# THE PIONEERING WORK ON LINEAR FRESNEL REFLECTOR CONCENTRATORS (LFCs) IN ITALY

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## Abstract

This paper presents some of the results of recent historical research on pioneering work on Linear Fresnel Reflector Concentrators done in Italy during the 19th and the 20th centuries, with special focus on the work by Giovanni Francia (1911-1980), a self-educated mathematician, once known as the father of solar thermoelectric power plants.

The research studies have been carried out on archive materials, such as notes, letters, articles, drawings and patents, identified and collected by GSES (Italian group for the history of solar energy) and CONASES (Italian Committee 'The History of Solar Energy') in the framework of the Italian Program on the History of Solar Energy.

Francia's personal archive, which his family donated in 2005 to the Museum of Industry and Work (Musil) in the northern Italian city of Brescia (www.musil.bs.it), provided much research material. This documentation unveiled Francia's pioneering but little-known work on LFCs in the early 1960s, which anticipated many of what are today the key aspects of this technology.

Keywords: solar history, solar concentration, Fresnel linear reflector, solar power plant, Giovanni Francia, Italy.

## 1. Introduction

Studies and experiments on burning mirrors and other solar technologies developed in Italy during the Renaissance period have received attention and cited often in literature [1].

On the contrary, Italian first attemps to develop solar concentration technologies to power industrial activities, produce steam and electricity are less well known. A challenge that Italy, lacking in coal and other fossil fuels, started to take at the beginning of the 19th century and found success in the work of Giovanni Francia (1911-1980), among the greatest solar pioneers of the 20th century.

With the aim of rediscovering that work, historical studies were started by the author in 1999 [2]. They are part of the Italian program on the history of solar energy, promoted by the Italian group for the history of solar energy (GSES) and by the Italian Committee 'The History of Solar Energy' (CONASES) [3]. One objective of GSES and CONASES is to make the results of this research accessible on the internet through a digital archive, which is currently being created with its on line debut slated for 2011 [4].

In the following paragraphs some of the results of this work, which is still in progress, are presented, with a focus on emerging concepts in Linear Fresnel Reflector Concentrators during the 19th century and on the unique contribution made by Francia, who was the first at world level to build and test an LFC in a real system prototype in the early 1960s.

## 2. Solar concentration in Italy for solar steam production prior to Francia

### *2.1 Mouchot, Pifre and Battaglia*

In 1860, 100 years before Francia came on the stage, Augustine Mouchot, a professor of mathematics at the Lyceé de Tours in France, began to explore the possibility of transforming the sun's heat into mechanical energy. In his well known book "La Chaleur Solaire et ses Applications Industrielles" of 1869 [5], he observed:

*One must not believe, despite the silence of modern writings, that the idea of using heat for mechanical operations is recent. On the contrary, one must recognize that this idea is very ancient and in its slow development across the centuries it has given birth to various curious devices.*

In 1878 Mouchot exhibited at the Universal Exposition in Paris what is commonly known to be the first and largest machine in the world to produce solar steam. Mouchot's sun machine was subsequently improved by his assistant Abel Pifre, by adopting a spherical parabolic solar collector to power a printing press [1].

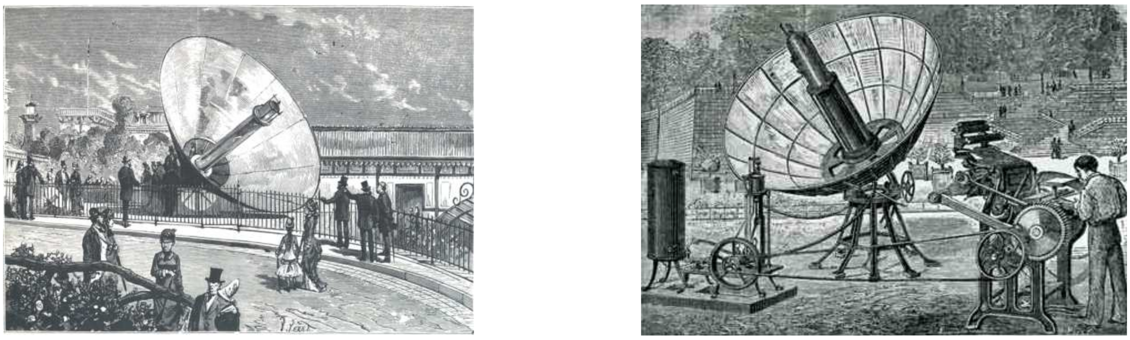


**Fig. 1. Left, Augustine Mouchot's sun machine, the largest of its time, on display at the Universal Exposition in Paris in 1878. Right, Abel Pifre's solar-powered printing press, exhibited at the Gardens of the Tuileries in Paris 1880 [1] [5].**

These developments in France were noted in several other countries, especially in those lacking in coal and other fossil fuels. In Italy, Alessandro Battaglia (1842 – n.a.), an Italian engineer from Acqui Terme, thought that the Mouchot-Pifre designs, despite their merits, also had several inherent limitations that he illustrated in 1884 at the Istituto di Incoraggiamento di Napoli (Encouragement Institute of Naples) [6].

In his paper "Sul modo e sulla convenienza di utilizzare il calor solare per le macchine a vapore" (On the methods and convenience of using solar heat for steam engines) Battaglia illustrated the limitations of the Mouchot-Pifre designs:

- It is not possible to build boilers of sufficient capacity to power industrial engines due to the fact that the boiler is mounted on the tracking collector, which limits its size;
- The boiler loses its heat easily because it is exposed to open air and cannot be insulated and protected;
- The tracking collector, as a single surface, is also limited in its total area.

To overcome these limitations, Battaglia proposed separating the boiler from the collecting reflector area. He proposed a horizontal cylindrical boiler 30 meters in length and 1 meter in diameter, enclosed inside an insulating brick oven with a window of the same length as the boiler and 1 meter in height, facing a separate collecting reflector area made up of 1250 small flat mirrors, one square meter each, distributed in 42 rows of 30 mirrors each. The system, which he described in economic and technical details, was estimated to have an output of 50 HP (37.3 kW), with an approximate cost of 100,000 lire in 1884 or 420,233 in 2008 Euros.

In 1884, Battaglia applied for a patent for his invention as a "Collettore multiplo solare" (Multiple Solar Collector), though with a boiler of just 10 meters and only 250 of the 1250 flat mirrors indicated in his paper. Battaglia's patent is illustrated in the following drawings in figure 2, courtesy of the Central State Archive, Rome, Italy.

The purpose of Battaglia's invention, as explained in his patent, is "to collect the solar rays that strike a specific portion of the earth's surface at any latitude, and to reflect them, concentrated in a specially shaped beam, onto a specific surface of limited size, in order to obtain a high temperature and a quantity of calories capable of causing a specific effect, at a cost relatively small for the size of the reflecting surface. The surfaces that receive and reflect the solar rays are metallic, silver-coated and burnished. The reflection must be continuous; that is, it must be aimed at the same point every day of the year, from sunrise to sunset [7]."

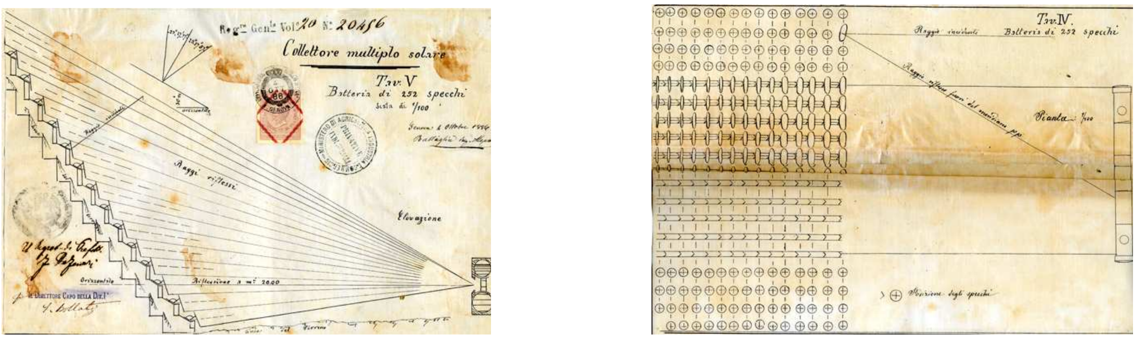



**Fig. 2. Left, Cross section of the collecting reflector area and the longitudinal grounded boiler, one meter in height, installed inside a brick oven, insulating and protecting the boiler and with an opened window facing the reflector area. Right, Plan of the collecting reflector area and of the longitudinal or linear boiler, roughly ten meters in length.**

The Multiple Solar Collector was Battaglia’s answer to the challenges of building large collectors, on which many scholars and scientists speculated during the 16$^{th}$ and the 17$^{th}$ centuries as illustrated in figure 3.

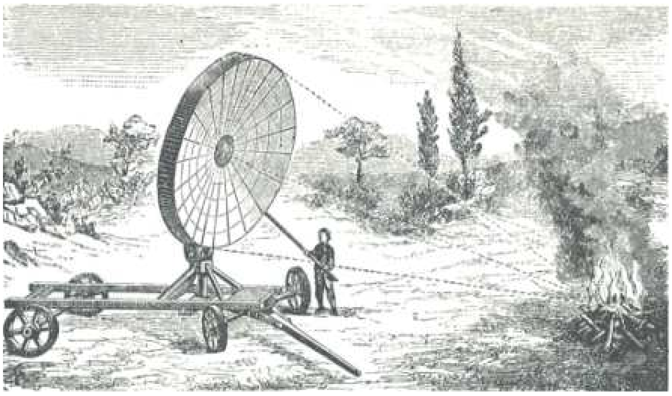


**Fig. 3. From a Golden Thread by Butti and Perlin: a large burning mirror of the late 1700’s built in sections [1].**

Battaglia’s approach, which won him special recognition from the Istituto di Incoraggiamento di Napoli, overcame, in theory, some of the limitations in the Mouchot-Pifre designs, though there still remained obstacles, that had already been encountered in the past, as shown in the image in figure 3. Judging from the drawings in Battaglia’s patent, the grounded boiler would require the mirrors to face downward and therefore are limited in the amount of sunrays they can capture and reflect toward the receiver.

In any event, Battaglia introduced new concepts, such as a longitudinal or linear receiver and a multiple reflector area made of many small and flat reflectors, each one tracking the sun independently. Both the reflector area and the boiler could therefore grow in size to collect large quantities of solar energy in order to meet modern industrial demands.

Historical research on Battaglia’s theories, as well as other work based on his patent registered in 1886, continue today. For example, research is being carried out to determine if Battaglia ever succeeded in building and testing a demonstration plant, as he was recommended to do by the Istituto di Incoraggiamento di Napoli during his presentation in 1884.

### *2.2 Other little known Italian attempts in the 19$^{th}$ century to produce solar steam*

Prior to Battaglia’s work, other Italians had considered the possibility of building large solar concentrators to produce solar steam during the 19$^{th}$ century. Among them it is worth recalling Pasquale Gabelli (1801 –1882) and Bartolomeo Foratti. Gabelli, a professor of mathematics and natural science, born near Pordenone in northern Italy, presented a handwritten document “Sopra un nuovo meccanismo per dirigere i raggi solari condensati ad usi speciali” (On a new mechanism to direct condensed solar rays for special purposes) at the

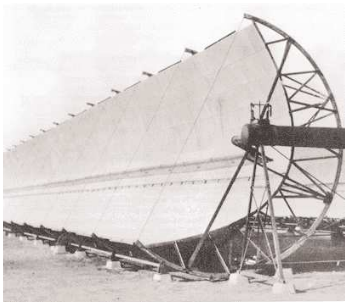
Ateneo Veneto, a scientific and cultural institute in Venice, on August 25, 1838. In references made to this 40-page document and its annexed drawings, Gabelli is said to describe a solar concentrating system made up of many small flat mirrors individually positioned and mounted on a large two axis heliostat, which he experimented in 1861 [8].

Bartolomeo Foratti further developed Gabelli’s solar concentration system and described it in a document entitled “Su d'un suo apparecchio per la concentrazione dei raggi solari e loro applicazione al riscaldamento” (Apparatus for concentration of solar rays and their application to heating), which he also presented at the Ateneo Veneto on July 8, 1869. Foratti envisioned the construction of what he referred to as a Pirocatoforo, similar to Gabelli’s design, to be used for heating boilers in steam powered stationary machines, to produce high temperatures for agriculture, heating greenhouses and desalination [9].

These 19$^{th}$ century Italian concepts and attempts by Gabelli, Foratti and Battaglia to produce solar steam seem to have been completely forgotten in the following decades. Research has thus far failed to turn up any traces in the Italian scientific literature of the late 1800s and early 1900s.

One explanation for this could be that at the time Italy was searching for alternatives to coal and oil, which it found in the use of hydro energy from the Alps. This Italian white coal was used to produce electricity and power the Italian industrial revolution, from textile to other manufacturing activities. In 1898, the first hydroelectric plant was built in Paderno d’Adda and at 10 MW, it was the largest in Europe at the time. Additional plants were built in the following years. Prior to WWII, hydro energy was providing 92% of all total electricity production in Italy [2].

In the first half of the 20$^{th}$ century, solar concentration technology throughout the world continued to be dominated primarily by parabolic troughs and dishes as shown from photos in figure 6, with a receiver mounted on curved mirrors. It wasn’t until the early 1960’s that a revolutionary new approach to solar concentration was made in Italy by Giovanni Francia, who, as Battaglia before him, separated the boiler from the reflecting area, but took a new approach by suspending a linear or point boiler above multiple reflectors with one or two axis tracking.



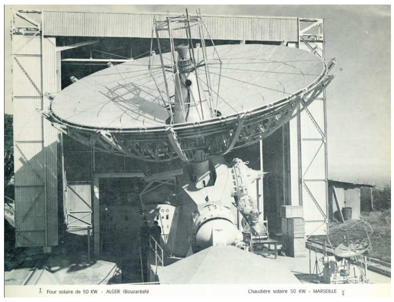


**Fig. 4. Left, Parabolic trough concentrator, Meadi, Egypt, 1912, for steam production used in powering a solar pump [1]. Right, a solar oven at the Observatoire de Bouzaréah in Algeria, which in the early 1950’s was among the most powerful in the world, with a collecting area of 50 m$^2$ (Marcel Perrot Archive).**

## 3. Giovanni Francia and the sun’s heat

### *3.1 Honeycomb structure and first solar boiler*

Born in Turin in 1911, Francia was a self-educated mathematician who made important contributions to various fields, such as motor vehicles, aircraft, space, textiles, and electro mechanics. Starting in the late 1950’s and continuing until his death in 1980, he developed a special interest in solar energy and devoted most of his time to developing solar technologies, rediscovering concepts and reinventing solutions that had already been considered in the past by other Italians. To learn more about Francia’s pioneering work in solar energy, see reference [10].

Francia presented his pioneering work on solar concentration in the 1968 issue of the journal Solar Energy [11].

He began working with the idea of collecting solar heat in order to obtain the high temperatures used in modern industries, such as to run large turbines at power plants. His first step toward raising the solar energy collection temperature was to invent the honeycomb structure, an array consisting of a large number of long, thin, parallel tubes made of glass, quartz or plastic. Being transparent to solar radiation but opaque to the heat rays emitted by the hot surface, the array served to reduce the collector's losses from re-irradiation and convection.

Figure 5 shows the design for the first honeycomb system that Francia built in early 1960 for the sole purpose of testing the theory he was elaborating. In this case, the honeycomb was made up of hexagonal tubes 8 mm in diameter and 160 mm long. The device produced temperatures of 230-240°C, far lower than the 500°C expected theoretically. Between 1960 and 1961, Francia built the first experimental solar station at Cesana Torinese, coupling a boiler with a concentrator protected by a honeycomb structure made up of 2000 thin glass tubes. Francia’s experimental station succeeded in reaching the temperature of 600°C.

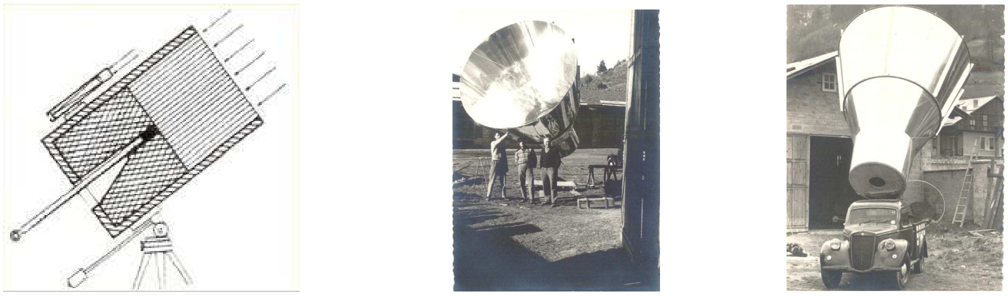


**Fig. 5. Left: first honeycomb absorber that Francia built in 1960; Right: Photos of the first boiler coupled with a concentrator and protected by a honeycomb structure tested in Cesana Torinese in 1960/1961 (Francia Archive, Musil Brescia).**

He then translated his honeycomb structure, theory and experimental results into his first solar patent [12], which he presented at the United Nations Conference on New Energy Sources (solar, wind, geothermal), held in Rome at the headquarters of FAO, the U.N. Food and Agriculture Organization [13], where he gained international recognition. At this Congress he met Marcel Perrot (1908-2006) of the Solar Research Group at the University of Marseille (France), with whom he started a fruitful cooperation in solar energy.

### *3.2 Francia and Linear Fresnel Concentrators (LFCs)*

Francia was the first person in the world to apply the Fresnel reflector concentrator concept in actual linear and point focus systems (LFCs and PFCs). He filed his first LFC patent in 1962, in Italy [14]. The next year, he designed and built the first LFC prototype, in Genoa, and in 1964 he assembled and tested it at the Lacédémone-Marseilles solar station, in cooperation with Marcel Perrot, and with support from France’s National Research Council (CNRS), NATO and COMPLES (Coopération Méditerranée pour l’Energie Solaire).

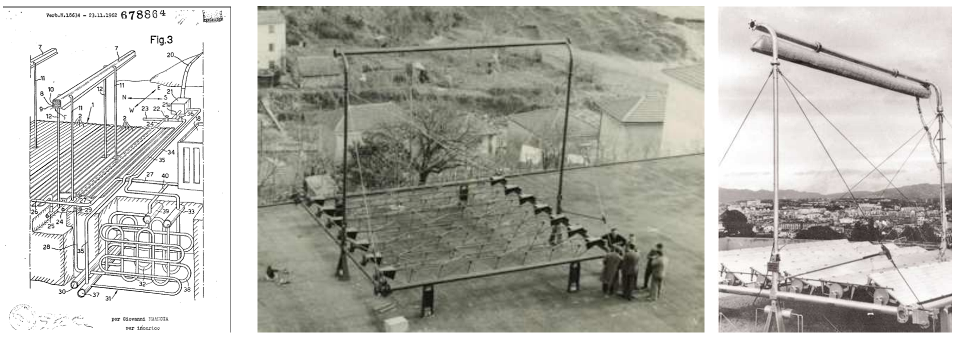



**Fig. 6. Left: drawing of the patented LFC; Right: Photos of Francia’s first LFC prototype (Francia Archive, Musil Brescia).**

As described in a note, this initial LFC unit was built by GRESUMG (Gruppo Ricerca Energia Solare Università Marsiglia Genova - Solar Energy Research Group, Marseilles and Genoa Universities) and stood on an area of approximately 8.2 x 7.9 $m^2$. It had 7 aluminum mirrors, 8 meters long and 1 meter wide, parallel to each other on an east-west line. Each mirror rotated around its lengthwise axis, concentrating solar radiation on a linear boiler positioned parallel to the mirrors at a height of about 6 meters. The rotary motion was the same for all the mirrors, and was obtained by means of an electronic command guided by the sun itself. The boiler was slightly less than 8 meters long and 25 centimeters wide. It was protected on the front (the side facing the mirrors) by the honeycomb structure and on the back by appropriate insulation and a lost-heat-recovery device [15].

Two flat vertical mirrors limited energy loss on the west side in the morning and on the east side in the afternoon; otherwise, reflected energy would reach the boiler only during the midday hours, due to the short length of the mirrors. In the design for the large solar plant described in Francia's patent no. 18634, of which the Marseilles plant was the first unit, the aluminum-mirror strips were much longer than the boiler is high, which eliminated the need of protective mirrors on the sides. Likewise, the Marseilles unit was designed to be scalable; the length of the strips of mirrors could be tripled or quadrupled and their number increased. The plant was built with off-the-shelf materials in order to simplify the construction and reduce costs, with the idea to perfect them based on the experimental results obtained with the prototype. The plant generated 38 kg/h of steam at 100 atm and 450°C.

The plant was expected to supply around 1200 thermal kWh annually per square meter of mirrors in Marseille, making a total of 67,200 kWh per year. If the plant had been built in Sicily, Francia calculated that production would have reached 1600 kWh per year per square meter, for a total of 89,600 kWh annually.

According to Francia's evaluation at the time, with a large-scale plant, the power output could be much cheaper per kWh than that generated from oil. For Francia, the use of flat mirrors was fundamental in order to build large-scale plants, as he stated in his correspondence with M. Touchais, a collaborator of Marcel Perrot [16] [17].

In the late sixties, Francia, in cooperation with his collaborators, elaborated the "Solar City Project – Hypothesis for an Urban Structure", by inventing a wholly new kind of urban complex for a population of around 100,000. This complex relied on the use of solar energy for natural and artificial lighting, for heating household water, for space heating and cooling, and for the production of electricity. The design centered around repeatable, independent and energetically autonomous units (18). The drawing in figure 7, dated circa 1965, shows Francia's vision of a large LFC integrated in an urban context.

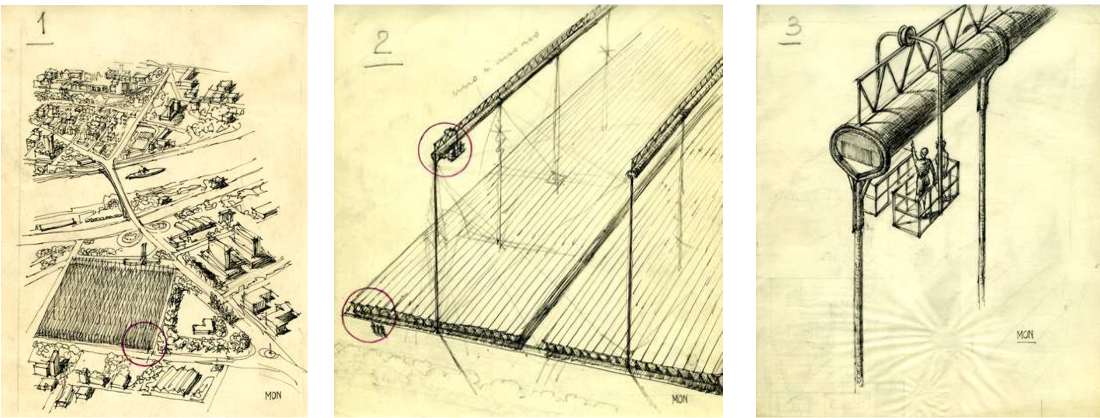



**Fig. 7. Francia's drawings of the envisioned large solar LFC power plant integrated in an urban context of circa 1965 (Francia Archive, Musil Brescia).**

After building his first LFC, Francia built the first PFC in 1965 at the Sant'Ilario solar station and began focusing mainly on solar towers, on which he devoted his efforts in the following years. He believed solar energy would become competitive for power generation only when solar boilers were improved to the point when they could produce steam at pressures above 150 atmospheres and temperatures above 500°C, a goal that seemed more likely achievable with solar towers than with linear concentration systems at the time. His work on LFC technology was thus put on the back burner.

In the late 1970s, Francia worked as a consultant for the construction of the industrial-scale solar tower facility at the Georgia Institute of Technology, in Atlanta, and for the 1 MW Eurelios power plant at Adrano, in Sicily, the first of its kind anywhere in the world to be connected to the electricity grid.

Despite the fact that from 1965 onward his focus was mainly on solar towers, Francia still continued to envision large-scale LFC plants as illustrated by the following artist's rendering, from a brochure written by Francia and his collaborators just before his death in 1980.

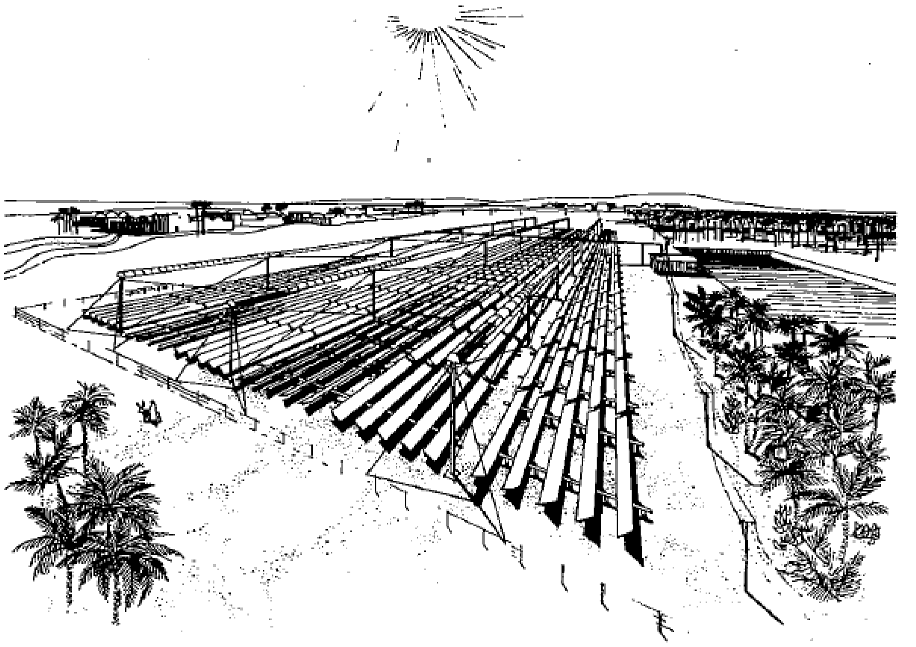


**Fig. 8 – Artist's rendering of an LFC solar power plant designed by Giovanni Francia and collaborators in late 1970s [19].**

## 4. Conclusion

The documentation from various archives, as briefly illustrated in this paper, gives us better insight into the pioneering work on LFCs in Italy. It shows that there were various attempts to develop large solar concentration systems by using a Fresnel type multiple collector area and increasing boiler efficiencies starting in the early 19th century.

In facing this challenge Giovanni Francia succeeded during the 20th century, in just a few years, from the late 1950's to the mid 1960's. After his first experiments on anti-radiating structures or honeycombs, he devoted his work to the development of LFCs and PFCs, not only proving to the world that solar energy could be collected at high temperatures to generate solar electricity, but also proposing the integration of large solar power plants in urban contexts, as it can be seen from his drawings and his solar city project.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