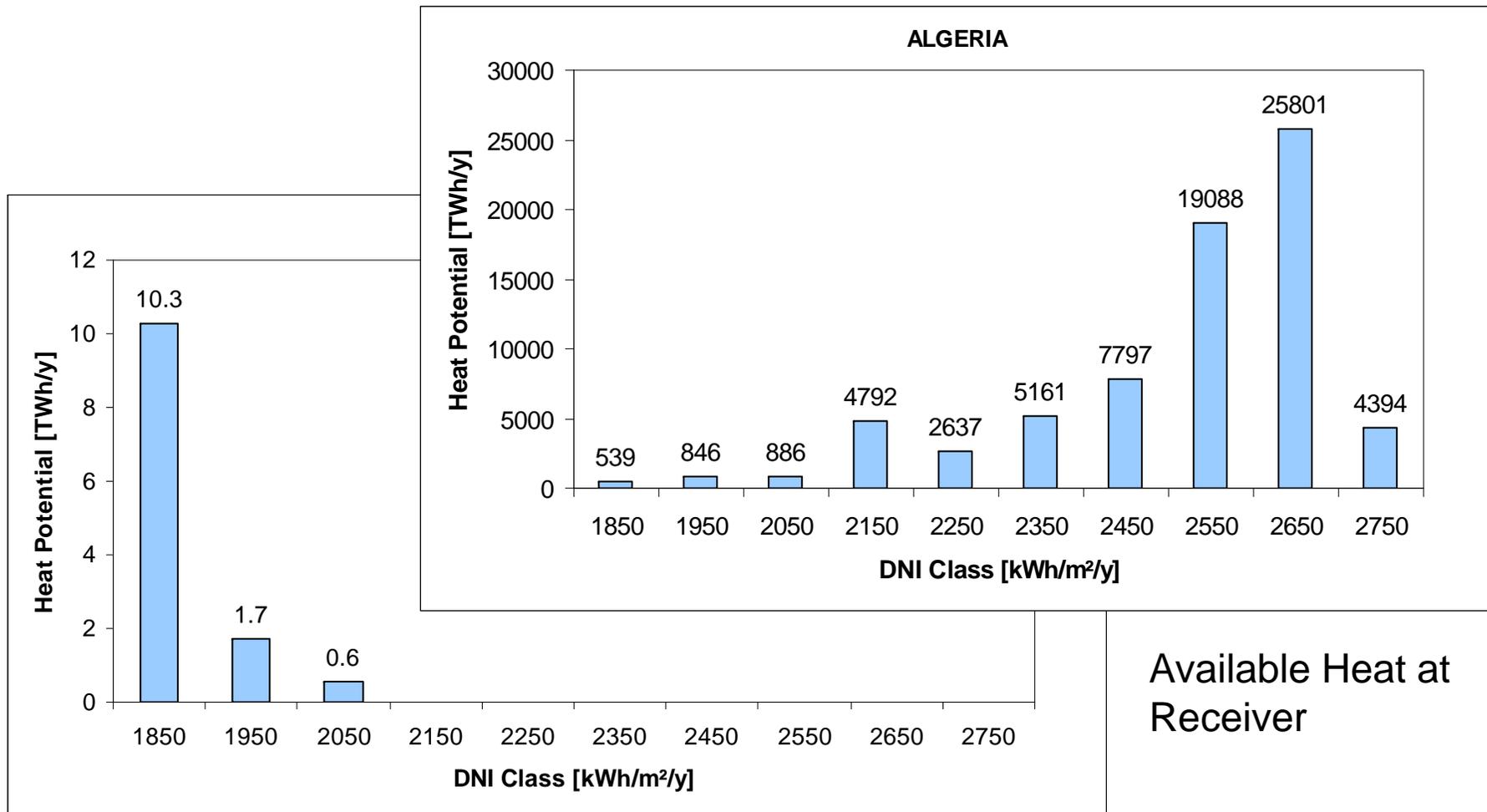
Overlay of Data Sets for Algeria



Overlay of Data Sets for Italy



Statistical Analysis



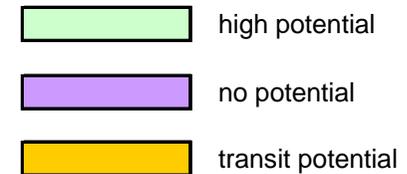
Market Scenario

- Overlay of Natural Gas and Solar Energy Potentials
- Scenario Analysis for Exporting and Importing Countries
- SOLREF Market Potential until 2050

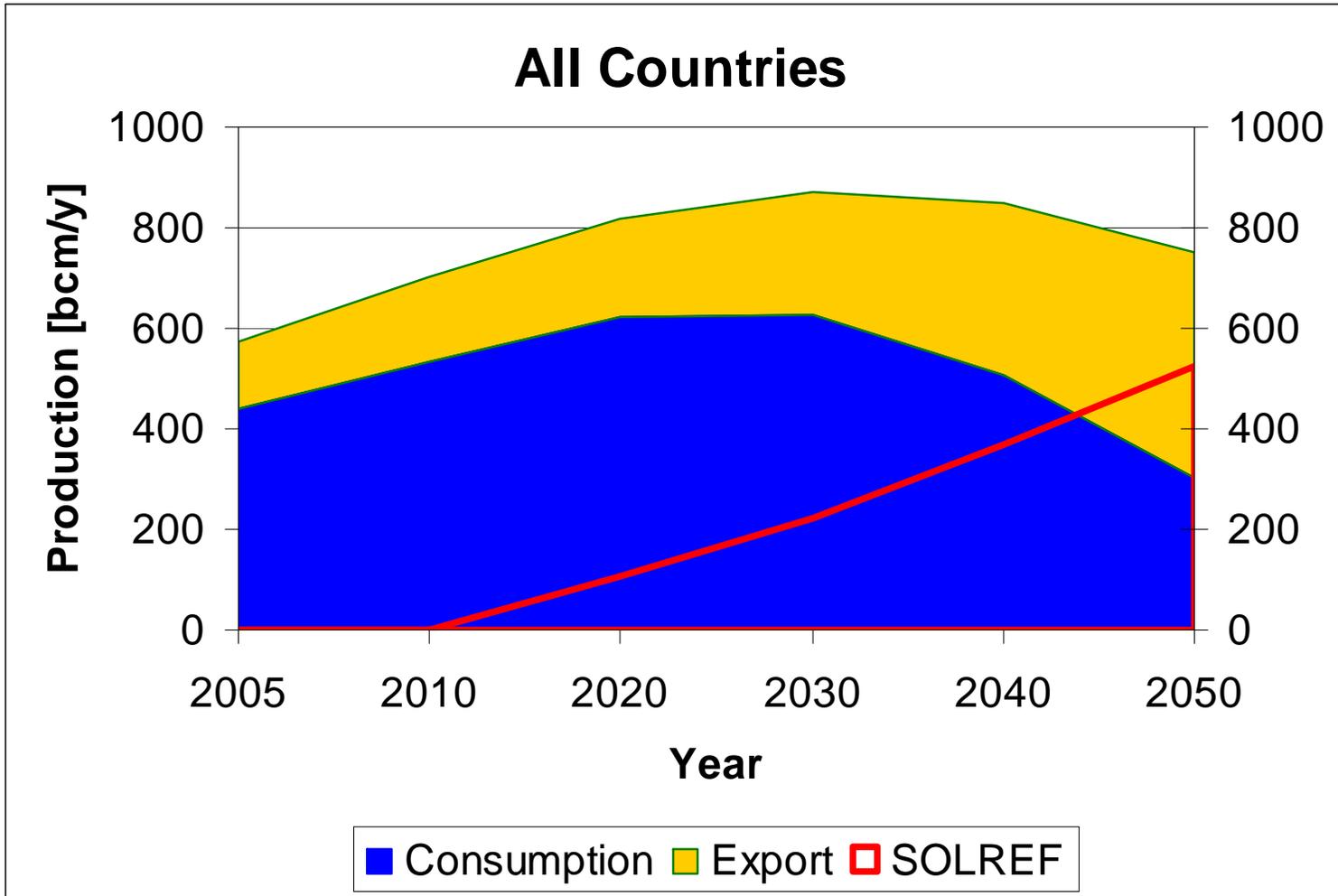


Overlay of Natural Gas and Solar Energy Potentials

Country	Technical SCCS Potential billion m ³ /y	Natural Gas Consumption 2005 billion m ³ /y	Natural Gas Export 2005 billion m ³ /y	Natural Gas Import 2005 billion m ³ /y	Proved Reserves 2005 billion m ³	R/P Ratio 2005 years
North Africa						
Morocco	971	0.1	0.0	0.0	2	33
Algeria	17639	21.8	65.5	0.0	4504	52
Tunisia	2891	4.1	0.0	1.7	75	18
Libya	7693	10.4	1.3	0.0	1491	132
Egypt	5590	23.4	19.1	0.0	2704	64
Middle East						
Jordan	1353	1.5	0.0	1.2	6	4
Lebanon	0	0.0	0.0	0.0	0.0	0
Israel	194	0.7	0.0	0.0	37	51
Syria	1948	8.5	0.0	0.0	240	28
Iraq	4766	2.5	0.0	0.0	3170	1268
Iran	n.a.	93.5	4.4	0.0	26740	273
Arabian Peninsula						
Saudi Arabia	4065	68.3	0.0	0.0	6570	96
United Arab Emirates	535	40.2	6.8	1.3	6071	129
Kuwait	118	12.6	0.1	0.0	1586	125
Oman	4369	6.3	10.4	0.0	829	50
Qatar	148	18.3	27.5	0.0	25633	560
Bahrain	0	10	0	0	88	9
Yemen	0	0	0	0	1	0
Europe						
Spain	246	30.5	0.0	30.7	2.4	16
Portugal	4	4.3	0.0	4.3	0	0
Italy	2	82.0	0.0	70.5	217	3
Greece	0	2.7	0.0	2.7	0.9	0
Turkey	1	26.0	0.0	26.0	8.0	0

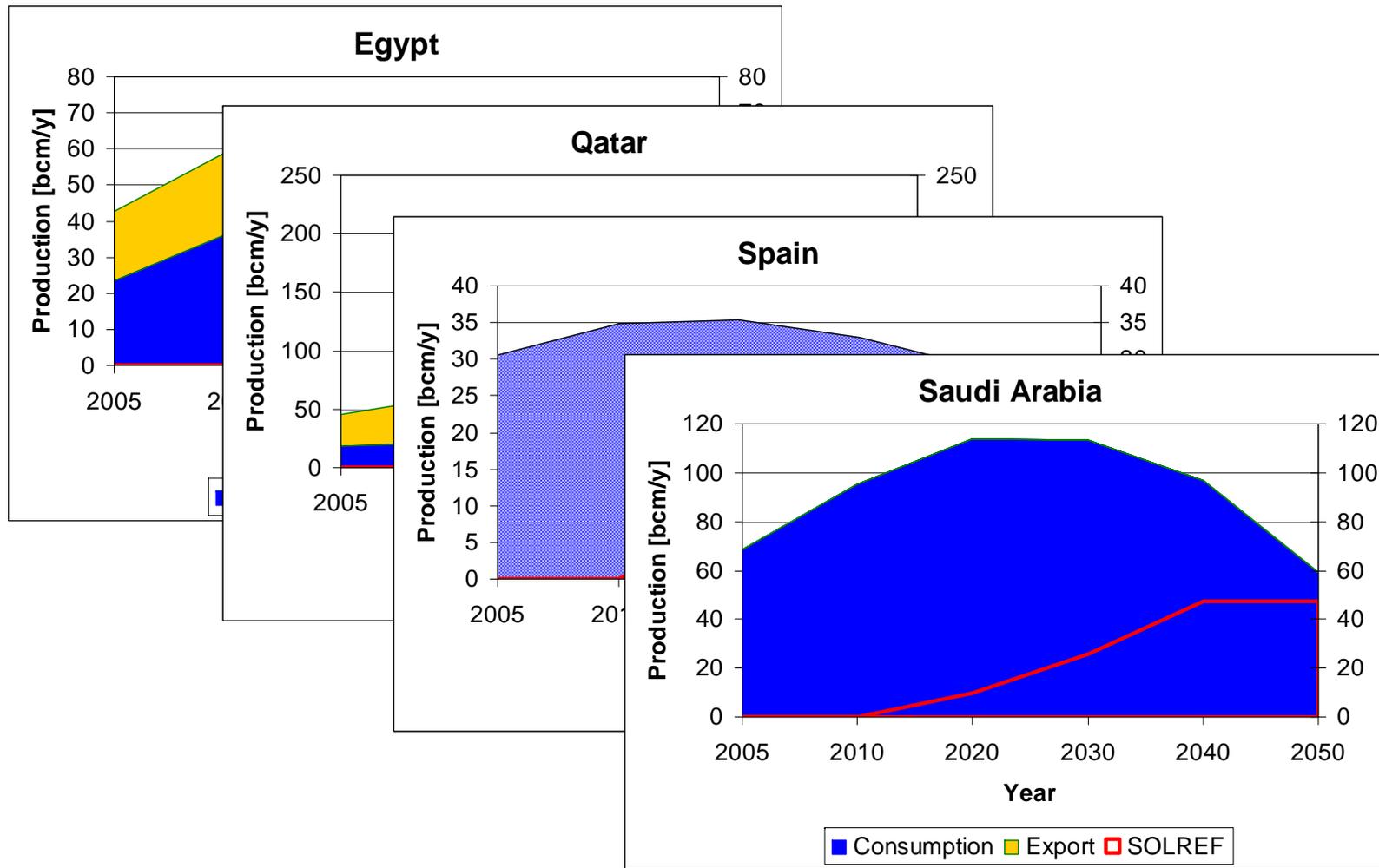


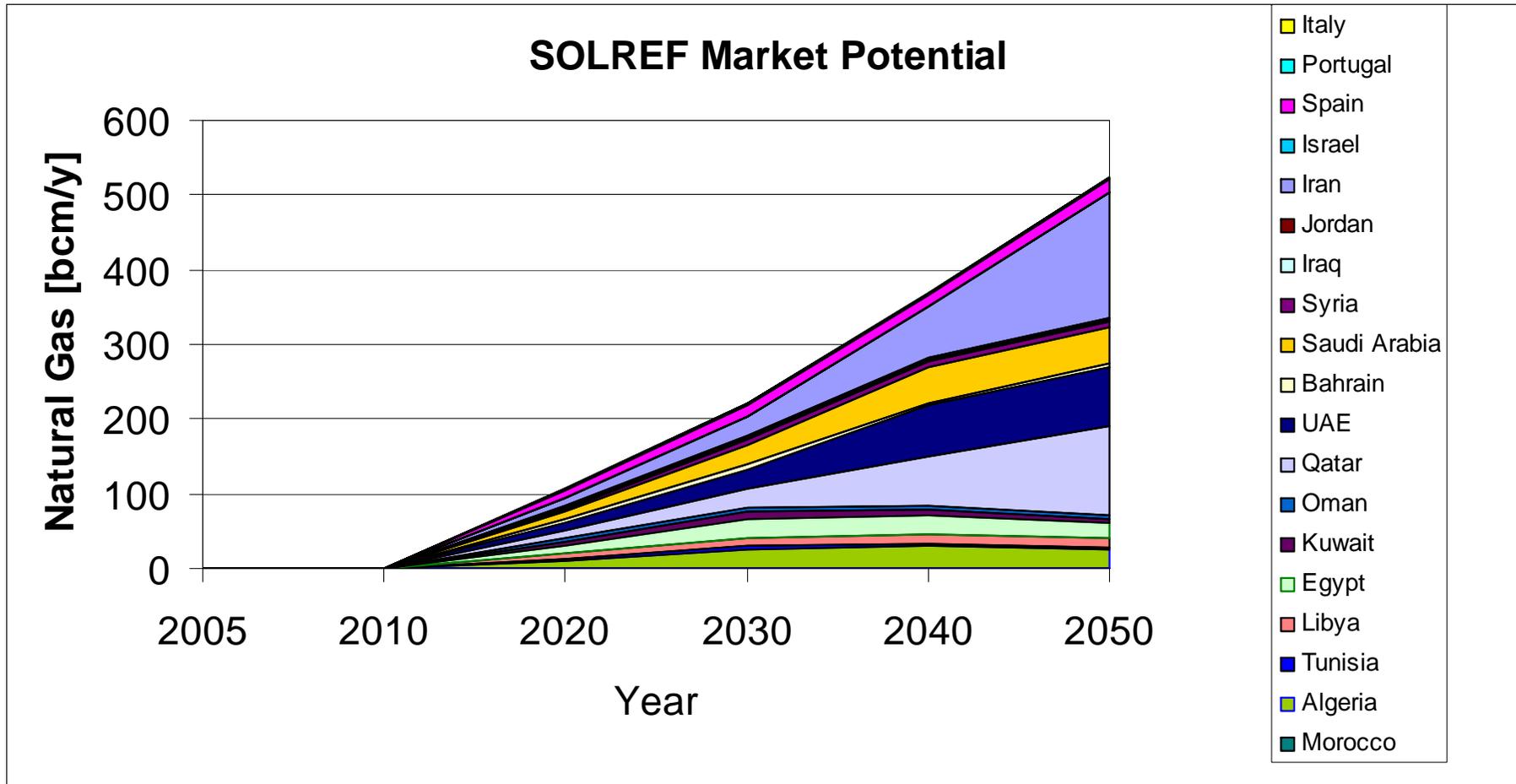
Natural Gas and SOLREF Markets

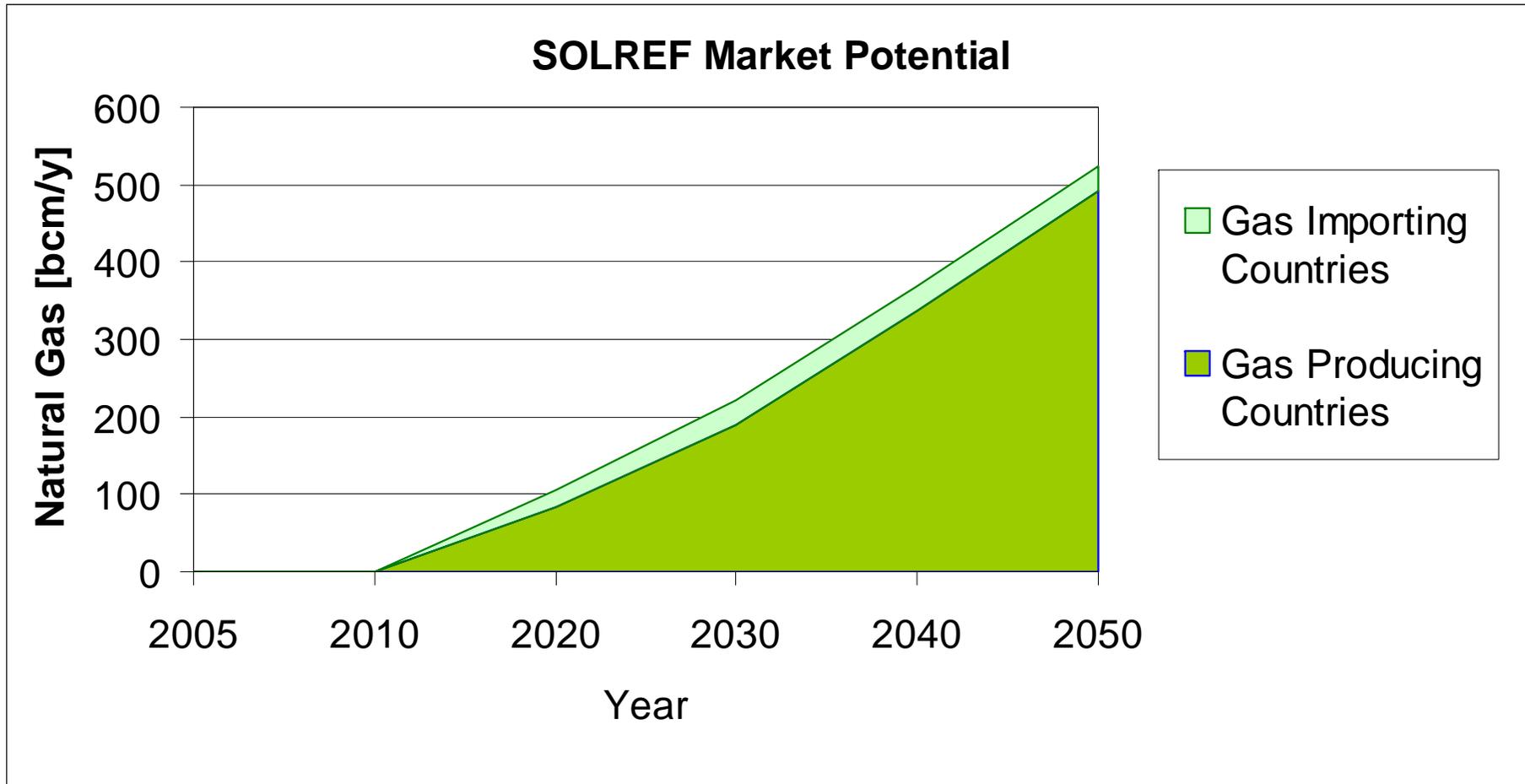


Production is consistent with MED-CSP and TRANS-CSP Scenarios









Environmental and Socio Economic Impacts

- Climate Change
- Land Use
- Energy Cost
- Energy Security and Availability
- Regional Cooperation



Acknowledgement

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- Thanks to all colleagues and partners who provided various contributions to this work.

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Thank you very much for your attention!

