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The Partanna Project: A First of a Kind Plant Based on Molten Salts in LFR Collectors

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Abstract. Molten Salts are nowadays the preferred choice to store thermal energy in CSP plants, either using MS Power Towers and "direct" storage or using parabolic troughs with MS "indirect" storage, employing thermal oil as Heat Transfer Fluid in the solar field. The use of Molten Salts as Heat Transfer Fluid with "direct" storage in linear parabolic troughs has been proposed and studied since 2000. Starting in 2001, ENEA fully developed such concept in its "Solar Thermodynamic" project. Such effort led to the construction of full size 100 m. test plant in 2003 at the ENEA Test Field, and to a 5 MW demonstrative unit by the Italian Utility ENEL (Archimede) commissioned in 2010. As the Linear Fresnel technology became more mature, also such type of solar collector begun to be studied to adopt molten salts as HTF. The Italian company Sol.In.Par, specialized in renewable energy plants, recently decided to adopt the Fresnel technology with Molten Salts both as Heat Transfer Fluid and storage Medium for the development of a new power plant in Partanna (Sicily), that comprises a 5.6 MW_e Photovoltaic section and a 4.26 MW_e CSP section. Since no plants of this type are actually in operation, such plant will be therefore a First Of a Kind of such concept. The paper describes the design and operative main data, presently in the construction phase and expected to be commissioned not later than spring 2020.

INTRODUCTION

The use of Molten Salts (MS) as Heat Storage Fluid is nowadays the most common choice in CSP plants for electricity production (see e.g. the SolarPACES database [1]).

Molten salt, State-of-the-art designs are based on two main concepts:

- **"Direct Storage"**, with Central Receiver Heliostat Field (Power Tower); MS is either the Heat Transfer Fluid (HTF) of the Central Receiver and Storage Fluid in a Two Tanks based Thermal Energy Storage (TES). Such concept was prototyped in Solar Two ([2]) and recently adopted in commercial units, see e.g. in Masen Noor III plant in Ouarzazate ([3]).
- **"Indirect Storage"**, with Parabolic Trough (PT) Solar Field using oil as HTF and MS Two Tank TES. The concept was at first introduced in AndaSol plants ([4]) and is now frequently adopted in commercial units, e.g. in Masen Noor I and Noor II plants in Ouarzazate. The TES and the solar field are coupled by an oil/MS Heat Exchanger, in this case. This fact increases complexity, reduces maximum steam temperature and production flexibility, and increase the physical size/upfront cost of the TES if compared to "direct storage", but allows to avoid the technical challenge of managing molten salts (solid at normal ambient temperature) in long piping networks as is the case of linear systems.

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The advantages of linear systems at some extent and in some environments (e.g. with high level of aerosol and/or environmental constraints) led to the effort of using MS direct storage also in linear collectors, either PTs or Linear Fresnel Receivers (LFR).

Starting in 2001, ENEA fully developed such concept by its "Solar Thermodynamic" project. Such effort led to the development of linear receivers able to operate in molten salt service at temperatures up to 550 °C, the construction of a full size 100 m. PT test plant in 2003, and to a 5 MW demonstrative unit by the Italian Utility ENEL (Archimede [5], [6], [7]) commissioned in 2010; unfortunately, ENEL effort did not lead to a commercial exploitation. Other efforts comprise a number of studies and proposals, mainly in the U.S. and in Germany (see e.g. [8]). As the Linear Fresnel technology became more mature, also such type of linear system became to be studied to adopt molten salts as HTF (see e.g. [9]). The company FRENELL (previously Novatec), specialized in LFR technology, decided to actively develop such option, testing it in a demonstration test plant at PE1 power plant in Spain [10].

After the decision to address the CSP market in Italy, in 2017 the Italian company Sol.In.Par, specialized in renewable energy plants, decided to adopt the Fresnel the MS-LFR technology for the development of a new plant in Partanna (Sicily), that comprises a 5.6 MWe Photovoltaic section and a 4.26 MWe CSP section. The design of such plant is the main object of the present paper.

Technical Issue to Face

The main technical issues to face in order to develop direct MS in linear systems at the time of first R&D efforts (early 2000) were:

1. The development of linear receivers able to efficiently and reliably operate in molten salt service at temperatures up to 550 °C
2. The design of devices and procedures to operate long piping networks in molten salt service (mostly the receivers lines themselves). Among these, special freeze protection devices are needed for receiver lines, while conventional electric heat trace equipment must be adopted for all piping and components into which molten salts circulates.
3. The demonstration that parasitic losses due to molten salt operation when the DNI is not present are not dramatic in terms of operation and additional fuel or electricity consumption.

While the first issue was practically solved with the explicit development, promoted by the early phase of ENEA project, of molten salts receivers (marketed by ASE since 2010 [11], now offered also by other manufacturers), the second was demonstrated at pilot plant scale ([7], [10]), the third is a matter of receivers efficiency at low temperature and DNI pattern; the more the DNI pattern is uniform along the year, the less the impact of parasitic losses on the need of additional heating (e.g. by gas heaters) during low DNI periods.

While the effect of parasitic losses on plant's yearly output can be better evaluated by accurate simulation, the demonstration of the operation in the real field must necessarily come from real experience at a significant scale.

Motivation of MS-LFR in the Italian Context

Average DNI in the Italian sites with the highest irradiation is in the order of 1900-2000 kWh/m^2 year, requiring public incentives to make possible to access to the electric market. Available land parcels are limited in size, the larger ones (able to host up to 50 MW size plants) often encountering difficulties due to environmental and authorization constraints. As a consequence, only projects in the category "up to 5 MWe" were able to fulfill the authorization process and to reach bankability in due time.

In addition, the Italian Feed-In-Tariff scheme does not allow the use of potentially polluting Heat Transfer Fluids – like mineral or synthetic oils – outside of industrial areas, while the use of "Solar Salts" is allowed. Further constraints come from the requirement, often imposed by the local regulations, to have a very low impact in terms of foundations.

In the Italian context, the Molten Salt Linear Fresnel Reflector (MS-LFR) technology offers the following advantages:

- Low environmental impact in terms foundations and visual footprint (with respect to e.g. Solar Tower) with better position in terms of public acceptance
- Simple and lightweight solar field structure, easily adaptable to the natural topography of available sites

In addition, previous operational experience with linear molten salt prototypes ([7], [10]), showed that molten salt management in LFRs promises to be easier and more reliable than in the case of PTs, due to the possibility to significantly reduce or even avoid at all the presence of flexible hoses in the solar field piping, since the receiver line is in fixed position; this fact has a positive impact in the management of the solar field in molten salt service.

PLANT DESCRIPTION

As mentioned, the renewable energy plant in Partanna comprises a flat plate photovoltaic section, sized at 5.6 MWe and a CSP section sized at 4.26 MWe. The electrical production from CSP units in Italy is subsidized by Law (art. 9 of Ministerial Decree of 23 June 2016) for a limited amount of plants admitted to the subsidy scheme. The feed-in tariff applied is up to 311 €/MWh. The Partanna project is one of the winners and beneficiary of the subsidy scheme. The solar field sizing has been therefore focused to the maximum energy production in the available area. A further constraint being the allowed maximum power authorized for the CSP unit Power Block, the resulting solar field is quite large (83,200 m2 of total active surface) with a Solar multiple in the order of 3. The Two Tanks Thermal Energy Storage is sized at 15 hours equivalent at full load production. The orientation is 26° NW, while the terrain slope (roughly 2°) is in South direction. In the picture (fig. 1) the whole plant's area is shown, with the LFR area in the center, the Power Block and the Storage Tanks in the North side and the three PV sections (in gray) filling the remaining available land parcel's area. The expected yearly DNI is not very high, in the order of 1800 kWh/m^{2}y.

FIGURE 1. Planimetry of the plant

The plant is realized by FATA EPC, part of Danieli group; ENEA acts as technical advisor on the most peculiar aspects related to solar energy and molten salt management.

Basic Plant Scheme

The basic plant's scheme in shown in fig. 2. The HTF/Storage fluid is binary "Solar salt" (60% NaNO3 / 40% KNO_3). The Solar Field (SF) is directly connecting the "Cold Tank" - operated at Nominal Temperature of 290 °C – to the "Hot Tank" - operated at Nominal Temperature of 545 °C. Such temperature is chosen according to a techno-economic assessment performed by the EPC, according to technical limits of the receivers and previous theoretical evaluations performed by FRENELL in view of commercial exploitation of the MS-LFR concept ([13]).

When DNI is sufficient, MS is pumped from the Cold Tank to the Hot Tank, therefore storing solar energy. Also the Steam Generator is directly connected to the two Tanks; when electricity production is needed, the available MS is pumped from the Hot Tank to the Cold Tank through the Steam Generator, implementing the electric production cycle. Store and Production cycles can be managed independently, provided the Tank levels be within limits, yielding the maximum flexibility. An additional device is the Gas Fired Molten Salt Heater, added to maintain the MS in liquid form during prolonged periods of DNI absence or in case of technical unavailability of the Solar Field. The Italian feed-in Law allows for a maximum annual fraction of energy coming from fossil fuels equal 15% of the whole annual thermal energy generation of the plant, therefore the Gas Heater can be used also to regularize the production during low DNI seasons, e.g. in Winter.

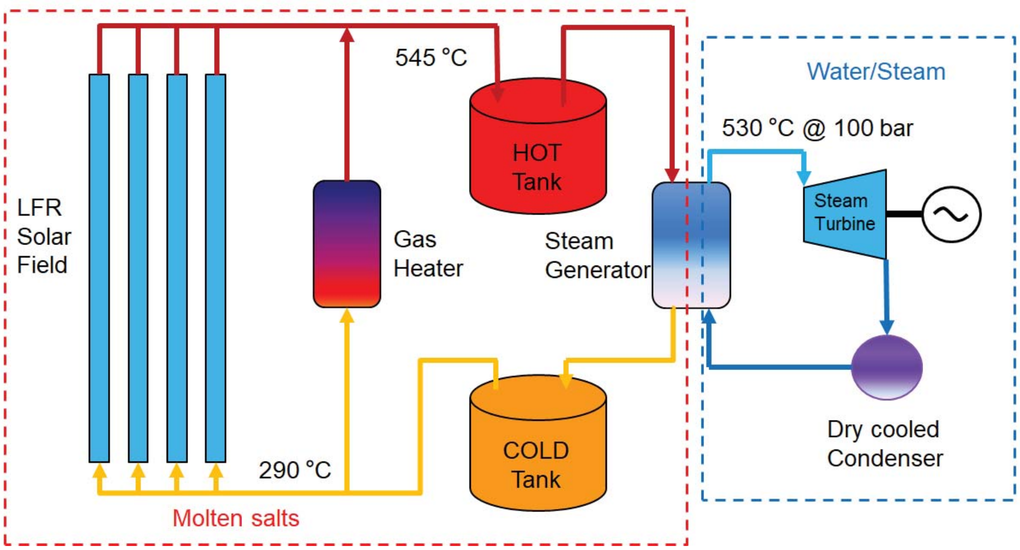


FIGURE 2. Basic scheme of the plant

Solar Field

The solar field is supplied by FRENELL. It is a special brand LFR solar field, designed for molten salt service. Such design implies that the receivers must be electrically insulated with respect to ground (see paragraph on Antifreeze System). It is organized into 9 loops, U-shaped, with inlet and outlet connected to two main headers. The length of each loop is 800 m., while the gross mirrors area of each loop is 400 m. long, 34 m. wide. In each loop 14 collectors in series are present, each with 16 mirrors lines. The absorbers are welded in series and surrounded by secondary reflectors; special provisions allow the thermal elongation of the two absorbers lines, independently from each other, without the use of flexible hoses. Each collector has its own PLC for mirrors tracking, with two drives per collector to perform the sun-tracking. To allow pre-heating and anti-freeze functionalities of the receivers lines by Joule effect, the absorbers lines are electrically insulated from the grounded holding structure.

Thermal Energy Storage (TES)

The Thermal Energy Storage is made with two cylindrical Tanks, Cold and Hot, with nominal operating temperature of 290 °C and 545 °C respectively. The flow through the Solar Field from Cold Tank to Hot Tank is assured by 3 MS pumps (two in operation, one reserve). The flow through the Steam Generator from Hot Tank to Cold Tank is assured by 2 MS pumps (one in operation, one reserve).

The dimensions of the Tanks are 12 m. of diameter by 10 m. of height, with a gross Capacity of 1000 m^3, yielding 180 MWh of Nominal Thermal Storage capacity, able to supply 15 h of equivalent hours of Storage.

Additional heaters in the bottom sides are provided for pre-heating and long term maintenance of salt in liquid form in case of long periods of unavailability of the Solar Field and of the Gas Heater.

Steam Generator and Power Block

The Steam Generator is a natural circulation unit, supplied by Lointek, Shell and Tube type, comprising three Heat Exchangers: Economizer, Evaporator and Superheater. The molten salts are in the shell side in the Economizer and Superheater, while they are in the tube side in the Kettle type, Evaporator. Heat tracing is provided in the Exchangers areas where molten salt is present; they are operated for pre-heating before SG filling or draining.

The Steam Turbine, supplied by Tosi, is condensing type, with reaction blades, 37 stages, 4 bleeds, 4.26 MW rated. Design data of steam at the Turbine inlet are 100 bar @ 530 °C. The turbine is very flexible; it can be put into operation from cold in less than 20 minutes, and can operate in a very high range of temperatures (down to 320 °C) and Power levels (down to 250 kW). The nominal gross efficiency of the thermal cycle is 35.36 %.

The electric generator, supplied by Nidec, is a 4 poles, 5 MVA, 6.3 KV synchronous generator with a rated efficiency of 98% at full load. The Condenser is air-cooled by air (dry-cooling type).

Gas Heater

A commercial 2 MW gas Heater, supplied by Sigma Thermal, is included in order to supply thermal power to the molten salts during long periods (days or more) of zero or insufficient DNI, referring to two typical situations:

- Maintain the molten salt temperature while circulating in the Solar Field, with limited amount of useful thermal energy remaining in the Cold Tank, as its temperature decrease below a safety limit
- Allow a more regular electric production during low DNI periods, within the limit of 15% of yearly fossil share allowed by the feed-in regulation, with respect to the Solar production.

The gas heater is fueled by Liquefied Natural Gas (LNG), due to the absence of a connection to the national gas pipeline network in the location of the plant. The LNG will be contained in a Tank, refueled by means of LNG trucks.

Antifreeze System

The Solar salt has a freezing point of 238 °C, therefore it must be kept in liquid form by means of thermal input; this is normally the DNI; additionally, the gas Heater can supply the required thermal input; finally, the “Anti-freeze” system, based on electrical devices, is present to cope with particular operative states.

At such purpose, all the pipes and components containing molten salt are thermally insulated and heat-traced or provided with additional heating. As will be described in the next section, Anti-freeze is normally not active during ordinary plant operation, but it is necessary to perform the following operations:

- Pre-heating before filling or re-filling the salt, or in case of maintenance draining
- Temperature keeping during maintenance or in case of faults, e.g. circulation failure, in order to avoid salt freezing
- Salt re-melting (thawing) after accidental freeze

Similarly, to previous experiences ([4], [5], [6], [9]) the Anti-freeze system is based upon two technologies:

- Conventional MgO insulated heat-trace cables are used for insulated piping and components like valves, molten salt instruments (Flow and Pressure measurements) and Heat Exchangers with molten salt in the shell.

- Joule effect heating is adopted to heat-up the absorbers lines, since in this case heat-trace by cables is not possible and also less effective.

Similarly, to what introduced in Archimede ([4], [5], [6]) and further tested in PE1 by FRENELL ([9]) the Joule heating is performed by means of direct injection of DC or AC current directly into the pipes, exploiting the steel electrical resistance to produce heat. In the case of Partanna, AC current injection is adopted, using a transformer as shown in fig. 3. The transformers used in Partanna will not be permanently installed in all the loops, as in Archimede ([4]), but will be based on three mobile systems to be positioned on the loop where is necessary to operate, e.g. in case of draining or thawing after an accidental freeze.

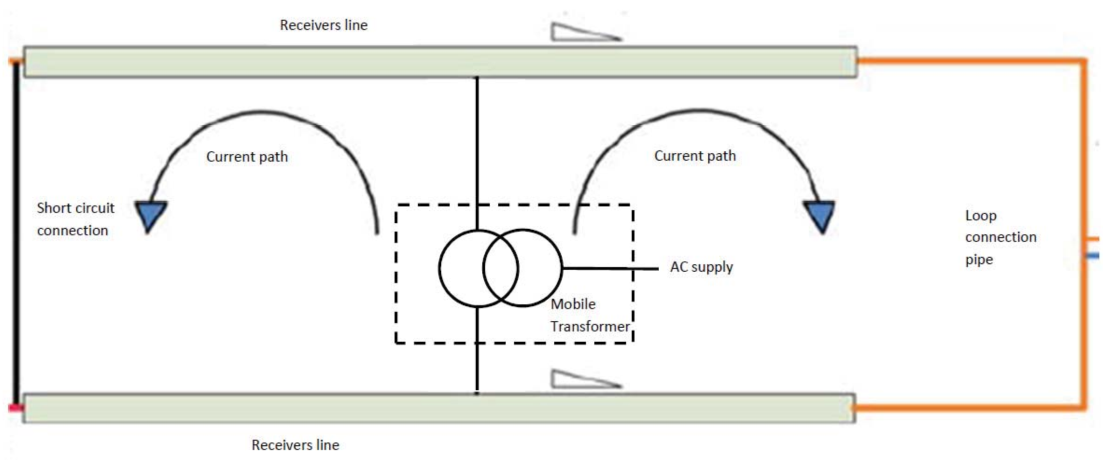


FIGURE 3. Scheme of Joule Heating for Partanna

The mobile transformer, with secondary connected to the center of the loop, will produce two current paths in the loop piping, comprising the two absorbers lines and the Loop connection pipe at the end of the loop, and closing the second path on the opposite side by means of a short circuit cable positioned at loop inlet.

For the purpose of Joule heating, the whole piping of the loop must be electrically insulated with respect to the holding structure, that is grounded to earth.

In order to allow not only pre-heating but also safe salt thawing in case of accidental freeze, the Anti-freeze system must be accurately designed and installed, coordinating insulation, instrumentation and heat-trace/Joule heating in detail,

PLANT OPERATION

Normal Operation

The basic operation of the plant involves two cycles, that can be performed independently:

- Solar charge: As DNI is sufficient, molten salt is pumped from the Cold Tank to the Hot tank, through the Solar Field, increasing the Stored thermal energy in the TES.
- Electricity production: depending on electric demand and/or energy content in the TES, molten salt is pumped from the Hot Tank to the Cold Tank through the Steam Generator, producing superheated steam for the Power cycle.

In addition, if the DNI is not sufficient to produce a salt output from the solar field with the required temperature (e.g. overnight or during cloudy periods) the salt from the Cold Tank is re-circulated through the solar field to the Cold Tank itself; in this case the enthalpy content of the Hot Tank is not reduced and the solar field is kept warm using the thermal energy stored in the Cold Tank.

In case the Cold Tank temperature decays below a safety limit, the gas fired heater will provide a thermal input to maintain the salt temperature within allowable limits, reasonably higher than the freezing limit (238 °C).

Plant Filling and Draining

Initial filling will be operated during commissioning; at first the molten salt charge will have to be melted and gradually introduced into the plant after plant's pre-heating, using either the gas heater and the Anti-freeze devices.

Plant's draining is possible either for single components or parts or for the whole plant, the latter not being a routine operation.

Normal routine draining will be performed, for maintenance purposes, either for the loops (e.g. to substitute damaged absorbers) or for other main components. Steam Generator and main piping can be drained into an auxiliary draining Tank, from which the salt will be sent back to the Cold Tank. Individual loop piping can be drained into mobile Tanks; due to the plant's lay-out, with the slope in the south direction, in the Partanna case such Tanks will be positioned in correspondence of the end of loop connection (South side).

To perform draining without problems (e.g. accidental freezing during draining) the correct piping slopes and provisions (draining and vacuum-breaker valves, insulations and heat-trace) must be accurately designed.

Anti-freeze Procedures

Given the extension of piping involved with molten salt, Anti-freeze procedures, coordinated with the Anti-freeze equipment, are very important to operate a MS-LFR or a MS-PT plant.

The main concept is that the best anti-freeze strategy, apart a good thermal insulation, is to assure molten salt circulation with high reliability. Circulation assures that even in case a quite long part of piping be at low temperature (below freezing point) freezing will not occur. In case of no-circulation for a long period, an anti-freeze device must be present in the involved parts of circuit or components to prevent freezing.

Before filling and draining, the lines should be pre-heated and maintained sufficiently warm (290 °C). This applies to commissioning and routine maintenance, not to normal operation.

During normal operation overnight or in cloudy periods, the salt is circulated in the solar field exploiting the energy content of the Cold Tank. This is sufficient in normal situations (e.g. overnight or few days of solar scarcity). In order to assure circulation, 3 pumps are installed in the Cold Tank; one is sufficient to circulate the salt at zero or low DNI. Power for Supervision and control is supplied by UPS. A Diesel Gen set is installed, able to supply power to main auxiliaries (e.g. circulation pumps, valves, main heat trace) in case of grid failure.

In case the Cold Tank temperature decrease below acceptable limits, the gas fired Heater will provide back-up heat for a longer time. In case of prolonged DNI absence and Heater failure, the heat trace will assure that the main piping and component will not freeze. In some situations, the main piping should better be drained; when stored in the Tanks, the salt can be maintained in liquid form for a long time, just by the internal electric heaters.

In case of severe faults, the solar field can be drained to the Loop drainage Tanks without the use of the heating transformer, just by gravity since the slope is quite high (4% slope).

Since freezing accidents due to unpredictable and multiple failures (e.g. loss of circulation AND power supply for a long time) cannot be excluded, the plant, in particular the solar loops, is designed to recover in acceptable time.

For such purpose, the anti-freeze equipment is designed in order to be able to thaw the frozen salt without damage (the salt expands during melting) in all the involved parts. A number of details are involved.

EXPECTED PRODUCTION AND PARASITIC LOSSES

The Partanna site is not characterized by a very high annual DNI, in the order of 1800 kWh/m^2y with a high seasonal pattern. This is illustrated in fig. 4, where the average daily DNI level from SolarGIS and the expected monthly thermal energy to the Power Block (a) and monthly gross electric energy production (b) are calculated for each month. The available DNI expected in December is 35% of the maximum level in July; since winter incidence angles are also higher in winter, the expected electrical production in December is expected as less than 7% of the production in July.

The average Load factor increases from 8% in December to 92.1% in July (fig. 5 (a)); due to the large solar multiple, even with a 15 hr storage, a significant fraction of available thermal energy will have to be dumped (defocusing the solar field) during summer (fig. 5 (b)).

Finally, in fig. 6 the average daily working hours of the gas fired heater (a) and net electric production compared to auxiliaries consumption (b) are shown.

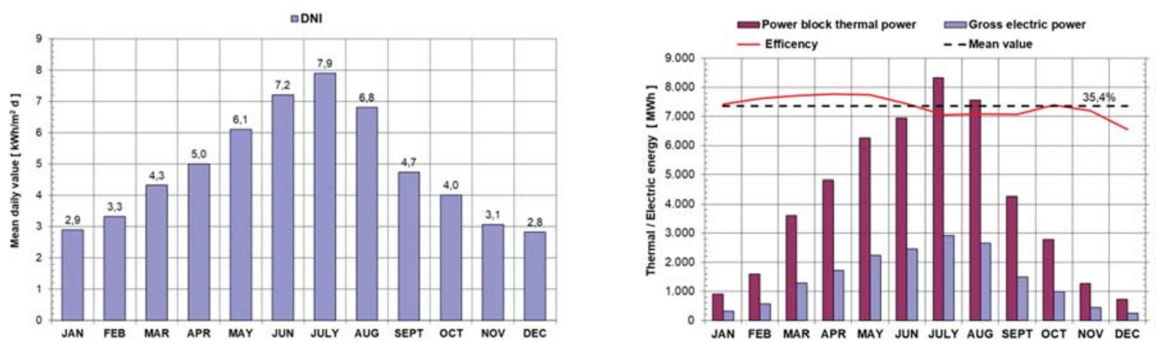
Gas heater will be quite intensely operated during winter, in order to maintain the correct temperature in the Cold Tank to compensate for thermal losses due to molten salt circulation in the solar field with zero or low DNI.

Nonetheless, the thermal input from gas is only 20% of total thermal losses, and the calculated gas consumption to compensate thermal losses is in the order of 2 % of the thermal energy produced by the solar field (945 MWh with respect to 49810 MWh of expected net thermal output), well below the 15% limit.

In principle, it will be possible to increase the net electrical production by 17% (from the calculated 15,155 MWh_e to 17,446 MWh_e) just exploiting the gas input up to 15% limit.

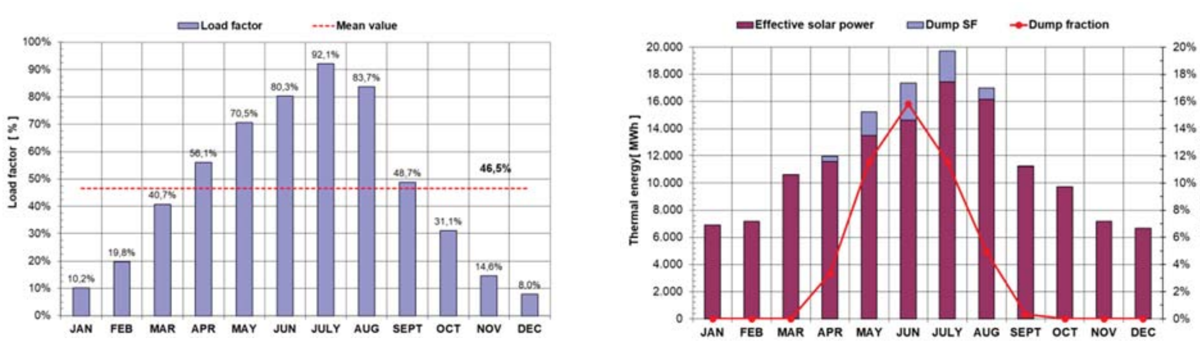
The calculated quote of auxiliaries consumption over net electrical production is high in winter (fig. 6 (b)), since the auxiliaries consumption is less influenced by the seasonal pattern.

All these figure should be more favourable in sites with higher DNI and less pronounced seasonal pattern.



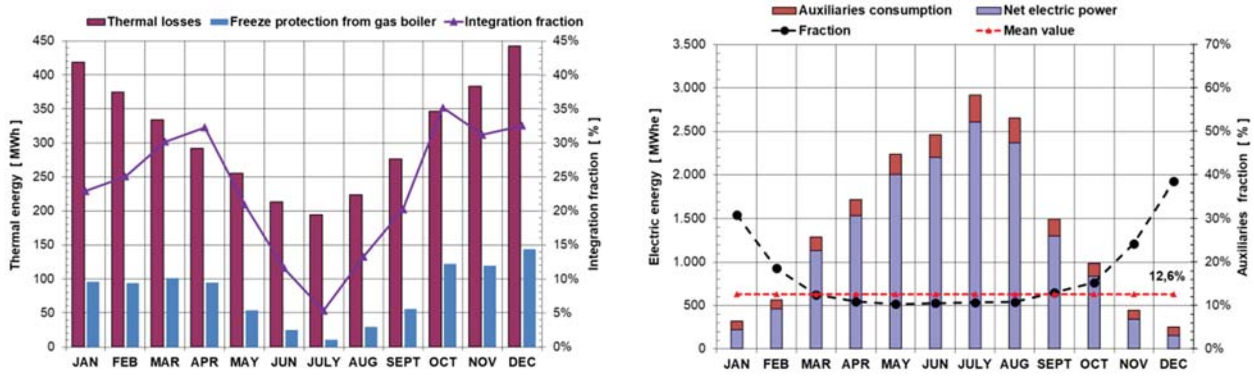
(a) (b)

FIGURE 4. (a): average daily DNI (kWh/m^2 day) expected from SolarGIS data (b): calculated monthly thermal energy input to Power Block and electricity production (MWh/month)



(a) (b)

FIGURE 5. (a): average Load Factor by month (b): Thermal Power from solar field and Dump fraction

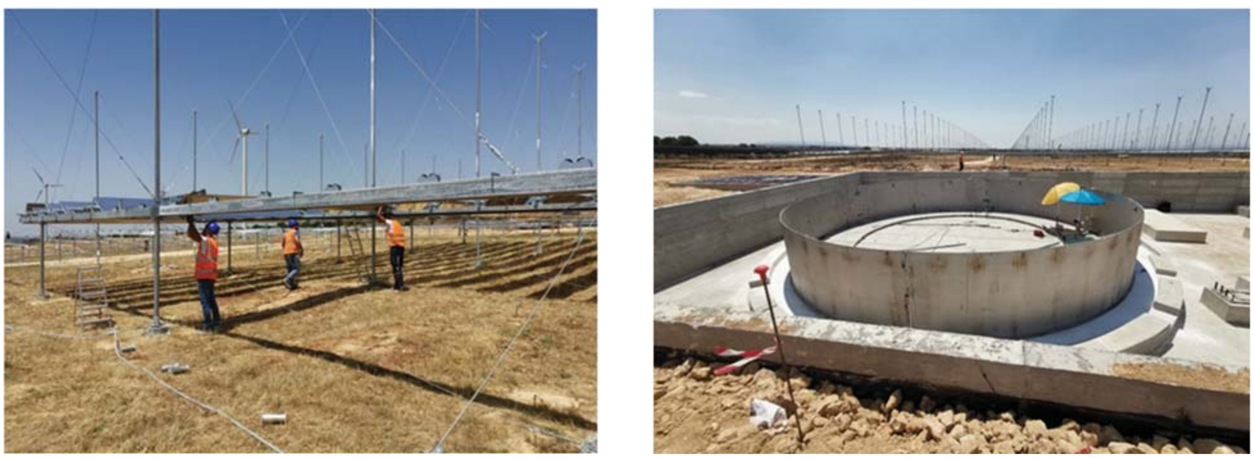


(a) (b)

FIGURE 6. (a): Thermal losses and contribute to freeze protection by gas fired heater, by month (b): net monthly electric energy and auxiliaries consumption and monthly fraction, by month.

PLANT STATUS

The plant is actually in the construction phase. Most of the equipment is yet installed or purchased. The main detailed design has been finalized. Two pictures show the building site, as of late spring 2019, fig. 7.



(a) (b)

FIGURE 7. Pictures of plant's installation, late spring 2019. (a): mounting the mirrors in the solar field structure. (b) fabrication of the Tanks; on the back, the absorbers supporting poles are visible.

The plant is expected to begin commissioning not later than Spring 2020.

UPGRADING THE CONCEPT

Similar projects are currently in development in Sicily and efforts are underway to complete the permission path. This line of plants is developed in a fully "commercial" environment, even if subsidized by the state. In order to be competitive in non-subsidized markets, the specific CAPEX must be reduced. For such purpose, it is probably necessary to increase the unit size. While the solar field specific cost is not expected to decrease, all other costs, namely the Power Block, enginering and permitting upfront costs are expecting to decrease significantly in specific terms for larger units. Considering an analysis of the LCoE (Levelised Cost of Energy) versus the Plant rated power of a MS-LFR plant, the LCOE is expected to be halved increasing the plant rated size from 5 MW to 50 MW and furtherly decrease up to a minimum LCOE expected around a rated plant size of 100 MW ([12, [13]). According to the company FrenellLCoE of this type of plants is expected to keep a constant value for rated power sizes larger than 100 MW ([13]).

CONCLUSIONS

The Partanna plant is a First Of A Kind of the MS-LFR concept; hopefully it will demonstrate the commercial maturity of this technology and allow Linear Fresnel technology to play a major role in the CSP market, expecially in situations where Power Towers cannot be applied or where available space is limited.

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