DE LA RECHERCHE À L'INDUSTRIE

HYBRIDIZATION OF A SMALL MODULAR REACTOR WITH A SOLAR POWER PLANT USING A SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLE

Q.T. Pham , N. Tauveron , N. Alpy
V. Vuillerme

3rd European Conference on Supercritical CO2 (sCO2) Power Systems, Paris, FRANCE
19 – 20 September, 2019

Summary

1. Context
    - *Small Modular Nuclear Reactors (SMR)*
    - *Solar power and existing solar power plant technology*
    - *Concept of nuclear-solar coupling in a hybrid power system*
2. Reference case for nuclear-solar energy hybridization
    - *Bibliography*
    - *Reference case*
3. Nuclear-solar hybridization at high temperature using sCO2 cycle
4. Nuclear-solar hybridization at low temperature using sCO2 cycle
5. Conclusions & Perspectives

Context & Objectives

❖ Context

✓ A state of advanced development of **Small Modular nuclear Reactor (SMR)** worldwide

✓ The deployment of **solar power plants** (Photovoltaic or Concentrating Solar Power)

✓ The attractiveness of **hybridization** and **integration** of **Thermal Energy Storage systems (TES)**

❖ Objective of SMR – Solar Power Plant – TES hybridization

✓ Provide **climate-friendly decarbonized** electricity

✓ Use the solar source to **boost** both **production and efficiency** of the hybrid power plants *(also possibly as source for auxiliary circuits of the SMR)*

✓ Integration of technologies to ensure scaleability and **flexibility**

❖ Nuclear technologies in SMR

- ✓ Light water reactors (ex: NuScale – USA, SMART – Korea, etc …)
- ✓ High temperature gas cooled reactors (ex: GTHTR300 – Japan, MHR-100 - Russia, etc …)
- ✓ Liquid metal (Sodium/Lead-bismuth) cooled fast reactors (ex: PRISM – USA, BREST-300-Russia, etc …)
- ✓ Molten salt thorium reactors (ex: IMSR-Canada, etc …)
- ✓ etc …

❖ Present study

- ✓ Similar design to the classical water cooled nuclear reactor
- ✓ Smaller size to be built in factories and shipped for installation

Small Modular Reactors

❖ **Technological advantages**
- ✓ Non CO2 energy solution
- ✓ Short construction duration
- ✓ Enhanced reliability
- ✓ Possibly enhanced safety due to passive safety
- ✓ Reduced complexity in design and human factor
- ✓ Suitability for non-electricity application

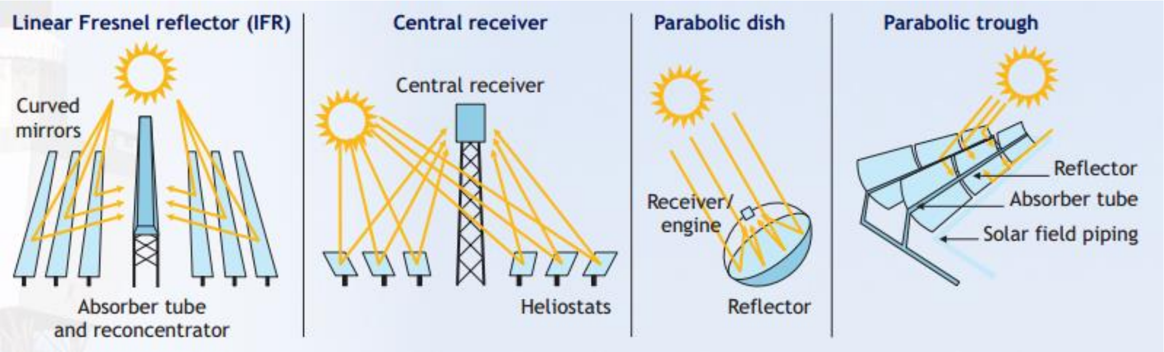
❖ **Non-technological advantages**
- ✓ Suitability for small electricity grids
- ✓ Option to match demande growth by incremental capacity increase
- ✓ Lower capital cost
- ✓ Small reactor can minimize terrorism risk
- ✓ Easier financing scheme

	Large nuclear reactors	Small modular reactors
Power	800 – 1600 MWe	< 300MWe
Construction time	4,5 – 6 years	1,5 – 2,5 years

Solar Power Plants

- Solar power is the conversion of energy from sunlight into electricity, either directly using photovoltaics (PV), indirectly using concentrated solar power (CSP), or a combination. Therefore, SPP must be situated in regions with suitable solar resources (strong and abundant sunlight)

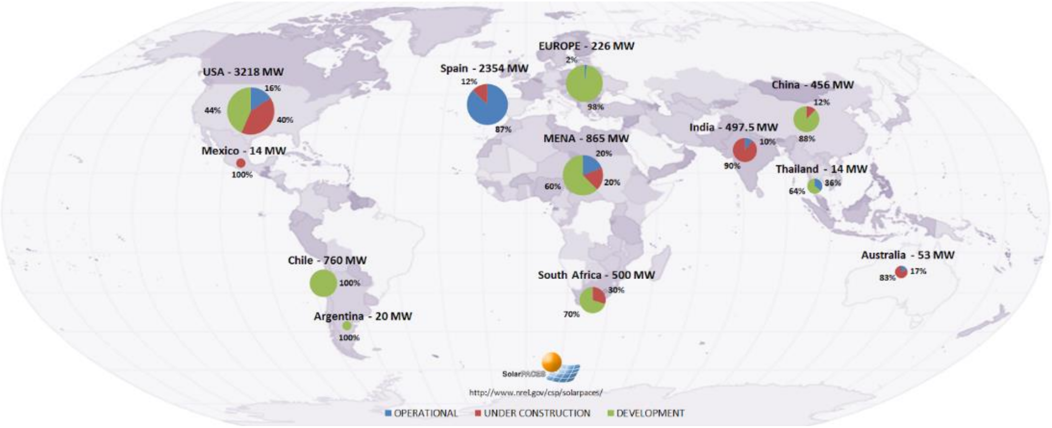
PV



CSP

- Current status of CSP Commercial Projects

https://www.evwind.es/



Concentrating Solar Power

❖ CSP key competitive advantages

- ✓ Produce clean environmentally friendly electricity without emission of CO2
- ✓ Renewable and free fuel cost
- ✓ Low operating and maintenance costs
- ✓ Solar power plants equipped with TES allows continuous generation of electricity
- ✓ Multiple Applications: generation of heat and electricity, water desalination…
- ✓ Use of many of the same technologies and equipments used by conventional power plants, which allows a minimizing of design and construction costs

❖ CSP issues

- ✓ Limited market
- ✓ Requirement of large area for sunlight collectors
- ✓ High investment cost

Why Nuclear-Solar-TES hybrid energy system?

❖ **Challenges for Nuclear Power Plants**

✓ Generally, NPPs are more economic when operated at high and constant power levels, sometimes leading to surplus of production

→ Needs for a subsystem to consume the excess nuclear heat to adapt the electricity supply to variation of power demand → can be a TES

✓ Current operating NPPs produce saturated steam at relatively low pressure

→ Possibility to increase the steam temperature at the outlet of steam generator to improve the efficiency of the NPPs?

❖ **Challenge for Solar Power Plants**

✓ Variability of the resource, which requires an highly flexible grid to meet the remaining electric demand.

→ Integration of TES helps solar power plants to overcome this drawback

❖ **Challenge for All kind of Power Plant**

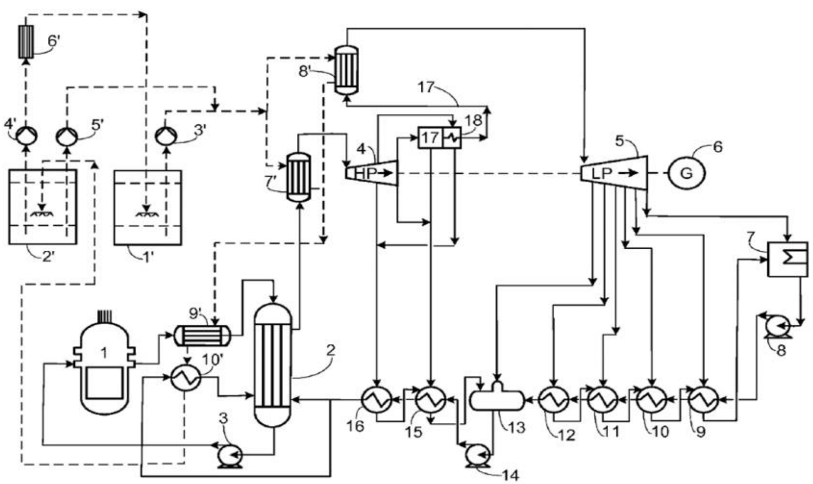
✓ Need for a flexible system, able to adapt its production to electric demand.

↓

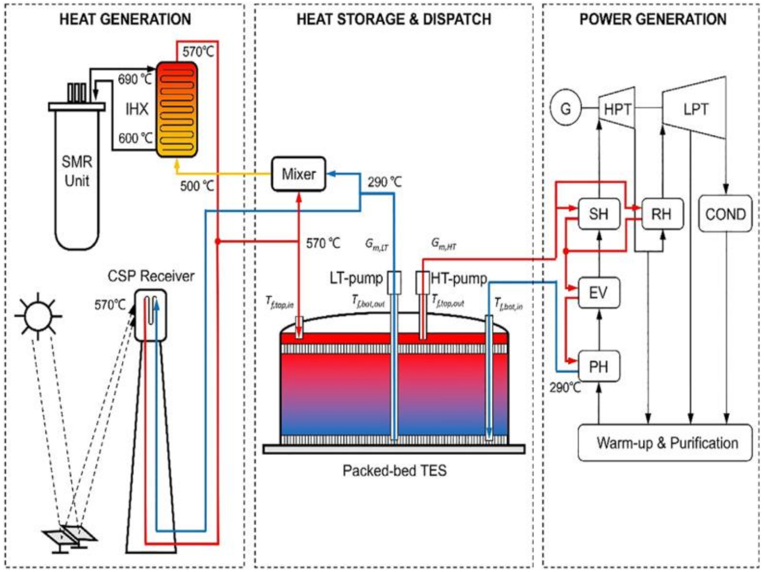
Nuclear-Solar-TES hybrid energy system

SMR-solar-TES hybridization

Solar-nuclear hybrid power plant,
US Patent 2015, Sakadjian B.B., Arnold W.A., Kraft D.L

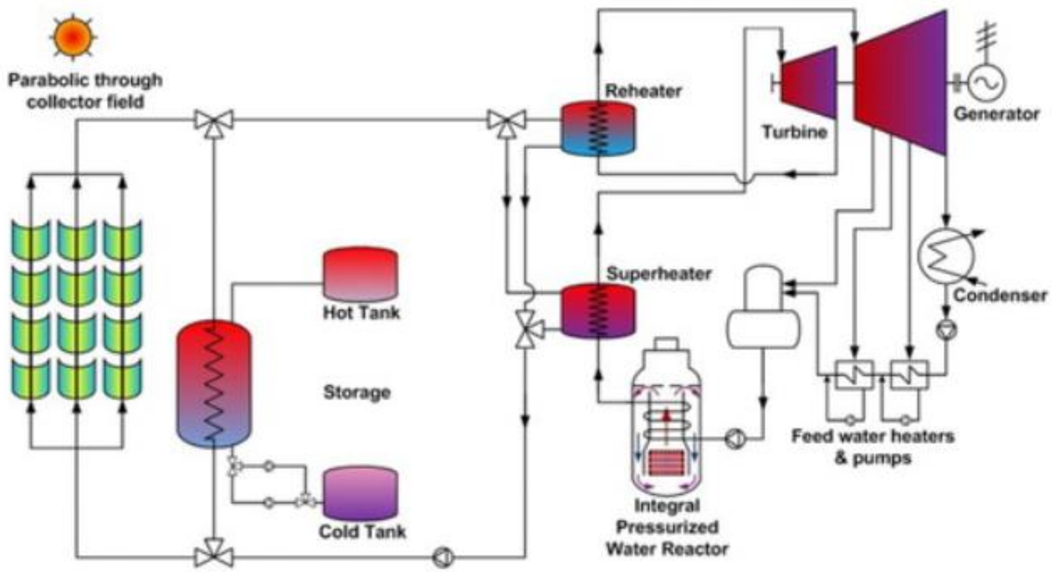


Conceptual design and preliminary performance analysis of a hybrid nuclear-solar power system with molten-salt packed-bed thermal energy storage for on-demand power supply, Energy Conversion and Management 166 (2018) 174–186,
Bing-chen Zhao, Mao-song Chenga, Chang Liu, Zhi-min Dai



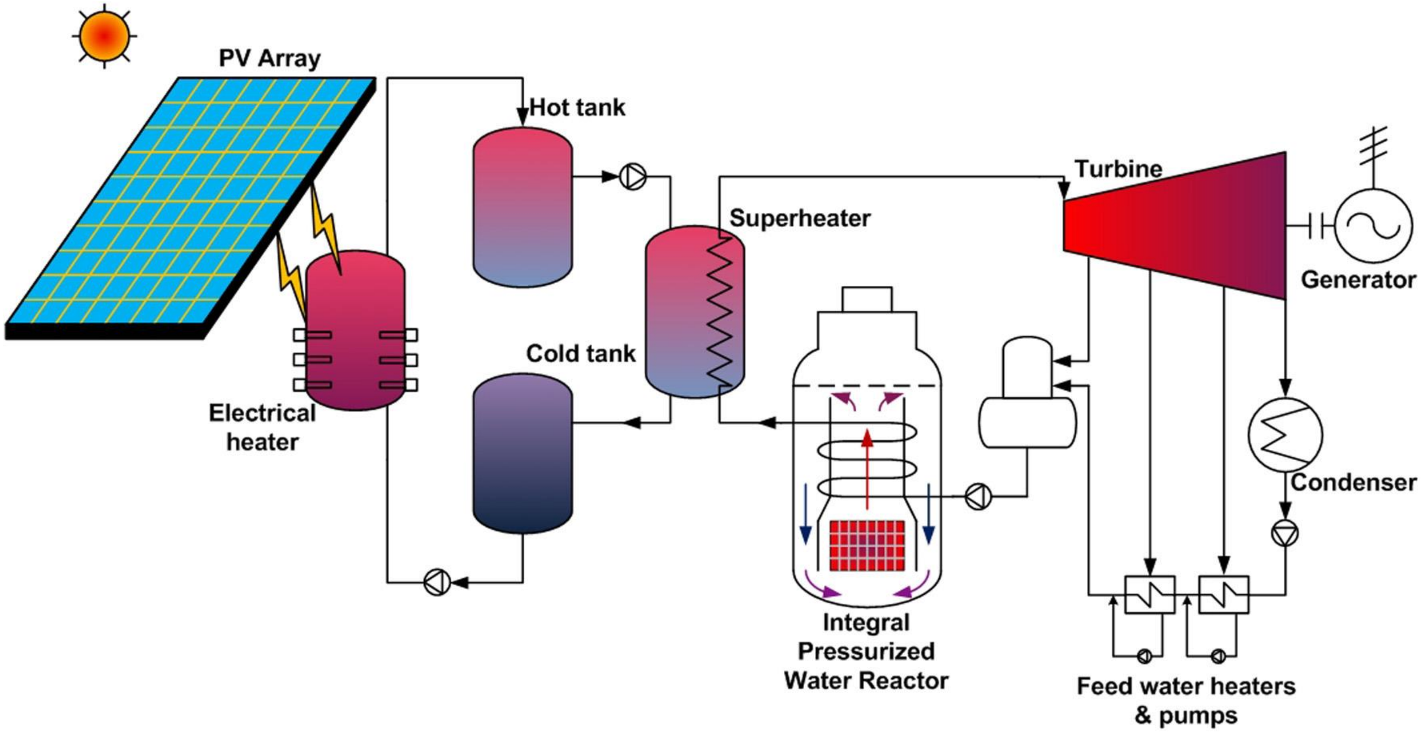
SMR-parabolic through solar-TES hybridization (NPP-PT)

Innovative configuration of a hybrid nuclear-parabolic trough solar power plant,
International Journal of sustainable energy, 2017, pp. 1-24
Popov et Borisova



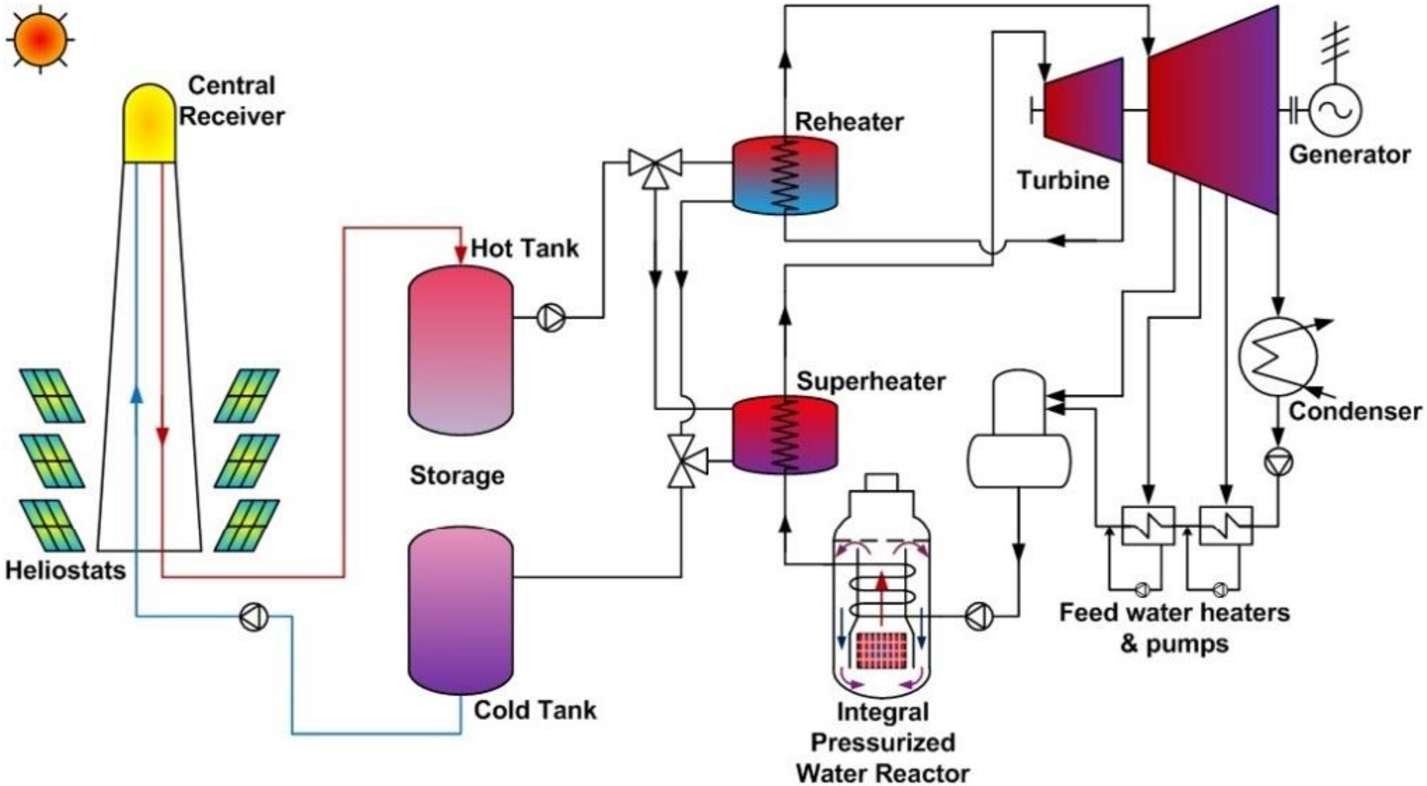
SMR-solar photovoltaics-TES hybridization (NPP-PV)

An option for the integration of solar photovoltaics into small nuclear power plant with thermal energy storage,
Suistainable Energy Technologies and Assessments, Vol. 18, 2016, pp. 119-126
Popov et Borisova

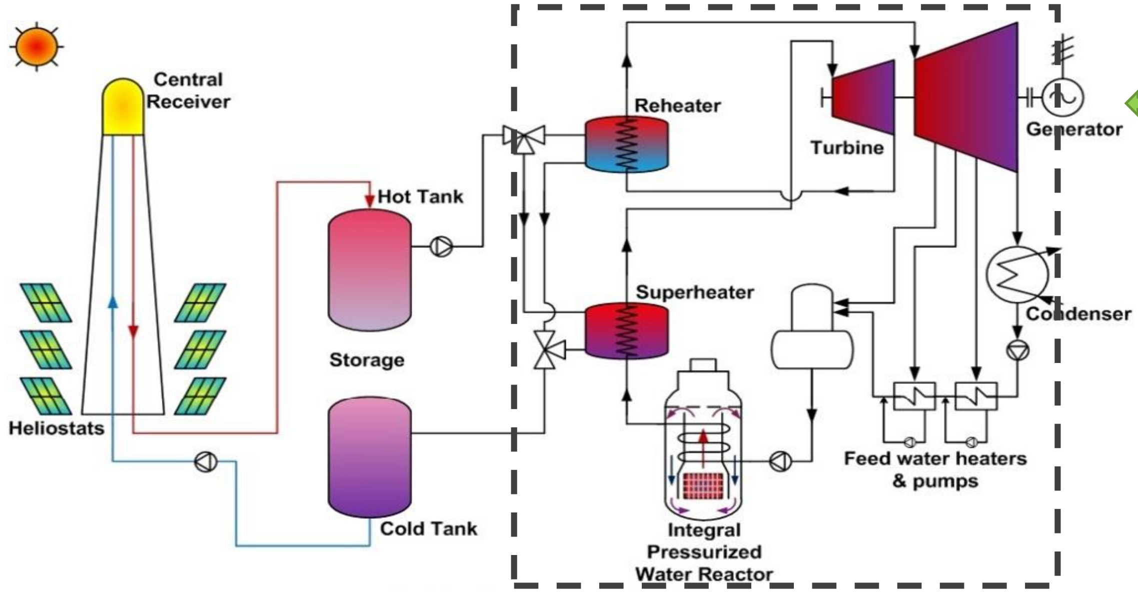


SMR-solar tower-TES hybridization (NSPP)

Innovative configuration of a hybrid nuclear-solar tower power plant,
Energy, Vol. 125, 2017, pp. 736-746
Popov et Borisova



SMR-Solar-TES hybridization (reference)



Rankine cycle

Plant parameters	NPP	NPP-PT	NPP-PV	NSPP (Tower)
Turbine inlet temperature [°C]	255	381	580	**555**
Turbine inlet pressure [bar]	31	30.4	30.4	**30.4**
Net electric power [kWe]	43911	69302	77970	**91833**
Thermal efficiency [%]	27.45	33.17	36.12	**37.47**

+10 pt !

Influence of solar share on NSPP efficency

Compare of NSPP and NPP with EES software

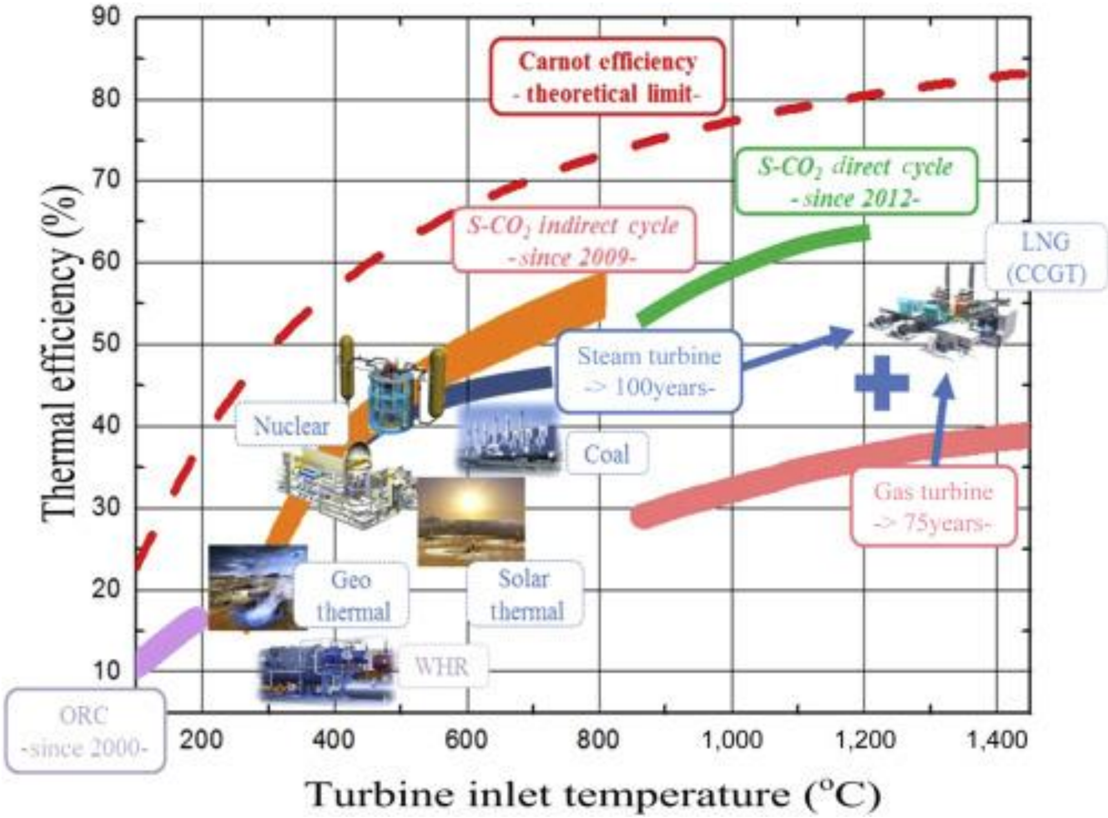
Case 2: NPP, $T_{inlet,turbin} = T_{outlet,steam\_generator}$

$T_{inlet,turbin}$	Nuclear power	Used solar power	Thermal efficiency	Note
°C	%	%	%	
255	100	0	27.45	Neither reheating nor superheating

Case 1: NSPP coupling, $T_{inlet,turbin} = T_{outlet,reheat} = T_{outlet,superheat}$

$T_{inlet,turbin}$	Nuclear power	Used solar power	Thermal efficiency	Note
°C	%	%	%	
555	100	99.13	37.47	Solar energy serves for both reheating and superheating
500	100	86.36	36.28	
455	100	76	35.3	
355	100	53.07	33.05	
255	100	30.69	31.03	No superheating, solar energy serves for reheating only

Potential application of SCO2 Brayton cycle for NSPP



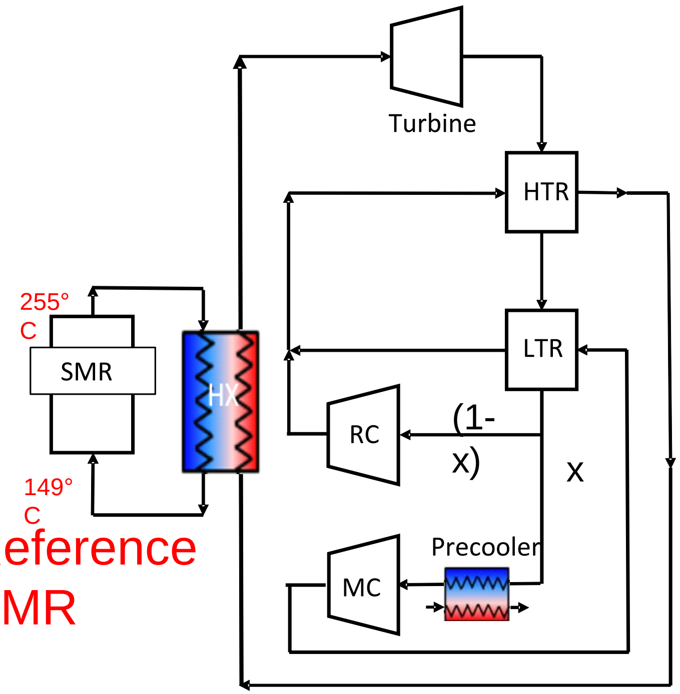
SCO_2 Brayton recompression cycle for SMR

Imposed conditions:

- P_{max} = 20MPa
- $T_{in,compressor}$ = Tambiant = 27°C (summer case)
- $E_{turbine}$ = 93 %
- $E_{compressor}$ = 89 %
- $E_{recuperator}$ = 95 %

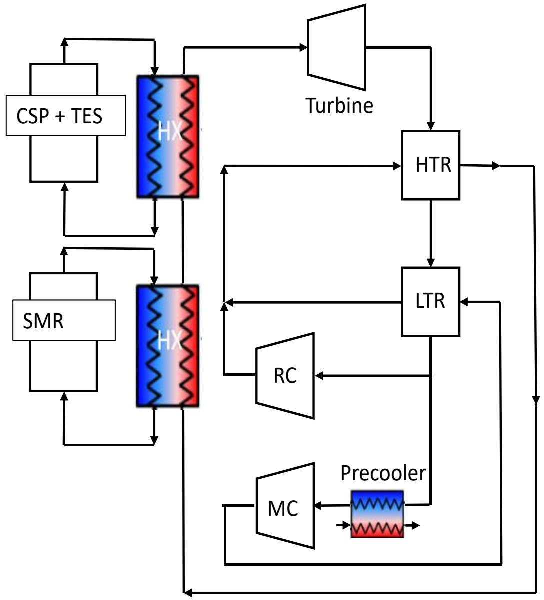
$T_{in,turbine}$	$P_{min,optimized}$	$x_{optimized}$	% cycle	T_{IHX}
240	8.235	0.684	27.96	138.7
255	**8.2338**	**0.684**	**29.46**	**148.5**
380	7.779	0.624	39.4	240.3
399	7.779	0.625	40.56	255.4
405	7.791	0.624	40.92	260.3
555	7	0.59	49.08	379.9

Reference SMR



2 pt efficiency improvent obtained with SCO2 Brayton cycle instead of Rankine cycle

High temperature hybrid plant with single SCO_2 Brayton recompression cycle



Summer

% used solar heat	Pmin	Split ratio	$T_{inlet,turbine}$	Efficiency (%)
0	8	0.6485	255	29.49
20	7	0.6435	267.6	29.7
50	6.8	0.7265	286.8	30.37
80	6.8	0.8189	306.1	30.84
100	6.8	0.8811	**319.1**	**31.08**

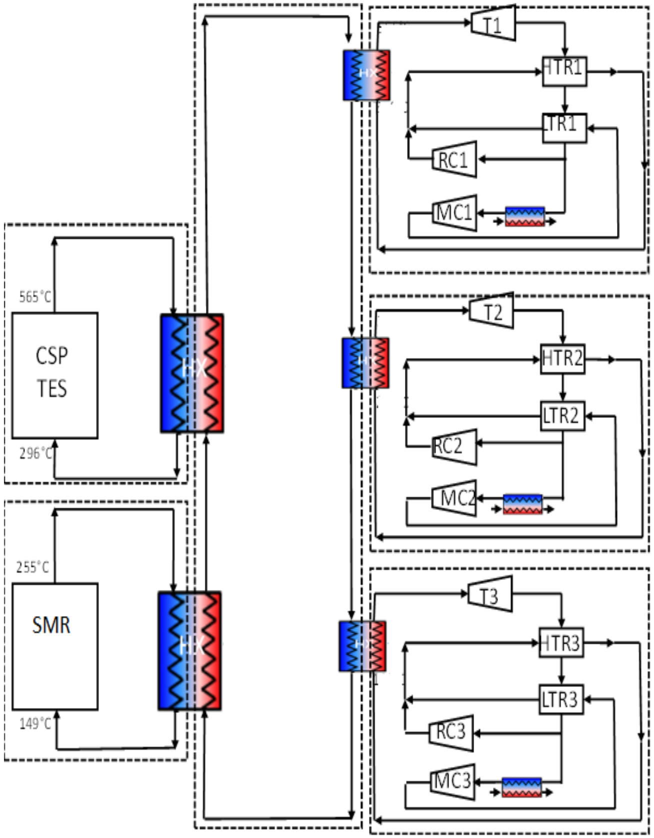
Winter

% used solar heat	Pmin	Split ratio	$T_{inlet,turbine}$	Efficiency (%)
0	7.6	0.5465	255	28.72
20	7	0.6178	267.6	31.78
50	5.8	0.6224	286.8	32.49
80	5.8	0.7	306.1	33.1
100	5.8	0.7522	**319.1**	**33.39**

- SMR constraints (T_{in}, T_{out}) & serial configuration → T_{in} @ turbine limited
- sCO2 recompression cycle: 1 parameter to optimize (split ratio)

→ Lower thermal efficiency obtained with SCO2 Brayton recompression in comparison to Rankine cycle

High temperature hybrid plant with cascaded SCO_2 Brayton recompression cycle



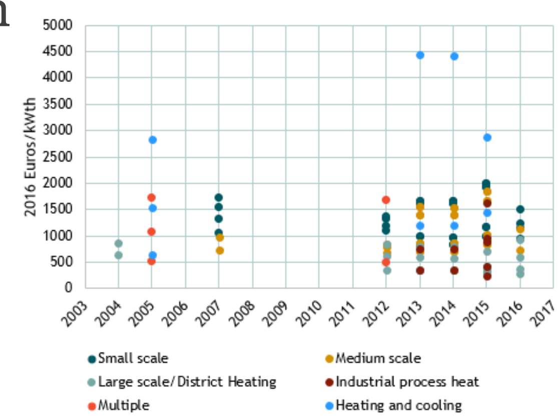
Loop	Imposed parameters	Optimised parameters	Loop efficiency
Top	P_{max} = 20 MPa **T_{OHX} = 555 °C**	P_{min} = 8.5 MPa **T_{IHX} = 392 °C** Split ratio = 0.658	47.35 %
Middle	P_{max} = 20 MPa **T_{OHX} = 392 °C**	P_{min} = 6.8 MPa **T_{IHX} = 247 °C** Split ratio= 0.575	40.91 %
Bottom	P_{max} = 20 MPa **T_{OHX} = 247 °C**	P_{min} = 8.2 MPa **T_{IHX} = 143 °C** Split ratio = 0.676	28.66 %

NSPP overall efficiency = 38.81%

+11 pt !

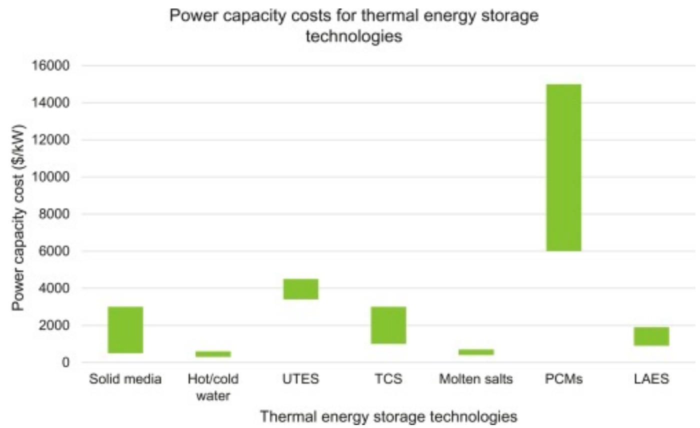
Low temperature hybrid plant with SCO2 Brayton recompression cycle

- ❖ An alternative to high temperature configuration based on technologies developed for industrial processes and district heating :
  - ❖ Low-temperature solar heat generation



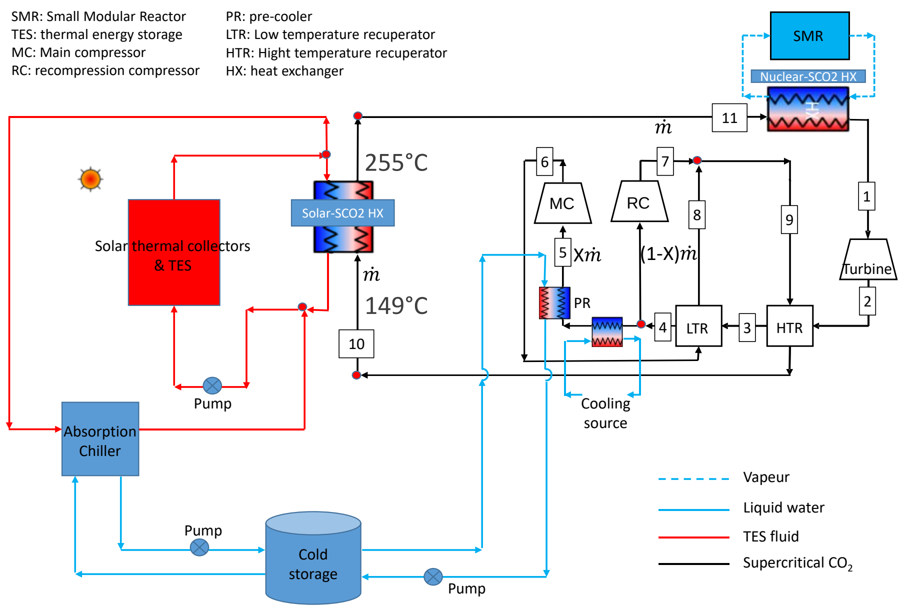
O. HOOGLAND, E. VEENSTRA, P. TORRES, I. IPARRAGUIRRE TORRES, H. KUITTINEN "Study on impacts of EU actions supporting the development of renewable energy technologies", Ref: 2017/RTD/SC/PP-05441-2017, 2018.

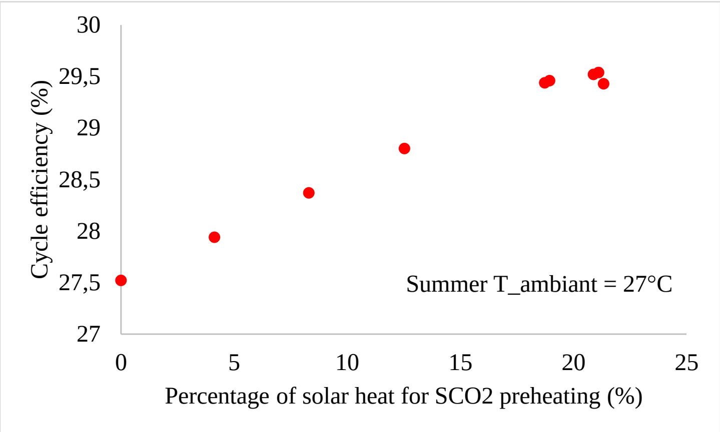
  - ❖ Low temperature heat storage

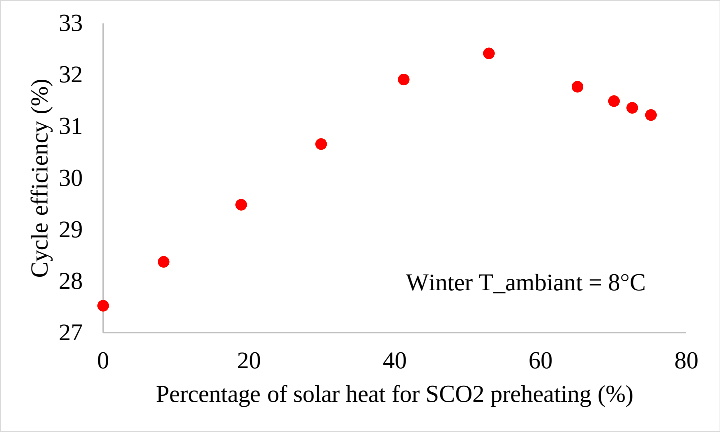


H. BINDRA, S. REVANKAR "Storage and Hybridization of Nuclear Energy, Techno-economic Integration of Renewable and Nuclear Energy", Elsevier, 2019.

Low temperature hybrid plant with SCO2 Brayton recompression cycle







2 to 5 pt efficiency enhancement due to hybridization

Conclusions

- Proposal of two configurations for **nuclear-solar hybrid power plant** operating at **high** and **low** temperatures in which **SCO2 Brayton** cycle is employed for the power block

- **Up to 10 pt** efficiency improvement obtained for **high temperature** hybrid configuration

- With the **low temperature** hybrid configuration, about **2 to 5 pt efficiency** enhancement could be achieved but other **potential economical advantages** are of interest

- Next future: to develop model for hybrid plant **operating strategy**

Next steps

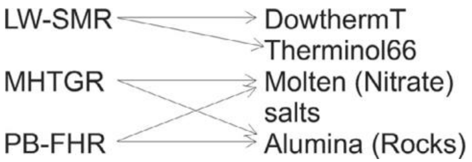
❖Application of operating model for different **locations** & **conditions** & **markets** (power, heat, cold, ...)

❖Replacement of LWR by other advanced concept of nuclear reactors in the NSPP → **sCO2 remains interesting for all concepts**

Reactor type	Coolant	Neutron spectrum	Peak temperature
SFR	Na	Fast	550 °C
LFR	Pb-Bi	Fast	550–800 °C
GFR-indirect	He	Fast	850 °C
GFR-direct	CO2	Fast	650 °C
LWR	H_2O	Thermal	300 °C
VHTR	He	Thermal	1000 °C
MSR	Fluoride salt	Fast/ thermal	700–1000 °C

[Conboy et al., 2015]

❖Selection of **TES technologies** adapted to NSPP temperature



[Edwards et al., 2016]

❖Technico-**economic** analysis

Thank you for your attention