

The Use of Solar Energy in Human Activities Throughout the Centuries

Steam and Electricity Generated From Solar Heat with Flat Mirrors: An Italian Story

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INTRODUCTION

This paper intends to present to the readers of *Annals of Arid Zone* an Italian solar energy story that spans more than 2,000 years, from Archimedes (212 B.C.) to the third millennium.

Though it had powered everything on Earth until 150-200 years ago, we usually think of solar energy (its direct and indirect forms, wind, hydro, forests and other biomass) as an aspect of our modern world. We easily forget that for thousands and thousands of years, the Earth's sole energy source, the sun, provided light, food, heat and fuel, and profoundly shaped human civilizations. Suffice it to think of discoveries made during what I would propose to call the *primitive or ancient solar age* that still have an important role in our daily lives.

The discovery of fire about 700,000 years ago, which enabled humans to use the solar energy stored in forest wood and other forms of biomass; farming and agriculture, powered also today by solar energy as the primary and principal energy source as they were from the earliest civilizations; basic principles of solar architecture and urban planning techniques that have been handed down for centuries by all civilizations.

The discovery of flat window-pane glass by the Romans in the first century A.D., which allowed to bring daylight inside buildings and at the same time prevent cold and winds from entering, exemplifies the importance of solar inventions of the past to our lives today: millions upon millions of windows provide daylight to homes and workplaces all over the world, thereby saving on artificial light produced with electricity generated by fossil and nuclear fuels. Historical window-pane glass used in Pompeii 2000 years ago can be seen at the National Archeology Museum in Naples, Italy.

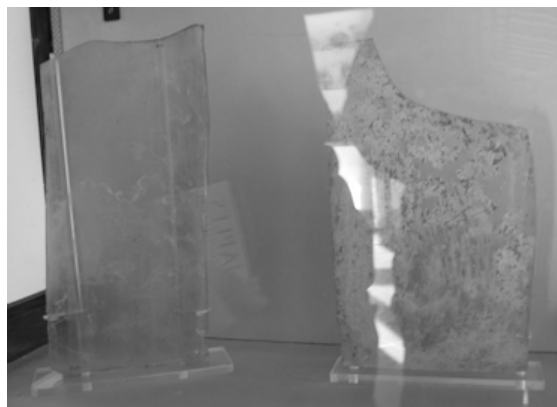


Fig. 1. Flat transparent pane glass from Pompeii, 1st century A.D. to capture sun's light and heat for houses and baths (Photo National Archaeological Museum, Naples, Italy).

Outcomes and technological developments of solar discoveries of the past are therefore a substantial part of our world today.

We have now entered what I would propose to call a *modern or future solar age* whose beginning could be dated more than 100 years ago when we produced the first solar hydroelectricity, marking

¹ GSES is an Italian non-profit volunteer organization founded in 2004, based in Rome, Italy. It is the operational arm of "Italian National Committee 'The History of Solar Energy'" (CONASES), a multidisciplinary non-profit entity, established by the Italian Ministry for Cultural Heritage and Activities in 2006.

the transition from ancient to modern times in the use of solar energy. Electricity is the form of energy that epitomizes the modern age.

Solar energy resources, at least over the last 10,000 years, have remained virtually unchanged. What has changed is our knowledge of these resources. Our ancestors had neither the scientific knowledge nor the technological means available to us today to observe, measure and monitor direct solar radiation and its indirect forms -- wind, falling water, biomass, etc. – over periods of days, months, seasons and years. With a combination of satellite data and field measurements, we can estimate the amount of direct solar radiation or the intensity of blowing winds and flowing waters, or forest and biomass availability anywhere on Earth. In a word, we can find out what solar renewable energy resources are available at any point on our planet.

The basis for these modern developments and inventions are in the many scientific and technological advancements made in the last 500 years, and lies, chiefly, in our ever more advanced understanding of optics, light and the structure of matter. This understanding has opened up fascinating prospects for the use of solar energy in the modern age, from solar cells capable of producing electricity directly from the sun's light with efficiency ratings of 50% or more, to smart glass, to solar photon architecture and city planning.

We now know for certain that it could be possible to build sophisticated energy infrastructures powered by solar energy to produce electricity, low-, medium- and high-temperature heat, fuels and other useful forms of energy.

In the late 1800s our forefathers would certainly never have imagined a transition from *primitive or ancient solar age* to fossil and nuclear fuels and thus to major changes in our energy infrastructures and habitats. And for us it is just as hard to imagine what the world might be like in the year 2100 and how today's ambitious projects such as DESERTEC² or the Indian "Jawaharlal Nehru National Solar Mission"³ will be implemented.

Will deserts furnish power when fossil fuel reserves run out? Is an epochal transformation possible, in which fossil and nuclear fuel powered societies can return to the sole use of solar energy in a modern way?

Electricity in advanced societies accounts for less than 20% of consumption, as opposed to 80% in the form of fuels and heat. The greatest share of heat is consumed at low temperatures, i.e. those that the sun makes available naturally.

While it was implicit in the lives of our ancestors until just 150-200 years ago, building a modern solar energy system as a whole today would be a monumental task, as we are addicted to energy abundance from fossil and nuclear fuels. Understanding a modern solar system as a whole, from solar energy sources, to the technologies used to convert them to useful forms of energy, also implies filling a series of cultural deficits that span many fields: science, technology, sociology, economics and politics, as well as the terminology used when we speak about solar energy. For example, the term "*solar energy*" itself, though encompassing many technologies, is often limited in meaning, for both laypeople and experts, to nothing more than solar thermal collectors or photovoltaic module technology. Among the cultural deficits there is also a lack of knowledge about the many attempts made in the past to use solar energy in a modern way.

It has been over 100 years since man began producing solar hydroelectricity from falling water on an industrial scale. An event that, as I said above, marks the transition from ancient to modern times in the use of solar energy.

² DESERTEC is based on the idea that covering just 0.3% of the area of African and Middle Eastern deserts with solar thermal concentrating plants is sufficient to generate all the electricity needed to meet local energy needs and at the same time those of Europe, where the electricity would be transported through highly advanced power lines.

³ The National Solar Mission is a major initiative of the Government of India and State Governments to promote ecologically sustainable growth while addressing India's energy security challenge. It will also constitute a major contribution by India to the global effort to meet the challenges of climate change.

With electricity, we can light our living and working spaces by day and by night, drive locomotives and factory machinery, and run home appliances and computers.

In today's world about 4,000,000 MW in power generation are installed, of which about 800,000 MW in hydroelectric plants. Just forty years ago we began to develop the production of electricity from solar renewable wind sources. According to the World Wind Energy Association (WWEA) as of June 2010 there were 175,000 MW in wind turbines installed worldwide. Over the past decade, the most innovative solar photovoltaic technology, capable of producing electricity directly from sunlight, has spread rapidly across the globe reaching more than 30,000 MW of power at the end of 2010.

Concentrating solar power (CSP) technology, after seeing a small peak of development in the early eighties, have returned to be a contender. Solar thermal, or thermodynamic, power plants convert the sun's heat, collected over a large area and concentrated onto a receiver, into steam driving a turbine connected to a generator for the production of electricity.

Since 2004, this technology has had a new impetus following the creation, especially in the United States, of dozens of startups that adopted various CSP systems, including linear trough or Fresnel concentrators, dish and power tower systems. This is raising many expectations in the idea to take advantage of the enormous solar energy potential of the endless and sunny desert areas of the world. This idea is not new; it was in the minds of solar energy pioneers around the world over the last two centuries.

Exploring the history of Italian mathematicians, physicists, engineers and scientists who pioneered work in the production of steam and electricity from solar heat with flat or almost flat mirrors, provides insight on how this technology could contribute today to the exploitation of solar direct radiation, particularly abundant in deserts and arid zones.

Solar heat

Over the past 200 years, the role of renewable solar heat has been eclipsed by the overwhelming advance of heat produced from coal, oil and gas (fossil sources of solar energy), and more recently produced from nuclear energy. With these sources, heat can be produced in the desired quantities and – most importantly – with the desired qualities in all seasons and at all times of day at a range of temperatures: low (<300° Celsius), medium (300° to 500°) or high (>500°). Medium and high temperatures are used to power the most advanced industrial processes, starting with those used to generate steam and electricity. With steam, we can run a turbine that in turn powers an electricity generator. These successes in the use of fossil and nuclear fuels have caused us to forget almost altogether the importance that the sun's renewable heat could have even in our industrially and technologically advanced societies.

Mirrors and the sun, from Archimedes to the third millennium

The story of Archimedes (287-212 B.C.) and his burning mirrors has encouraged scientists in all eras to explore ways to concentrate and use the sun's heat. Was this a legend, or was there something true in the ancient account of the defense of Syracuse against an attack by the Roman fleet under the consul Marcellus in 212 B.C.?

Generations upon generations of mathematicians and physicists have labored to answer this question. In medieval times, Arabic culture helped to perfect and disseminate the classical Greek world's studies in geometric optics, in particular works on how various kinds of mirrors – curved, flat, spherical, elliptic, hyperbolic, parabolic, etc. – function. These studies were taken up again in the Renaissance by scientists such as Leonardo da Vinci (1452-1519), Galileo Galilei (1564-1642), Gerolamo Cardano (1501-1576), Giovan Battista Della Porta (1540-1615), Rafael Mirami, who published *Specularia*, his work on the science of mirrors, in 1582^[1], and Bonaventura Cavalieri (1598-1647), author of a 1632 treatise on burning mirrors^[2].



Fig. 2
Front cover of Rafael Mirami's 1582 treatise
Source: Internet

Extensive documentation exists on burning mirrors and the use of mirrors to concentrate solar radiation. An overview of the topic is included in K. Butti's and J. Perlin's 1980 book *A Golden Thread: 2500 Years of Solar Architecture and Technology*^[3].

The accounts covered in this essay refer to Italy in the last 200 years.

In the early 19th century, the fast-growing use of coal led some Italian scientists to wonder whether Italy could produce steam from solar heat at the same levels that other countries were obtaining from fossil fuels, which Italy lacked.

Most of these accounts are little known, yet the work of the people involved continues to contribute to the development of innovative solar thermodynamic plants around the world.

The forgotten solar thermodynamic systems of the 19th century

Pasquale Gabelli (1801-1880) and the heliostat

The idea of using solar heat to produce steam for industrial purposes was investigated in the first half of the 19th century by the Venetian mathematician and naturalist Pasquale Gabelli (1801-1882). In 1831, Gabelli presented a paper at *Ateneo Veneto* (of which he was a corresponding member) on "the way of exploiting solar rays by means of a heliostat that conveys the current of heat constantly on a given surface."

Gabelli's proposal met with skepticism at the University of Padua, the reason being the inconstancy inherent in the availability of solar radiation. This assessment was judged "valid for Lombardy and the Veneto," in the overcast northern regions of Italy, though "not for Apulia or Sicily, and certainly not Africa."^[4]

Gabelli presented his solar project again on August 25, 1838, in a 40-page manuscript with drawings entitled *Sopra un nuovo meccanismo per dirigere i raggi solari condensati ad usi speciali* (*A new mechanism for directing condensed solar rays to special uses*). His manuscript was found in June 2010 at the Italian Central State Archive and is currently being studied for publication.

Additional references to it can be found in scientific literature, beginning with Giacinto Namias, Scientific Secretary for the *Ateneo Veneto*, in his report for the 1837-38 academic year:

"Corresponding Member Pasquale Gabelli reported on the calorific power of solar rays, describing a device of his that condenses them and puts them to use where there is need of a great quantity of heat. He sets an iron rod in the direction of the world's axis, curved semi circularly in the middle, and joined there to another rod that moves around that point and supports a paraboloid of rotation whose focal point nearly corresponds to the center of the semicircle.

"The machine is rotated by appropriate devices so that the plane of the axes includes the center of the sun, and it continues its motion uniformly so that in 4 hours it completes one turn around its own axis in the direction opposite to the sun's. Inserted in the paraboloid are some mirrors that convey the images of the sun to the center of the semicircle and greatly multiply their heat.

“In that semicircular hollow Mr. Gabelli places any body that he wants to heat up, or a hollow sphere connected by a pipe to a boiler, which he sets on the burner attached to the machine, so that he can ignite it when the clouds conceal us from the sun’s gaze. After the liquid has been poured in, the vapors that form inside the metal sphere flow through the pipe and the boiler, bringing it to a boil.”

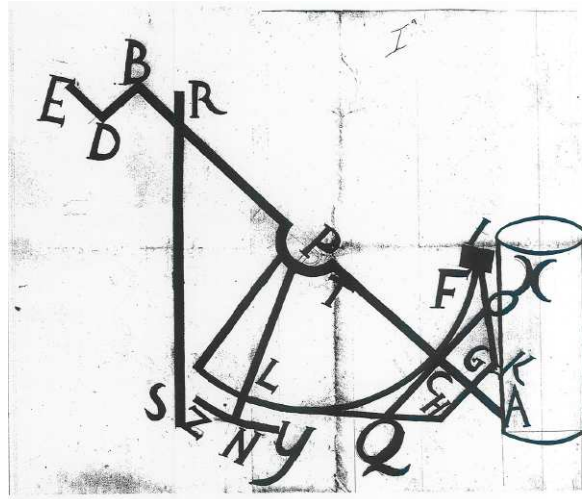


Fig. 3 – A drawing by Pasquale Gabelli shown during the presentation of his solar concentrating system on August 25, 1838 at *Ateneo Veneto*. Source: Italian Central State Archive.

After this description, Namias points out that these studies were influenced by research done by Count Georges-Louis Leclerc of Buffon (1707-1788), who *“with a congeries of flat mirrors mounted on curved surface succeeded in burning wood at a distance of 200 feet and melted metals at a distance of 5, thus making more likely the wonders produced by the genius of Archimedes, who is said to have burned the enemy ships of Rome from the heights of the walls of Syracuse. Let experience decide whether the cost of this machine, which might turn out to be profitable in the tropics and for people sailing in those parts, would be equally profitable for us, despite the impossibility of exploiting it when the sky is overcast.”*^[5]

Bartolomeo Foratti (dates unknown) and the “Pyrocathoper”

Thirty years later, Gabelli’s idea was taken up by Bartolomeo Foratti, who likewise presented his work at the *Ateneo Veneto*; Gabelli himself was in the audience. Foratti reminded his listeners that Gabelli had been the first to lay the groundwork of a system *“that he had been working on since 1849, and that, completed and tested in 1861, was granted a patent by the former government in 1864.”*

Foratti then presented his own system, which he called the Pyrocathoper, an instrument capable of *“condensing solar rays and directing them against a target so as to bring to bear on it a large, constant and continuous current of heat”* that could be used for many different practical purposes.^{[6][7]}

The Pyrocathoper would be made up of *“a multitude of flat mirrors, each one mounted on a small stand with a spherical joint, fitted with screws and pressure. All the stands are spread across and fixed in a large square or grid that can revolve around two perpendicular shafts, one vertical and the other horizontal, so that it can be arranged in the best position for receiving solar rays on its mirror-covered surface. Because of a preliminary arrangement of the system, the rays received by each mirror can be directed by reflection onto a small surface, which by receiving a great amount of calorific rays in this way, is strongly heated up.”*

“After describing the device, Dr. Foratti extends his principle to gigantic apparatus capable of producing the most powerful technical effects, then concludes his report by mentioning the applications, which would be heating the boilers of fixed steam engines or boilers used for distillation and other industrial uses, producing a high temperature on farmland and in greenhouses, evaporating water from salt solutions, etc.”

After 1871, we have no more reports about the Pyrocathopher, but in 1886 Gabelli’s idea of a concentration type solar thermal system was mentioned by Paulo Fambri in a commemoration published in the *Proceedings of the Ateneo Veneto*.^[8]

Fambri recalled that Gabelli’s project had aroused the interest of physicists and mathematicians who thought that *“40 years ago [the concept] fit the conditions and the means, and today it should be examined again, taking account of the many advances made since then in the scientific and above all the industrial world.”* Gabelli himself, a few years before his death, observed that his project ought to be studied again *“on the immensely enlarged basis of the new means that science gives the experimenter today.”*

Alessandro Battaglia (1842-date unknown) and the “Multiple Solar Collector”

In history books, the construction of the first thermal engine powered by solar steam is attributed to Augustine Mouchot (1825-1912), a high-school math teacher in Tours, France. In 1860, Mouchot began to explore the feasibility of converting the sun’s heat into mechanical energy.

In his well-known 1869 book *La chaleur solaire et ses applications industrielles*, Mouchot remarked that, *“We must not think that despite the silence in modern writings, the idea of transforming heat into mechanical energy is recent. To the contrary, we must recognize that the idea is very ancient, and in its slow evolution it has given rise to the creation of various curious devices.”*^[9]

In 1878, Mouchot presented at the World’s Fair in Paris what is commonly known as the first and largest solar steam generator. It consisted of a conical mirror with a surface of around 20 square meters (215 square feet), which reflected solar radiation onto a boiler set in the center of the mirror (Fig. 4).

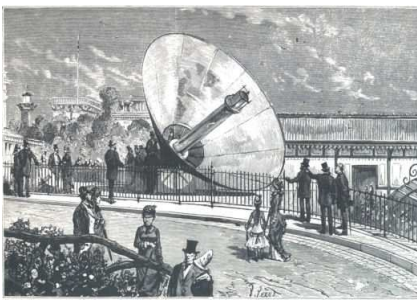


Fig. 4

Augustine Mouchot’s machine, the largest in its day, on display at the Paris World’s Fair in 1878.

Source: Image from K. Butti’s and J. Perlin’s 1980 book *A Golden Thread*.

Mouchot’s machine, whose whistle (the sound of the solar steam pouring out of the boiler) attracted the whole world’s attention, was the object in 1884 of a careful analysis, and of precise criticisms regarding its operating limits, by an Italian scientist and engineer, Alessandro Annibale Battaglia. Battaglia’s work seems to have remained unknown in the 20th century, but it was rediscovered in the last four years by GSES, which presented it to the international solar thermal community at the SolarPaces conference held in Berlin in September 2009.^[10]

We still know very little about Battaglia as a person and as a professional. He was born in 1842 in the little Piedmont town of Acqui Terme; his family was from Germignaga, in the province of Varese. Later on, he lived in Genoa and Ascoli Piceno. On April 17, 1884, we find him in Naples;

during an academic meeting at the Institute of Encouragement, he presented his ideas about Mouchot's machine and pointed out its limitations in a paper read by the physicist Eugenio Semmola, *On the Way and Advantage of Using Solar Heat for Steam Engines*.^[11]

According to Battaglia, Mouchot's invention would not lead to any great results. Since the boiler and the mirror moved together in tracking the sun, neither could be large. Moreover, the boiler was exposed to the air, so it would disperse outward the energy that the mirror had concentrated on it. To overcome these limitations and build concentration systems capable of collecting solar heat in the quantities needed for industrial processes, Battaglia proposed to detach the boiler from the mirror.

He designed a system made up of two independent subsystems. The solar field was formed with 1,250 small flat mirrors, circular in shape, each with a surface of about one square meter, lined up in 42 rows of 30 mirrors each. The boiler – a cylinder one meter in diameter and 30 meters long – was set up in front of the solar field, inside an insulating brick furnace.

Each mirror could track the sun and reflect its radiation onto the boiler. Battaglia described its technical features and economic aspects in detail. He estimated the system's power potential at 37.3 kW and its cost at around 100,000 lire (equivalent to around €420,000 in 2008).

In 1884, Battaglia applied for a patent on his new invention.^[12] This "Multiple Solar Collector" was smaller than the one he had presented at the Naples Institute of Encouragement. The boiler shown in the patent application is 10 meters long and the solar field is made up of 252 mirrors (Fig. 5).

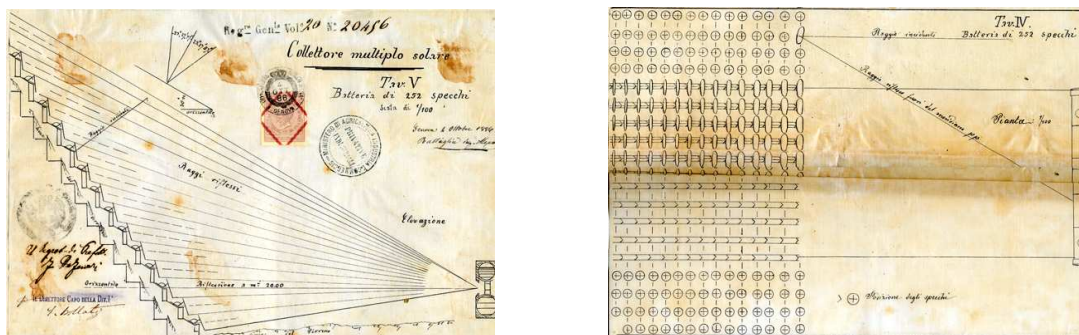


Fig. 5

Alessandro Battaglia patent's application on a "Collettore multiplo solare, Multi Solar Collector" registered in Genoa (Italy), Oct. 13, 1886, (courtesy Italian Central State Archive). Left, one meter in diameter mirrors are aimed at a boiler of one meter height, insulated with bricks. Right, the linear boiler, whose estimated length is about 10 meter, protected by bricks.

Note: The patent was found in 2007 during research by GSES on patents awarded in Italy during the last two centuries for devices related to the use of solar energy.

Source: Images by courtesy of the Italian Central State Archive, Rome.

The Multiple Solar Collector was Battaglia's answer to the challenge of designing solar fields that could be built of any size, hence able to meet the energy demands in modern industrial processes.

We still do not know whether Battaglia ever actually built and tested his Multiple Solar Collector, as physicist Eugenio Semmola urged him to do at the presentation of his paper at the Naples Institute of Encouragement. Nor do we know whether his invention and his patent were ever noticed or taken up by other scientists. To date we have found no trace of them in literature.

Our theory is that Battaglia's idea of producing solar steam to drive an engine may have been overshadowed by the important developments in the use of hydro energy in Italy to generate electricity for the country's factories.

In the very same years that Battaglia was developing his invention and working on putting it into practice, the first hydroelectric plants were being built in Italy. For instance, the one at Vesta,

near Tivoli (Rome), was inaugurated in 1884, the same year that Battaglia presented his invention at the Naples Institute of Encouragement.

Low-temperature solar thermodynamic installations in the first half of the 20th century

In the first half of the 20th century, hydro energy from Alpine lakes powered Italy's first round of industrialization. Even before World War II, more than 90% of the country's electricity came from water power. As suggested above, these developments may have obscured most people's recollections of the 19th century's solar thermal inventions for the generation of steam and electricity.

Nonetheless, some people continued to explore the feasibility of using solar heat to generate mechanical force and run motors, but with the conviction, among some academics – for example, Mario Dornig (1880-1962), at Milan Polytechnic, and Luigi D'Amelio (1893-1963), at the University of Naples – that it would be better to avoid the complications caused by the use of mirrors, and rely instead on thermodynamic cycles based on low-boiling-point liquids such as sulfur dioxide (the substance was readily available because it was used in refrigeration systems), which could be heated with a simple flat solar heat collector to temperatures lower than 100° Celsius. Daniele Gasperini (1895-1960), a native of Rovereto and a refrigeration expert, designed a solar motor based on these concepts in the early 1930s, when he was employed in Libya. The idea of the solar motor came to him under the desert sun. With the collaboration of Giovanni Andri (dates unknown), in July 1936 he presented a prototype of his “Elio Dinamic” motor at the Tripoli trade fair. The outbreak of World War II prevented him from further developing his invention, but he took it up again at the end of the war, with the collaboration of Ferruccio Grassi (1897-1980), an engineer from Lecco and a manager of the Badoni company. Together they invented an ingenious solar pump, the SOMOR, that could be used to pump underground water to the surface. The SOMOR, named for the company that built it, was shown at the first World Solar Energy Fair, held in Phoenix, Arizona, in 1955 (Figs. 6 and 7).^[13]

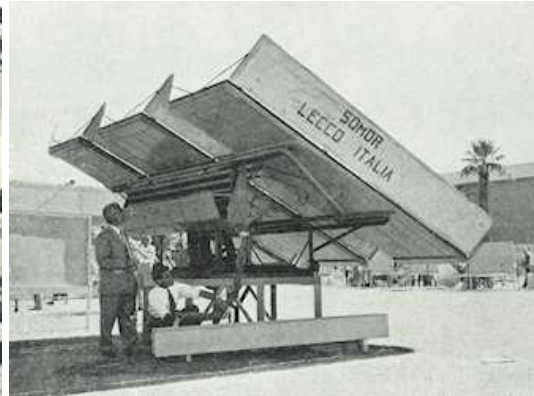


Fig. 6

Left to right: Enrico Gasperini (son of Daniele), Luigi D'Amelio and Mario Dornig at the first world solar energy fair, in Phoenix, Arizona, 1955. They are standing around a paraboloid used here to cook food in a saucepan.

Source: Photo from the Vittorio Storelli archives, donated by his heirs to the Italian National Archive on the History of Solar Energy.

Fig. 7

The Italian SOMOR pump on display at the Phoenix fair.

Source: Photo from the Ferruccio Grassi archives, donated by his heirs to the Italian National Archive on the History of Solar Energy.

Giovanni Francia (1911-1980) and his linear and point-focus Fresnel concentration solar thermal systems based on flat or almost flat mirrors

In the second half of the 20th century, the concentration type solar thermal field was revolutionized by the inventions of Giovanni Francia, who can be considered one of the world's greatest modern-day solar pioneers⁴. A first overview of Francia's work on solar energy was reported at the history session of ISES Solar World Congress in 2005.^[14]

Francia, the eldest of four children, grew up in the town of San Germano Chisone, near Turin. At 18, he lost his father and at the same time fell sick with tuberculosis. The disease forced him to drop out of engineering school and study on his own at the Agnelli sanatorium. In 1935 he was awarded his degree in mathematics. In 1938 he moved to Genoa, where he taught at the university and worked as a consultant. Starting in the 1950s, he produced many important inventions for the motor vehicle, aircraft, space and textile industries, and, in the last twenty years of his life, above all in the field of solar energy.

Francia thought that solar heat – abundant but at low density and low temperature – should be collected in such a way as to obtain the temperatures necessary to run the machinery used in technologically and industrially advanced societies, starting with electricity generators.

To achieve this goal, Francia (who apparently never knew of Alessandro Battaglia's work) followed the same conceptual path as Battaglia: separating the mirror from the boiler.

He was the first in the world to demonstrate, between 1960 and 1965, that it is possible to produce steam at high pressures and high temperatures with solar heat, using Fresnel⁵ type linear and point-focus solar concentrating systems; that is, with fields of flat or almost flat mirrors that can be thought of as resulting from the “fractioning” of a large linear parabolic mirror or a large spherical parabolic mirror (Figs. 8 and 9).^[15]

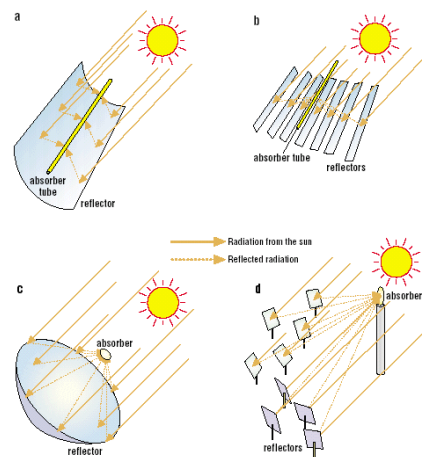


Fig. 8

Concentration of sun light:

a) Linear parabolic collector or trough; b) Linear fresnel collector.

Fig. 9

c) Point focus parabolic spherical mirror or dish d) Point focus fresnel collector or solar tower and mirror field.

Source: <http://www.solarpaces.org>.

Francia took the following considerations as the basis of his concentrating solar system. It's easier to make multiple flat or almost flat mirrors than a large curved mirror. Since the flat mirrors will be less exposed to the force of the wind than large curved paraboloids, the support structure can be simpler and its weight much lighter – even as little as 30% - than what would be needed for a field

⁴ Pionieri in primo piano: Giovanni Francia (1911-1980) <http://www.gses.it/pionieri/francia.php>

⁵ The “mirror fields” proposed by Francia are called “Fresnel type” because they recall the procedure that led the physicist Augustin-Jean Fresnel to invent the lens that bears his name, obtained by breaking up a spherical lens into a series of concentric ring-like sections called Fresnel rings.

of parabolic mirrors with the same reflecting area; the cost implications are obvious. Moreover, curved parabolic mirrors must track the sun jointly with the receiver, which entails a series of implications regarding its construction (for instance, its dimensions, which must necessarily be limited).

Conversely, in the plants conceived by Francia the receiver (or boiler) is independent of the movements of the mirrors or reflectors. It is fixed, it can be supported by sturdy towers, and it can be sized to collect the radiation reflected by a large solar field. When the water in the receiver comes to a boil, the steam collects in the upper part, just as happens in a pot boiling on the stove. This facilitates extraction of the steam.

A field of Fresnel reflectors can be more compact and occupy a smaller area than a plant with the same reflecting surface and the same power rating, but built with linear or disk parabolic concentrators, which must be set farther apart from each other (Fig. 10).

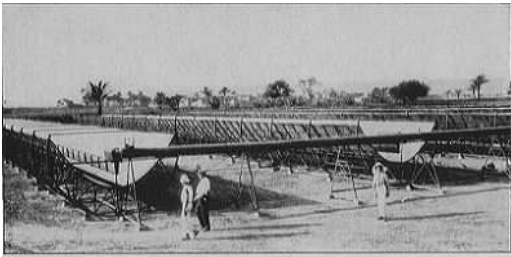


Fig. 10
Solar fields with linear parabolic collectors in the Meadi desert, Egypt, 1912
Source: Photo from K. Butti's and J. Perlin's 1980 book *A Golden Thread*

Based on these concepts, Giovanni Francia envisioned from the very start a new architecture for future concentrating type solar plants, different from those experimented with most up till then. Replying in a letter dated January 17, 1962, to a French colleague who had suggested that he use linear parabolic mirrors – already tested in the United States by Boeing – in his pioneering plant at Marseilles (France), Francia claimed that “large solar plants can be built only with flat mirrors.”^[16]
[17]

Pictures of the plants that Francia built and tested for the first time in the world document the extraordinary work he did in the early 1960s (Figs.11 and 12).

After 1965, Francia focused on concentrating plants with point-focus, central or tower-mounted receivers. He built and perfected other prototypes. In the mid seventies, he began to collaborate with the Ansaldo engineering company, and he participated in the construction of an experimental facility at Georgia Tech, in Atlanta, U.S. (Fig. 13).

In the wake of the 1973 oil crisis, politicians and the industrial community in Italy, as elsewhere, began to look once again at solar energy. This renewed interest led to a decision to build a concentrating type solar power plant based on the principles that Francia had developed and tested at Sant’Ilario, in the township of Nervi, near Genoa.

The world’s first large (1 MWe) Fresnel concentrating-type solar plant to be connected to a national power grid was built in Sicily by ENEL, the national electric utility, in collaboration with the European Economic Community. Eurelios (the plant’s name) was located near Adrano, in the province of Catania (Fig. 14). It was completed at the end of 1980 and put in service the next spring. Italy now held an important world record, but it was soon forgotten.

The Eurelios tests were completed in 1985, and ENEL published the results in 1991. The authors of the report concluded that the per-kWh cost of electricity generated by Eurelios would be far from acceptable even if the up-front costs of the plant were reduced. The report ended with this statement: “*This conclusion, which is shared by the great majority of world experts, leads us to think that tower and mirror-field solar plants will not give rise, even in the medium and long term, to industrial applications of any importance.*”^[18]

Several factors, including Giovanni Francia's death, in 1980, ENEL's conclusions about Eurelios, falling fossil fuel prices, and, in the United States, the advent in 1981 of Ronald Reagan's presidency, which substantially changed the nation's energy policy from that of the Carter administration, with inevitable effects on the energy policies of other countries as well, led to a general reluctance to pursue solar energy in general and, in Italy, the point-focus or tower concentrating plants, which Francia pioneered, inspiring their development worldwide. That same reluctance can also be seen in other choices made in Italy. In the early 1980s, ENEA (the Italian national energy agency) built a pilot solar facility called "La Capanna" at its Casaccia research center, near Rome. In 1983, a tower concentrator was built there for experimental purposes (Fig. 15). This installation was disassembled a few years later, without ever having been used. The only traces left of it are a few photos and a mirror salvaged by ENEA at the request of GSES, for the solar section of the Museum of Industry and Labor, in Brescia.

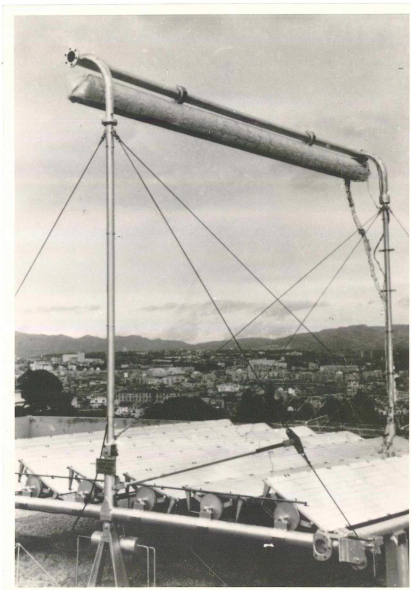


Fig. 11 -World's first linear Fresnel concentration-type solar plant, built and tested at Marseilles (France) in 1963
Source: Photo from the Giovanni Francia archive, donated by his heirs to the Museum of Industry and Labor, Brescia



Fig. 12 - World's first solar tower plant, with field of point-focus Fresnel mirrors, built and tested at Sant'Ilario, near Genoa (Italy), in 1965
Source: Photo from the Giovanni Francia archive, donated by his heirs to the Museum of Industry and Labor, Brescia



Fig. 13 Solar tower plant built at Georgia Tech, in Atlanta (U.S.), with the collaboration of Ansaldo and Giovanni Francia

Source: Photo courtesy of the G. Parodi archives, 1979



Fig. 14 The Eurelios plant, view of the heliostat field and the boiler tower *Source:* Photo courtesy of the G. Parodi archives, 1982

Fig. 15 “La Capanna” experimental solar station at ENEA’s Casaccia Research Center
Source: Photo courtesy of ENEA, 1983

Nobel laureate Carlo Rubbia and the storage of solar heat with molten salt

After Eurelios was shut down and the “Capanna” tower installation disassembled, in the mid-1990s, concentrating solar technology was practically forgotten in Italy for the next 15 years.

It resurfaced in 2000, when Nobel laureate Carlo Rubbia launched a project that he called Archimedes.

When Rubbia suggested using molten salts (a mixture of potassium nitrate and sodium nitrate) as the thermo vector fluid in the receiver/boiler of a linear parabolic concentrating system, which would make it possible to store solar heat and thereby enable the system to operate more regularly, the solar community’s reaction was skeptical.

Since molten salts begin to solidify at 240° Celsius, they were thought unsuitable for circulation in the receiver of a linear parabolic concentration system, where the maximum temperature that could be reached in the pipe at that time was around 400°C. A drop in the temperature could cause the salts to start solidifying, with all the consequences that would entail.

Today this skepticism has been reconsidered. For one thing, the Archimedes experimental project, the first and only in the world, has been inaugurated on July 7, 2010. Thanks to a series of innovations, the salts can be pumped at temperatures between 260° and 550° C, and the receiver pipe can reach the latter temperature. For another, people are beginning to propose to use molten salts in other linear plants.

An interesting example can be seen in a published interview with Arnold Leitner, founder and former C.E.O. of the Colorado startup SkyFuel.^[19] For Leitner, the solar alternative to the generation of electricity from fossil and nuclear fuels could materialize in a linear Fresnel concentration plant that SkyFuel is calling the Linear Power Tower (LPT). The LPT can obtain high enough temperatures in the receiver tube to use molten salts both as the thermo vector fluid and to store solar heat, as in Carlo Rubbia's Archimedes plant.

Unlike the Archimedes plant, the LPT has a fixed receiver that is independent of the mirrors' motion. It thus combines Giovanni Francia's innovative ideas from the 1960s for Fresnel plants, and Carlo Rubbia's ideas from the year 2000.

The application of basic principles of solar thermodynamic technology invented by Giovanni Francia is growing around the world

Current developments in solar thermodynamics based on flat or almost flat mirrors would merit a paper of their own, because this technology has been growing fast.

Here I would simply call the reader's attention to three out of dozens of solar companies that have cropped up in the United States in the past few years: Ausra, eSolar, BrightSource Energy.

All three started out around 2007 with venture capital, and in recent years all three have been widely noticed at world level. They are committed to proving that a kWh of solar electricity can be generated at the same cost as a kWh generated in a power plant fired by fossil or nuclear fuel.

In December 2009, *Power Engineering Magazine* and the PennWell Corporation awarded eSolar a prize for the best solar power plant built in 2009; Ausra received an honorable mention.^[20] That same month, the World Economic Forum listed eSolar as one of the world's 26 most innovative companies.^[21]

In February 2010, Ausra was bought by the French nuclear giant Areva.^[22] Likewise in February 2010, BrightSource Energy received a loan guarantee from the U.S.

Department of Energy for a \$1.37 billion loan to build a plant of 392 MWe and 840 MWt in the Ivanpah Valley, Mojave desert, California.^[23] The construction of this plant started in October 2010,^[24] based on the experimental results of a first prototype of 6 MWth, built at BrightSource Energy's Solar Energy Development Center in the Negev desert, Israel, in 2008 (Fig.18)⁶.

Photos of these three companies' installations, where it is easy to see how they apply basic concepts invented and tested in Italy for the first time anywhere in the world, demonstrate better than any words Italy's contribution to CSP technology being developed today.



Fig. 16
Areva Solar (formerly Ausra) 5 MWe Kimberlina solar plant, put in service in 2008

Source: Photo courtesy of Areva Solar (formerly Ausra)

Fig. 17

e-Solar 5 MWe Sierra Sun-Tower, put in service in 2009

Source: Photo courtesy of eSolar

⁶ The Italian engineer Giancarlo Scavizzi designed the solar boilers of both Eurelios in late 1970s and the BrightSource Energy experimental plant in the Negev desert about thirty years later. Scavizzi passed away in October 2010.

The start of construction in California's Mojave Desert of the Ivanpah plant, one of the largest solar thermal power plants in the world, made up of 173,500 mirrors positioned around three towers, occupying an area of 13 km², in one of the most dynamic countries in promoting technological innovation, is therefore an important moment for the CSP industry .

Arnold Goldman, entrepreneur and founder of BrightSource Energy, drew on his previous experience of a large parabolic trough concentrating solar plant built in the early eighties in the Mojave, with a total capacity of 354 MWe, which is still operating today. However, with the new plant, Goldman opted for concentrating solar thermal tower and fields of flat mirrors. Among the reasons is that *"it is easier to build flat than curved mirrors."* Is Goldman on the right track? What are the challenges laying ahead?

A central issue, when it comes to large renewable energy installations is their integration in the natural and built environments.

The image of a model rendering of the Ivanpah Solar Electric Generating System in the Mojave Desert, shown in Fig. 18, gives a view of the three units.

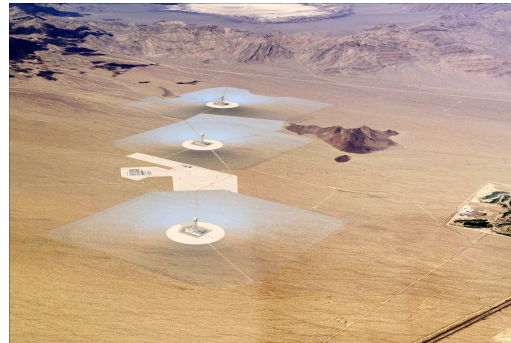


Fig. 18 – 6 MWth Luz Power Tower (LPT), in the Negev desert (Israel), put in service by BrightSource Energy in 2008. - Source: Photo courtesy of BrightSource Energy

Fig. 19 - A model rendering of BrightSource Energy's Ivanpah Solar Electric Generating System – Source: Image courtesy of BrightSource Energy

The process of locating the plant took more than three years of analysis and evaluations in order to assess the environmental impact of the facilities, schedule public hearings and formalize the required permits prior to beginning construction.

Thermodynamic solar plants are generally large in size, on the order of hundreds of MW, therefore requiring large tracts of land exposed to direct sunlight, in addition to availability of water and access to the electric grid. In the U.S., the Bureau of Land Management (BLM) of the Department of the Interior plays a key role in identifying areas where plants may be located.

The Obama administration's "American Recovery and Reinvestment Act 2009" includes specific policies promoting solar installations via the BLM, which controls large areas of federal public lands. This has led many large solar companies, such as BrightSource Energy, to opt for areas managed by the BLM, rather than private property for their installations.

It is interesting to note that these policies promoting solar installations have been made in a country whose potential for solar energy, with large desert areas abundant in direct solar radiation in California, Nevada, Arizona, New Mexico, Colorado and Utah, is the greatest among industrialized nations.

On December 15, 2010, seven large concentrating solar plants were approved by the California Energy Commission, with a total capacity of totaling 4,193 MW, the equivalent, in terms of power output, of nearly three nuclear power plants. The approval came at the end of discussions between those who think of deserts as unique environmental and natural areas to be defended from the impact of large solar projects and those who instead consider them as huge resources to be exploited.

Similar debates and discussions will affect desert use for solar energy not only in the U.S. but everywhere in the world.

The construction of large solar thermal power plants in the U.S. is therefore an important reference for the entire world, both in terms of size of the facilities proposed as well as for bringing attention to the potential risks associated with the industrialization of desert areas at levels previously unknown.

The web site of BrightSource Energy includes documentation on how the company had to accept a series of conditions before obtaining permission to build its plant, including an NPR report on its involvement in protecting a particular species of desert tortoises threatened with extinction, which had to be transferred from the site of the plant to a secure site for their future survival⁷.

The transfer of turtles and other measures to protect the flora, fauna and environment of the desert resulted in additional costs for BrightSource Energy to the tune of roughly \$40 million. A small sum when compared to the total investment of 1.37 billion dollars, but still significant and contrary to the common thinking that vast virgin deserts are available to be easily colonized with thousands of MW in solar CSP or photovoltaic.

Solar radiation (direct and diffused) is the largest energy resource on Earth (Fig. 19). Today, it contributes to the production of electricity with solar photovoltaic systems in about 30,000 MW and 1,000 MW in solar thermal concentrating or thermodynamic plants.

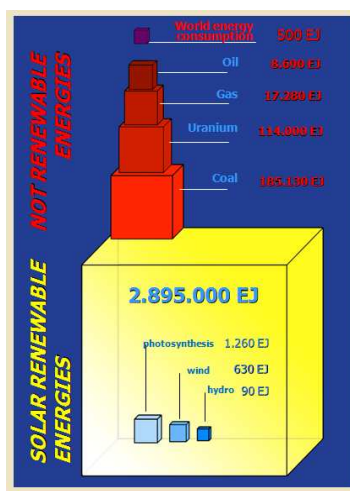


Fig. 20 – Schematic graph, not drawn to scale, comparing estimated energy sources quantities on Earth
 EJ = Exa Joule = 10^{18} J - 1 = 4.8×10^{10} J toe - 500 EJ ~ 10 billion toe (tons of oil equivalent) of world energy consumption in 2010 circa. *Source: GSES*

With improvements in efficiencies and reduced costs, PV has experienced rapid growth in recent years. A trend that is continuing, and judging by the news of the last months of 2010, seems to be guiding lenders and investors alike to focus on major photovoltaic projects rather than CSP. The cost of the former is currently around 3 to \$4 per installed W as opposed to 6 ÷ \$10 of the latter. According to experts, photovoltaic technologies are today ahead of CSP due to their economic competitiveness. However, CSP is better positioned in the development of utility-scale solar thermal storage technology than is photovoltaic electric battery storage.

In the U.S., Solar Reserve, a start-up founded in late 2007, is at the forefront of storage development with molten salt. Its technology enables operation also when there is no sun, during the night or on cloudy days, as illustrated in Fig.20. Solar Reserve was authorized in December 2010 to build two solar thermal power plants with a nominal net generating capacity of 100

⁷ "The Tortoise And The Solar Plant: A Mojave Story", NPR, October 30, 2010
<http://www.npr.org/templates/story/story.php?storyId=130923524>

megawatts (MW) in Nevada and 150 MW in California. ^{[25][26]} A first Solar Reserve plant of 50 MW is already under construction in Spain.

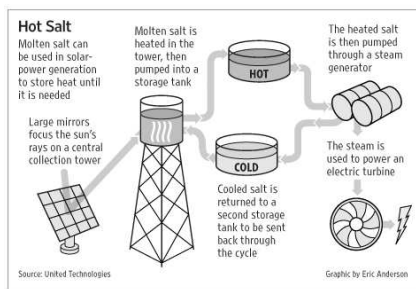


Fig. 21 – Left - Scheme of a new type of solar-power plant that will use molten salt to store the sun's heat so it can be converted to electrical power even when the sun isn't shining creating utility-scale storage technology. Right – A model rendering of Solar Reserve plant at Crescent Dunes, near Tonopah, Nevada – *Source:* Images courtesy of Solar Reserve

CSP storage however, must prove that it can compete with the falling costs of electric battery storage (about 3\$/W today) that many experts foresee, bringing them to predict the end of CSP. Is this risk also faced by BrightSource Energy and Solar Reserve and other companies that have adopted solar power tower technology?

It is hard to say. For experts, the electricity market from direct and diffuse solar radiation will tend to be dominated by one single technology that can offer better and cheaper electrical service. In this regard solar thermal power technology still needs to provide proof that it can compete with photovoltaic, and this holds true also for tower and field mirrors. However, tower technology has an additional and unique feature that makes it more competitive than all other solar thermal power technologies: solar energy is collected by a mirror field and transmitted optically to a central receiving point. Other solar systems with distributed receivers involve the collection of solar radiation throughout the collector field that must be then transported to a central energy conversion plant via a thermo fluid vector (parabolic trough and linear Fresnel concentrator) or electric wires (dish concentrators).

Tower and flat mirror technology adopted in large plants promises to produce electricity at higher efficiencies (solar/electric 20% for solar power tower compared to 14% for solar trough) and at lower costs (mirror fields 160 \$/m² solar power tower as opposed to 250 \$/m² for trough) than other solar thermal power systems, a concept clearly understood almost 50 years ago by the Italian mathematician, Prof. Giovanni Francia (1911-1980), recognized as the father of solar thermal power plants.

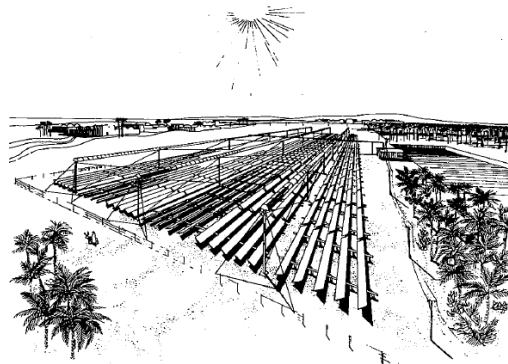


Fig. 22. Artist's rendering of an Linear Fresnel Concentrator solar power plant designed by Giovanni Francia and collaborators. *Source:* The Francia Archives donated by his heirs.

Conclusions

The examples of pioneering work in solar energy in Italy presented here as well as the modern day applications of technologies studied in the past demonstrate the importance of research on the history of solar energy as well as the need to conduct similar studies in other countries with the hopes of uncovering important discoveries that have been since been forgotten.

The prospects for the development of solar technologies would undoubtedly benefit from more attention to pioneering work in the field in the last 200 years, especially in schools and universities. While it is difficult to predict the future, it is interesting to consider the thoughts of a visionary, Hanns Günther, who published in 1931 his now famous book entitled "*In a hundred years: the world's future energy supply.*"^[27] In his book, Günther provides an overview of all possible energy sources and technologies suitable to confront the depletion of coal reserves: from large wind towers, to wave power stations, thermoelectric and photoelectric systems, fuel cells and atomic batteries. He imagines that in one hundred years, i.e. in 2031, technology could allow the production of electricity to end the "*vicious circle through the boiler, steam turbine and generator of electricity.*" The discovery of the photovoltaic cell in 1954 has effectively already opened the way for the possibility of Günther's idea to become a reality one day.

He does not give much importance to concentrating solar thermal power technologies, which he judged as "*lamentable attempts, using expensive optical means, of those who want to heat a small boiler concentrating sunlight on it.*"

For Günther one day mankind might laugh at "*the huge thermal and hydraulic plants which provide electricity to man today.*" He predicted that "*instead of satisfying the voracity of giant boilers with precious fuels such as coal and oil, or rather than building numerous dams, new small machines able to release atomic energy will be built, with the result that their power will exceed by thousands of times that of their predecessors. At that point everything related to the transport of fuel from one part of the Earth to the other will disappear, given that the annual needs of a power plant may be contained in a bottle, and therefore electricity will be used everywhere for all types of work.*"

Currently the atomic bottle envisioned by Günther is not yet on the horizon and, almost certainly, it will never be. On the contrary battery technology to store electricity produced by solar photovoltaic cells is rapidly developing in combination with swift progress in efficiency as well as falling costs of solar cells. A trend which, according to experts, is making competition for CSP harder and harder. Independently of who will win this competition, for now the only bottle in sight is a "solar bottle" and it can be either photovoltaic or CSP.

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