Renewables, Grid, Energy Storage
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Solar methane steam reforming in a gas turbine power plant

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<u>Marco Pellegrini</u> has a degree in Engineering Mechanics in 2006 from the University of Bologna. He was a research fellow at the Department Mechanical Engineering (DIEM) University of Bologna. He is currently attending the last year of the doctoral program in "Engineering machines and energy systems“ and leads research on the efficiency and the environmental impact reduction of systems energy production from biomass. He has more than 30 publications of national and international interest.

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Renewable energy

The realization of renewable energy potential is often impeded by important technological barriers, like:

- dilution;
- intermission;
- unequal distribution.

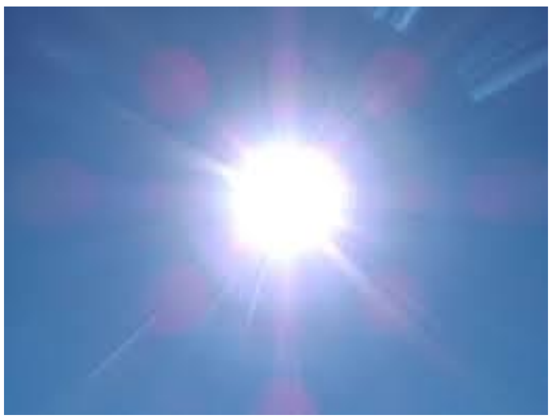


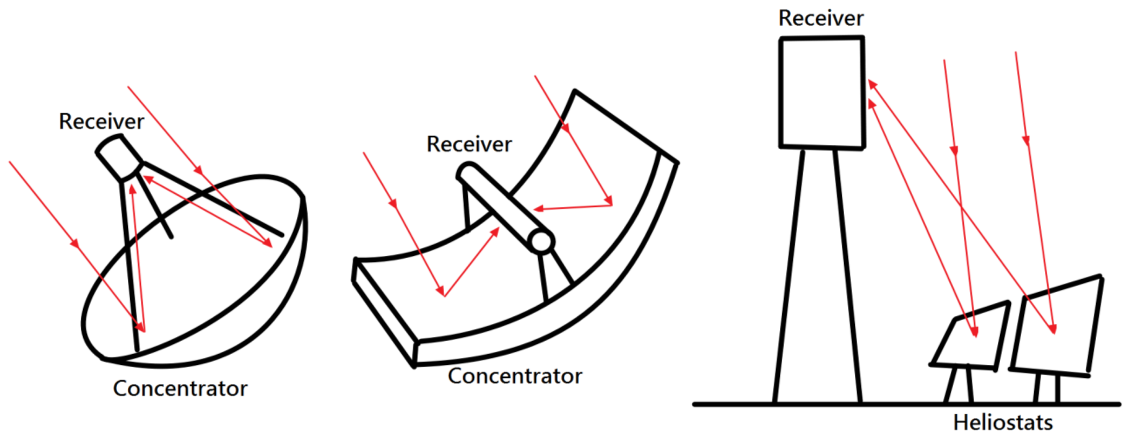
Considerable improvements are therefore still necessary to achieve traditional resource performances.

Concentrating Solar Power (CSP) technology is one of the most promising industrial scale power plants fed by renewable energy. CSP is a proven technology: the first commercial plants began operating in California in the period from 1984 to 1991.


Concentrating Solar Power

CSP devices concentrate energy from the sun's rays into a heat receiver at relatively high temperatures. The receiver temperature depends on the solar concentration ratio C, that is a non-dimensional ratio between the solar flux intensity (measured in "number of suns") achieved after concentration and the normal insulation of incident beam.





Dish **Trough** **Tower**

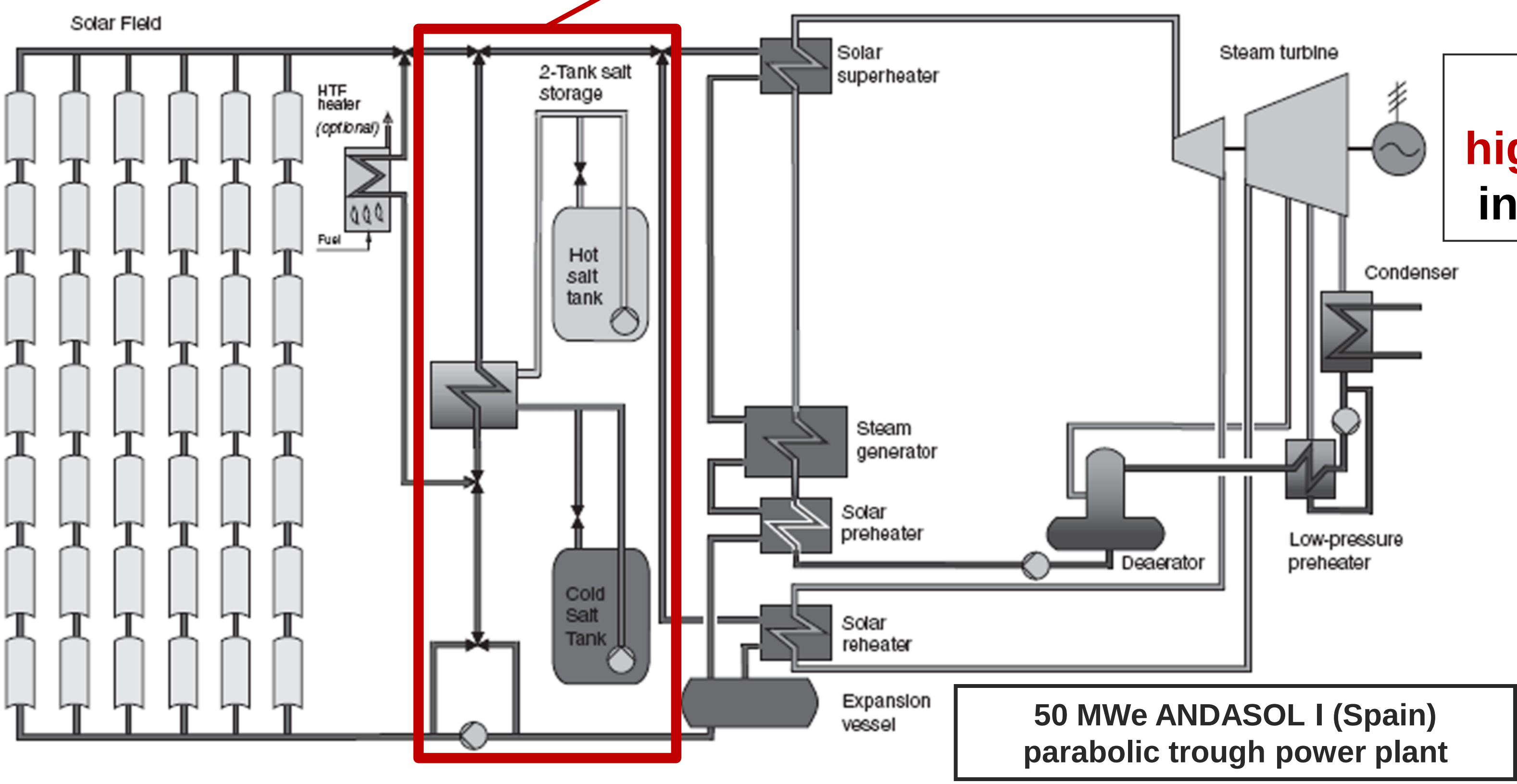
	Dish	**Trough**	**Tower**
Concentratio ratio C	1.000-10.000	30-100	500-5.000
Receiver temperature	>1.000°C	400-600°C	>1.000°C

Concentrating Solar Power – thermal storage?

These kinds of power plants are often installed where direct solar radiation is consistent and steady enough, i.e. in hot desert countries. Both cost effective reduction and efficiency increase of CSP technology can be achieved only by consistent improvements in the fields of:

- energy **storage**;
- energy transport.

Molten salts energy storage (up to 550°C)



… but high product and installation cost

50 MWe ANDASOL I (Spain) parabolic trough power plant

Methane Steam Reforming

Methane Steam Reforming (MSR) is the most important **commercial** massive **hydrogen production process**; it is based on the following two reactions of methane steam reforming (1) and water gas shift (2):

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ ΔH_0= +206 kJ/kmol (1)

$CO + H_2O \leftrightarrow CO_2 + H_2$ ΔH_0= -41 kJ/kmol (2)

which together (3) yield:

$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$ ΔH_0= +165 kJ/kmol (3)

The reactions are reversible, but under the preferred reforming conditions, however, the position of the thermodynamic equilibrium makes reactions (1) and (2) essentially irreversible. Parameters that affect the position of the chemical equilibrium are:

- **temperature** (higher T, higher conversion), usually T=800°C;
- **steam-to-methane molar ratio** (higher ratio, higher conversion), usually ψ=2,5;
- **pressure** (higher p, lower conversion), usually 1-3 bar;

Solar Methane Steam Reforming

Solar thermochemical processes convert solar radiant energy into chemical energy.

CSP

Methane

Methane Steam Reforming

Steam

SYNGAS (+17% Lower Heating Value)

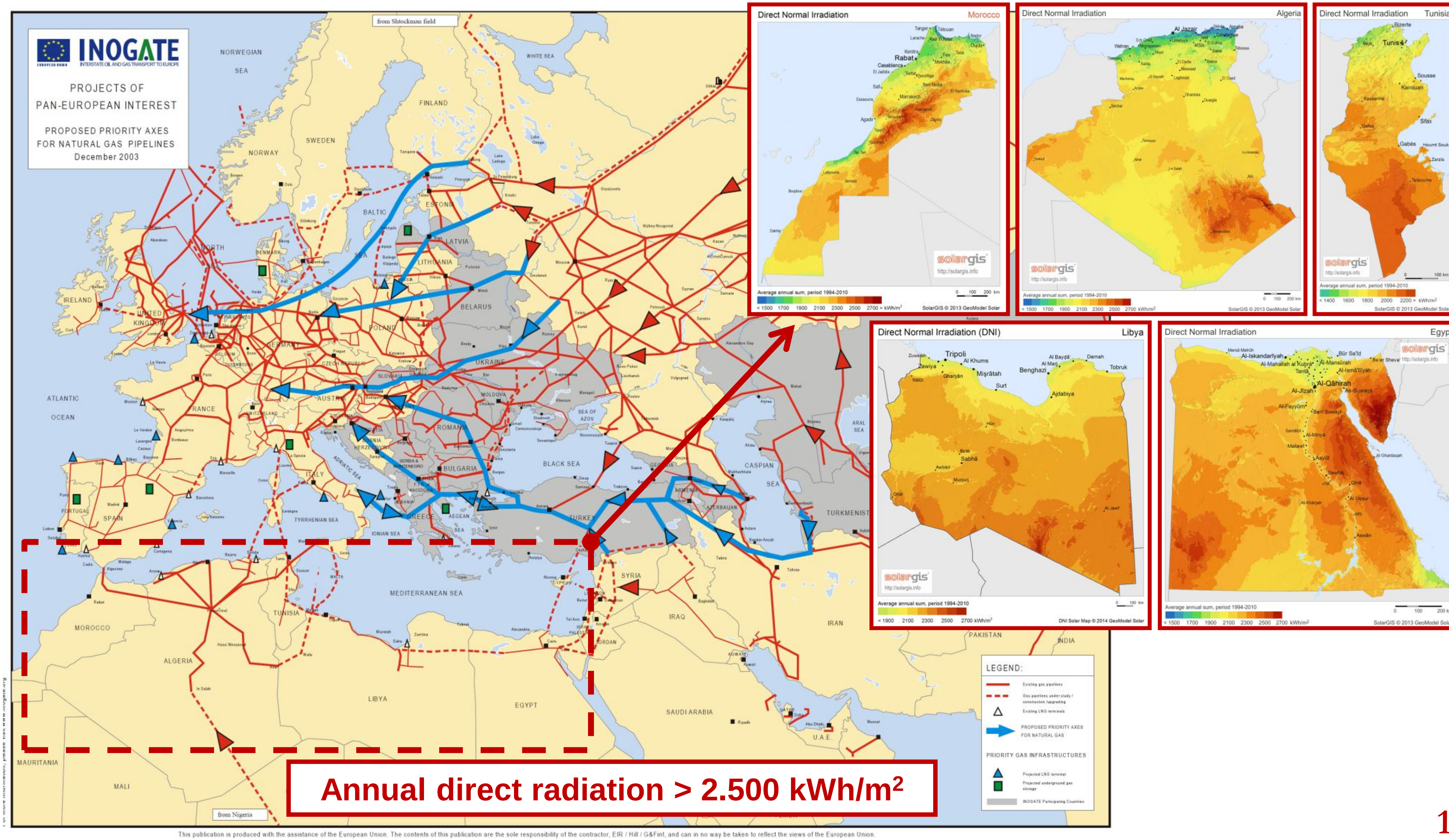
Syngas production by steam reforming of natural gas wherein concentrated solar radiation is the energy source of process heat for driving methane steam reforming (MSR) is a process called "Solar Methane Steam Reforming".

Syngas production by solar MSR has been investigated in detail in recent years and seems to be one of the most promising solution for solar energy:

- **no thermal storage, since it realizes "chemical storage";**
- **opportunity of using the existing methane grid for syngas transport.**

Solar Methane Steam Reforming: where?

High direct solar radiation and methane grid presence



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Solar MSR optimisation

UNIBO objective was to optimize solar MSR plant by:

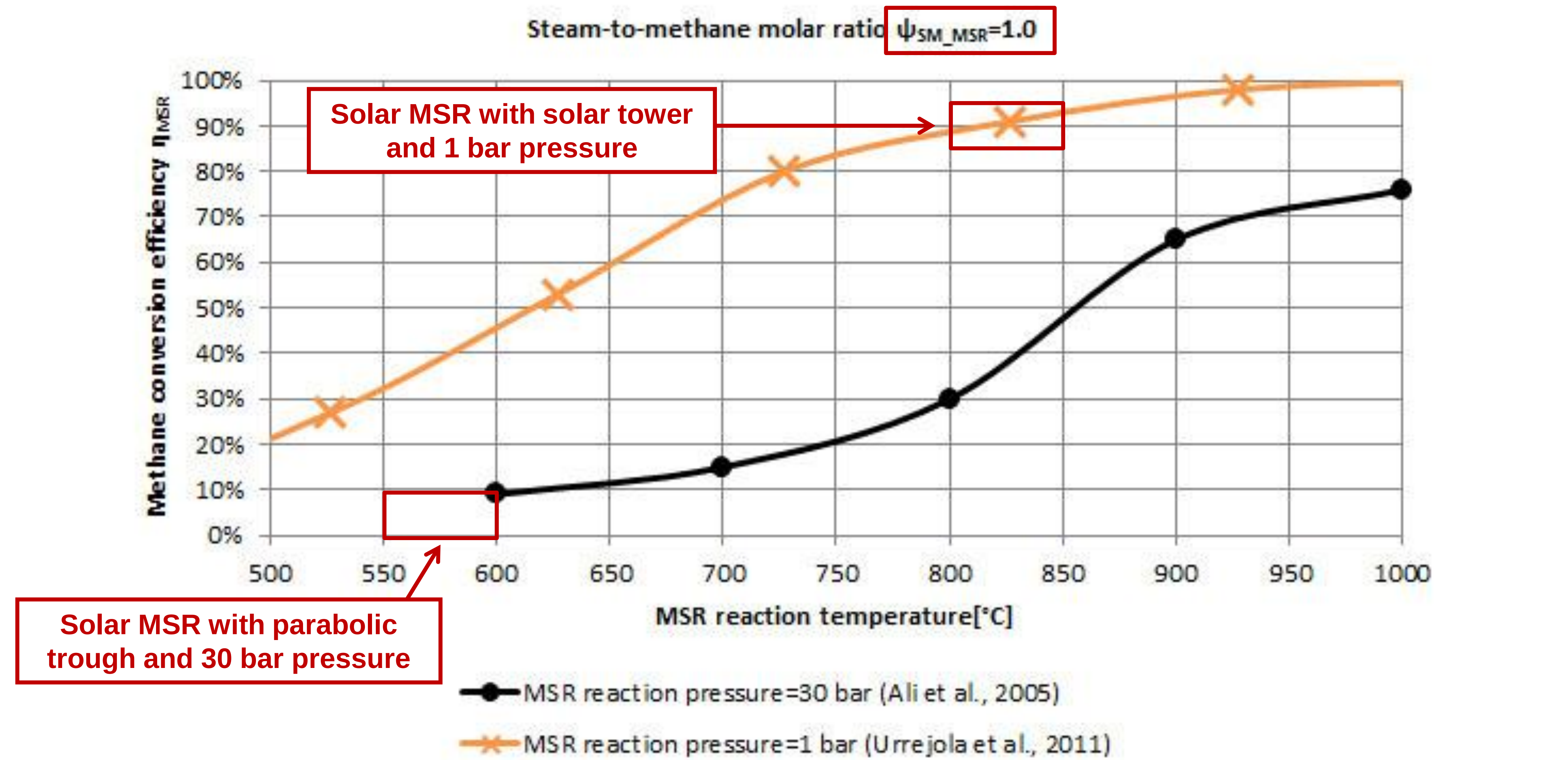
- **increasing reliability,**
- **reducing cost , and**
- **ensuring high methane conversion efficiency.**

From a conceptual point of view, it is possible to increase reliability and reduce costs through the application of strong design solutions like using parabolic trough CSP technology and working at higher operating pressure.

Design solution	**Positive effect**	**Negative effect**
Parabolic trough CSP (instead of solar tower)	Proven technology, high reliability	**Lower conversion efficiency** (due to low temperature)
High process pressure (up to 30 bar instead of 1 bar)	Compact design, Cost reduction	**Lower conversion efficiency** (due to high pression)

How much lower?

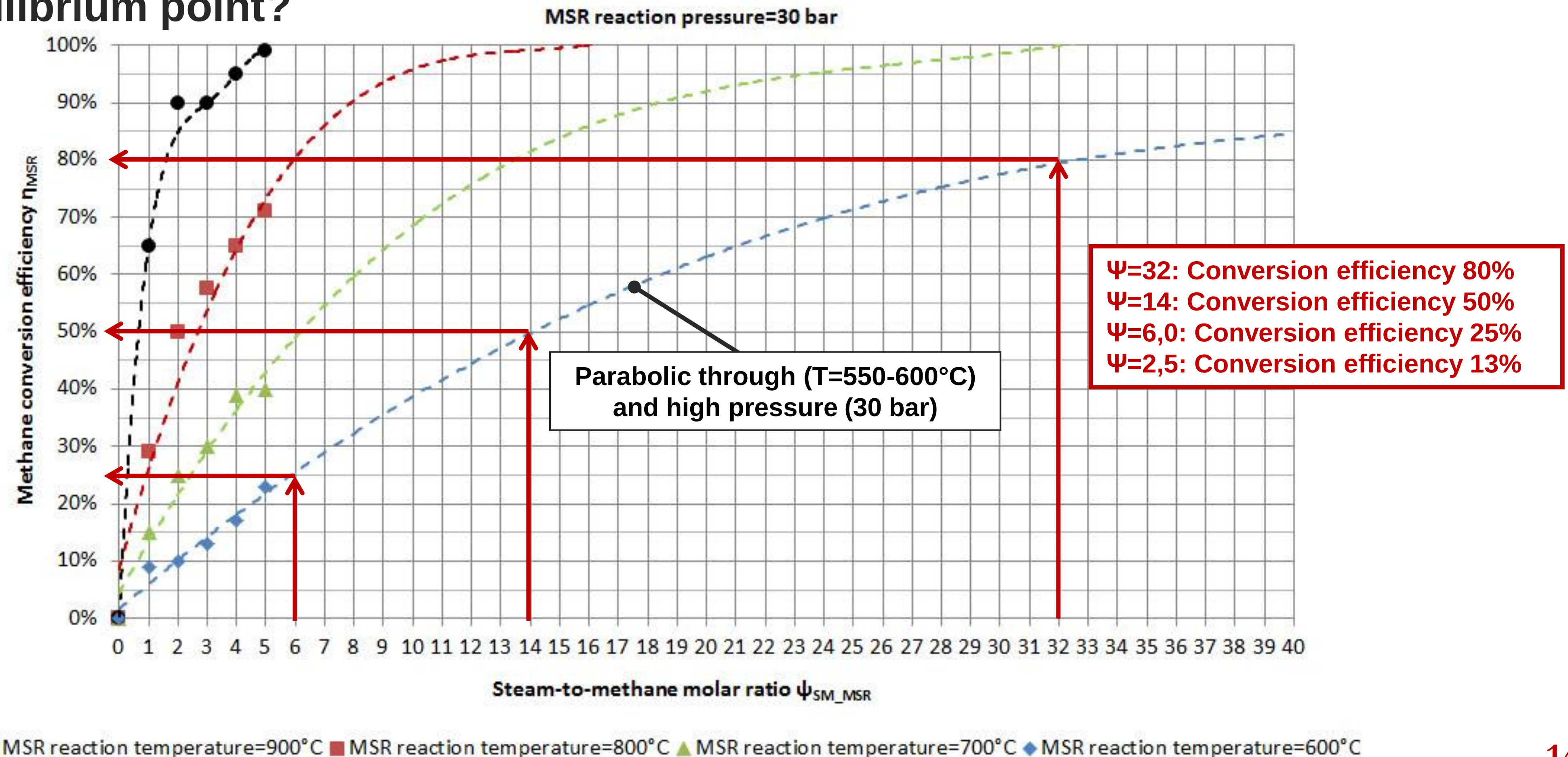
Solar MSR optimisation



The proposed changes lower methane conversion efficiency from 90% to less than 10% if steam-to-methane molar ratio is equal to 1 (standard value).

Solar MSR optimisation

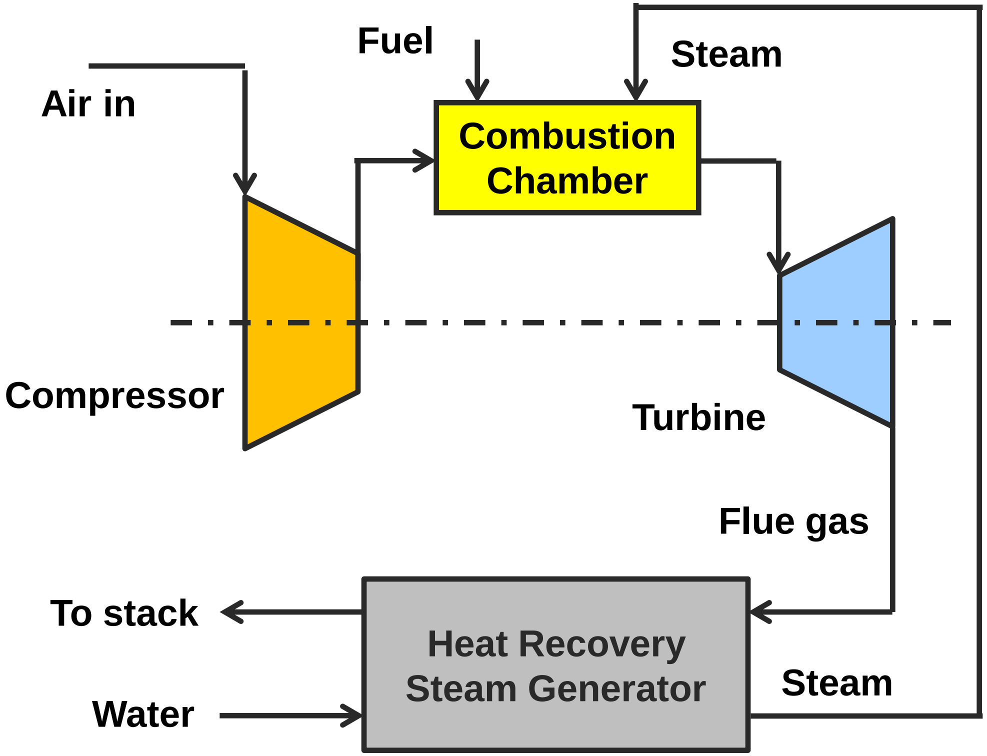
The only lever that can be used to increase methane conversion efficiency is **steam-to-methane molar ratio increasing**. An higher steam-to-methane molar ratio has positive effects both on MSR equilibrium achieving and catalyst saving, but it is very negative from an energetic point of view. Which is the equilibrium point?



Gas turbine steam injection

The **injection of steam into a gas turbine** (GT) **combustion chamber** is a proven technology and results in an efficiency gain of about 10 points, a power increase of about 50-70%.

On the other hand, the amount of steam that can be ultimately injected is limited (steam-to-fuel molar ratio of about 1,78) by a rapid rise in CO emissions, accompanied by flame instability: steam injection reduces NO_x by lowering the flame temperature but suppresses the rate of CO oxidation.



Steam injection is an **efficient and low cost alternative to combined cycle** at electrical power output plant lower than 50 MWe.

In fact, GT steam injection eliminates steam turbine and all associated equipment including generator, condenser and cooling tower, thus making it simpler, more compact and less expensive than a combined cycle plant.

Gas turbine steam injection and solar MSR

Generally, flame instability occurs at a steam-to-fuel molar ratio of about 1,78.

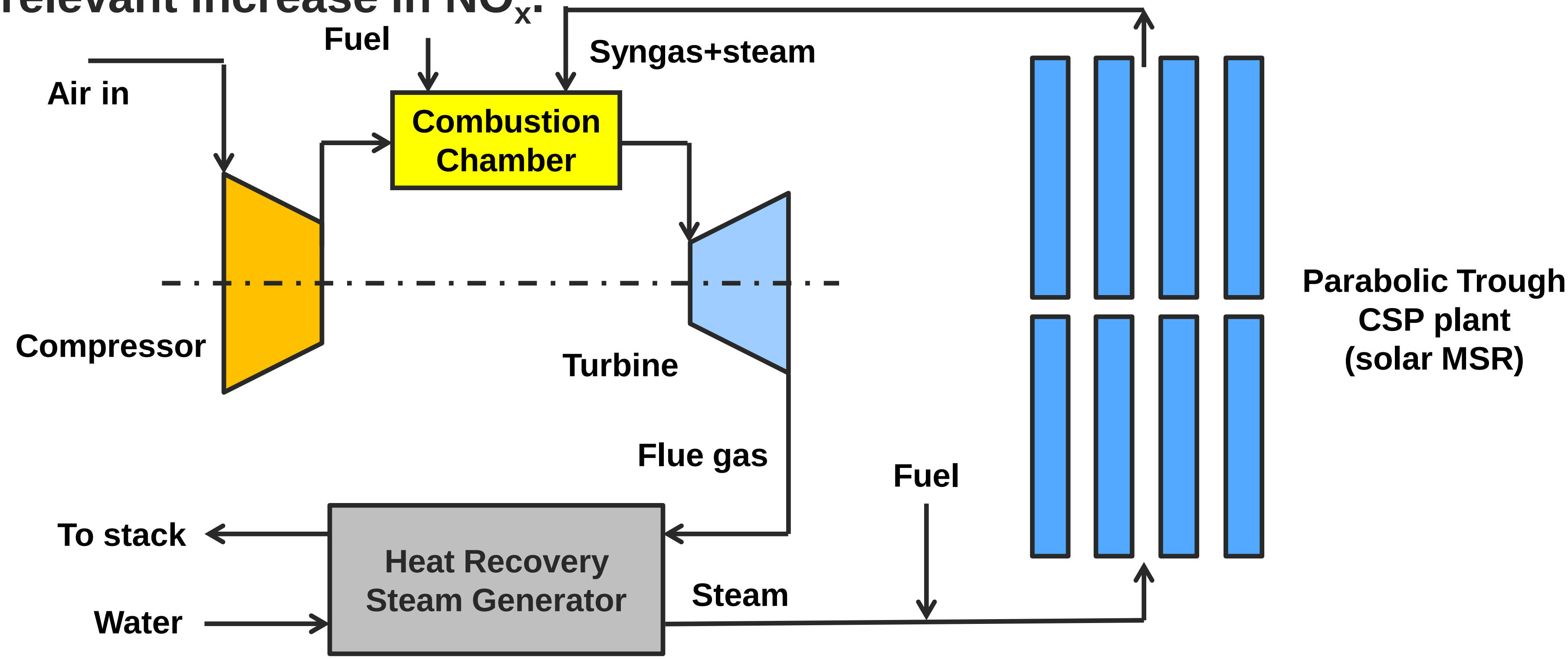
Cheng developed a solution to favor homogeneity by steam and methane pre-mixing before combustion chamber injection. This solution is named Cheng Low NO_x (CLN) and makes it possible to raise steam-to-fuel molar ratio to 3,56 without increasing CO emissions.

When the GT combustion chamber is fed by a mixture of mostly methane and solar MSR syngas, the combination of CLN with a solar MSR plant makes it possible to overcome the steam-to-methane molar ratio limit with regard to the MSR process and also steam-to-methane molar ratio with regard to gas turbine steam injection.

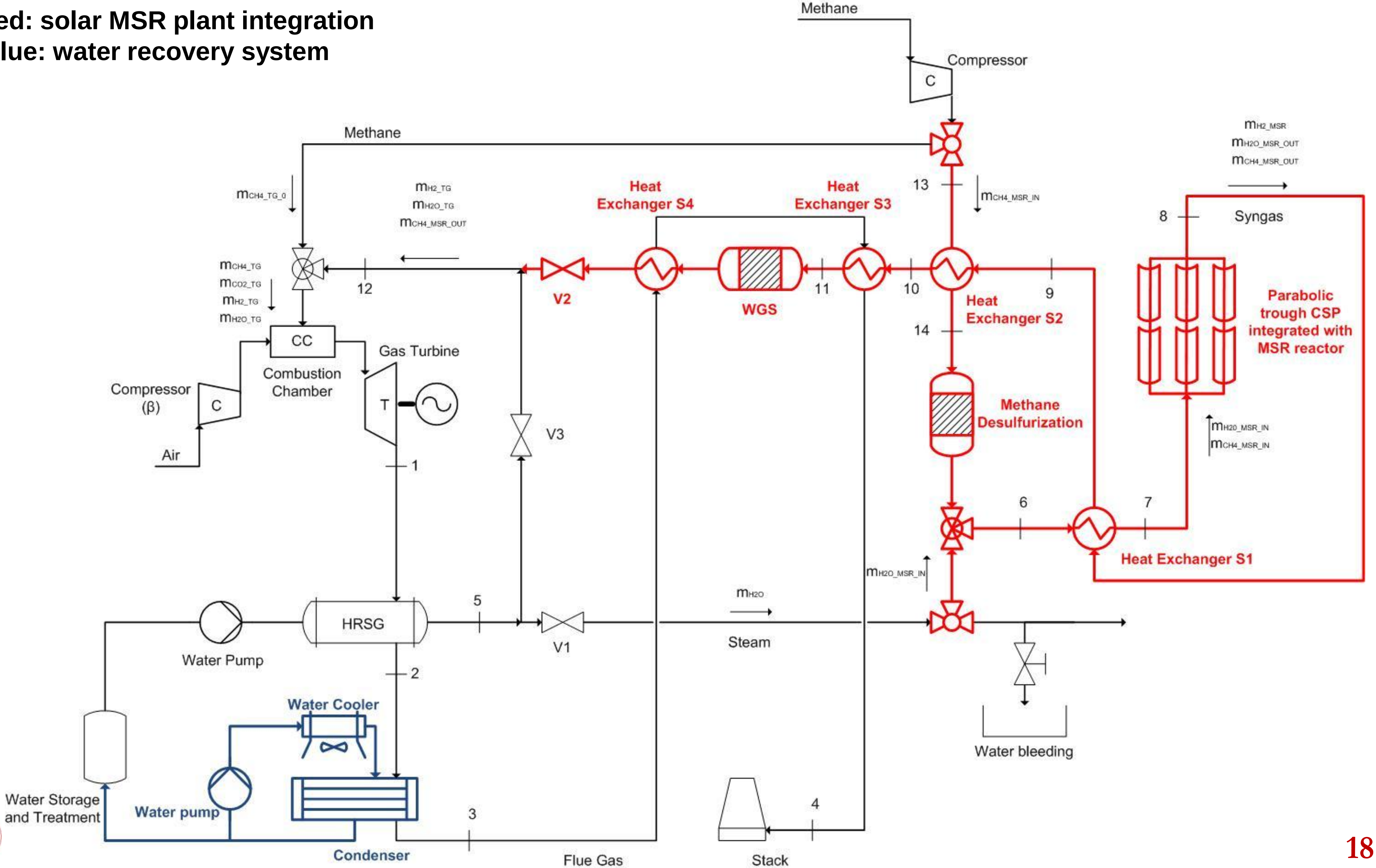
One possible solution for a more efficient production of syngas from solar MSR is integration with Cheng Low No_x process.

Hybrid power plant: Cheng Low NO_x Cycle + solar MSR

1) it is possible to optimize steam production because **steam is used not only in the MSR reaction but also (and mainly) in the turbogas plant**;
2) steam-to-methane CLN limit due to steam negative effects on CO production should be overcome by taking into account the **positive effect of hydrogen injection in the combustion chamber**: a reduction of about 30% CO emissions is possible by addition of only 4% hydrogen in weight without a relevant increase in NO_x.



In red: solar MSR plant integration
In blue: water recovery system



Hybrid power plant – preliminary design

The turbogas plant is compared with a hybrid power plant wherein 10% of the nominal GT feeding natural gas is sent to the solar methane reforming reactor before being injected in the GT combustion chamber.

The percentage of 10% was chosen because if the substitution of natural gas is limited, the effects of syngas on turbine operation can be ignored and should not modify turbine performance.

Characteristics	**Turbogas plant GE LM2500 STIG**	**Hybrid plant**
Power output [MW_e]	26,4	30,0 (+2,6 by excess steam)
Power output percentage increase	-	**+13,6%**
CO_2 savings [ton/year]	-	685
Methane percentage savings	-	1,70%
CSP plant size [MW_{th}]	-	**2,1**
CLN Steam-to-methane molar ratio	3,56	4,00
Solar MSR Steam-to-methane molar ratio	-	**37,6** (85% methane conversion)

The hybrid plant described is suitable for integration in a smart energy grid, because it can be used both as a solar energy converter and as an integration power plant fed by natural gas on peak demand.

Hybrid power plant – economic assessment

Investment costs

Investment costs [1.000 €]	Turbogas plant GE LM2500 STIG	Hybrid plant
Gas turbine	12.400	-
HRSG	7.600	-
Water treatment	1.500	-
Piping	100	80
CSP+MSR – Parabolic Trough (256€/m^2)	-	890
Water Gas Shift reactor	-	500
Heat Exchangers	-	370
Others (design, safety, authorization)	2.000	2.300
TOTAL	**23.600**	**4.140**

18% of turbogas plant investment

Yearly Costs vs. Profits of the hybrid plant

Item [1.000 €]	Cost	Benefit
Operation and maintenance (5% of investment)	212	-
Electricity production increase (0,09€/kWh, North Africa price)	-	850
Natural gas consumption decrease (0,129€/Nm^3)	-	41
TOTAL PROFIT - COSTS		**+679**

6 years payback time

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An innovative hybrid power plant that integrates the solar MSR process with a steam injected gas turbine power plant (26 MWe) has been shown. A comparison was made between an existing steam injection gas turbine power plant and the hybrid plant, showing how with a minimal integration (10% of gas turbine nominal feeding methane used in a solar MSR, payback time of the investment equal to 6 years) it is possible to reach important results, such as:

- **natural gas savings (685 tons CO_2/year saved);**
- **NO_x and CO emissions under limits;**
- **increase (+5,1%) in electrical energy produced every year.**

Under evaluation – future application

Integration of solar MSR process with natural gas processing plant to:

- **produce solar syngas by solar MSR;**
- **treat the syngas with existing infrastructure of natural processing;**
- **use the methane grid as a storage element for the solar syngas.**

Conclusions

<u>Looking for industrial partners</u>

Secure, clean and efficient energy
Work Programme 2016-2017 (draft)

Call – Competitive Low-Carbon Energy (LCE)

LCE7-b-2017: Developing the next generation technologies of renewable electricity and heating/cooling

"*In spite of cost reductions in recent years, cost competitiveness remains a crucial barrier to the deployment of CSP plants. Several innovative concepts for new cycles and power blocks with a potential for lifecycle cost reduction are being explored. The challenge is to validate the feasibility of these concepts in relevant environment*".

Technology Readiness Level (TRL): 4-5 (validated in lab - relevant environment)
EC Grant: 2-5 million €