La conversione termodinamica della energia solare con innovativi motori termici

- strumenti per la sostenibilità –

energia pulita e accessibile - città e comunità sostenibili - lotta contro il cambiamento climatico

G. Di Marcoberardino, C. Invernizzi, P. Iora
DIMI

The Sun: a primary energy source, I

Sun, although in an indirect way, ★ is responsible for the greater part of the different "renewable" energy sources on the earth, and it can so ★ be considered and classified as a primary energy source.

The energy from the Sun is the result of specific nuclear fusion reactions: hydrogen is converted into helium, that, in its turn, ageing the star, is converted in heavy nuclides. When the mass number of the products reach a value about 60 (iron and nikel) the fusion reactions stop … in some billions of years https://www.youtube.com/watch?time_continue=16&v=FyLSjkOV2H8

The Sun: a primary energy source, II

The heat produced by the nuclear reactions keeps the *core* temperature at several millions degrees.
The high temperature sustains the fusion reactions and the produced energy is then transferred on the surface and irradiated into the outer space.

For a terrestrial observer, the Sun looks like:

- a black body with a temperature of ≈ 6000 degrees and,
- with a thermodynamic availability of ≈ 0.93

- Average distance sun – earth: ≈ 150 x 10^6 km
- Sun diameter: ≈ 1.5 x 10^6 km
- Earth diameter: ≈ 1.3 x 10^4 km
- Solar constant: 1367 W/m^2

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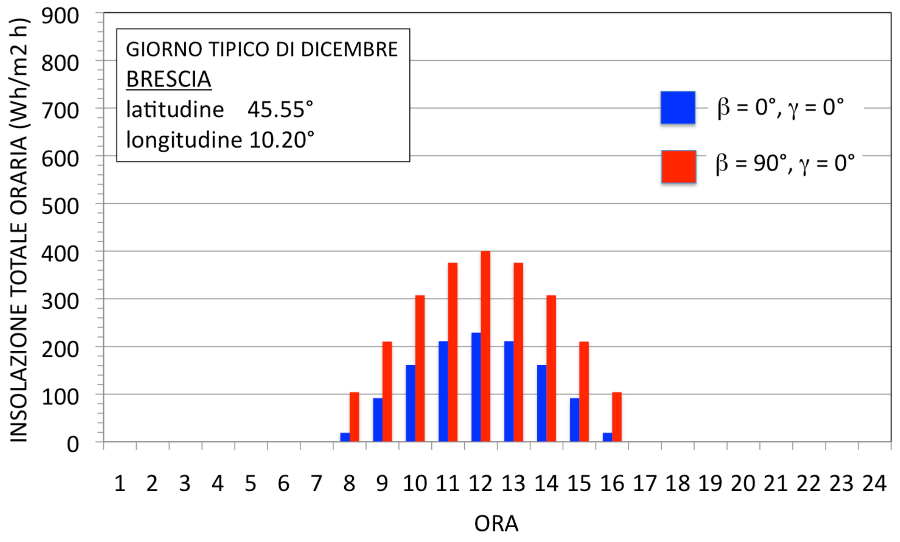
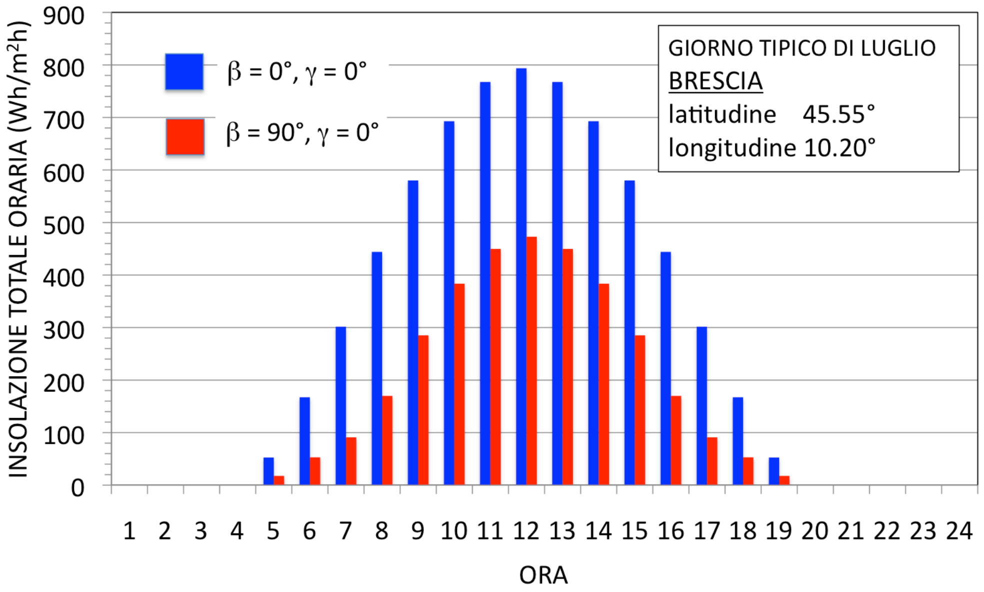
The Sun: the available energy, I



Potentially, the energy from the Sun is unlimited. But,

(1) The solar radiation is very diluted, intermittent and not uniformly distributed;

(2) At the Earth level the collected energy depends on the inclination and on the orientation of the surface and on the year season too.



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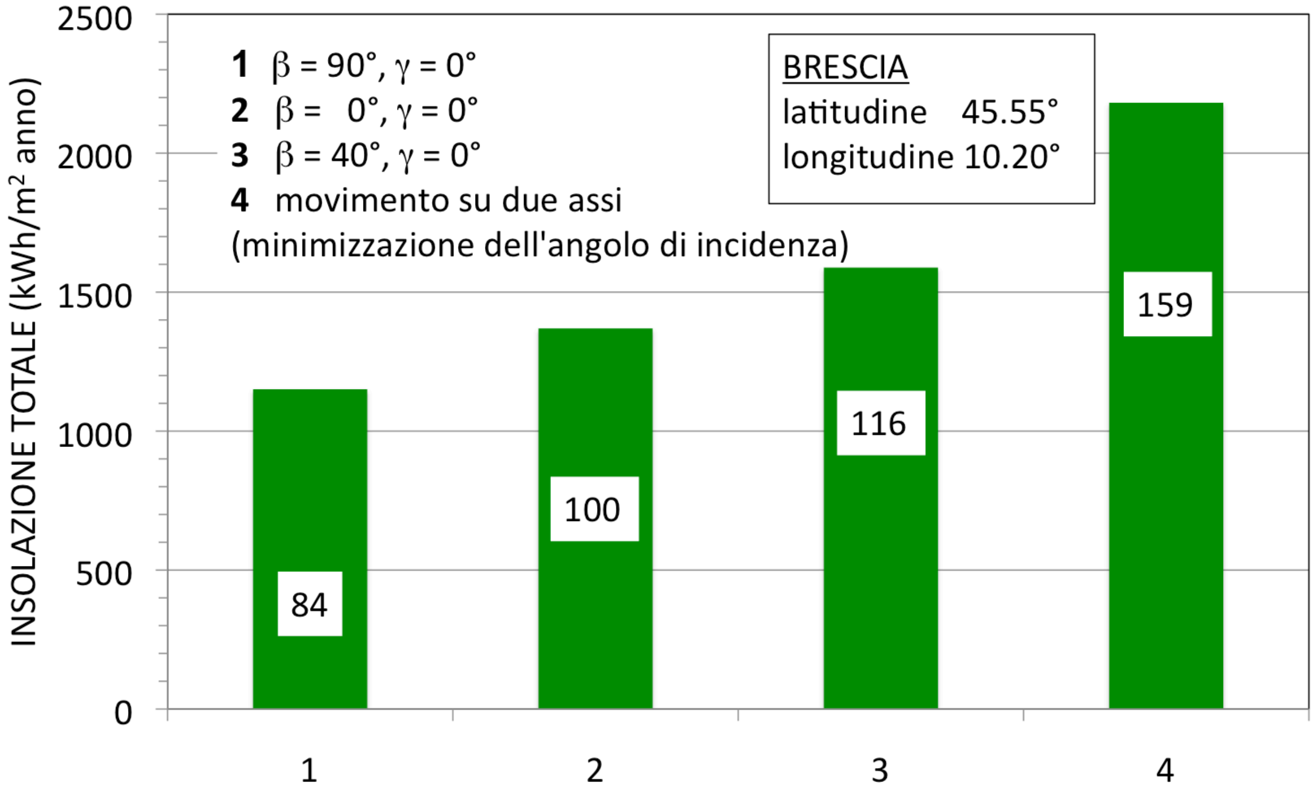
The Sun: the available energy, II

- $\beta = 0°$ e $\gamma = 0°$: 1370 kWh/m^2 year (= 100)
- $\theta = 0°$ (tracking surface about two axes): 2181 kWh/m^2 anno



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The “solar thermodynamic”

The thermodynamic conversion of the solar energy

The thermodynamic conversion of the solar energy in electric energy takes place, in sequence, by:

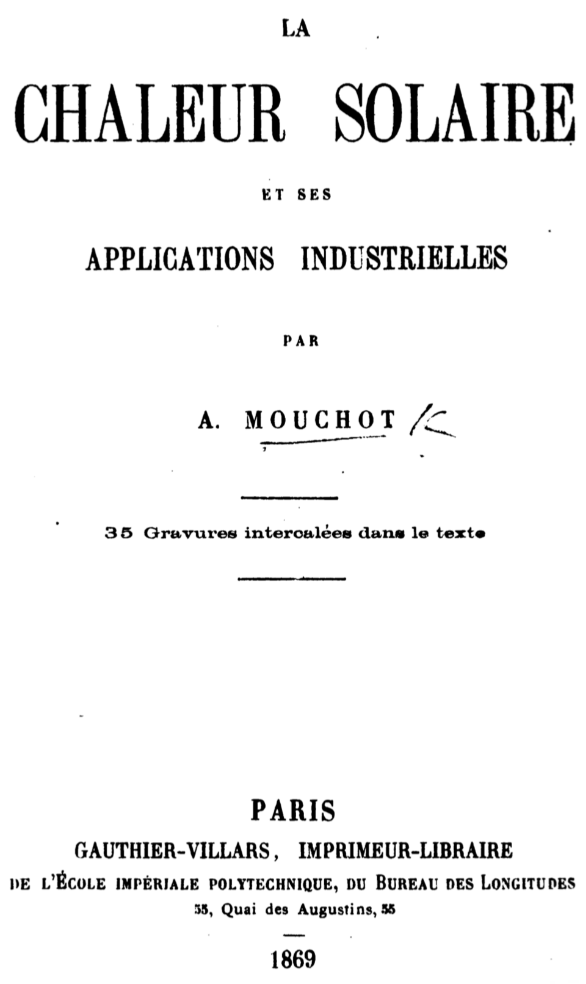
- the collection of the solar radiation as heat on surfaces with a high absorption coefficient at the highest possible temperature;
- transferring the heat to a lower temperature heat sink (usually the environment) by means of a thermodynamic cycle - a heat engine - producing mechanical energy.

The first HT solar engines – in Europe

Augustin Mouchot (7 April 1825 – 4 October 1912): 1860 - << … coal will undoubtedly be used up. What will industry do then? … Reap the rays of the Sun! >>

The solar powered printing press of Abel Pifre, August 6th 1882. While exhibiting it at the Gardens of the Tuileries, he printed five hundred copies of the *Le Journal de Soleil* (a journal specially composed for the occasion).

Abel Pifre (1852 - 1928) an engineer, an assistant and a collaborator to Mouchot.



LA

CHALEUR SOLAIRE

ET SES

APPLICATIONS INDUSTRIELLES

PAR

A. MOUCHOT

35 Gravures intercalées dans le texte

PARIS

GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE

DE L'ÉCOLE IMPÉRIALE POLYTECHNIQUE, DU BUREAU DES LONGITUDES

55, Quai des Augustins, 55

1869

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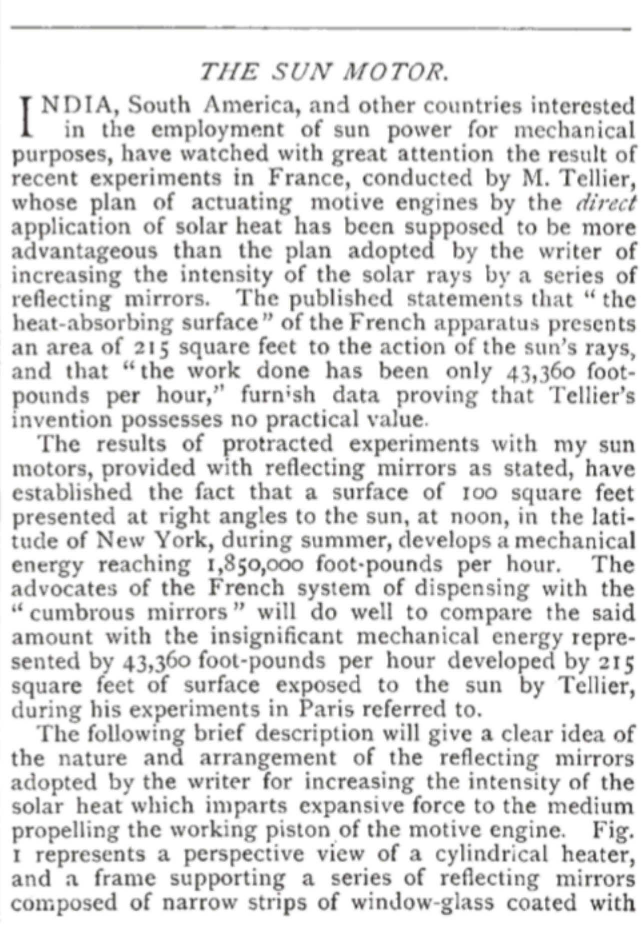
The first HT air solar engines – in America



THE SUN MOTOR.

INDIA, South America, and other countries interested in the employment of sun power for mechanical purposes, have watched with great attention the result of recent experiments in France, conducted by M. Tellier, whose plan of actuating motive engines by the *direct* application of solar heat has been supposed to be more advantageous than the plan adopted by the writer of increasing the intensity of the solar rays by a series of reflecting mirrors. The published statements that "the heat-absorbing surface" of the French apparatus presents an area of 215 square feet to the action of the sun's rays, and that "the work done has been only 43,360 foot-pounds per hour," furnish data proving that Tellier's invention possesses no practical value.

The results of protracted experiments with my sun motors, provided with reflecting mirrors as stated, have established the fact that a surface of 100 square feet presented at right angles to the sun, at noon, in the latitude of New York, during summer, develops a mechanical energy reaching 1,850,000 foot-pounds per hour. The advocates of the French system of dispensing with the "cumbrous mirrors" will do well to compare the said amount with the insignificant mechanical energy represented by 43,360 foot-pounds per hour developed by 215 square feet of surface exposed to the sun by Tellier, during his experiments in Paris referred to.

The following brief description will give a clear idea of the nature and arrangement of the reflecting mirrors adopted by the writer for increasing the intensity of the solar heat which imparts expansive force to the medium propelling the working piston of the motive engine. Fig. 1 represents a perspective view of a cylindrical heater, and a frame supporting a series of reflecting mirrors composed of narrow strips of window-glass coated with

Nature, August 2, 1888, p. 319

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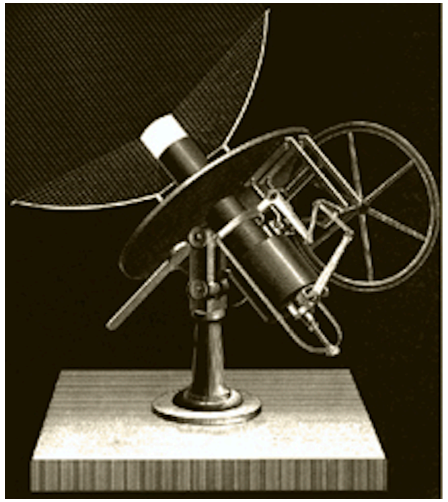
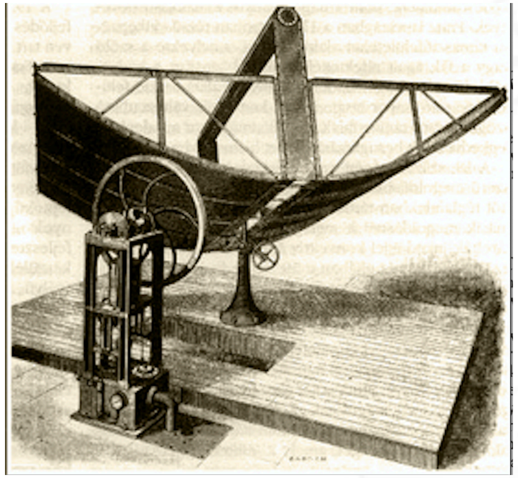
John Ericsson (July 31, 1803 – March 8, 1889)



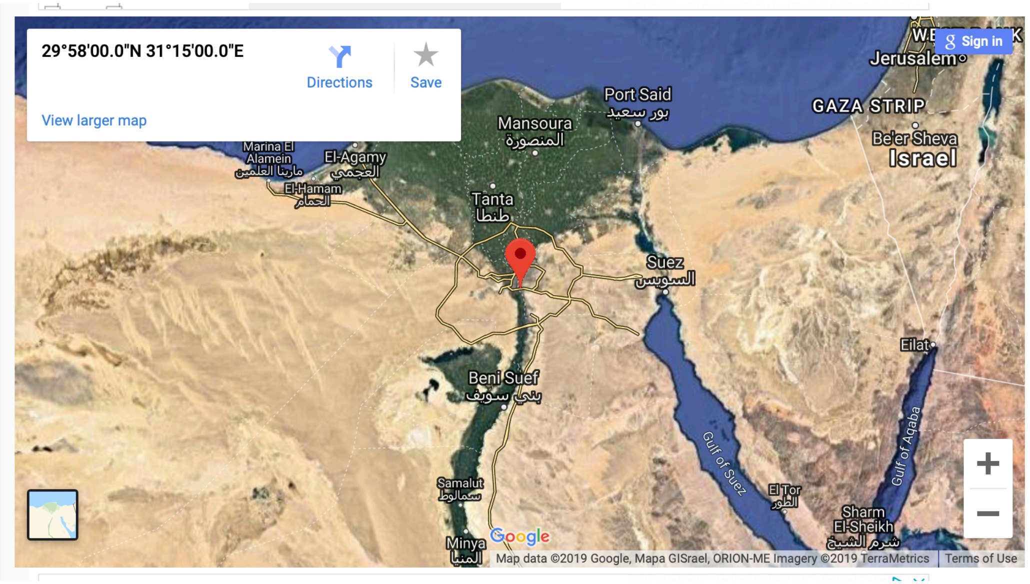
1872 – rappresentazione del - primo - motore ad aria con concentratore puntuale

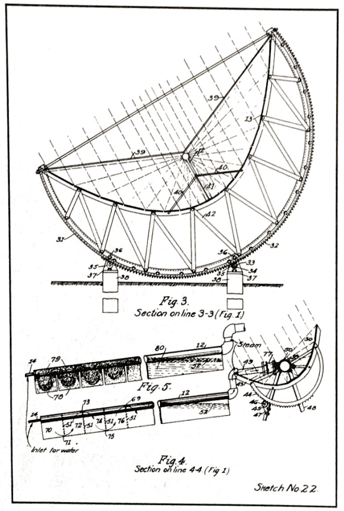


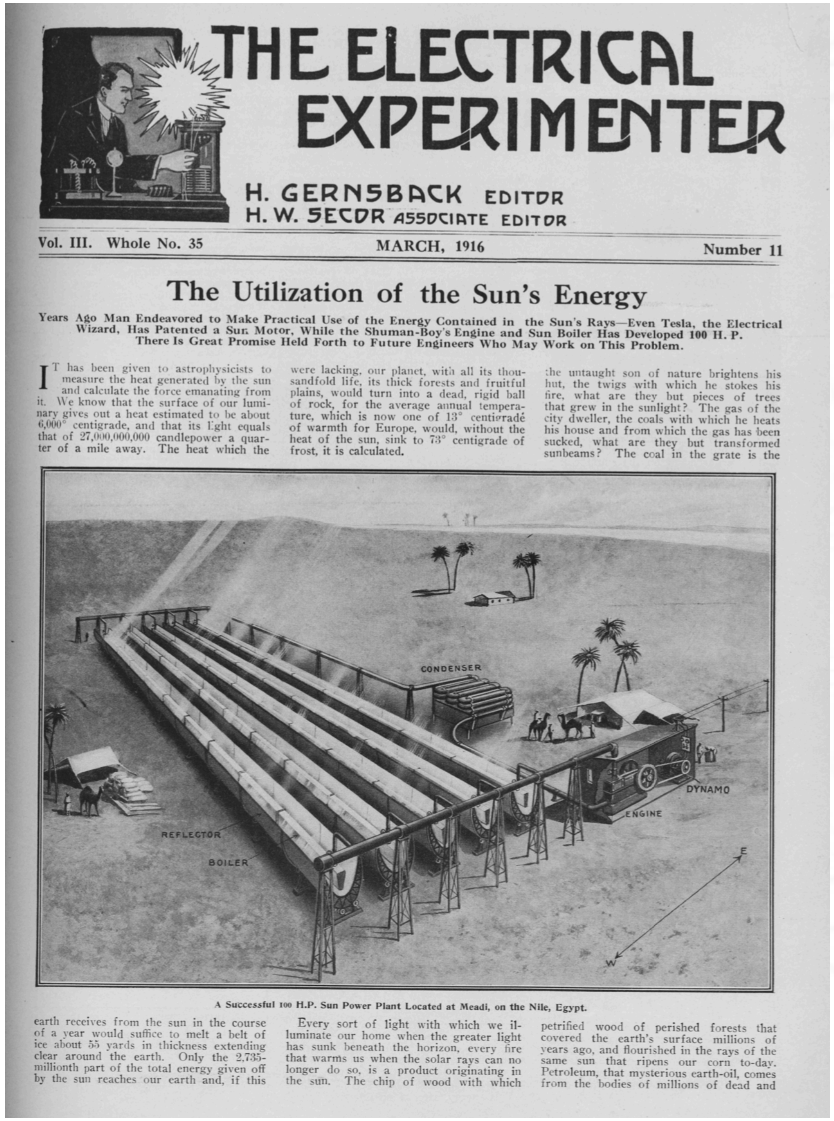
1884 – concentratore parabolico

Ericsson felt he could not << *recommend the erection of solar engines in places where there is not steady sunshine until means shall have been devised for storing up the radiant energy in such a manner that regular power may be obtained from irregular solar radiation* >>. From J. Perlin, Let it Shine, New World Library, 2013, p. 106

The first practical solar engine – in Al Meadi – Egypt, 1912







THE ELECTRICAL EXPERIMENTER

H. GERNSBACK EDITOR
H. W. SECOR ASSOCIATE EDITOR

Vol. III. Whole No. 35 MARCH, 1916 Number 11

The Utilization of the Sun's Energy

Years Ago Man Endeavored to Make Practical Use of the Energy Contained in the Sun's Rays—Even Tesla, the Electrical Wizard, Has Patented a Sun Motor, While the Shuman-Boy's Engine and Sun Boiler Has Developed 100 H. P. There Is Great Promise Held Forth to Future Engineers Who May Work on This Problem.

IT has been given to astrophysicists to measure the heat generated by the sun and calculate the force emanating from it. We know that the surface of our luminary gives out a heat estimated to be about 6,000° centigrade, and that its light equals that of 27,000,000,000 candlepower a quarter of a mile away. The heat which the earth receives from the sun in the course of a year would suffice to melt a belt of ice about 55 yards in thickness extending clear around the earth. Only the 2,735-millionth part of the total energy given off by the sun reaches our earth and, if this were lacking, our planet, with all its thousandfold life, its thick forests and fruitful plains, would turn into a dead, rigid ball of rock, for the average annual temperature, which is now one of 13° centigradé of warmth for Europe, would, without the heat of the sun, sink to 73° centigrade of frost, it is calculated.

Every sort of light with which we illuminate our home when the greater light has sunk beneath the horizon, every fire that warms us when the solar rays can no longer do so, is a product originating in the sun. The chip of wood with which the untaught son of nature brightens his hut, the twigs with which he stokes his fire, what are they but pieces of trees that grew in the sunlight? The gas of the city dweller, the coals with which he heats his house and from which the gas has been sucked, what are they but transformed sunbeams? The coal in the grate is the petrified wood of perished forests that covered the earth's surface millions of years ago, and flourished in the rays of the same sun that ripens our corn to-day. Petroleum, that mysterious earth-oil, comes from the bodies of millions of dead and

A Successful 100 H.P. Sun Power Plant Located at Meadi, on the Nile, Egypt.

55 HP (≈ 40 kW) of power, enough to pump 6000 gallon of water per minute (≈ 23 m^3/min). 200 square feet/HP collector area (≈ 25 m^2/kW).

Frank Schuman (1862 - 1918) and **Charles Vernon Boys** (1855 – 1944)

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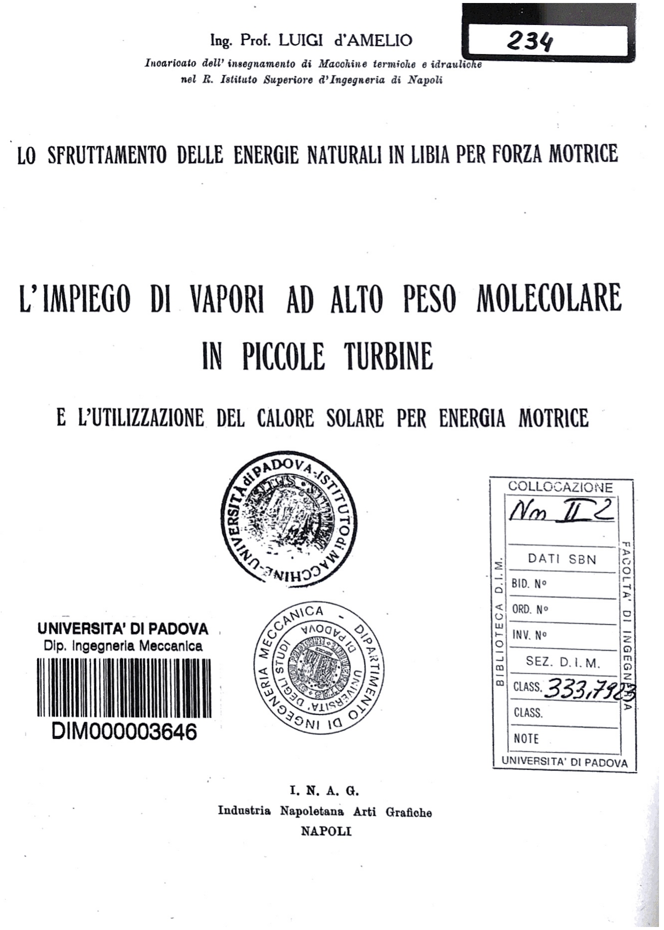
The LT "solar thermodynamic" in Italy 1920-1960

- **Tito Romagnoli** – between 1923 and 1930 – built a series of engines (of small power, 2 HP (≈1.5 kW), and low efficiency).
- **Luigi d'Amelio** (1893-1967), in 1935, designd a turbine solar engine.
- **Daniele Gasperini** (1865 - 1960) e **Ferruccio Parri** (1897 – 1980) in 1955, at the fair of the Solar Energy in Phoenix (USA), presented their "solar pump SOMOR".



Ing. Prof. LUIGI d'AMELIO

Incaricato dell'insegnamento di Macchine termiche e idrauliche nel R. Istituto Superiore d'Ingegneria di Napoli

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LO SFRUTTAMENTO DELLE ENERGIE NATURALI IN LIBIA PER FORZA MOTRICE

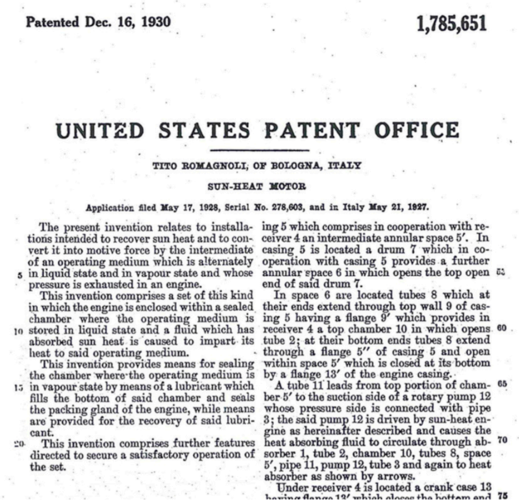
L'IMPIEGO DI VAPORI AD ALTO PESO MOLECOLARE IN PICCOLE TURBINE

E L'UTILIZZAZIONE DEL CALORE SOLARE PER ENERGIA MOTRICE

I. N. A. G.

Industria Napoletana Arti Grafiche

NAPOLI



Patented Dec. 16, 1930 — 1,785,651

UNITED STATES PATENT OFFICE

TITO ROMAGNOLI, OF BOLOGNA, ITALY

SUN-HEAT MOTOR

Application filed May 17, 1928, Serial No. 278,603, and in Italy May 21, 1927.

The present invention relates to installations intended to recover sun heat and to convert it into motive force by the intermediate of an operating medium which is alternately in liquid state and in vapour state and whose pressure is exhausted in an engine.

This invention comprises a set of this kind in which the engine is enclosed within a sealed chamber where the operating medium is stored in liquid state and a fluid which has absorbed sun heat is caused to impart its heat to said operating medium.

This invention provides means for sealing the chamber where the operating medium is in vapour state by means of a lubricant which fills the bottom of said chamber and seals the packing gland of the engine, while means are provided for the recovery of said lubricant.

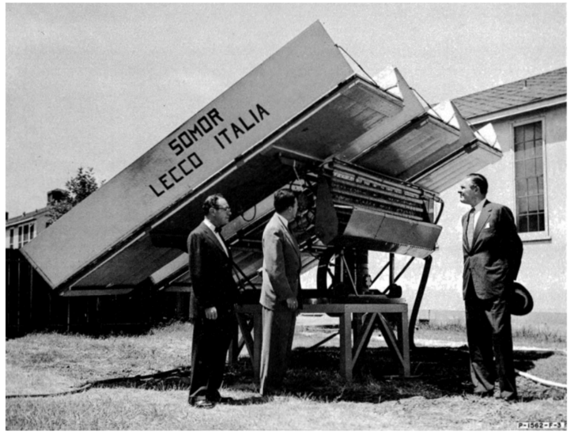
This invention comprises further features directed to secure a satisfactory operation of the set.

ing 5 which comprises in cooperation with receiver 4 an intermediate annular space 5′. In casing 5 is located a drum 7 which in cooperation with casing 5 provides a further annular space 6 in which opens the top open end of said drum 7.

In space 6 are located tubes 8 which at their ends extend through top wall 9 of casing 5 having a flange 9′ which provides in receiver 4 a top chamber 10 in which opens tube 2; at their bottom ends tubes 8 extend through a flange 5″ of casing 5 and open within space 5′ which is closed at its bottom by a flange 13′ of the engine casing.

A tube 11 leads from top portion of chamber 5′ to the suction side of a rotary pump 12 whose pressure side is connected with pipe 3; the said pump 12 is driven by sun-heat engine as hereinafter described and causes the heat absorbing fluid to circulate through absorber 1, tube 2, chamber 10, tubes 8, space 5′, pipe 11, pump 12, tube 3 and again to heat absorber as shown by arrows.

Under receiver 4 is located a crank case 13



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The LT "solar thermodynamic" in Italy 1970-1980

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- **Angelino G**., Facchini U., **Gaia M.**, **Macchi E.**, **Sassi G.** *Motore solare della potenza di 3 kW per il pompaggio di acqua – Programma e stato dei lavori*, Condizionamento dell'aria, Riscaldamento, Refrigerazione, No 11 (1977), 884-887.
- Gaia M., Macchi E., *A comparison between Sun and Wind as Energy Sources in Irrigation Plants*. In: Proceedings of International Solar Eneregy Society (ISES) Congress, Delhi (India), January 1978. Vol I, 265-272.

  - **Macciò C.**, **Tomei G.**, Angelino G., Gaia M., Macchi E. *Operational Experience of a 3.0 kW Solar Powered Water Pump*. In: 1979 Silver Jubilee International Congress of the International Solar Energy Society (ISES), May 28 – June 1, Atlanta, Georgia (USA): Sun II, Vol 2, pp 1501-1505, Pergamon Press.
  - Gaia M., Angelino G., Macchi E., **De Heering D**., **Fabry J. P.** Risultati sperimentali del motore a fluido organico sviluppato per l'impianto solare di Borj Cedria. energie alternative HTE anno 6 no 27, gennaio-febbraio 1984, 31-34.
  - Angelino G., Gaia M., Macchi E., **Barutti A.**, Macciò C., Tomei G. *Test Results of a Medium Temperature Solar Engine*, International Journal of Ambient Energy, July 1982, Vol. 3, No. 3, pp. 115-126.

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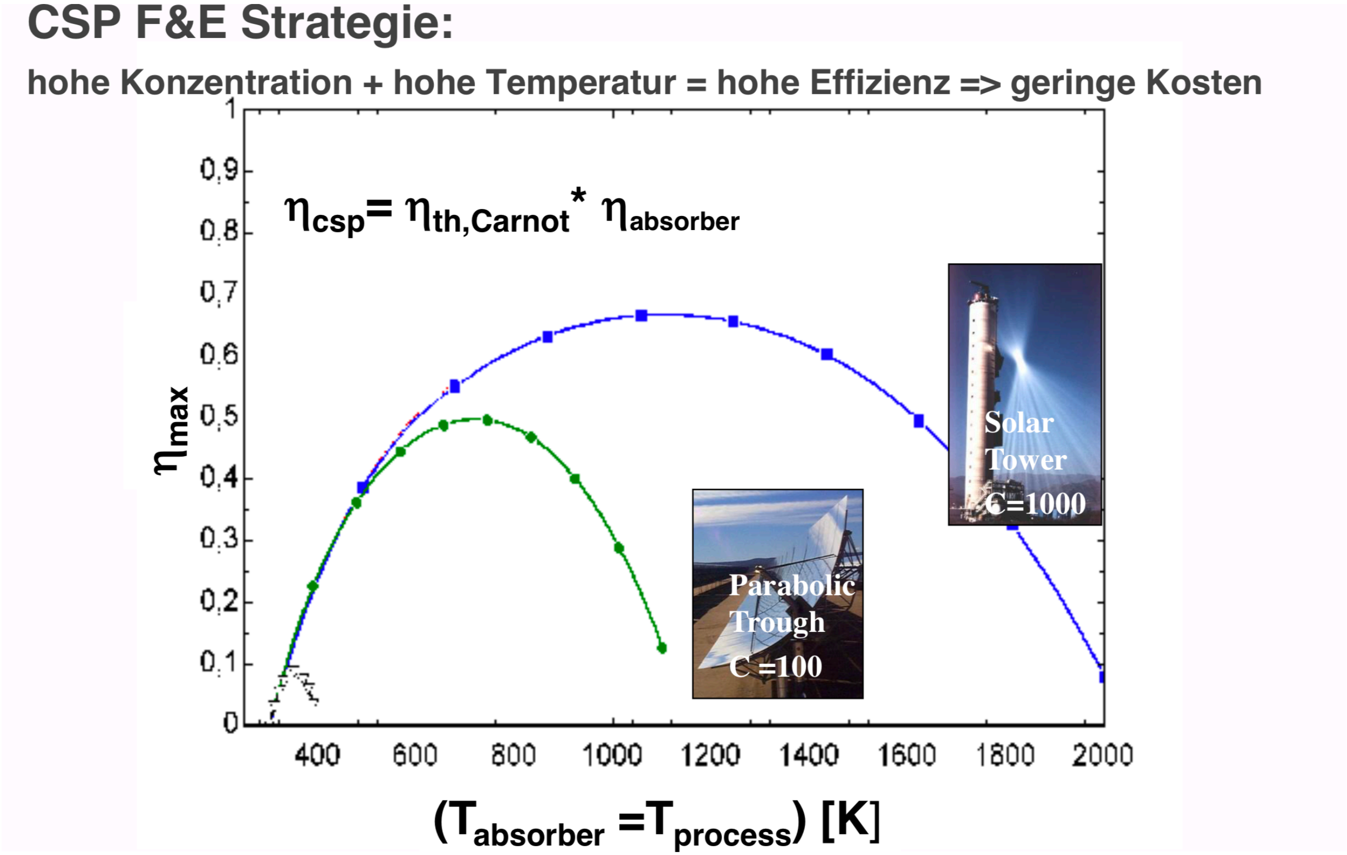
The opportunity to concentrate the solar energy



Greater concentration ratio →

→ Higher temperatures →

→ High efficiency →

→ Lower electricity production costs

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The solar power tower plants, I

Power plants	Installed maximum capacity *(MW)	Yearly total energy production (GWh)	Country	Developer/Owner	Completed
Ivanpah Solar Power Facility	*392 (U/C)*	650	United States	BrightSource Energy	2013
Ashalim Power Station	*121 (U/C)*	320	Israel[7]	Megalim Solar Power<	2018
Crescent Dunes Solar Energy Project	*110 (U/C)*	500	United States	SolarReserve	2015
PS20 solar power tower	20[8]	44	Spain	Abengoa	2009
Gemasolar[9]	17	100	Spain	Sener	2011
PS10 solar power tower	11[10]	24	Spain	Abengoa	2006
Sierra SunTower	5[11]		United States	eSolar	2009
Jülich Solar Tower	1.5[12][13]		Germany		2008
Greenway CSP Mersin Solar Tower Plant	5[14]		Turkey	Greenway CSP	2013
National Solar Thermal Test Facility	1 (5 - 6 MWt)		United States	U.S. Department of Energy	1978

The solar plants PS10 (Planta Solar 10) and **PS20** (Planta Solar 20) in Sanlucar la Mayor vicino Seville, Andalusia, Spagna. ●1255 collectors, ● 80 hectares ● Nominal power 20 MW ● capacity factor 27%, ● Net energy 48 GWh/year

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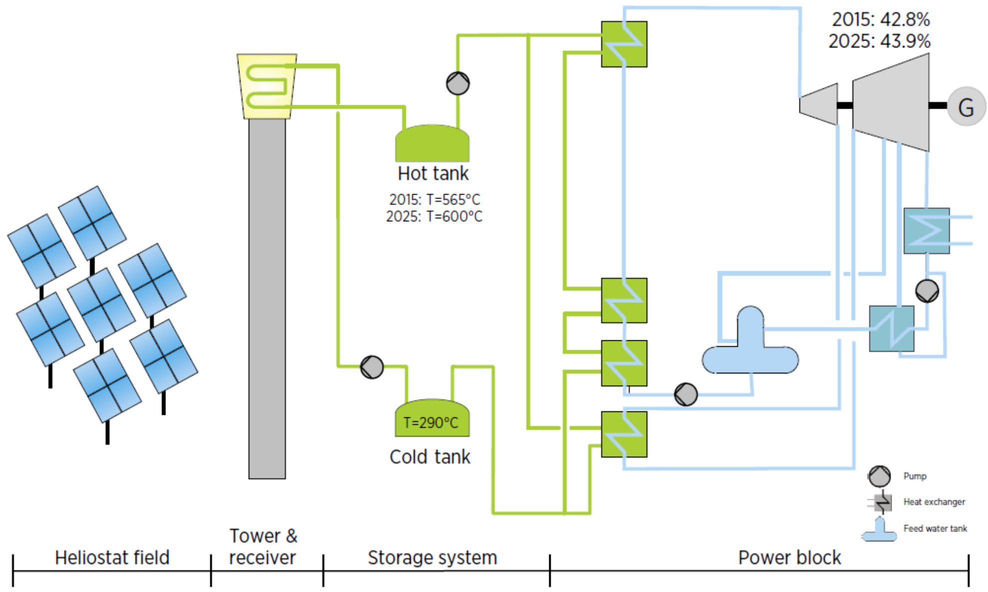
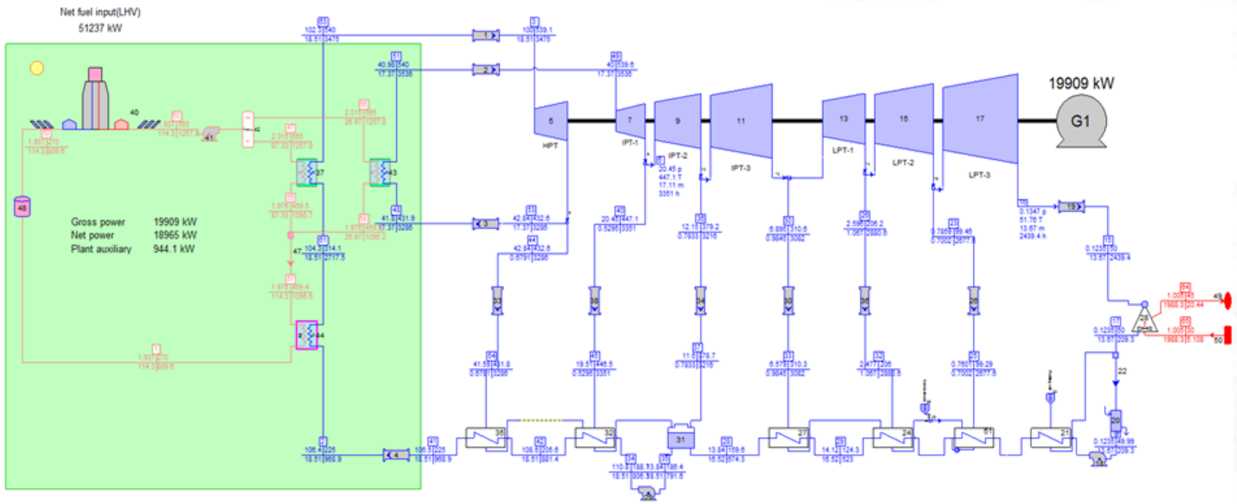
The solar power tower plants, II



Source: DLR, 2016.

Note: Molten salt is used as the heat transfer fluid and storage medium (green). The water/steam circuit is also shown (blue). The letter "G" represents the generator.

☚ The plant scheme – simplified – of the traditional solar power tower plants.



The steam cycle (the "power block") – simplified – of the traditional solar power tower plants.

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The "SCARABEUS" project, I

SCARABEUS: Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plants

❖ The Concentrated Solar Power (CSP) plants have currently a Levelized Cost of Electricity (LCoE) of about 150 €/MWh, still far from the level targeted (100 €/MWh), except for few installations in exceptionally good locations.

❖ A way pursued today to reduce the electricity cost is to resort to thermodynamic cycles with carbon dioxide (CO_2) instead of steam as working fluid.

❖ But, carbon dioxide (a gas, at ambient pressure and temperature), does not allow the recourse to the condensation(*) in locations where the air temperature is greater than 30 °C.

(*) The condensation – when possible – improves noticeably the useful power and the efficiency of the heat engine.

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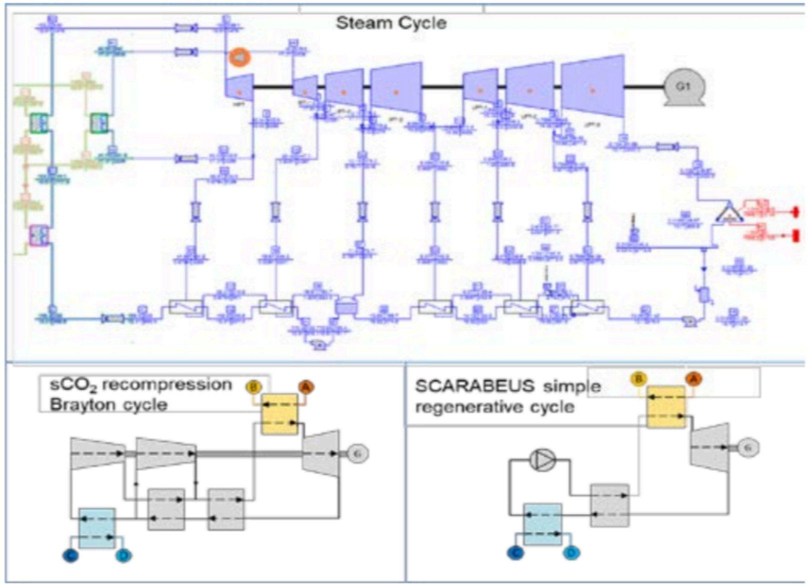
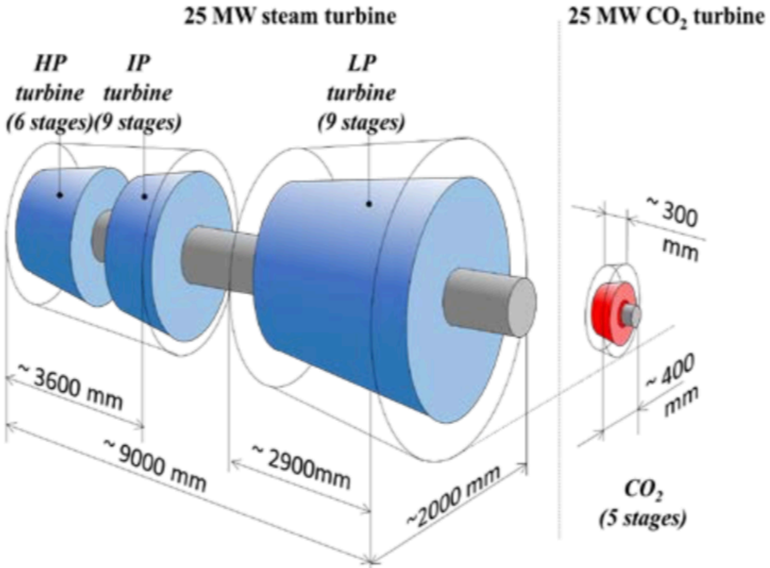
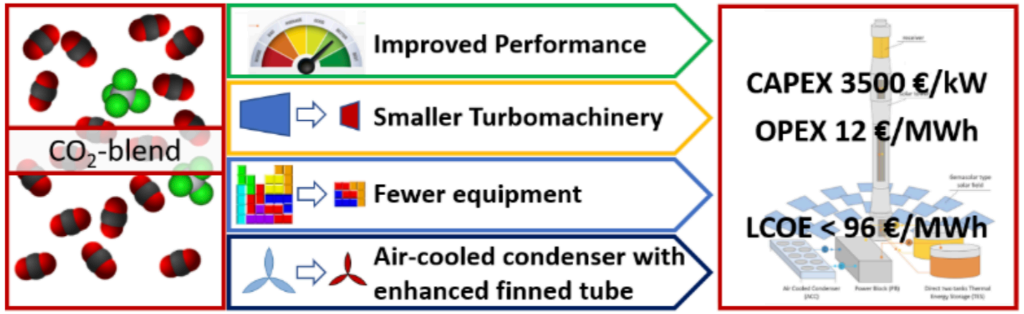
SCARABEUS

The “SCARABEUS” project, II





”power block” and turbines dimensions for thermodynamic cycles with steam and carbon dioxide.



The aim of the project is to develop • an innovative thermodynamic cycle using blends of CO_2, thus improving the efficiency from the current 42% to over 50%, and to demonstrate • a reduction of the **capital** costs (CAPEX) of 30%, and of the **operating** costs (OPEX) of 35% with respect to state-of-the-art steam cycles and exceeding the reduction achievable with standard supercritical CO_2 technology.

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SCARABEUS

The “SCARABEUS” project, III

◉ It is a project of 48 months, started in April 2019 and it will continue until March 2023.
◉ Coordinator: Politecnico di Milano.
◉ The project is founded by the European Uninion’s Horizon 2020 research and innovation programme, under grant agreement n. 814985.

<u>SCARABEUS Partners</u>:

Academia and R&D	Industry
Politecnico di Milano (IT)	Exergy (IT)
Università di Brescia(*) (IT)	Kelvion (FR)
University of Seville (ES)	Abengoa (ES)
City University of London (UK)	Quantis (CH)
Vienna University of Technology (AT)	

(*) at the Università di Brescia is assigned the WP2: CO_2 Blend Development

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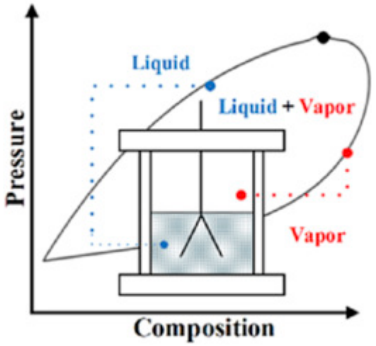
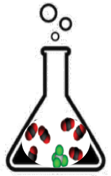
SCARABEUS

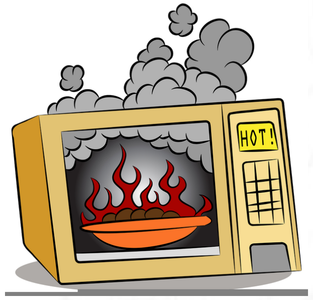
The "SCARABEUS" project, IV

- Determine the most promising fluid for blending the CO_2
- Assess the thermodynamic properties of the blended CO_2 in terms of critical curve and their stability up to 700 °C
- Demonstrate the thermal stability of the two CO_2 blends for 2000 hours





Stable at high T?
Good properties?



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SCARABEUS

The "SCARABEUS" project, V

Personale coinvolto

Full professor of Energy Systems
Head of ERGO's group and Fluid Test Lab
Research interests: Organic Rankine Cycles, thermodynamics of working pure fluid and mixtures, modeling and optimization of advanced power cycles

Full professor of Energy Systems
Member of ERGO group and GECOS (Milan)
Research interests: advanced power cycles, fuel cells modeling, electric vehicles

Assistant professor since November 2018
Phd Politecnico di Milano
Research interests: advanced power cycles, fuel cells modeling, experimental analysis

Phd candidate
Graduated in Mechanical Engineering from Capital University of Science and Technology Islamabad
Research interests: Thermodynamics of mixtures for closed power cycle

Technician
Many years laboratory experience in thermal stability tests
Highly skilled in finding circuit leakages and fixing them.

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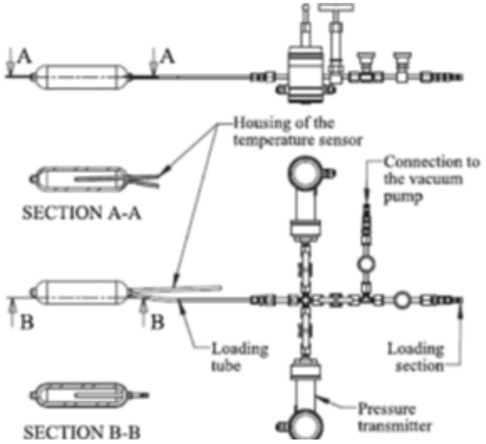
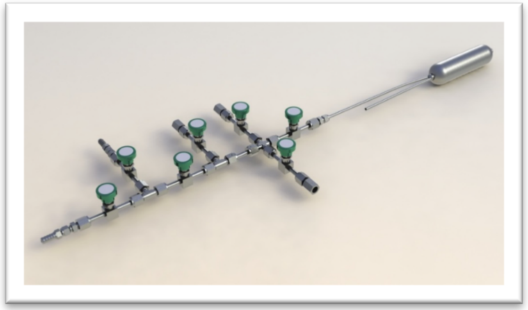
SCARABEUS

The "SCARABEUS" project, VI





Thermal stability test procedure

The thermal stability of the CO_2 blends need to be experimentally verified. The method we adopt, is based on the analysis of the deviations in the vapor pressure curve of the fluid after subjecting it to thermal stress tests at increasing temperature according to the following procedure:

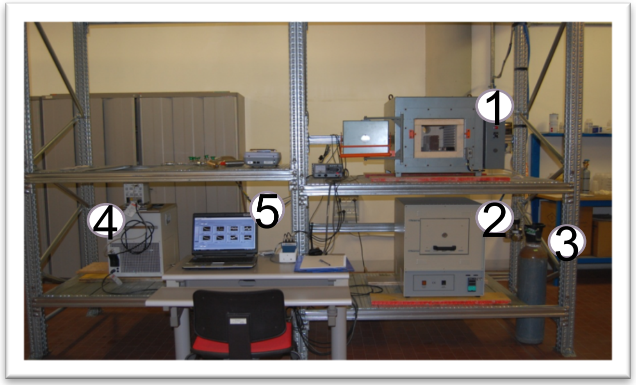
(a) loading the sample fluid in the test circuit

(b) evaluation of the reference vapor pressure of the virgin fluid

(c) thermal stress test in a furnace

(d) measurement of the vapour pressure curve and comparison to the reference value

Thermal stability test facility



(1,2) muffle furnace for stress tests, **(3)** helium bottle for leakege test, **(4)** thermostatic bath [-40°C,50°C] where the saturation pressure curve is measured, **(5)** Data Acquisition System to record T and p during the tests

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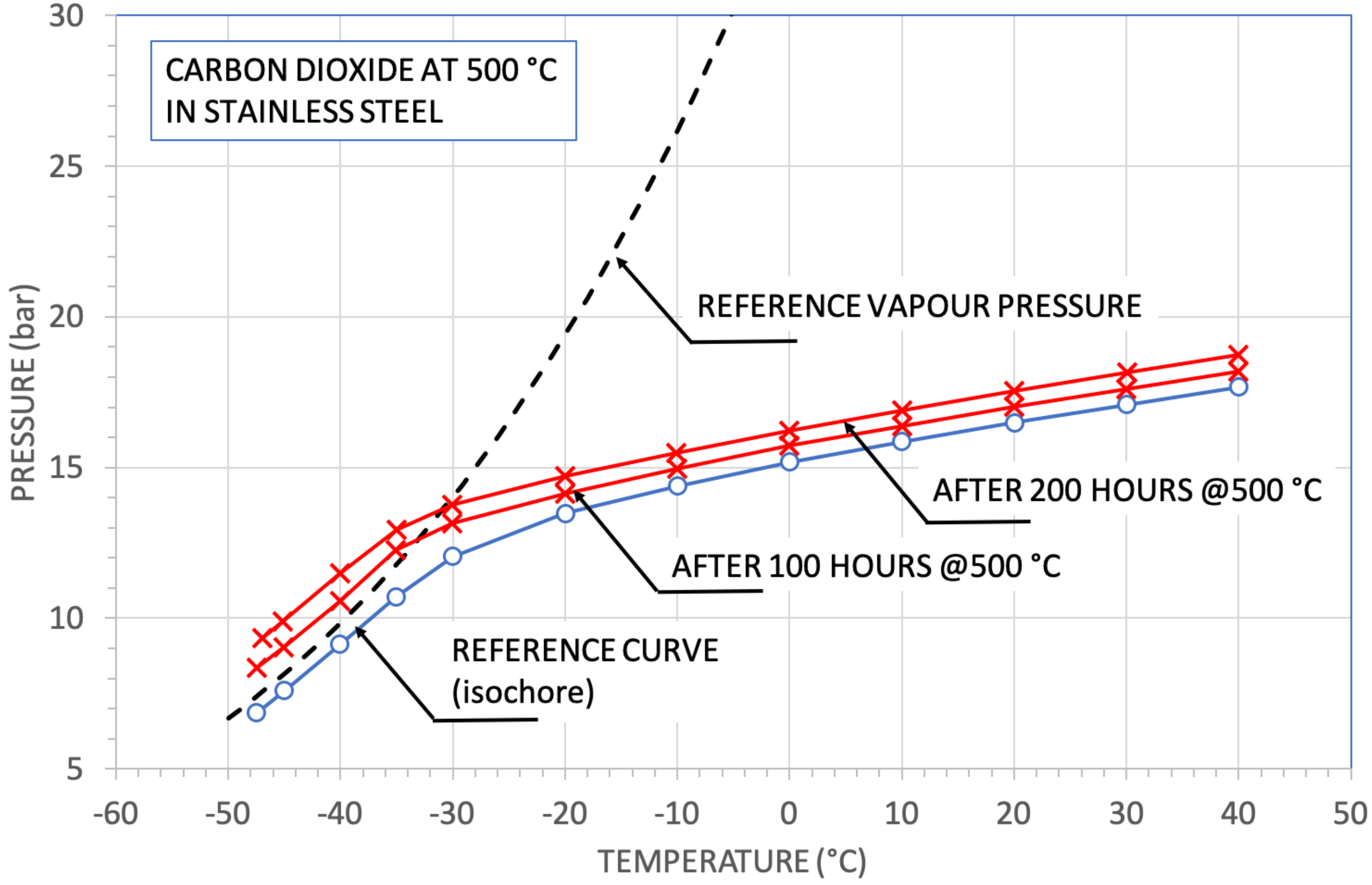
SCARABEUS

The "SCARABEUS" project, VII



Thermal stress analysis of CO_2 in stainless steel at 500 °C. Clear sign of decomposition can be evidenced.

What's a stable fluid?

Many factors can influence the thermal stability of a working fluid, such as the materials and the presence of contaminants. Thus, in a power plant, it is important to select the proper materials particularly for the high temperature sections.

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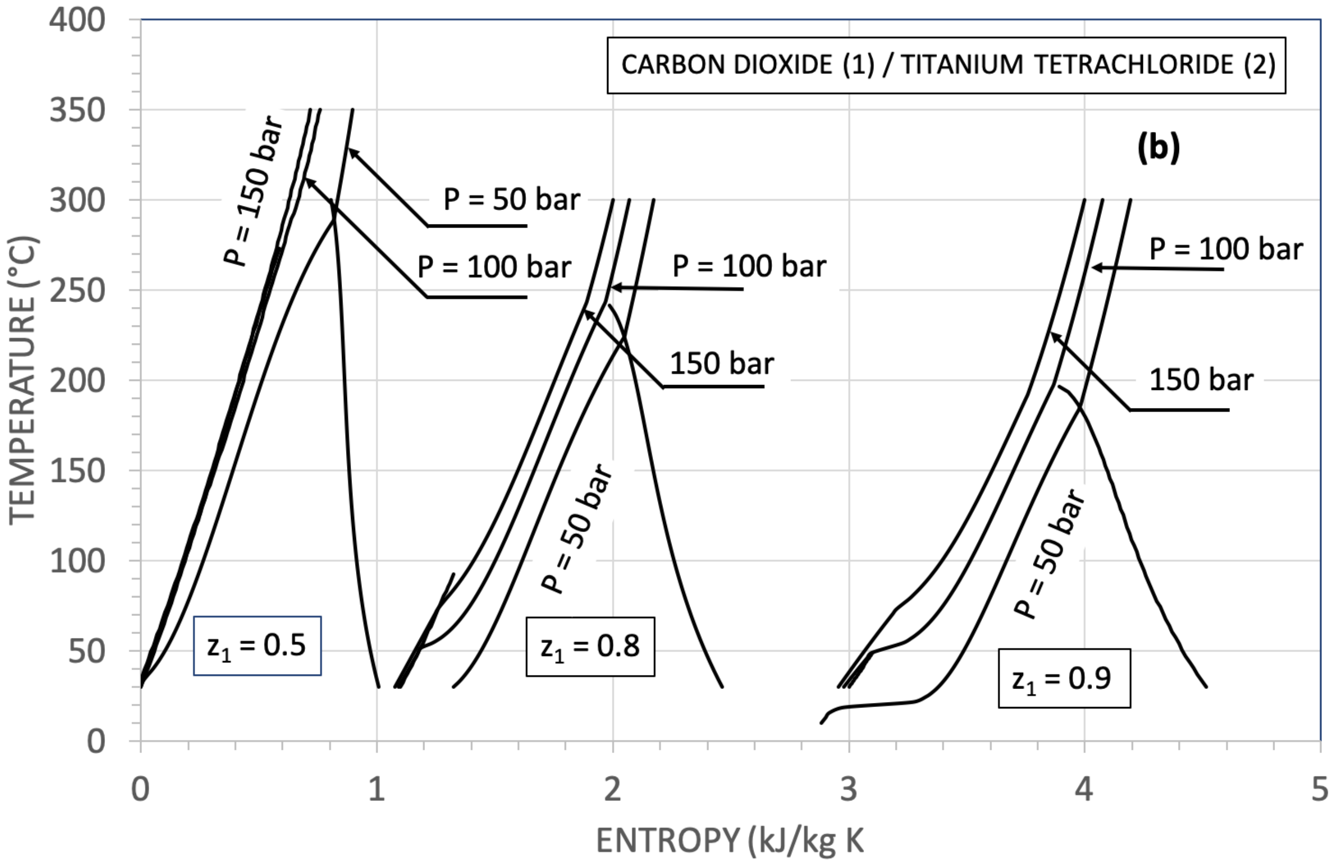
SCARABEUS

The “SCARABEUS” project, VIII



T-S diagram at different compositions of the the $TiCl_4$-CO_2 mixture, resulting in different critical temperatures and in different thermodynamic properties.

An example: a mixture of carbon dioxide (CO_2) and titanium tetrachloride ($TiCl_4$)

- Liquid phase at T = 50 °C benefits in terms of reduction of the compression work.
- The resulting power cycle based on the $TiCl_4$-CO_2 mixture may have higher efficiency than that with pure CO^2 as working fluid.

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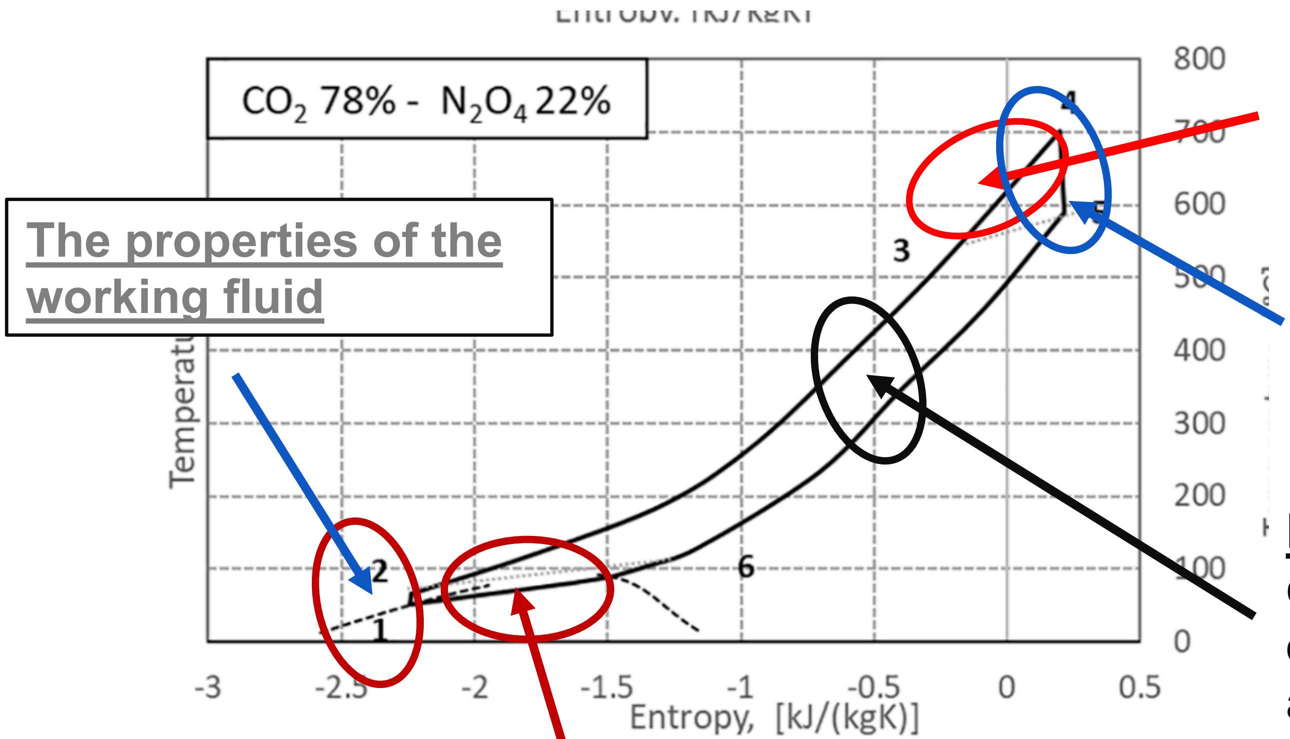
The "SCARABEUS" project, IX

Some technological challenges



Heater: thermo-chemical compatibility of the working fluid with the materials – Mechanical properties of materials

Turbine: fluid-dynamic design and optimization

Recuperator: mechanical design, thermal effectiveness – Thermal and pressure-drop design

Condenser: mechanical design, thermal effectiveness – Thermal and pressure-drop design

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Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plant

Ambiente, Salute e Sostenibilità
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