WAS THE ITALIAN SOLAR ENERGY PIONEER GIOVANNI FRANCIA RIGHT?

David Mills

Co-founder and former Chief Scientific Officer of
Solar Heat&Power (SHP Pty Ltd) and Ausra Inc. (now Areva Solar)
15 Thomas Avenue, Roseville, NSW, Australia 2069

Summary

This paper describes the background to Giovanni Francia's developments in solar energy, and asks whether they will still be important in the future.

1. Introduction

Giovanni Francia (1911-1980) was a mathematician, inventor and visionary engineer who from the 1950s onward made numerous contributions to several industries, notably the first anti-skid braking system for automobiles which he invented in 1955. But it is in the field of solar power where his legacy is relatively the most important, influencing the basic designs used by later designers of solar concentrating systems up to the present day. This paper examines whether his vision is likely to continue to influence future progress in the renewable energy market transformation.

Fig. 1. Giovanni Francia in 1957.

2. Fresnel Reflector Systems

Giovanni Francia was born into a middle class family in 1911. His early life has been well documented by Silvi [1], who describes his father was a keen inventor. As a student he was unable to attend University, being confined to a sanatorium because of tuberculosis. However, he self-studied and became a special assistant at the Royal Polytechnical Institute in Turin, obtaining a degree in mathematics in 1937. In 1938, he began teaching in the University in Genoa, and after the war became increasingly involved in work for industry, notably inventing the first anti-skid braking system (ABS) for automobiles in 1955.

Francia became interested in the possibilities of solar power in the 1950s and from 1960 to 1965 he and his colleagues built a series of concentrator prototypes, the most influential of which were a linear fresnel reflector (LFR) prototype built at Marseille, and a central receiver (PT) prototype built at S. Ilario (Genoa).

These two plants shared a common principle - the solar absorber or receiver of solar radiation (often a high temperature boiler) was relatively large and was separated from the mirror field at a height such that every mirror in the field could illuminate some part of the receiver during the whole day. In this way, the high intensity illumination of the receiver was created by overlapping the reflections of many flat or nearly flat reflectors called heliostats.

This idea of separating the receiver and heliostats was not new. It had been used earlier by Count Georges-Louis Leclerc of Buffon (1707-1788), who “with an [assemblage] of flat mirrors mounted on a curved surface succeeded in burning wood at a distance of 200 feet and melted metals at a distance of 5”. This was in an attempt at imitation of the supposed burning of Roman ships by mirrors of Archimedes at Syracuse.

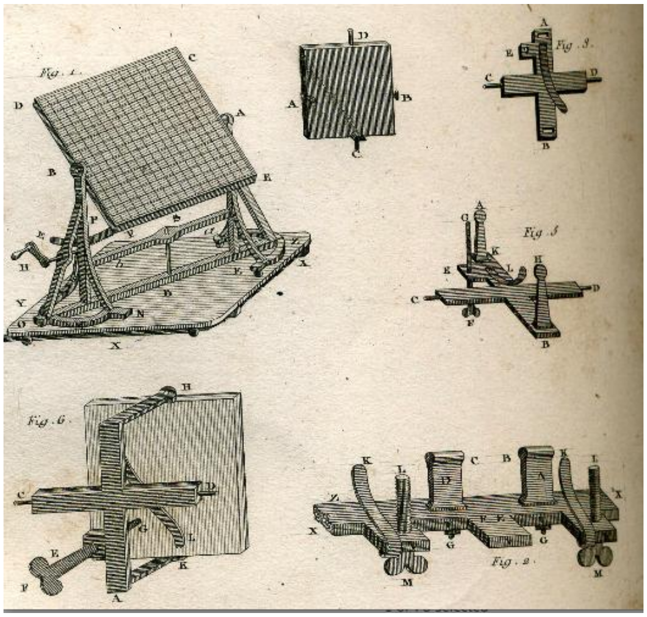


Fig. 2. Details of an apparently contemporary drawing of details of the heliostats used by Buffon. These were tracked by hand-turned handles. (origin unknown).

Fig. 2 shows a contemporary drawing of the manually tracked heliostats used by Buffon. Geometrically, this is similar to the idea of a separated field of many mirrors and single receiver used by Francia, except that the receiver in Buffon’s case was a wooden or metal object.

The term ‘fresnel reflector’ is usually used in homage to Augustin-Jean Fresnel (1788-1827) seems, therefore, inappropriate. Fresnel made great progress in our understanding of the wave nature of light, and introduced the Fresnel lens made up of many refracting flat-faced elements, but it is Buffon who invented heliostats. He only lacked a boiler. However, these days the term ‘Fresnel reflectors’ is standard. Both Linear Fresnel Reflector and Power Tower (PT) fields using 2-axis tracking mirrors called heliostats come under this classification. Power towers are often called “central receivers” but this paper will use the former term “power tower” or PT.

Following the introduction of steam boilers during the previous century by Denis Papin, Thomas Savery, Thomas Newcomen and James Watt, Pasquale Gabelli (1801-1880) of Venice designed a solar paraboloidal mirror to heat up a small boiler in 1838, the vapour from which was used to heat a larger ground mounted boiler tank. However, the reflector was a single entity composed of smaller flat mirrors moving as one unit rather than many reflectors having differentiated motion.

Thirty years later, Bartolomeo Foratti, also of Venice, described - with Gabelli present - an improved system called the Pyrocathopher, described as “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." This sounds very like the 1965 Power Tower prototype of Francia, but the detailed layout is not clear from the description and there exists no drawing.

In 1878 at the Paris Exhibition, Frenchmen Mouchot and Pifre demonstrated at a solar steam boiler based upon a 20 m^2 conical reflector; it was used to run a small printing press. Aessandro Battaglia, born in 1842 in Piedmont, carefully analysed the system and decided that for commercial systems, larger arrays of mirrors were needed with large boilers, and he proposed the system shown in Fig. 3. These days, unless used on a very large planar hill, the support costs for such a multi-megawatt reflector structure would be prohibitive. However, Battaligia's use of a PT system allows collection of energy at the boiler without pipes, as used in PT systems today. There is no record of Battaglia's system being built, but it was patented and a fuller description of it is given by Silvi [3].

Interestingly, however, an Ansaldo brochure [5] apparently authored by Francia, shows a design (Fig. 4) very similar to Battaglia's design. While possibly a coincidence, it leaves open the possibility that Francia was aware of the Battaglia's work, perhaps through the Mont-Louis plant built in the French Pyrénées in the 1950's using a similar design.

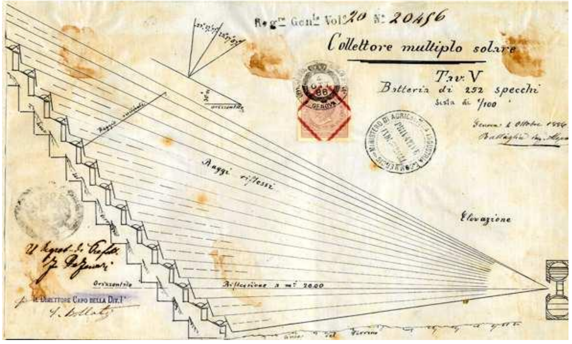


Fig. 3. Battaglia's design for a solar boiler [3]

As in all human progress, there were many attempts made before someone finally catalysed the field. In solar concentrating systems, that person was Francia. How much did he owe to former work in Italy? No one knows; no other evidence has so far been discovered of his access to previous Italian work on fresnel systems.

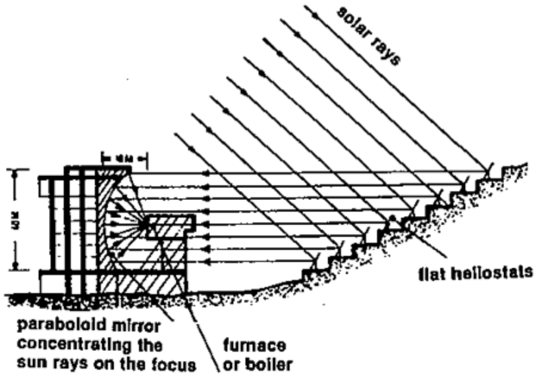


Fig. 4. A design from Francia's brochure.

3. Francia's Developments

In his 1968 paper in Solar Energy, Francia described his experiments with the LF and PT prototypes. These are described in greater detail in a 1981 Ansaldo SpA report [6] that contained portions written by Francia before he died in 1980.

Francia's first experiments were performed in 1960/61 with a cone-like reflector system with the receiver covered by a convection suppression honeycomb made of 2000 thin glass tubes (Fig. 5). This was intended for laboratory experiments rather than development into a commercial system, but performed well with 70% collector efficiency at 500-600°C. The honeycomb effectively provided very effective transparent insulation, and performance at 400°C went to zero efficiency if the honeycomb was removed. However, it was far too materials intensive to be economic. It was not a fresnel system.

Fig. 5. The initial Francia cone collector. Source: Italian Group for the History of Solar Energy (GSES)

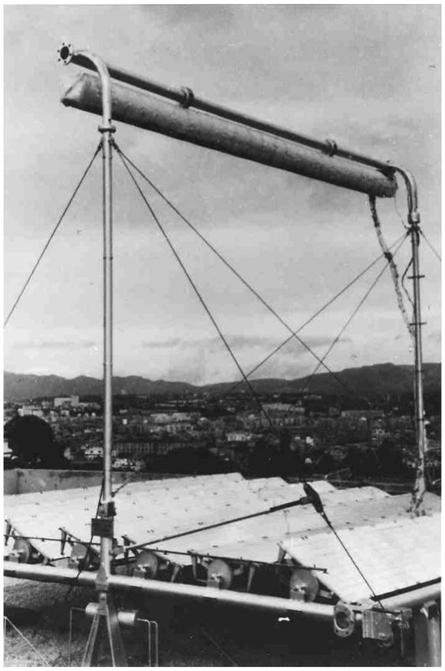


Fig. 6. The Francia LFR prototype at Marseille built in 1962. From [6].

Francia then moved on to a linear fresnel system (Fig. 6) which used a linear receiver with the downward facing aperture covered with glass honeycomb tubes. The system was unstable in operation, with steam/water oscillations in the initial arrangement of many parallel tubes intended to achieve many ray bounces in the cavity to increase absorption but was stable when a single tube boiler was substituted. The resulting best performance of 60% efficiency at 450°C was considered too low and Francia decided that designing a higher concentration PT system was more practical and abandoned the LFR approach. This action was to steer development in the direction of PTs for power production and away from LFRs, but the decision was caused by high honeycomb costs and the lack of a suitable spectrally selective absorbing surface for high temperatures above 400°C; such surfaces have only been developed in the last decade for both unevacuated and evacuated tubular receivers. That being said, there was still some interest in LFRs for applications below 300°C in the intervening years (Itek,Paz, SHP, Industrial Solar, etc) and when higher temperature surfaces became available, LFR manufacturers like Areva Solar (Fig. 9) and Novatec Solar have moved to development of >500°C power generation systems using high pressure conventional steam turbines. Although these require pipes for heat transfer fluid in the field not required by power towers, the collectors are easier and less labour intensive to install than two-axis PT heliostats and tracking through one axis is comparatively simple. Cleaning LFR mirrors is also much easier than for large PT heliostats. Near the end of his life Francia in 1979, when chrome black selective coatings had become available, Francia sketched a larger LFR system that bears a strong resemblance to modern systems (Fig. 7).

Francia's move to the PT design in 1965 built at St. Ilario in Genoa and was funded by CNR and NATO. The reflectors were tracked by a complex mechanical system linking all reflectors in the field. It achieved 70% efficiency at 500°C and 100 atm. The project produced a series of three gradually improved receiver designs, the last being a prototype receiver (Fig. 8) for a much larger 400 kW(th) PT that was built in the USA at Georgia Tech in the late 1970s. This was the first PT built in the USA and was followed by a solar test facility of 5 MW(th) at Albuquerque and an experimental tower of 10 MW(e) at Barstow (Solar 1). In Europe, plants were installed in Sicily (Eurelios, 1 MW(e)) and at Odeillo, France (Themis, 2MW(e). Francia personally worked on the 1MW(e) Eurelios plant near Adrano in Sicily constructed by Ansaldo, Enea, CETHEL and MBB (funded by the EEC) but he died before it was commissioned in 1981. Eurelios was shut down in 1987 but Themis and Albuquerque facilities have been renovated and are active as experimental towers today. All of this activity proceeded from Francia's early work.

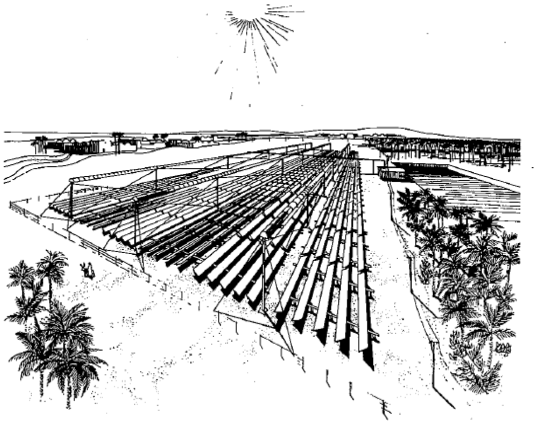


Fig. 7. Francia's vision of a large future LFR in 1979, from Ref [5] page 39.

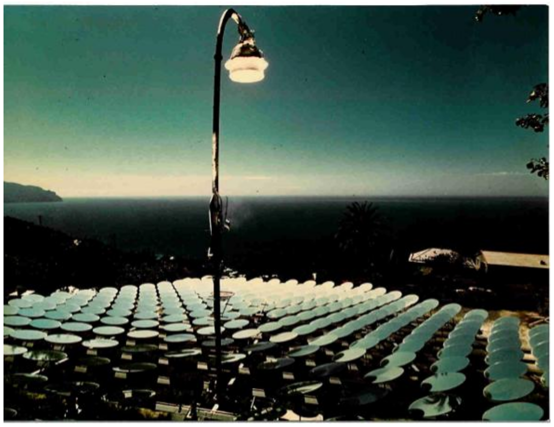


Fig. 8. The third iteration of Francia's Genoa PT test facility using a receiver of the type later installed at Georgia Tech in the USA.

In contrast, recent work in LFRs had to wait until modern spectrally selective absorber coatings appeared and was not commercially used until 2006 by SHP in Australia. The CLFR concept from the early 1990s [8] was developed in ignorance of Francia's work, and was somewhat different, but Francia was cited after 1994 after literature searches by Mills and Morrison [8]. Francia's contribution again became recognised but several of his technical approaches (glass honeycombs, linked mirror rows) were not used.

To summarise, Francia's work was the original driver for both LFR and Central Receiver systems in the 1960s and he actively assisted the development of European and US power towers that would follow in a direct developmental line to companies like Brightsource, Solar Reserve, Abengoa and Torresol. Francia felt that large plants with many small, nearly flat, reflectors and large solar absorbers were inherently more economic than parabolic troughs and dishes with highly curved glass and many smaller solar absorbers. Increasingly this intuition seems to be correct, with both LFR and PT plants trending upward. Francia also wanted to see his LFR designs embedded into cities so that thermal and electrical energy could be both supplied, but this role is now more likely to be carried out by PV.

4. Present Day Development

In the last decade there has been a great expansion of solar thermal electricity plants, mostly parabolic troughs built under the Spanish feed-in-tariff programme. Such troughs have gradually moved to molten salt thermal storage. Large LFR projects by Areva [10] and Novatec [11] have also appeared, and Areva is working with Sandia Laboratories on a molten salt storage system for their CLFR (Fig. 9).

Fig. 9. An Areva CLFR line at Kimberlina near Bakersfield California, operating as a superheating line at 400°C. More recent development is moving to 500°C and beyond.

Tower PT systems are gaining large commercial momentum, beginning with Abengoa‘s PS10 in 2007 [9] and more recently the new storage plants like Terrasol Gemasolar plant (Fig. 10) [12] in Spain and Brightsource [13] and Solar Reserve [14] plants in the USA. Brightsource previously developed non-storage tower projects but has recently joined the movement to molten salt storage.

Fig. 10. Spanish 20 MW(e) Gemasolar PT plant with 15 hours of molten salt storage. Source ref [12].

At this time plants of both LFR and PT types are moving toward 550°C operation with troughs and most LFRs are likely to use evacuated tubes such as the Italian-developed Archimede [15], which operates up to 580°C. Later, 650°C operation may be anticipated for PT plants. Field cost appears to be lower with the LFR plants but PT plant costs are dropping as well. LFRs have construction cost advantages and excellent modularity but PT plants are ultimately capable of higher temperature and greater turbine efficiency. It is unclear at the time of writing which approach will yield the lower long term generation cost. In general, all systems are currently using or developing molten salt storage, but many advanced storage projects are now under development. LFRs and Towers can use the same storage/heat transfer fluid, so any advantage of one over the other is likely to primarily lie in a more favourable ratio of the capital and maintenance costs of the collector field to the annual electrical energy collected.

Thus, there is intense competition between different types of STE, but also there are other competitors for the clean energy market. What will that market look like?

In 2011, we showed [16,17] that systems could be assigned to two categories, *flexible* and *inflexible* and these can be combined to meet a system-wide electricity load without there being any necessity for using baseload. In this way of thinking, baseload power is an inflexible power source because it cannot adapt to the load. Wind and solar power without storage are also inflexible because they also cannot adapt to the load. Inflexible sources require the addition of flexible sources like hydroelectricity or solar with battery storage to meet the load, but *baseload is not essential to the system*. In principle, a functioning system can be made *entirely* of flexible electricity sources. Wind and solar have been assumed by many to be in the category of inflexible, but the addition of energy storage puts them into the flexible category.

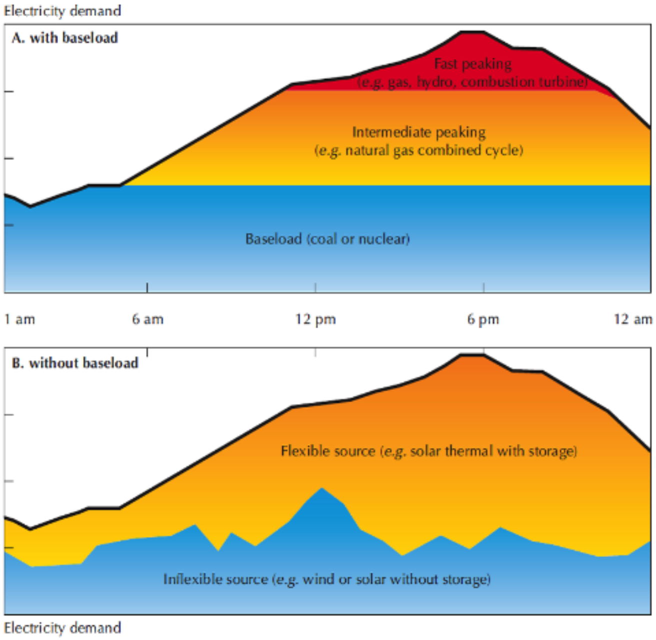


Fig. 11. Diagram showing how a load can be satisfied not only by a combination of peaking and baseload, but a combination of an inflexible variable source and a flexible variable source with no need for baseload. This drawing was from the IEA Solar Energy Perspectives Report 2011 [16], based on drawings by the author in Mills and Cheng [17].

This insight means that we are soon to enter a new type of electricity system, where a combination of literally millions of independent flexible renewable energy generators - some on grid, some on roof - can meet the entire electricity load at any point in the system, and also replace many loads now satisfied by direct fossil fuel. Buildings can use heat pumps instead of gas or oil to heat and cool, and induction for cooking. Vehicles can be powered by electricity instead of petroleum, and can be also used as an energy sink for rooftop overproduction, and to power the home during emergency blackouts. In such a new system, will Francia’s vision for LFR and PT systems still be make sense?

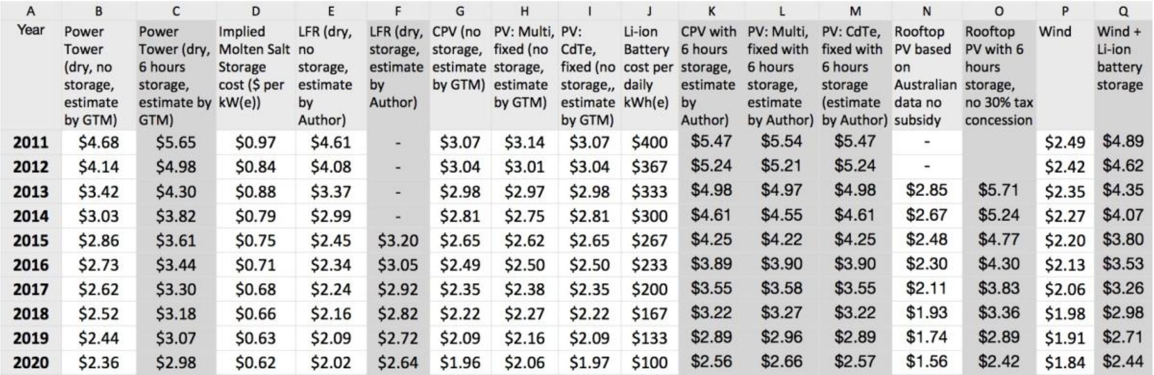
5. The Competition

Since 2010 there has been a spectacular drop in PV prices to residential and commercial consumers, particularly in Germany where large ground mounted arrays are being installed for about $2280 per kWh(e) and Australia, where prices of installed systems are close to $2850 per kW(e). Wind generation is now below fossil fuel generation in many areas. Both are still dropping in cost quickly [18].

Various sources suggest EVs now have battery wholesale costs of $400 per kWh(e) [19, 20]. Elon Musk, the CEO of Tesla Motors (battery electric vehicles) says that "in the battery costs should be about $200 per kWh(e). This can be taken seriously because Tesla has industry-leading experience in battery systems and already sells PV house storage units to the SolarCity PV leasing company. Although twice the storage cost of the advanced molten salt projects, the timeline for Li commercialisation is similar. What does this mean for the prospects of Francia's concepts?

A relatively recent look at forward renewable electricity costs is provided by the GTM company [18], which includes not only numerous solar technologies but wind and combined cycle gas. In Table 1, the author has chosen a few favourable cases (white columns) from the GTM report including utility PT, Wind, CPV, Flat Multicrystalline PV, and Thin Film PV. The author then introduced a non-storage current technology LFR in Column E by using other included GTM cost data (apparently for the Areva LFR) which was very close to the non-storage PT (13.7 cents per kWh vs 13.9 cents respectively), and cost is assumed proportional the PT until 2015 when the LFR begins to use high temperature vacuum insulated absorber tubes that improve thermal efficiency using a 550°C output temperature instead of 480°C.

Table 1. This table includes the GTM non-storage cases for a dry-cooled PT, CPV, utility multicrystalline PV, utility Cadmium Telluride thin film PV and an introduced column for a non-storage LFR. Calculations of the equivalent technologies with storage are presented in the dark columns. By 2020 most technologies are close in cost, lying between $2.44 ppW and $2.98 ppW. All the storage units assumed are 6 hours at maximum output.



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Year	Power Tower (dry, no storage, estimate by GTM)	Power Tower (dry, 6 hours storage, estimate by GTM)	Implied Molten Salt Storage cost ($ per kW(e))	LFR (dry, no storage, estimate by Author)	LFR (dry, storage, estimate by Author)	CPV (no storage, estimate by GTM)	PV: Multi, fixed (no storage, estimate by GTM)	PV: CdTe, fixed (no storage,, estimate by GTM)	Li-ion Battery cost per daily kWh(e)	CPV with 6 hours storage, estimate by Author)	PV: Multi, fixed with 6 hours storage, estimate by Author)	PV: CdTe, fixed with 6 hours storage (estimate by Author)	Rooftop PV based on Australian data no subsidy	Rooftop PV with 6 hours storage, no 30% tax concession	Wind	Wind + Li-ion battery storage
2011	$4.68	$5.65	$0.97	$4.61	-	$3.07	$3.14	$3.07	$400	$5.47	$5.54	$5.47	-		$2.49	$4.89
2012	$4.14	$4.98	$0.84	$4.08	-	$3.04	$3.01	$3.04	$367	$5.24	$5.21	$5.24	-		$2.42	$4.62
2013	$3.42	$4.30	$0.88	$3.37	-	$2.98	$2.97	$2.98	$333	$4.98	$4.97	$4.98	$2.85	$5.71	$2.35	$4.35
2014	$3.03	$3.82	$0.79	$2.99	-	$2.81	$2.75	$2.81	$300	$4.61	$4.55	$4.61	$2.67	$5.24	$2.27	$4.07
2015	$2.86	$3.61	$0.75	$2.45	$3.20	$2.65	$2.62	$2.65	$267	$4.25	$4.22	$4.25	$2.48	$4.77	$2.20	$3.80
2016	$2.73	$3.44	$0.71	$2.34	$3.05	$2.49	$2.50	$2.50	$233	$3.89	$3.90	$3.90	$2.30	$4.30	$2.13	$3.53
2017	$2.62	$3.30	$0.68	$2.24	$2.92	$2.35	$2.38	$2.35	$200	$3.55	$3.58	$3.55	$2.11	$3.83	$2.06	$3.26
2018	$2.52	$3.18	$0.66	$2.16	$2.82	$2.22	$2.27	$2.22	$167	$3.22	$3.27	$3.22	$1.93	$3.36	$1.98	$2.98
2019	$2.44	$3.07	$0.63	$2.09	$2.72	$2.09	$2.16	$2.09	$133	$2.89	$2.96	$2.89	$1.74	$2.89	$1.91	$2.71
2020	$2.36	$2.98	$0.62	$2.02	$2.64	$1.96	$2.06	$1.97	$100	$2.56	$2.66	$2.57	$1.56	$2.42	$1.84	$2.44

In Table 1; the darker columns include the equivalent technologies with storage. Thermal storage cost (column D) is obtained by taking the difference between the non-storage and storage peak watt costs for the PTs in columns B and C. The capacity factor for the storage PT is given by GTM as 43%, suggesting 6 hours of storage [19] and 6 hours is therefore also used for the storage cases using Li-ion batteries. The LFRs and PT's are assumed to use similar storage technology.

The GTM report concludes that the utility grade PT with storage is a better investment than PV without storage even though the capital cost is higher. There are two deficiencies in this argument however:

- The potential PV cost drop for 2013 has been seriously underestimated in the report according to recent German and Australian data, especially Australian rooftop PV data [20].

The utility PV cases use the GTM data applicable to the USA which are slightly above $3ppW but can be regarded as behind the curve given the achieved value of $2.25 for large ground-mounted arrays in Germany. Importantly, Table 1 includes estimates for rooftop mounted PV for both storage and non-storage cases. These data in Column N came from the Australian rooftop PV program, the largest in the world, where many installation efficiency gains have been realised [20]. It differs by lacking the 30% Tax credit in the US market. Nevertheless, the suggested costs drop from US$2.85ppW in 2011 to US$1.56ppW by 2020 because these have already been achieved in the Australian market; the $2.85 figure is the average Australian installation cost in 2013 and $1.56 is the *lowest* current cost - probably achievable as an *average* cost by 2020. The reference [20] claims that unlike Germany and the USA, where much larger ground mounted arrays are the norm, the Australian market is mostly rooftop and residential. Australian PV installers now see smaller residential systems as an advantage rather than an obstacle to be overcome: "The small system sizes allow for more standardised approaches, enabling installers to complete jobs more quickly and efficiently, resulting in a learning curve that Germany and other countries were only able to attain at much higher installed PV capacities."

- Battery storage drops for Wind and PV have not been included in forward estimates.

Information from various sources [21, 22] suggests that current Li-ion battery storage is currently $400 per kWh and Elon Musk, CEO of the Tesla Motors electric car company, a leader in the field, says may be $200 'in the not too distant future' [23] which many interpret as mid-decade. In Table 1 the assumption used is a linear reduction from $400 per kWh(e) in 2011 to $100 by 2020, which yields $191 by 2018, in approximate agreement with Musk's statement. While such price drops might seem faster than previous battery cost reductions, there has been much accelerated activity in battery research recently due to electric vehicle requirements. In particular, there has been a very significant breakthrough in the stability of highly conductive silicon anodes by Northwestern University, using easily-produced graphene to protect the anodes from degradation [24, 25]. The researchers claim silicon anodes should allow 10 times the charge density in otherwise conventional Li-ion batteries and 10 times faster charging [26]. The author has chosen 2020 somewhat arbitrarily as the "when" for $100 storage because the Northwestern University silicon anode upgrade can be implemented relatively easily since "the aerosol synthesis can be operated in a continuous mode at large scale and does not involve extensive engineering of Si nanoparticles". The $100 figure is therefore possibly conservative; $40 may be ultimately expected from the Northwestern University development for the battery alone, although the reduction in associated control electronics and installation may be less dramatic.

In thermal storage, advanced developments also suggest a reduction to $37.5 per kW(e) is possible, probably after 2020 [27]. The 2020 figure used in Table 1 is less optimistic at $60. There appears to be some convergence between thermal and battery storage on cost, but there are many other battery research programs and the battery approach may ultimately show the greatest cost reduction potential. For example, recent announcements from the U. of Illinois [28] speak of 2000 times the charge density of conventional batteries using a more radical redesign. Should this ever be commercialised, molten salt storage would be surely finished.

6. Results of Analysis

According to GTM, a current Power Tower with molten salt storage currently yields twice the return to a utility than the cheapest large field PV with no storage even though its current peak watt cost is higher. This is because such a plant can preferentially generate during high earning peak power periods. But Table 1 shows a much more closely matched ppW cost by 2020 if all technologies use low cost energy storage. It is true that the cost per kWh(e) will be somewhat affected by the original non-storage system capacity factor, but to a lesser degree because all systems with storage will prioritise earning throughout peak periods, and any remaining stored electricity will be used during low earning off-peak periods.

Certain situations stand out:

- Rooftop PV offsets retail cost, so with 6 hours of storage at an installed system cost of $2.42 per peak watt is likely to be unbeatable by central grid technologies in good solar climates. Thousands of high production small size installations like Australian rooftop PV are already lower in peak wattt cost than utility scale PV and STE, in spite of their lacking a 30% US tax credit assumed for the other central grid technologies in Table 1. Any electricity usage able to be offset by rooftop PV is thus likely be largely closed to LFRs and PTs and the other technologies in Table 1 unless buildings have small roofs (apartments) or are shaded. “Rooftop” in this case would also include PV on a local ground area very close to the usage point.

- Table 1 capital and maintenance costs are not LCOE figures and so do not account for weather. In windy or cloudy climates, wind generators with storage would prevail over PV and solar thermal.

- The majority of transport in most modern countries is composed of private cars. Using plug-in technology, much of the power for private vehicles can come from adjacent building roofs. Battery buses and trucks are also under development, but these would likely use the grid-based infrastructure. The commercial sector often has large roof sites. Much of the vehicle market could become a primary market of rooftop PV.

- The most likely future electricity markets for grid-based LFRs and PTs are industry and public transport, plus buildings that cannot produce their own power.

Clearly the option exists of having several flexible technologies - LFR, PT, Rooftop PV, large field fixed PV, Tracking CPV and Wind in addition to traditional hydro long term storage. So is Francia’s vision a relevant part of that future?

Francia’s concepts will find it very difficult to compete against rooftop PV if the PV has low cost storage. However, survival against grid-based PV and wind is also going to be difficult in a few years; the key will be the relative cost of thermal and electrical storage.

Even if LFR's and PTs with thermal storage were the same ppW cost as rooftop PV using low cost battery storage, a vast web of smaller and much simpler rooftop PV plants controlled by building owners may be more practical and socially advantageous, providing local employment near cities and requiring a smaller residual distribution network.

6. Conclusion

Francia's vision was very powerful and his LFR and Power Tower concepts are beginning to gain the ascendancy in the area of solar thermal power. Indeed, if LFR and PT technologies were the only environmental choice, replacement of fossil fuelled electricity could still be done at a cost cheaper than new coal.

Yet Francia seems not to have included wind, a strong competitor to STE in large scale projects. The great drop we have seen in PV and CPV prices in just a few years would have also been beyond his imagination. Francia's vision of integration of LFR plants in city landscapes was bold, but the integration of solar inside a city appears much more practical and elegant with PV. Aided by modern heat pump technology, much of the annual heating and cooling can be PV rooftop-powered. EVs can be powered by embedded PV integrated into parking lots, above railways and highways, and into building facades in a way Francia's technologies cannot.

What ultimately happens in the electricity market will depend upon one component that was not developed by Francia - storage. Storage is definitely becoming standard for solar thermal power plants and will soon become so for PV systems. But the success of the LFR/PT scenario will only remain so long as advanced thermal storage remains significantly cheaper than batteries for PV and wind.

The alternative scenario is also possible. In this scenario, Francia's technologies take over a important transitional role as large scale grid generators until batteries become low enough in cost so that both PV and wind can offer flexibility at a lower cost. However, LFR PT technologies may also be permanently useful in high temperature industrial process heat supply as no energy conversion from heat to electricity is required.

The market will make its own economic decision within a few years; it is not an environmental question because the technologies in question all have low emissions. But whether his solar ideas endure or not, Francia was a giant among solar researchers and had in his heart the noblest of aspirations for his work. It has been very important for solar researchers to develop as many options as possible, and we are beginning to see an extraordinary result where there are now many paths to a solar future, all of them comparable to, or below, fossil fuel in capital cost.

Francia's own solar concepts are currently highly competitive. Just that alone would a salutary achievement for a 1960s university professor, but to have contributed significant technology to many fields is remarkable.

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