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Department of Planning and Environment
Division of Resources and Geoscience

Coal Innovation NSW Fund

Final Report

Project: RDE493-32
300-200MW ultra supercritical hybrid solar/coal R&D pathway study

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Acknowledgement and Disclaimer

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Executive Summary

The main goal of the project was to implement a development pathway for Ultra Super Critical (USC) Solar/coal plants.

The feasibility study for the Hybrid Solar/Coal plant was conducted with the aim to show that coal can remain an integral part of the future energy mix and that it can be competitive in the rapidly changing low emission market, where a large focus in the future is on dispatchable generation. The methodology and scope for this study were broken down into three Horizons, which are Horizon 1, 2 and 3.

Horizon 1 scope was defined to utilize the current commercially available technologies with an initial fixed percentage for the renewable share and defining the steam cycle according to the limitation of the known technologies. By doing this, the study of the integration would not rely on undeveloped, unstable technologies or unachievable pressures and temperatures.

Horizon 2 was defined as to improve the overall cycle efficiency by increasing the temperature of the steam on the renewable side of the cycle to better match the boiler conditions. It was also intended to increase the renewable share by a range of design alternatives and reviewing the energy storage limitation.

Horizon 3 was defined with the ultimate intention to drive the CO_2 emissions to zero by combining a CO_2 capture system to the horizon 2 configuration and further evaluating the economic impact of such addition.

The unit location was selected to be Hunter Valley region in NSW since there is already coalmines and transmission systems for the existing thermal power stations. Ambient weather conditions have been obtained from the Meteonorm database for a typical meteorological year. Hunter Valley domestic thermal coal has been used for this study.

The solar/coal hybrid plant operational principle in the study was proposed considering the general boiler operational characteristics regarding the main steam pressure and Steam Turbine Generator (STG) load control. During this study however, it was found that the operation where steam flow equivalent to 200MW or more coming from the boiler; is the only case in which a parallel operation can be accepted since the main steam pressure can be held constant and match the Concentrated Solar Power (CSP) system pressure regardless of the amount of steam flow rate coming from the CSP. Controlling the boiler steam pressure freely regardless of the steam flow going into the High Pressure turbine is not practical for a supercritical boiler under the current commercialized technology and it was not evaluated during the study. The CSP Power plant has been designed and optimized according to the restriction imposed by the USC Boiler of operating in parallel only at a minimum load of 200MW. Flexibility on the ramping and pressure control was not evaluated on the study however, it was noted that having such flexibility on the CSP side will ease the boiler restriction and will allow an increase in the power generated from the solar plant, leading to an increase in the plant renewable share overall enabling more options that are commercial. It is expected that this can be covered if there were a further study to examine the control methodology effectively relaxing the current restriction.

During the study, a unique conceptual plant flow diagram was proposed as to fit the configuration of the plant. One of the important features of the plant process flow is that it has two non-identical HP FWH trains with two non-identical SFPs since the pressure and flow for the coal side and CSP side need to be managed independently. The conceptual plant control logic was also proposed for the following three operational modes:

- Boiler Only Operation Mode,
- Hybrid Solar/Coal Operation Mode, and
- Boiler plus PV Operation Mode.

The boiler and steam turbine are designed considering the boiler only mode operation at rated load. It is important to mention that even though the operational range for the steam turbine and feedwater system would be different from a conventional coal-fired plant due to the mixture of steam coming from the CSP, there is no need for any special design philosophy or specification for the boiler and the steam cycle from the mechanical design point view.

The number of Heliostats, Thermal Energy Storage (TES) capacity, solar receiver capacity and PV capacity was optimised through a parametric study. The optimization was done based on the design features set for Horizon 1 but the difference that could be obtained for Horizon 2 and 3 was deemed not significant because the capacity of the main equipment was not changed across the Horizons and the operational restrictions remained.

The operational profiles for the conditions of a typical day were proposed. Based on these operational profiles and conditions, the renewable share could reach almost 50% on a clear summer day. It could also be more than 40% even in a clear equinox day. In an average annual climate condition, it is estimated to be around 29% on average. According to the high-level research performed in the study it could be concluded that this plant can reduce the coal fuel requirement by around 30% which means that it would reduce CO2 emissions by approximately 30% compared to a conventional coal-fired plant with the same capacity. However, this number may vary between plus or minus 5% depending on the frequency of low-efficiency operation such as the minimum load operation and the ramp-up speed. For the horizons, renewable share comparison is important to notice that even though there is an increased steam temperature for Horizon 2 and 3, the ratio between renewable share and boiler share did not changed.

Table Power Generation Share

An average day	Renewable share	Boiler share
Horizon 1	29.28%	70.72%
Horizon 2&3	30.10%	69.90%

For Horizon 2 and 3, and according to what was proposed for the study it was analysed how to obtain a steam outlet temperature of 600ºC; it was then proposed to use an electrical steam booster heater (BH) charged from a dedicated Photovoltaic Panels (PV) through the Lithium-ion batteries that were added to the existing nitrate salts CSP tower. The advantages of this configuration to achieve higher temperatures against applying other salts like carbonates (with higher operating temperature) resides in the fact that nitrates are currently an available technology at a commercial scale as an Heat Transfer Fluid (HTF) and it would mean a faster implementation.

For this study, the PV for dispatch purposes and the PV for charging the batteries for the electrical steam Booster Heater are in a separate arrangement. However, it was found that a further improvement is possible if the PV's are configured as one system along with the batteries and by doing so the PV dumping can be minimized. Furthermore, with this approach it is possible to connect the batteries to not only the BH but also the grid. This configuration with the batteries being connected to the grid will greatly contribute to stabilizing the electrical output to the grid, especially in case of a sudden change in PV output due to a large abrupt change in the weather. This would be especially important if it is considered that the the boiler cannot follow the sudden PV output change in a short time due to its low ramp rate this limitation however, was studied when proposing the sizing of the PV system.

The plant general layout was refined and proposed for Horizon 2. All of the main equipment for the steam cycle and thermal storage cycle should be arranged in the centre circle. It is important to arrange the equipment so that the area of the centre circle can be minimized. A detailed layout study would be required in order to analyse the practical and optimized layout in the centre circle considering all of the equipment. The selection and layout of the steam exhaust cooling system could potentially pose a challenge for this power block. This system is highly dependent on the actual location condition where a power plant would be built on or hybridised. The coal yard location could be also another challenge because it takes a significant land space so it will conflict with minimizing the area of the centre circle. During the study, it was acknowledged that there are a significant number of areas where the project could be studied further.

As proposed in the funding deed and evaluated in the study the conventional air combustion boiler for Horizon 2 could be replaced by an oxyfuel combustion boiler for Horizon 3 with minor changes of the auxiliary system. There are no restrictions nor negative effects arising for the plant operation due to the change to the oxyfuel combustion boiler. The heating surface area of the boiler is the same as Horizon 2. The oxyfuel boiler is capable to operate in both air combustion mode and oxyfuel combustion mode. For Horizon 3, the plant net efficiency is lower than the one found for Horizon 2 due to the sizeable increased auxiliary power mainly from Air Separation Unit (ASU) and the CO_2 Compression and Purification Unit (CPU). The efficiency was estimated to decrease from 40.3% of Horizon 2 to 26.8% for Horizon 3. The auxiliary power consumption rate exceeds 38% for Horizon 3. Improving the plant net efficiency, utilizing “dumped” PV power to complement the auxiliary power is one of the ideas; however, it was not fully explored since it was not part of the main goal of the project. On this configuration option is important to consider that approximately 15% of annual PV power is dumped hence the merit for a significant improvement to the plant net efficiency if this “dumped” power is utilized in the plant to offset the auxiliary power.

Capital cost, Operation and Maintenance cost and Levelized Cost of Electricity were estimated for all Horizons and then compared with the conventional coal-fired plant, a standalone CSP plant and a standalone PV plant. Comparing the Horizon 1 and 2 and a general CSP plant, it was found that Horizon 1 and 2 have similar or better economic performance than a general CSP plant. The outcome of the economic study was unexpected since intuitively it would have been expected for the hybrid plant to be worse than a general CSP plant. The fact is different. The capital cost per kW and LCOE of Hybrid Solar/Coal plant can be lower than a CSP due to the increased kW capacity and high capacity factor. This result suggests that a new CSP plant can economically perform better if hybridized with a coal-fired boiler. Hybrid Solar/Coal plant not only has a better economic performance than a CSP it is also highly dispatchable which is a necessary feature for modern grids.

Lay Summary

Investment in an ultra-supercritical (USC) coal-fired plant is a challenge due to the politics around renewables and carbon-based generation. However, the ultra-supercritical coal-fired plant should still be considered since it provides a large generation with remarkable performance capable of providing inertia as well as stable baseload output to the grid. One of the possible ways that was investigated to still consider USC coal fired plants was to take advantage of other modern renewable technologies and explore the possibility of a hybridization in order to get a modern stable solution satisfying today's climate requirements with outstanding grid performance.

Therefore, the main goal of this project was to implement a development pathway for the Hybrid Solar/Coal plants. The hybrid/renewable component of the project was selected by considering the need of thermal energy storage as a key feature therefore for this project it was selected the concentrated solar power (CSP) and photovoltaics (PV) system. CSP plant consists of molten salts tower where by the usage of mirrors or heliostats is heated and then stored for future use to generate power. The PV's are a well-known renewable technology that offers the possibility to expand the renewable share and cover the shortcomings of a complex CSP operation.

As result of these aforementioned technologies, the project envisioned a "Hybrid Solar/Coal plant" as the combination of electrical generation from a conventional USC coal-fired boiler and a concentrated solar power (CSP) technology and photovoltaics (PV).

The feasibility study for the Hybrid Solar/Coal plant was conducted with the aim to show that coal can remain an integral part of the future energy mix and that it can be competitive in the rapidly changing low emission market where a large focus in the future is on dispatchable generation. The methodology for this study was broken down to three Horizons, which are Horizon 1, 2 and 3.

Horizon 1 was defined based on the commercially available technology. The main equipment specification, flow diagram and plant control logic were studied and the equipment capacity for CSP and PV were optimized. For Horizon 2 the aim was to increase the steam temperature from Horizon 1 in order to improve the plant efficiency. It was also included the study of using concept technology that is not considered widely commercially applied. For Horizon 3 it was devised the addition of a CO_2 capture system to further reduce CO_2 emissions to the Horizon 2 configuration.

The economical evaluation was conducted for each Horizon and how would they stand if compared with a conventional coal-fired plant and a standalone renewable energy plant. The result of this evaluation showed that Horizon 1 and 2 have similar or better economic performance than a standard CSP plant. This outcome of the economic study was unexpected since intuitively it would have been expected for the hybrid plant to be worse than a standard CSP plant. The study has shown different. The capital cost per kW and LCOE of Hybrid Solar/Coal plant can be lower than a standard CSP due to the increased kW capacity and high capacity factor. This result suggests that a new CSP plant can economically perform better if hybridized with a coal-fired boiler. Hybrid Solar/Coal plant not only has a better economic performance than a CSP it is also highly dispatchable which is a necessary feature for modern grids.

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List of Abbreviations

CINSW	Coal Innovation NSW
TIC	Toshiba International Corporation
ASU	Air Separation Unit
AUSC	Advanced ultra-supercritical
BH	Booster Heater
BMS	Battery Management System or Burner Management System
BS	Battery System
CAPEX	Capital expenses
CCS	Carbon capture and storage
CPU	CO_2 Compression and Purification Unit
CRH	Cold Reheat
CRV	Combined reheat valve
CSP	Concentrated solar power
CV	Control valve
DC	Direct current
DNI	Direct Normal Irradiation
FDF	Forced Draft Fan
FGD	Fuel Gas Desulfurization
FWH	Feedwater Heater
GEN	Generator
GPS	Global positioning system
HHV	Higher Heating Value
HRH	Hot Reheat
HTF	Heat transfer fluid
HP	High pressure
IDF	Induced Draft Fan
IP	Intermediate pressure
ITS	Inverter Transformer Station
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LP	Low pressure
LV	Low Voltage
MPPT	Maximum power point tracking
MST	Molten salts Tower
MSV	Main stop valve
MV	Medium Voltage
O&M	Operation and Maintenance
PAF	Primary Air Fan
PCC	Post-Combustioin Capture
PFD	Process Flow Diagram
PM	Performance Model
PPI	Producer Price Indexes
PV	Photovoltaics
SFP	Steam Feed Pump
SGS	Steam Generator System
STG	Steam Turbine Generator
TCDF	Tandem Compound Dual Flow
TES	Thermal energy storage

TMY	Typical meteorological year
USC	ultra-supercritical

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The main goal of the project (as stated on the Attachment 4 of Funding Deed) was to implement a development pathway for USC Hybrid Solar/Coal plants. This pathway was set to reduce emissions substantially as compared to the existing subcritical plants in NSW. Initially by adopting a 300 MW class USC Hybrid Solar/ Coal plant with an energy ratio of 25%/75%, solar and coal respectively. The long-term objective is for a pathway to enable the transition to a flexible USC Hybrid Solar/Coal plant with an energy ratio of 75%/25%, which includes molten salt storage and CO_2 capture using oxy-firing.

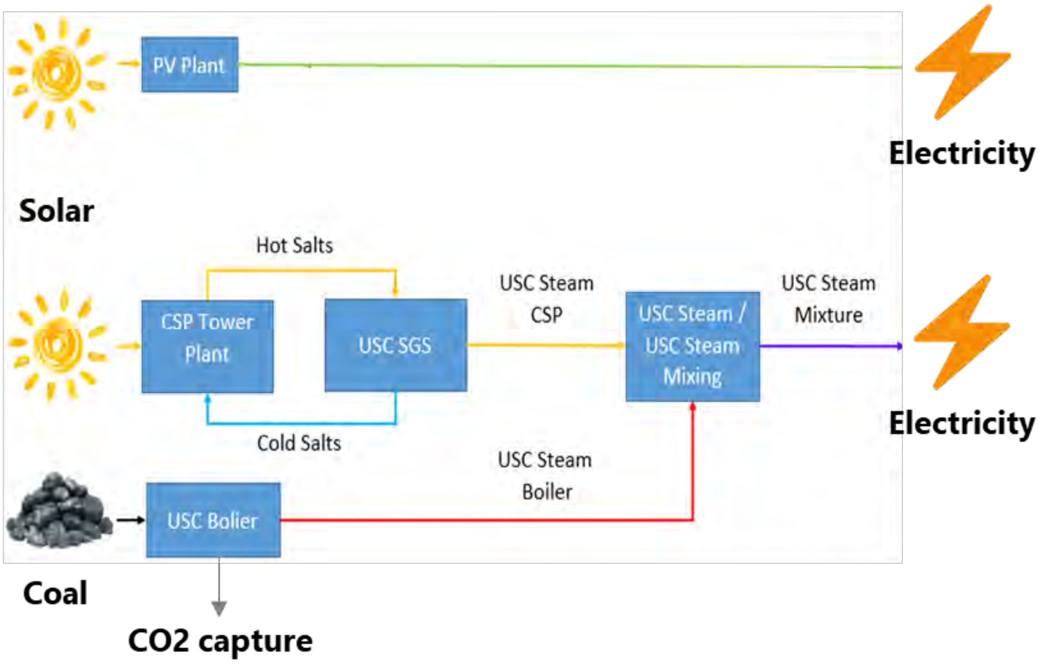

Figure 1 The Concept of Hybrid Solar/Coal plant

1.2 PROJECT AIMS AND OBJECTIVES

A key aim of this research was to show that coal can remain an integral part of the future energy mix and that it can be competitive in the rapidly changing low emission market where a large focus in the future is on dispatchable generation. The USC Hybrid Solar/Coal plant showed that it has significant commercial and technical advantages over alternative hybrid dispatchable solutions such as standalone solar or wind plus battery storage solutions.

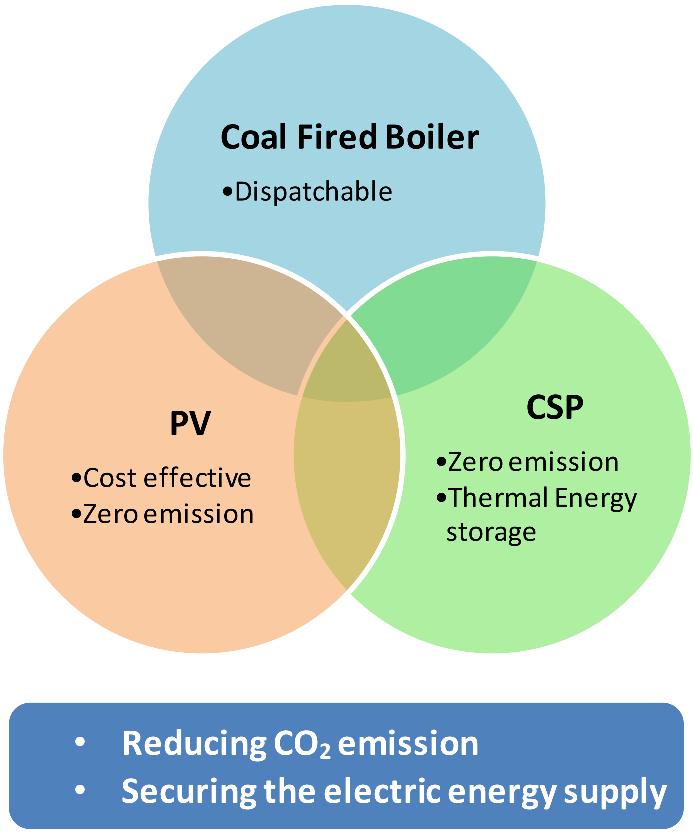

Figure 2 The Advantages of Hybrid Solar/Coal plant

1.3 PROJECT MILESTONES AND PERFORMANCE MEASUREMENT

The methodology for this study was broken down to three Horizons. The definition of each Horizon and Project Milestones were shown in the Attachment 4 of the Funding Deed. However, the definition of each Horizon was changed along with the progress of the study. The revised definition of Horizons is shown in Section 2.3. These revisions had been properly informed to CINSW through the series of Quarterly Reports and Stage Gate Reports.

Additional revisions to the project milestones were done along with the progress of the study and during early discussions with CINSW. The revised Project Milestones are shown in Table 1. In line with the project requirements, all of the milestones have been properly completed.

Please note that the "Closed Cycle Cooling Water System" examination was not conducted due to the original concept of a 'once through open cycle' system being consider not practical based on the conceptual plant layout. However, the cooling system specification itself is not a critical issue for this study. Any other prevailing cooling system such as water cooling with cooling towers or air-cooled condenser system should be applicable. Please refer to Section 7.6.3 for further details.

Table 1 Project milestones summary

Milestones	Main Activities related to milestones	Status (%)	Relevance to project and achievement
Kick-Off Meeting (M1)	(Solar and Coal specialists attending Toshiba @Sydney	100%	The meeting was held in 13th and 14th February 2019 in TIC with representatives from Abengoa, IHI, and Toshiba. The representative from CINSW was also invited.
Cycle Definition (M2)	Power plant (cycle) general description	100%	The unit location was reasonably selected to be Hunter Valley region where is the centre of the coalfield and thermal power station in NSW. Steam/Water Cycle design conditions and main equipment capacity was defined in Horizons definition (Section 2).
	Steam Turbine Unit Engineering	100%	
	Generator Unit and its Aux.	100%	
	Aux. Steam System Definition	100%	
Conceptual design and sizing of the Solar subsystem, Boiler systems and Steam turbine (including auxiliaries) (M3)	Solar Power plant general description	100%	Solar power plant general description was delivered (Section 3). The number of Heliostat, TES capacity, solar receiver capacity and PV capacity was optimized (Section 6.6). The general plant layout for Solar island was developed based on the optimized sizing result.
	Solar plant sizing	100%	
	General plant layout	100%	
	Solar Field layout and tower coordinates	100%	
Conceptual design and sizing of the Boiler subsystem (M4)	Boiler conceptual design	100%	The pulverized coal boiler specification for Hybrid Solar/Coal plant was delivered (Section 4). Any special specification and R&D would not be required for the boiler compared with the conventional one.
	Boiler Pulveriser conceptual design	100%	
	PA and FD fans conceptual design	100%	
	Coal bunker bay systems including steel structure design	100%	
R&D integration of the solar molten salt steam generator into the coal-fired boiler and the seamless transition of the steam supply between coal and solar operation. (M4)	Turbine Bypass System	100%	Solar/coal hybrid plant operational principle was proposed considering the general boiler operational characteristics regarding the main steam pressure and STG load control (Section 6.2 and 6.3). Originally, the once-through open-loop water cooling system was assumed to be applied for this study but it found that it would not practical considering the general plant layout and potential location. However, the cooling system itself is not critical for this study at all. Any other prevailing cooling system such as water cooling with cooling towers or air-cooled condenser system should be applicable (Section 7.6.3).
	Feedwater Pumps and Drives	100%	
	Closed Cycle Cooling Water System	-	
	Main Equipment list for the tower, TES and SGS system	100%	
	Main Equipment datasheet for the tower, TES and SGS system	100%	
Meetings to finalize the Work/configuration for the horizon 1 FEED and review draft Horizon 2 & 3 reports (M5)	Advanced PFD SG system- Solar	100%	The conceptual PFD for Horizon 1 was developed. The steam cycle configuration was revised from the original concept because of the necessity to control the feedwater pressure and flow for the boiler side and CSP side independently (Section 6.3). Boiler island electrical control was proposed but it is not so special against the conventional one (Section 4.5). Fuel oil system and Air compressor system conceptual design are proposed (Section 4.6). Any special specification and R&D would not be required for these compared with the conventional one.
	Advanced PFD system from and to Turbine Island and Solar circuit	100%	
	Advanced PFD system from and to Turbine Island and Solar circuit	100%	
	Boiler Island Electrical Controls	100%	
	Fuel oil system (excluding fuel oil storage system) and Air compressor system conceptual design	100%	
End of project presentation meeting where the final reports for Horizon 1, 2 and 3 are presented. (M6)	Plant modification finalization for Horizon 2	100%	The result of the detailed study for Horizon 1 was expanded to Horizon 2 and 3 (Section 7 and 8). The economic study was conducted from the point of the capital cost, O&M cost and LCOE and they were compared with the conventional coal-fired generation and the other renewable energy systems (Section 9).
	Plant modification finalization for Horizon 3	100%	
	Economic estimation of procurement and shipping of all equipment	100%	
	Economic estimation of erection and commissioning	100%	
	Final Reports preparation	100%	Final Report was completed as this document.

2 PLANT CONDITIONS

2.1 LOCATIONAL CONDITIONS

2.1.1 Location data

In accordance with the aim of the Coal Innovation NSW Fund, the unit location was selected to be in NSW. Specifically, the Hunter Valley region was carefully examined as it provides many benefits as a location for a new hybrid plant since it already has an existing infrastructure for coal supply, transmission and distribution, large areas of land for placement of a solar field and water for cooling.

After the examination of a specific area was selected, the geological point in which Liddle Power Station locates was nominated. Table 2 shows the target location data.

Table 2 Target location

Latitude	32.3715° S
Longitude	150.9773° E
Altitude	142 m above sea level

2.1.2 Ambient Weather Conditions

Ambient weather conditions were obtained from the Meteonorm database for a typical meteorological year (TMY). Hourly data was extracted for the project location including:

- Global Tilted Irradiation: Average global tilted irradiation measured on the PV plant (W/m^2)
- Direct Normal Irradiation: Average direct normal irradiation measured on the solar field (W/m^2)
- Ambient Temperature: Average dry bulb temperature measured on the solar field (deg.C)
- Relative Humidity: Average relative humidity (%)
- Wind Speed: Wind speed average 15min (m/s)
- Wind Speed peak: Wind speed max 3sec gust (m/s)
- Wind direction: Wind direction average 15min (ø NESW)
- Ambient Pressure: Average ambient pressure (mbar)
- Accumulated annual Direct Normal Irradiation for project location is **1746.88 kW/m^2**. Figure 3 shows the average hourly DNI at the site location from January to December.

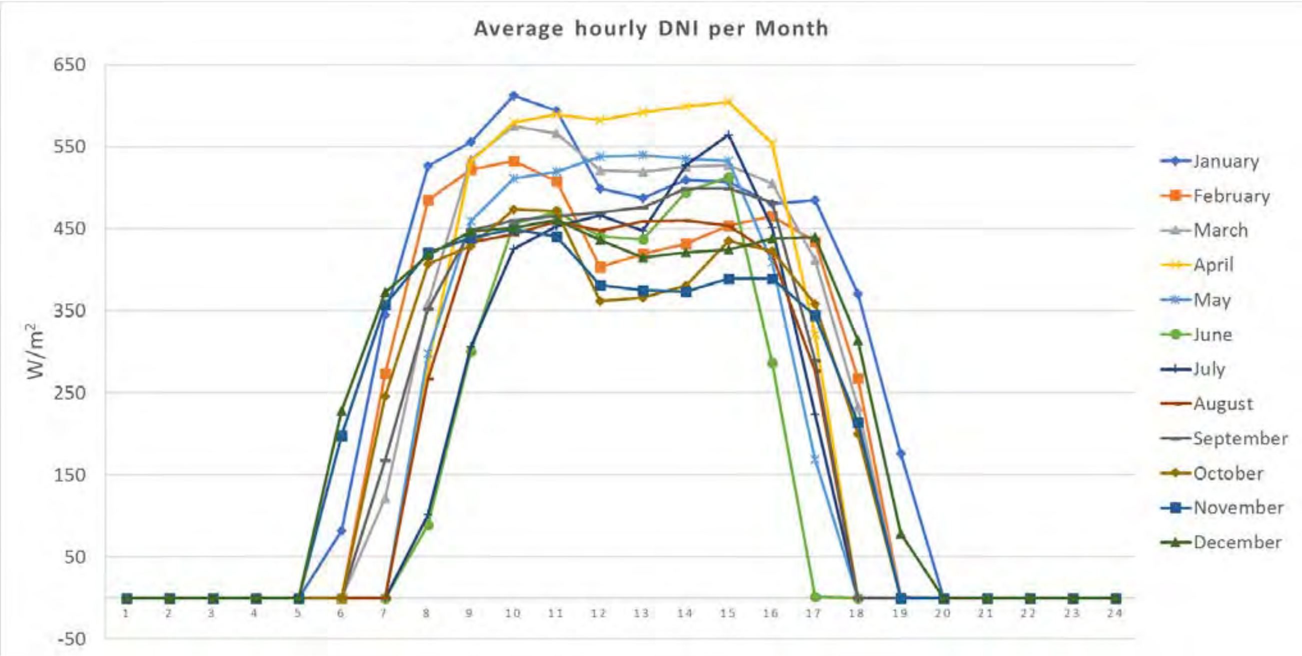

Figure 3 Average hourly DNI per month for a typical year

2.2 FUEL CONDITIONS

Table 3 shows the coal specification that was applied for this study. As it was established on Section 2.1.1 for the specific location, the Hunter Valley domestic thermal coal was used and found reasonable for the objectives of this study. It is important to notice that some extent of the Hunter Valley coal is exported abroad so the coal specification used refers to the one that is consumed in the domestic coal-fired units.

Table 3 Hunter Valley Domestic Thermal Coal Specification

Proximate Analysis (air-dried basis)		
Moisture	weight %	3.3
Ash	weight %	21.4
VM	weight %	30.2
FC	weight %	45.1
Higher Heating Value (HHV)	MJ/kg	25.2
Total Moisture	weight %	8 (Max 10)
Ultimate Analysis (dry ash-free basis)		
Carbon	weight %	83.4
Hydrogen	weight %	5.1
Nitrogen	weight %	1.5
Sulphur	weight %	0.5
Oxygen	weight %	9.5
Ash Fusibility (Flow condition)	deg.C	1600
Chlorine %	weight %	0.02
HGI	-	48

2.3 STEAM/WATER CYCLE DESIGN CONDITIONS AND CAPACITY

2.3.1 Main Steam/Water Cycle Design Conditions

Ambient and fuel conditions are dependent on the plant location, but the steam/water cycle conditions can be determined freely. Hence, it was crucial to determine the plant performance according to the steam/water cycle conditions since this sets the design parameters for the main equipment and therefore the cost of the equipment and installation.

In the Funding Deed, the main steam conditions and equipment capacities were described for each Horizon. However, some of the technical constraints were only discovered through the project research and the careful examination of the solar selected technology so, some parameters were modified as follows.

- Steam temperature
  The original concept was to increase the steam temperature from around 565-590 deg.C in Horizon 1 to 700 deg.C by Horizon 3. An AUSC (700-deg.C class) boiler with minimum 300MW capacity could possibly operate at this temperature but it was found that there are high technological risks for the CSP system. Currently, CSP technology could provide steam at a temperature range of 550 deg.C by using nitrates salts as HTF. There exists alternative fluids such as carbonates, which are currently under research and evaluation to obtain a steam temperature in the range 600-700°C but are not stable. Additionally, now, there is no commercial or large-scale pilot plant experience using carbonates or similar so it was decided that carbonates could not be considered for a short-term scenario. In order to address this issue, the CSP OEM proposed the usage of an electrical heater, not Carbonates, in order to increase the steam temperature from 550 deg.C (generated with Nitrate salts) to 600 deg.C. Please refer to the Section 7.1 to 7.3 for further details. Also through the discussion in before mentioned sections, it was concluded that increasing the steam temperature to more than 600 deg.C at this point in time is not realistic. Therefore, the steam temperature was limited at 600 deg.C for Horizon 2 and 3.

- Boiler capacity
  The original concept was to downsize the boiler capacity from 300MW through Horizon 1 to 3. However, it was found that the actual minimum MW capacity for an USC boiler is 300MW . Less than 300MW might be technically possible but it would not be cost-effective at all. Therefore, the boiler capacity was kept at 300MW for Horizon 2 and 3 as well.

- CSP and PV capacity
  The original concept was to upsize the CSP capacity from Horizon 1 to 3. However, it was found that the standard output capacity for a CSP plant with one tower is generally 100MW to 150 MW dependent on the DNI on that location. At the nominated project location, for a single tower of CSP (of capacity of approximately 100MW) the area of land required was estimated at 1.1 km radius. Please see Section 7.6.2. Even though there were no set restrictions regarding the land utilisation, TIC 's view was that expanding the CSP capacity beyond one tower was not realistic.

- Thermal Storage Capacity
  The original concept was to increase the thermal storage capacity gradually from Horizon 1 to 3. However, the optimum thermal storage capacity was set at 14 hours considering the CAPEX, generation power and solar energy dumping. The thermal storage capacity was fixed for the remainder of the study regardless of other improvements to the power plant configuration. Please see Section 6.6.1.

Table 4 summarises the steam/water conditions and the design capacity for all the Horizons.

In summary;

- The difference between Horizon 1 and 2 is the main and reheat steam temperature.
- The difference between Horizon 2 and 3 is the design with or without CO_2 capture system.

Table 4 steam/water conditions and the design capacity

	Unit MW	Capacity factor -	Annual Production GWh/year	MSP / MST / RHT (@Turbine inlet, from the boiler)	MSP / MST / RHT (@steam generator outlet, from CSP)	Boiler capacity MW	PV capacity MW	CSP capacity MW	Thermal storage hour	STG	CO2 capture
Horizon 1				250 bar / 582 /593	250 bar / 550 /550						N/A
Horizon 2	300	0.85	2234	250 bar / 600 / 600	250 bar / 600 / 600	300	290	100	14	TCDF	
Horizon 3											Oxy-firing

2.3.2 Maximum Design Capacity

Regarding the equipment capacity, the steam turbine was based on a 300MW capacity due to the plant proposed capacity of producing 300MW gross output continuously even if no solar power nor thermal storage are available. However, considering the change in cooling water temperature during the summer season and degradation of the equipment over the design life, the boiler was proposed with a design margin in order to generate enough steam even during these conditions. The boiler as then designed with 10% additional capacity and so it was the steam turbine.

The capacity of the CSP system steam generator was set at 100MW. This capacity is close to the largest capacity that one solar field may have at the specified target location with minimum solar thermal energy dumping.

The generator was designed for 300MW rated output at rated power factor.

The capacity of the PV system was set to at least 210MW so that the coal-fired boiler can operate with the minimum load of 90MW with overall plant still achieving an output of 300MW. However, considering the climate at the site location and accounting for the variable nature of the DNI, the PV system capacity was set at 290 MW peak load in order to generate 210MW on average throughout the year as detailed in Section 6.6.1.

The following Table 5 summarises the design capacities for this study.

Table 5 Maximum Design Capacity

Equipment	Boiler	CSP	Steam Turbine	Generator	PV
Capacity (MW)	330MW	100MW	330MW	300MW	290MW

2.4 PLANT OPERATIONAL CONDITIONS

Table 6 shows the general plant operational conditions.

Generally, the main equipment for coal-fired power station is designed and operated for around 35 to 40 years. The CSP plant was also designed for 35 years so it is reasonable to assume that the overall plant life would be 35 years. In light of this, the plant design lifetime can be safely assumed to be 35 years.

Capacity factor was set to 85%, which is a general percentage for a coal-fired power plant.

Plant annual gross electric power generation was calculated as follows.

$$300\ \text{MW}\ \times 24\ \text{hr}\ \times 365\ \text{days} \times 0.85\ \div 1000 = 2233.8\ \text{GWh/year}$$

The plant power generation profile was assumed a constant 24 hours per day, 7 days per week taking advantage of as much clean energy generation as possible.

Table 6 Plant Operational Conditions

Description	unit	value
Lifetime duration	Years	35
Plant Gross Power	MW	300
Capacity factor	-	0.85
Plant annual gross electric power generation	GWh	2233.8
Plant electric power generation profile	300MW	constant 24/7

3 SOLAR ISLAND CONCEPTUAL DESIGN

The proposed Solar technologies to be used for hybridization with Coal power plants are:

- Photovoltaics (PV)
- Molten salts Tower (MST) concentrated solar power (CSP) plant with thermal energy storage (TES)
- Booster heater
- Lithium-Ion batteries modules

3.1 PV PLANT

For the PV plant, photovoltaic devices generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, sending electricity to the grid.

3.1.1 Technology

The PV Plant will have a total inverter nominal power (MVA) to ensure the required Nominal power (MWac) delivery at the Point of Interconnection. Accordingly, the peak power of the photovoltaic generator field (MWp) will be determined by the sum of the peak power of the photovoltaic modules. For the configuration of the plant, the following technology was considered for each of the main equipment:

- DC System: Configured at 1500V DC voltage
- Photovoltaic modules: Crystalline-Si (silica) technology
- Tracker: One Axis trackers with backtracking strategy
- Photovoltaic inverters: Centralized inverter with an integrated system

3.1.2 Configuration description

1-axis trackers with backtracking were proposed to support the PV modules. The tracker proposed allows easy and fast field mounting as well as easy operation and maintenance. In order to optimize the installation, the distance between rows was calculated to maximize the amount of radiation that each individual module can collect (and consequently electrical production) while minimizing installation costs, which lead to get the optimum cost for produced energy.

The modules, installed on the structures, were connected in strings. To determine the number of modules in each string the input voltage range of the inverter was taken into account so that the maximum system voltage is within the Maximum Power Tracking Point (MPTP) range for the site conditions. This design criterion maximizes the electrical production, helping the inverters to operate at the best performance point.

Each group of strings was designed to be connected to a DC Bus by means of connectors that include fuses for the protection of strings against short circuits. Several DC buses were connected to the input of each inverter of the Inverter Transformer Station (ITS), where each one was protected against short circuits by fuses. The ITS would be basically an integrated set of Low and Medium Voltage formed by a group of inverters, a step-up transformer and a block of MV switchboards, as well as LV switchboards, communications, etc. The transformer and the MV switchboards used can be factory assembled on a ‘skid’ or containerized, fully wired and interconnected. The ITS´s are typically delivered at the site and would be integrated as an outdoor or indoor type on a foundation designed for the equipment.

Finally, a set consisting of modules, structure, cables, tables, SB's, etc ... connected to an ITS are called PV Block.

3.1.3 PV installations

Both PV installations (PV for exportation and PV for charging the Lithium-ion batteries) were designed using the same components, which are described below:

- Photovoltaic Module

Photovoltaic modules are based on Monocrystalline-Si technology. Longi Solar modules have been used for the simulation of both installations, which is a first-class and bankable manufacturer (Table 7). Accordingly, these modules would be manufactured in their own facilities that are certified according to ISO 9001 standards. This supplier has the certificate according to the standards of IEC 61215, 61730 for design and safety. The technical characteristics of the photovoltaic modules (power, voltage, current, etc.) are controlled during manufacturing and properly classified before delivery in order to minimize mismatch losses during installation. Longi Solar modules data sheet is attached in Appendix E: PV Configuration and Data Sheet.

Table 7 PV module peak power

Technology	Peak Power (Wp)
Si-Monocrystalline	380 (*)

(*) Module peak power at Standard Test Conditions (STC): 1.000 W/m2, Cell T: 25 deg.C, AM = 1.5

- Inverter Transformer Station (ITS)

The Inverter Transformer Station (ITS) is an integrated set of Low and Medium Voltage formed by a group of inverters, a step-up transformer and a block of MV switchboard, as well as LV switchboards, communications, etc. The proposed ITS model is Outdoor type SKID, with the different outdoor components, integrated into a SKID type metal platform made of hot galvanized steel. The transformer and the MV switchboards would be

factory assembled in a metallic Skid, fully wired and interconnected. The Inverter is technologically the most important component in any solar power system; it converts the direct current generated in photovoltaic cells into alternating current suitable for the grid.
Ingeteam is proposed for this project as the equipment used in the simulation. Datasheet attached in Appendix F: ITS Data Sheet.

· Trackers

Galvanized steel structures have been proposed. The blocks will be composed of rows of module structures arranged according to the configuration indicated in the PV layouts. The modules would be fixed to the structure by appropriate connections according to module manufacturer indications. Mounting of the modules to the structure would be done by attaching the under-mount frame of the module directly to the structure using clamps.
The assembly system type should facilitate the overall assembly and removal of the solar modules, as well as the ease of maintenance and cleaning. The structures were designed to comply with the design conditions of the site related to wind resistance, standard weather conditions, etc. The optimal distance between rows has been designed to minimize shadow losses. The distance between the front edge of the module and the floor is according to the manufacturer's specifications.
Soltec was used for this project as the tracker used in the simulation. The datasheet was attached in Appendix D: Main Equipment Data Sheet for CSP Plant.

3.2 CSP PLANT

In addition to the PV facility, a Molten Salts Tower plant (MST) was selected as CSP technology to be integrated into the USC Solar/Coal hybrid plant. It is important to notice that in the current times, an MST is the existing CSP technology with the greatest potential in terms of cost/performance. The basic MST plant concept is illustrated in Figure 4.
Heliostats focus sunlight on a heat exchanger located at the top of the tower. Nitrate salt enters the receiver at a temperature of 290 °C and then are heated to 565 °C. The high-temperature salt exchanges thermal energy with water and steam in a steam generator and the steam is used in the steam turbine to generate electricity (Siva V, 2016) (Behar O, 2013).

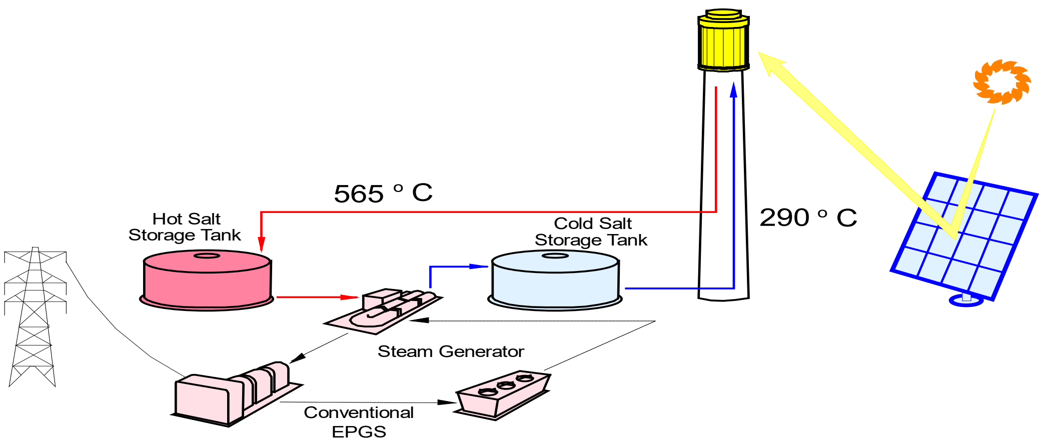

Figure 4 MST plant concept

The MST plant is composed of the main following systems:

- Nitrates salts as the heat transfer fluid
- Solar field
- Solar Receiver
- Storage system
- Electric heat tracing system
- Steam generator system

3.2.1 CSP plant systems

Using Nitrates salts as HTF

Currently, CSP power plants use the so-called "solar salts" (60% $NaNO_3$ - 40% KNO_3 by weight mixture) as the heat transfer and storage fluid. Properties such as low vapour pressure, high energy density, and good thermal stability compatible with the operating range of current existing steam turbines, non-flammable, non-toxic performance, and low cost make these materials good candidates for the HTF. Moreover, nitrate salts are a well-known heat transfer fluid due to previous experience in other sectors such as the chemical and metallurgy industry. Following figure (Figure 5) shows the phase diagram for $NaNO_3$-KNO_3.

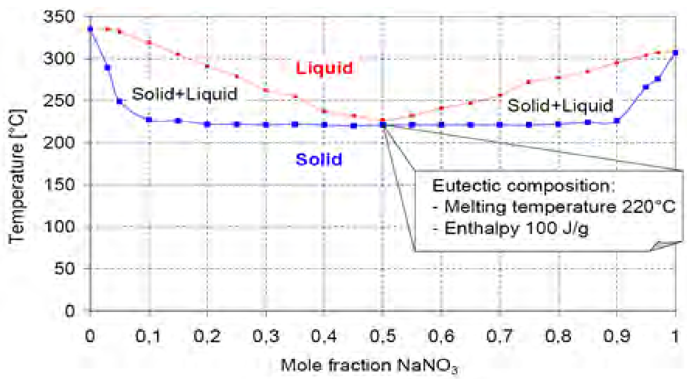

Figure 5 $NaNO_3$-KNO_3 phase diagram

As in any system there are some limitations and drawbacks, one of the most important drawbacks inherent to solar salts is the corrosiveness associated with this fluid at high temperature. The molten nitrate salts in combination with the metallic components (storage tanks, piping, heat exchangers, and valves, among others) of solar power plants constitute a corrosive system with the molten salt acting as an electrolyte. The corrosive effect is inherent to the nitrate to nitrite equilibrium of these fluids at a given temperature. Once the reduction reaction from nitrate to nitrite is produced, the anionic oxidation of the alloy is carried out in the corrosive medium. This issue was solved by performing a proper materials selection for the different components and equipment during the design and installation phase of the project, ensuring the lifetime of the facility in terms of corrosion.

The Nitrates salts used for CSP applications are high-quality $NaNO_3$ and KNO_3 grades containing a low amount of impurities. Table 8 shows the typical commercial sodium and potassium nitrate composition for solar applications:

Table 8 Typical purity and impurities for $NaNO_3$ and KNO_3 in CSP applications

Purity/Impurities	$NaNO_3$	KNO_3
Purity (%wt.)	98 – 99.5	99.3 – 99.6
Chloride (%wt.)	0.1 – 0.6	0.1 – 0.2

Purity/Impurities	$NaNO_3$	KNO_3
Sulfate (%wt.)	0.10 – 0.50	0.05 – 0.5
Carbonate (%wt.)	0.10	0.02 – 0.1
Nitrite (%wt.)	0.02	0.02
Magnesium (%wt.)	0.02 – 0.1	0.01 – 0.05

Solar Salts have several thermophysical properties that make it suitable as an HTF and the selection for this project, including:

- High densities, in the range of 1,700 to 1,900 kg/m^3
- Acceptable thermal conductivities, in the range of 0.50 to 0.56 W/m-C
- Acceptable specific heats, in the range of 1.50 to 1.55 kJ/kg-C
- Low absolute viscosities, in the range of 0.0010 to 0.0036 kg-m/sec
- Very low vapour pressures, on the order of several Pascals
- Low corrosion rates for carbon steels at temperatures up to 400 °C, and low corrosion rates with stainless steels and nickel base alloys at temperatures up to 600 °C

The high freezing point of the salt mixture together with its corrosion characteristics effectively defined the operating temperature range of 250 °C to 565 °C. To provide a safety margin on the freezing point, a lower temperature limit of approximately 280-290 °C was used.

Solar Field

The solar field of the plant is made up of special mirrors mounted in metallic structures called heliostats, which are distributed in one heliostat field and located around one central receiver tower. The main function of the heliostats is to track the sun maintaining the reflected energy on the receiver panels. The required position of the heliostat is calculated via a system of equations specifically developed for this purpose. The heliostat reaches the required position using actuators for the elevation and azimuth axes. This functionality and many others that are crucial for the safe and proper performance of the solar field were implemented in the PLC contained in the heliostat control box.

In specific, the heliostats used in this project are called ASUP 140 (140 m^2 rectangular mirror surface) designed by Abengoa. This heliostat reflects and concentrates the sunrays to the receiver (Figure 6). The reflecting element of a heliostat is typically a low-iron thin glass mirror. This heliostat is composed of several mirror module panels (facets) rather than a single large mirror. A substrate backing to form a flat mirror surface supports the thin glass mirrors. Individual panels on the heliostat are canted towards a point on the receiver. Accordingly, each heliostat of the field has a shape in the form of a revolution paraboloid with a focal length equal to its distance from the receiver.

Main components of the heliostat are as follow:

- Driven mechanism. The heliostat is equipped with a mechanism that allows the aiming to a point defined by two angles: azimuth and elevation. Under normal operating conditions, the axis of the heliostat will be pointing to a direction such that the reflected sunlight converges on the receiver. In the absence of sun (at night) or in adverse weather conditions (wind, hail, etc.) the heliostat adopts the position of survival or stow

- Structures shall support the facets and all external loads without permanent deformation

- Pedestal and foundation to assembly the equipment in the solar field
- Facets: 32 units consisting of a frame, mirror, brackets and screws. The facet shall be 3.220 x 1.355 mm approximately with high energetic reflectivity. As stated before, they shall have a paraboloid of revolution formed according to their distance from the receiver
- Absolute angular sensors. Encoders and inclinometers are used to monitor both movements, movement associated with azimuth axis and elevation axis
- Local control box. Local control boxes shall be suitable for housing all elements and compatible with the electric power supply of the facility

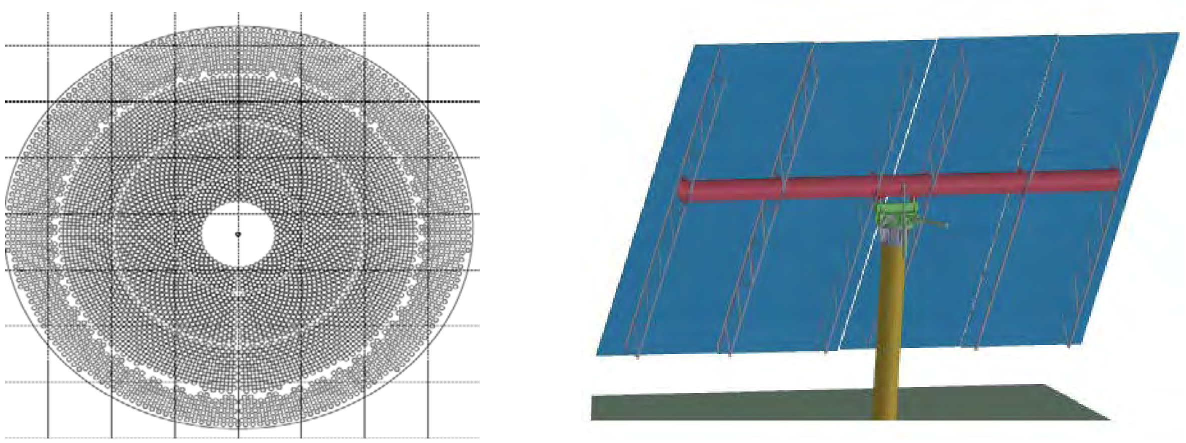

Figure 6 Typical solar field and Heliostat sketch

The heliostat array controller, resident in the distributed control system, maintain supervisory control over the heliostat field. The array controller includes the sun position algorithms, X-Y coordinates for each heliostat, the receiver coordinates, and software for the static aim point processing system, the dynamic aim point processing system, and the beam characterization system. The operator interface will be through the distributed control system.

Solar Receiver

The molten salts solar receiver is the equipment used in the CSP facility to increase the temperature of the salts allowing a typical thermal step in the range of 290 °C - 565 °C. The main design consisted of a heat exchanger with several tube panels at the top of the tower forming an external circumferential arrangement with an effective transfer height in the range of 15 meters. Then, the solar receiver is supported by a steel structure located at the top of the concrete tower where the panels are attached all around creating an external polygon. Each panel is composed of a certain number of tubes with thin wall thickness. Panel tubes were arranged in a vertical position to facilitate draining and venting. Moreover, panel tubes could be seamless or welded ones with the longitudinal weld joint located on the back of the tube, not exposed to the solar flux. The tubes are not welded to each other along their length to maximize the lifetime of the equipment. Finally, tubes are manufactured in high resistant super-alloy to withstand the thermal-mechanical loads and salt corrosiveness.

At the start and at the end of the panels, the tubes are bent and provided with welded nozzles connected to the flow distribution manifolds, also called headers. A zigzag flow path from one header to another minimizes the length of interconnecting piping within the overall receiver design. Therefore, it reduces the pressure parts, weight, overall pressure drop and the pump consumption. The configuration arrangement chosen for this equipment consisted of two circuits with panels in series with a crossover (zigzag configuration). This configuration helped to better distribute the solar incident flux through a whole day and year. All of this can be seen in Figure 7.

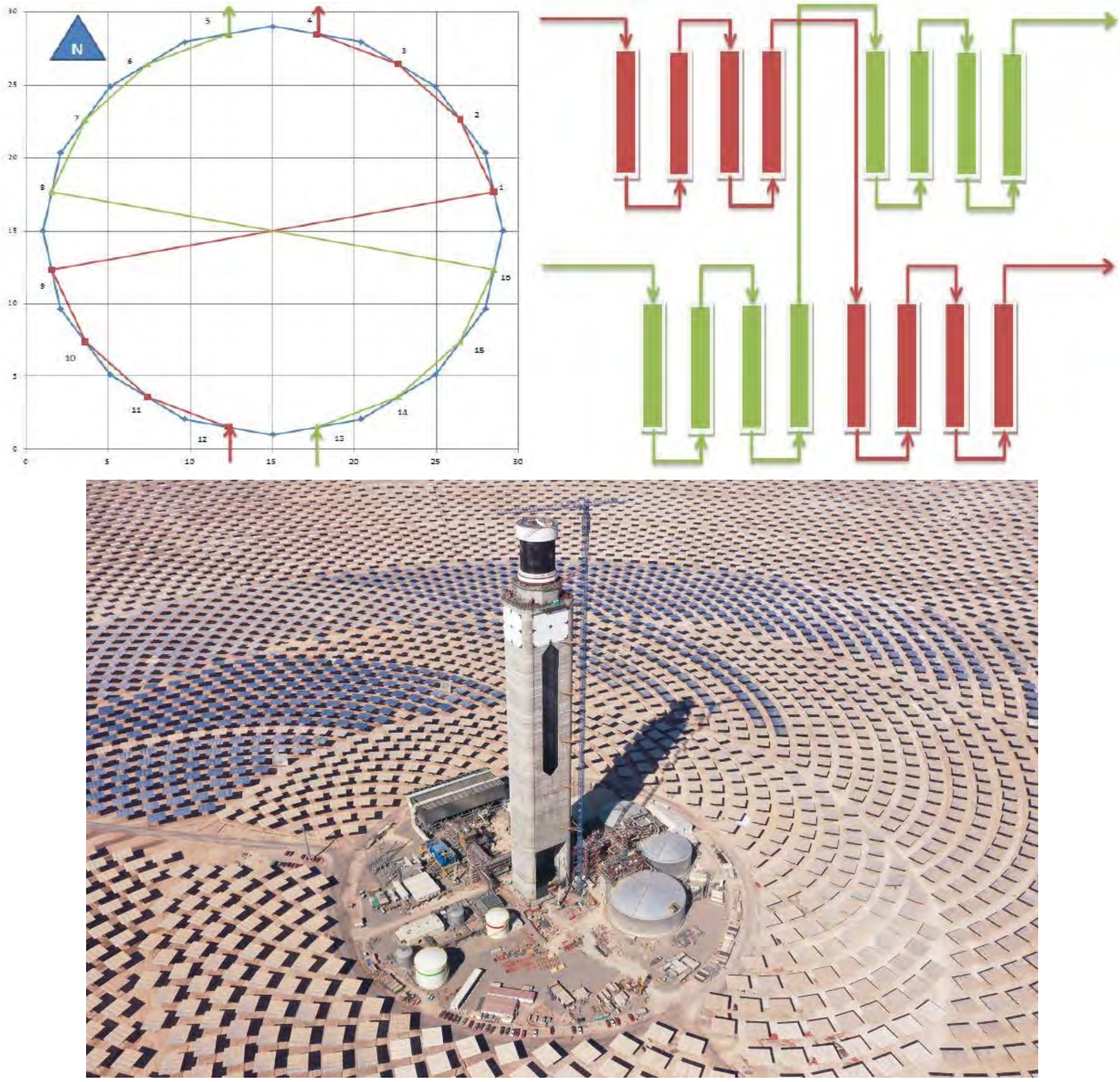

Figure 7 (up) Receiver sketch (Typical configuration composed by panels in series with a cross-over with a zig-zag layout.) and (down) receiver in commercial Molten Salt Tower plant (Cerro Dominador, Chile)

Storage system

The storage system stores high-temperature salt from the receiver for use by the steam generator and stores low-temperature salt from the steam generator for use by the receiver. The storage system components include the following: Cold salt tank; hot salt tank; tank foundations; nitrate salt inventory; electric recirculation heaters; and tank insulation (Gonzalez-Roubaud, Pérez_osorio, & C, 2017).

Nitrates salts are stored in metallic tanks. The hot and cold molten salt tanks will be of vertical cylindrical design with a self-supporting dome type roof (Figure 8, up). To limit the volume and the cost of the inactive salt inventory, the tanks will use a height-to-diameter ratio as large as practical. The foundations of tanks have the aim of supporting the load of the tank and reducing the heat losses and heat radiated from the tank. Accordingly, individual foundations for each of the molten salt tanks were designed.

Molten salts pumps are used to circulate nitrates salts from cold tank to hot tank going through the receiver and to pump salts stored in the hot tank to the steam generator to produce steam, which will be used in the turbine. A typical long shaft molten salt pump is shown in Figure 8, down. The pumps are designed to be vertical, with an extended shaft, and mounted on a platform above tanks to avoid sumps below grade. Pumps bearings are self-lubricated by the salt.

Figure 8 Nitrates salts storage tanks and Typical Long Shaft Molten Salt Pump (source: Abengoa)

Electric heat tracing system

The heat trace system provides thermal protection to stop the salts from freezing in low ambient temperatures and thermal conditioning for all process equipment and components of the proposed facility. This system consists of the following components:

- Mineral insulated heat trace cables
- Installation hardware, cold leads, and termination kits
- Temperature elements, either thermocouples or resistance temperature detectors
- Temperature signal conditioning instruments and transmitters
- Power conditioning equipment, including solid-state contactors

Heat tracing is an element required on salt heat exchangers, piping, instruments, valves, vents, drains, and pressure relief valves (Figure 9) and included in the design on this project. In addition to the use of mineral insulated cable heaters, various plant components require other forms of electric heating. Examples include recirculation heaters for the salt storage tanks and radiant heaters for the receiver ovens.

Figure 9 Electric heat tracing system in a molten salts pipeline (source: Abengoa)

Steam Generator system

The steam generation system will use the thermal energy coming from the salt inventory to produce main and reheat steam at the conditions required by the turbine-generator and auxiliary steam system. In CSP applications, the steam generation system includes the following heat exchangers: superheater; reheater; evaporator; preheater; and start-up feedwater heater. Within this project, the hot salt is supplied to the steam generator from the hot salt tank by means of vertical turbine pumps to produce steam at "project USC CSP conditions" which then will be mixed with the steam stream coming from USC boiler to feed the turbine.

3.2.2 CSP plant typical operation modes

The CSP plant typical operation considered and studied on the project:

- Long Term Hold / Overnight Hold: The heliostats are in the stow position, the receiver is drained, and the electric heat trace circuits are inactive.

- Standby: The heliostats are focused on the standby aim points, and the receiver pump is in operation. Salt is flowing in the riser, the receiver bypass line, and the downcomer.

- Preheat: The receiver electric heat trace circuits are active, the preheat heliostats are focused on the receiver, and the receiver pump is in operation. Salt is flowing in the riser, the receiver bypass line, and the downcomer.

- Normal Operation: All of the available heliostats are focused on the receiver, the receiver flow rate is controlled to achieve an outlet temperature of 565 °C, and the electric heat trace circuits are de-energized at normal operation temperature set points.

3.3 ELECTRICAL HEATERS

The use of Electric Flow Heaters proposed in Horizon 1 allowed the optimization of the thermal storage of the CSP plant, and then the TES can store the surplus of the PV solar field. The Electric heater will be used to heat by Joule effect the molten salt flow, which then will be stored in the hot molten salt tank. Then the stored heat can be used to produce electric power by means of the power block located in the CSP plant. The electrical heater consists of a bundle of tubes based on a conventional shell-and-tube heat exchanger (see

Figure 10), thus, the positive turbulence effect for heat transfer, which is achieved with cross-flow of molten salt is maintained. Resistor elements are placed inside these tubes, providing power by the power supply unit, the resistors are heated and thus the tubes finally heat the molten salt, which flows in the component.

Figure 10 Electrical flow heater by Vulcanic®

The electrical Booster Heater installed in Horizon 2 is an electrical flow heater that increases the steam temperature from 550 deg.C to 600 deg.C. The equipment was custom designed to provide high efficiency, fast response heating. The electric superheaters utilizes rugged electric resistance heating elements mounted in an ASME pressure vessel. The temperature control provides full modulation to maintain the desired steam temperature during the discharge of the CSP. The nominal capacity is designed to cover 14 consecutive hours at full capacity (TES capacity). See Section 7.3 for details.

3.4 LITHIUM-ION BATTERIES MODULES

Batteries were proposed for Horizon 2 and 3 to feed the electrical steam heaters when no solar resource is available.

The Battery System (BS) will provide the electrical energy storage/discharge capability thanks to the chemical reactions that take place inside the battery cells. The BS is composed of batteries and the Battery Management System (BMS). The smallest and basic units of the batteries are the battery cells, inside which the chemical reactions take place. Cells are placed inside the battery modules and are connected between them to provide a higher voltage. Modules include voltage and temperature sensors to monitor the status of the cells. Modules are placed in racks and connected in series to increase the output voltage level of the battery system. A rack is the basic unit of the BS at the system level. Figure 11 shows an image of battery cells, battery modules, control and protection modules, and racks for illustrative purposes (note that the elements in the image are not on the same scale).

Figure 11 Cells, modules and racks of a Battery System

The racks also include a control and protection module, which typically includes fuses and contactors to prevent any damage to the equipment, and voltage and current sensors to provide measurements to BMS to monitor that the BS is operating with the operational limits set.

Table 7 shows the typical characteristics of a battery module supplied by a top qualified manufacturer.

Table 9 Battery module typical characteristics

Item	Module	Rack
Cell Capacity (Ah)	100	100
Energy (kWh)	8.8	221
Operating Voltage (V)	38.4-49.8	960-1245
Dimension (mm)	370x637x160	876x711x2289
Weight (kg)	61	1650

The batteries sizing was carried out according to the Booster heater capacity, it was sized so it is able to cover 14 consecutive hours of the BH working at full capacity. See Section 7.5 for details.

4 BOILER ISLAND CONCEPTUAL DESIGN

4.1 BOILER DESIGN CONDITION

This section describes the general specification used for the boiler design. The plant conditions described in Section 2 was used for the boiler design. As stated in Section 2.3.1, the difference between Horizon 1 and 2 is the main and reheat steam temperature, and the difference between Horizon 2 and 3 is the design with or without CO_2 capture system. Therefore, a conventional supercritical coal-fired boiler was applied for Horizon 1 and 2 and the oxyfuel combustion boiler was applied for Horizon 3.

Table 10 Boiler Design Condition

		Horizon 1	Horizon 2	Horizon 3
Type / Brand Name		Stationary, One Through Variable Press, Reheat type		
Number		1 (one) boiler		
Load		BMCR		
Ambient temperature	deg.C	25	25	25
Steam generating capacity at boiler maximum load (main steam flow)	T/H	912.4	892.2	892.2
Steam generating capacity at boiler maximum load (hot reheat steam flow)	T/H	745.8	729.7	729.7
Feedwater pressure (@Economizer Inlet)	bar	313.8	313.8	313.8
Steam pressure (@SH Outlet)	bar	259.2	259.1	259.1
Steam pressure (@Reheater Inlet)	bar	58.41	58.43	58.43
Steam pressure (@Reheater Outlet)	bar	55.09	55.11	55.11
Feedwater temperature (@Economizer Inlet)	deg.C	288.8	288.2	288.2
Steam temperature (@SH Outlet)	deg.C	585.0	603.0	603.0
Steam temperature (@Reheater Inlet)	deg.C	356.3	372.5	372.5
Steam temperature (@Reheater Outlet)	deg.C	595.0	602.0	602.0
Combustion system		Coal firing system		
Draft system		Equilibration draft		

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4.2 BOILER PERFORMANCE

Table 11 to Table 13 show the predicted boiler performance data. The "Load" in the table means the steam turbine generator load at the boiler single operation without steam coming from the thermal storage system.

Table 11 Boiler Performance Data for Horizon 1

Load		–	BMCR	100%L	200MW (67%L)	90MW (30%L)
Main steam flow		[T / H]	912.4	824.5	522.1	250.0
Hot reheat steam flow		[T / H]	745.8	678.9	441.6	217.8
Steam pressure	(@SH Outlet)	[bar (abs)]	259.2	257.5	253.0	92.11
	(@RH Outlet)	[bar (abs)]	55.09	50.24	32.92	15.65
	(@RH Inlet)	[bar (abs)]	58.41	53.27	34.85	16.64
Steam temperature	(@SH Outlet)	[deg.C]	585.0	585.0	585.0	585.0
	(@RH Outlet)	[deg.C]	595.0	595.0	595.0	532.0
	(@RH Inlet)	[deg.C]	356.3	352.4	322.5	355.7
Feedwater temperature	(@ Eco Inlet)	[deg.C]	288.8	283.1	256.6	217.7
Boiler Efficiency (HHV base)		[%]	88.40	88.50	88.42	87.81
Fuel Flow		[T / H]	113.920	104.160	70.510	35.580
Air excess ratio	(@ Boiler Outlet)	–	1.15	1.15	1.23	1.5
O_2 / CO_2	(@ Boiler Outlet)	[vol %]	2.8 / 16.3	2.8 / 16.3	4.0 / 15.2	7.1 / 12.4
Gas Temperature	(@ Eco Outlet)	[deg.C]	367	362	338	311
	(@ GAH Outlet) Uncorrected / Corrected	[deg.C]	133 / 127.4	130 / 124.1	123 / 114.9	114 / 101.7
Air Temperature	(@ GAH Inlet) Primary / Secondary	[deg.C]	39.0 / 29.5	39.0 / 29.0	39.0 / 27.0	39.0 / 27.0
	(@ GAH Outlet) Primary / Secondary	[deg.C]	334.1 / 340.5	329.6 / 335.8	308.0 / 313.6	283.7 / 291.7
Gas Flow	(@ GAH Inlet)	[T / H]	1,110.94	1,015.76	731.62	444.12
	(@ GAH Outlet)	[T / H]	1,172.04	1,076.71	797.47	515.18
Air Flow	① (@ PAF Outlet)	[T / H]	263.57	255.12	203.83	151.74
	② (@ PAF Outlet)	[T / H]	102.51	100.63	69.91	43.28
	③ (@ GAH Primary Outlet)	[T / H]	103.53	97.11	71.93	41.57
	④ (@ FDF Outlet)	[T / H]	812.79	733.53	530.69	326.61
	⑤ (@ GAH Secondary Outlet)	[T / H]	797.33	718.08	514.95	310.57
Higher Heating Value (as fired basis)		[MJ / kg]	24.0	24.0	24.0	24.0
Lower Heating Value (as fired basis)		[MJ / kg]	23.0	23.0	23.0	23.0

Table 12 Boiler Performance Data for Horizon 2

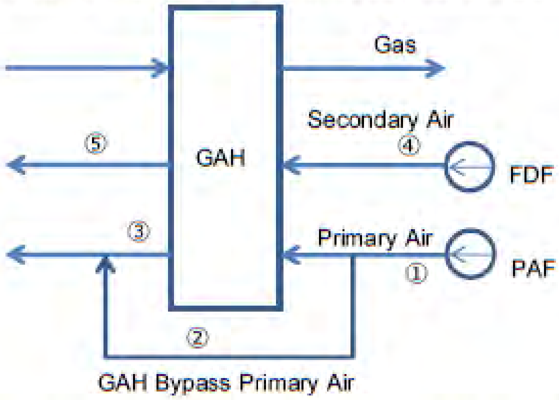
Load		–	BMCR	100%L	200MW (67%L)	90MW (30%L)
Main steam flow		[T / H]	892.2	807.5	517.8	240.5
Hot reheat steam flow		[T / H]	729.7	664.2	437.2	210.0
Steam pressure	(@SH Outlet)	[bar (abs)]	259.10	257.50	253.10	92.02
	(@RH Outlet)	[bar (abs)]	55.11	50.23	33.21	15.48
	(@RH Inlet)	[bar (abs)]	58.43	53.26	35.20	16.42
Steam temperature	(@SH Outlet)	[deg.C]	603.0	603.0	603.0	603.0
	(@RH Outlet)	[deg.C]	602.0	602.0	602.0	542.0
	(@RH Inlet)	[deg.C]	372.5	368.8	341.2	364.5
Feedwater temperature	(@ Eco Inlet)	[deg.C]	288.2	283.1	258.7	217.7
Boiler Efficiency (HHV base)		[%]	88.40	88.50	88.42	87.80
Fuel Flow		[T / H]	112.860	103.200	70.330	34.770
Air excess ratio	(@ Boiler Outlet)	–	1.15	1.15	1.23	1.5
O_2 / CO_2	(@ Boiler Outlet)	[vol %]	2.8 / 16.3	2.8 / 16.3	4.0 / 15.2	7.1 / 12.4
Gas Temperature	(@ Eco Outlet)	[deg.C]	367	362	338	311
	(@ GAH Outlet) Uncorrected / Corrected	[deg.C]	133 / 127.4	130 / 124.1	123 / 114.9	114 / 101.7
Air Temperature	(@ GAH Inlet) Primary / Secondary	[deg.C]	39.0 / 29.5	39.0 / 29.0	39.0 / 27.0	39.0 / 27.0
	(@ GAH Outlet) Primary / Secondary	[deg.C]	334.6 / 341.0	330.1 / 336.3	308.4 / 314.0	284.1 / 292.0
Gas Flow	(@ GAH Inlet)	[T / H]	1100.80	1006.58	729.87	434.08
	(@ GAH Outlet)	[T / H]	1161.34	1066.98	795.56	503.56
Air Flow	① (@ PAF Outlet)	[T / H]	262.38	253.98	203.64	149.56
	② (@ PAF Outlet)	[T / H]	102.85	100.93	70.13	43.46
	③ (@ GAH Primary Outlet)	[T / H]	102.53	96.19	71.67	40.71
	④ (@ FDF Outlet)	[T / H]	804.10	725.68	529.12	317.79
	⑤ (@ GAH Secondary Outlet)	[T / H]	788.68	710.27	513.40	301.84
Higher Heating Value (as fired basis)		[MJ / kg]	24.0	24.0	24.0	24.0
Lower Heating Value (as fired basis)		[MJ / kg]	23.0	23.0	23.0	23.0

Please refer to Section 8.1 regarding the general technical description about oxyfuel combustion boiler.

Table 13 Boiler Performance Data for Horizon 3

Load		–	BMCR	100%L
Main steam flow		[T / H]	892.2	807.5
Hot reheat steam flow		[T / H]	729.7	664.2
Steam pressure	(@SH Outlet)	[bar (abs)]	259.10	257.50
	(@RH Outlet)	[bar (abs)]	55.11	50.23
	(@RH Inlet)	[bar (abs)]	58.43	53.26
Steam temperature	(@SH Outlet)	[deg.C]	603.0	603.0
	(@RH Outlet)	[deg.C]	602.0	602.0
	(@RH Inlet)	[deg.C]	372.5	368.8
Feedwater temperature	(@ Eco Inlet)	[deg.C]	288.2	283.1
Boiler Efficiency (HHV base)		[%]	87.80	87.93
Fuel Flow		[T / H]	113.64	103.87
O_2 / CO_2	(@ Boiler Outlet)	[vol % wet]	2.6 / 73.5	2.6 / 73.5
Gas Temperature	(@ Eco Outlet)	[deg.C]	357	352
	(@ GAH Outlet) Uncorrected / Corrected	[deg.C]	161 / 154	158 / 154
Air Temperature	(@ GAH Inlet) Primary / Secondary	[deg.C]	56 / 45	56 / 45
	(@ GAH Outlet) Primary / Secondary	[deg.C]	327 / 332	322 / 327
Gas Flow	(@ GAH Inlet)	[T / H]	1115	1019
	(@ GAH Outlet)	[T / H]	1196	1099
Air Flow	① (@ PAF Outlet)	[T / H]	335	323
	② (@ PAF Outlet)	[T / H]	162	156
	③ (@ GAH Primary Outlet)	[T / H]	97	92
	④ (@ FDF Outlet)	[T / H]	742	668
	⑤ (@ GAH Secondary Outlet)	[T / H]	737	663
Higher Heating Value (as fired basis)		[MJ / kg]	24.0	24.0
Lower Heating Value (as fired basis)		[MJ / kg]	23.0	23.0

Each air flow in the table shows air flow rate at the point in below figure respectively.



Boiler efficiency is calculated based on ASME PTC 4, the 2013 edition of "Steam Generating Units – Power Test Code", based on higher heating value.

The formula for boiler efficiency calculation is as below.

$$E_B = \left[\left[1 - \frac{L_1 + L_2 + L_3 + L_4 + L_5 + L_6 - (B_1 + B_2 + B_3)}{H_0} \right] \times 100 \right] - (L_7 + L_8)$$

E_B	:	Boiler thermal efficiency based on high heating value	%
H_0	:	Higher heating value of fuel	kJ / kg of fuel
L_1	:	Heat loss due to dry gas	kJ / kg of fuel
L_2	:	Heat loss due to water formed from the combustion of H_2	kJ / kg of fuel
L_3	:	Heat loss due to water formed from in actual coal	kJ / kg of fuel
L_4	:	Heat loss due to moisture in air	kJ / kg of fuel
L_5	:	Heat loss due to unburned carbon in residue	kJ / kg of fuel
L_6	:	Heat loss due to surface radiation and convection	kJ / kg of fuel
L_7	:	Unaccounted Loss	%
L_8	:	Maker's margin	%
B_1	:	Heat credit due to entering dry air	kJ / kg of fuel
B_2	:	Heat credit due to entering moisture in entering air	kJ / kg of fuel
B_3	:	Heat credit due to auxiliary equipment power	kJ / kg of fuel

4.3 HORIZON 1 COMPARISON WITH HORIZON 2

Fuel flow, combustion airflow and boiler outlet gas flow were slightly reduced compared with Horizon 1 due to the improved steam condition. However, there was no significant influence on fans and pulveriser specifications.

In Horizon 2, the Boiler heating surfaces of the primary and final superheater were slightly larger compared with Horizon 1, but other equipment than the heating surfaces was kept the same.

For major piping, there were no material changes from Horizon 1 as shown in Table 14. The only change was that the thickness of the pipe increases, especially for the main pipe.

Table 14 Major Pipe Specifications

Boiler pipe	Material	Outside diameter [mm]	Thickness [mm] Horizon 1	Thickness [mm] Horizon 2	Number of strains [-]
Main steam pipe	SA335P91	406.4	70	81	1
Cold reheat pipe	SA106C	610.0	26	28	1
Hot reheat pipe	SA335P91	660.0	47	49	1
Feedwater pipe	SA106C	457.0	77	77	1

4.4 HORIZON 2 COMPARISON WITH HORIZON 3

The air combustion boiler for Horizon 2 was proposed to be replaced by an oxyfuel combustion boiler for Horizon 3 with changes of the auxiliary system. There were no restrictions nor negative effects arisen for the plant operation due to the replacement to the oxyfuel combustion boiler with the exception of the start-up and shutdown of the boiler. The heating surface area of the boiler was kept the same as Horizon 2 so the general arrangement of boiler was not changed from Horizon 2 to Horizon 3.

4.5 BOILER ELECTRICAL CONTROL SYSTEM

The C & I system of Boiler is comprised by several inner major system.

4.6 OTHER BOILER AUXILIARY SYSTEM

In this Section, general specifications used for the other boiler auxiliary system for Horizon 1&2 are described.

4.6.1 Air and Flue Gas System

Air & flue gas system is composed of the following four systems:

- Primary Air System
- Secondary Air System
- Boundary Air System
- Boiler Flue Gas System

Primary Air System
The functions of the primary air system are:

- To supply of cold air to the Gas Air Heater (GAH) for air preheating and flue gas cooling.
- To supply of cold primary air to the pulverisers for sealing and primary air tempering.

- To supply of hot primary air to the pulverisers for coal drying, pulverizing and transporting of pulverized coal to the burners.

Secondary Air System

The functions of the secondary air system are:

- To supply of secondary air to the boiler for combustion of ignition oil and pulverized coal in the furnace.
- To supply of secondary air to the boiler for purging explosive fuel and flue gas remaining in the furnace and flue gas ducts before firing.

Boundary Air System

The functions of the boundary air system are:

- To supply of boundary air to the boiler for reducing slagging.

Boiler Flue Gas System

The functions of the flue gas system are;

- To transfer the flue gas from boiler to GAH outlet.
- To transfer heat from the flue gas to primary and secondary air by GAH.

The flue gas from the boiler passes through the GAH.

The functions of GAH are;

- To preheat the primary air from PAF for coal drying, pulverizing and transporting pulverized coal to burners.
- To preheat the secondary air from FDF for boiler combustion.
- To recover heat energy waste from flue gas.

4.6.2 Air Compressor System

The compressed air system supplies control air and station air.

This system consists of three air compressors, one air dehumidifier and piping equipment including two supply headers. Three air compressors are installed as common facilities for control and station use, and two air receivers are provided downstream.

The control air is distributed from the air receiver to the boiler and other facilities via the control air header at the downstream of a dehumidifier. Air from air receivers passes through the pre-filter installed at the inlet of the dehumidifier to remove particulates, incident water, and oil droplets in the air. The after filter installed at the outlet of the dehumidifier is designed to remove particulates. The station air is distributed from the air receiver to each supply destination via the station air header. Components received station air are categorized into two types. One type should be secured some air source in case of shutting down of electrical power by a blackout. In addition, others are able to stop air supply in case of emergency.

4.6.3 Fuel Oil System

The fuel oil pipe system supplies fuel oil for the starting ignitor. This fuel oil system is supplementary fuel system for unit start-up, shut down, and supplemental fuel to obtain stable combustion during Pulveriser start-up, shutdown operation. The air supply system to ignitor is also shown in the drawing.

Fuel oil is pressurized by a fuel oil pump to the required pressure of each ignitor and led to ignitor through the flow control valve and other valves.

In order to prevent combustion instability and misfiring due to a decrease in the oil pressure at the burner inlet when the burner is ignited, an accumulator is installed as the device that prevents unacceptable fluctuation of oil pressure for the burner.

A pressure relief line is installed at a necessary location for pressure relief when the oil in the pipe expands due to heating or direct sunlight when the system is stopped.

4.6.4 Fire Fighting System

The fire-fighting system for boiler typically consists of the following system.

- Fixed Water Spray and Detection Systems

The following table shows the outline of the fixed water spray and detection systems to be provided.

Table 15 Fixed Water Spray and Detection Systems

AREA	TYPE OF SYSTEM
Boiler Firing Faces	Water Spray Deluge Systems Hose Reels
Air Heater	Internal water spray
Bunkers	Fire alarms - heat detection and hydrants

Fire systems located within a hazardous area will be designed in accordance with the particular hazardous areas requirements.

5 TURBINE ISLAND CONCEPTUAL DESIGN

5.1 STEAM TURBINE TECHNICAL DATA

Table 16 shows the steam turbine technical data for each Horizon.

Table 16 Steam Turbine Technical Data

Measurement	Horizon 1	Horizon 2 & 3
Operating speed	3000 rpm	
Steam condition	25000 kPa / 600 deg.C / 600 deg.C	25000 kPa / 600 deg.C / 600 deg.C
Vacuum condition	5.3 kPa	
Type	TCDF	
	Tandem Compound, Single Reheat	
	Double-Flow exhaust Condensing Turbine	
Turbine configuration	2 Casings (HIP, LP)	
Cylinder method of fastening	Upper & Lower half bolted at horizontal joint	
Thrust bearing	Between HIP and LP, Pad type	
HIP turbine		
- stages(HP/IP)	14 / 10	
- rotor material	12Cr	
- blade material	12Cr	
- journal bearing	2, DTP type	
- Shaft seal	Fin type	

Measurement	Horizon 1	Horizon 2 & 3
LP turbine		
- stages	6 x 2	
- rotor material	NiCrMoV	
- blade material	12Cr	
- journal bearing	2, Elliptical type	
- Shaft seal	Fin type	

5.2 STEAM TURBINE DESIGN CONDITION

Table 17 shows the steam turbine Design Condition for each horizon.

Table 17 Steam Turbine Design Condition

Measurement	Horizon 1	Horizon 2 & 3
Target gross power output at the generator terminal (kW)	300,000	
Heat Balance Condition (specified value)		
Main steam pressure at main stop valve inlet (kPa a)	25,000	
Main steam temperature (deg C)	582	600
Reheat steam temperature (deg C)	593	600
Condenser back pressure (kPa)	5.3	
Reheat pressure drop from turbine exhaust flange to CRV inlet excluding CRH NRV (%)	8.5	
CRH NRV pressure drop (%)	0.5	
Total Change in Enthalpy across BFP and BP (kJ/kg)	42.8	
Boiler blowdown (kg/hr)	0	
Generator Power Factor	0.85	
Generator Hydrogen Pressure (kPag)	410	
Heat Balance Condition (confirmed value)		
Top HP heater feedwater outlet temperature (deg C)	283.1	
TD (HP8 / HP6) (deg C)	-1.1 / -1.1	
TD (HP7 / LP4 - 1) (deg C)	0.0 / 2.8	
DC (All Heaters) (deg C)	5.6	
The steam pressure drop between turbine casing outlet nozzle connections and feedwater heater extraction steam connections excluding NRV (HP8-6/ Dea-LP3/ LP2-1) (%)	3.0/5.0/5.0	

5.3 GENERATOR

Table 18 shows the generator technical data. This is common across Horizons.

Table 18 Generator Technical Data

Type form	Three-phase, rotating field, cylindrical rotor, horizontal type synchronous generator
Installation	Indoor
No. of phase	3
No. of poles	2 poles
Output	400,000 kVA continuous (at a rated hydrogen pressure of 410kPag)
Voltage	17 kV
Frequency	50 Hz
Speed (R.P.M.)	3,000 R.P.M
Power factor	0.85 lagging – 0.90 leading
Short circuit ratio	Not less than 0.5 0 (at rated kVA base)
Cooling method	
- Stator winding	Indirect hydrogen cooled
- Rotor winding	Direct hydrogen cooled
Connection of stator winding	Wye. Both ends of each phase winding are brought out from the generator stator through high voltage bushings. Six (6) bushings are provided for a generator.
Cooling water temperature	30 deg C
Antifreeze liquid	No antifreeze agent
Insulation class	
- Stator winding	Class F (B rise)
- Rotor winding	Class F (B rise)
Direction of rotation	Counter-clockwise (CCW), viewed from the turbine top

Connection of turbine	Directly coupled to the turbine
Excitation system	Static excitation system
- Response ratio	Not less than 2.0
- Ceiling voltage	Not less than 200% of rated field voltage
- PSS input	Power input and frequency input

6 INTEGRATION FOR THE HYBRID SYSTEM FOR HORIZON 1

6.1 SOLAR/COAL HYBRID PLANT CONFIGURATION

The proposed configuration for Horizon 1 was based on a hybrid facility using PV and MST as main solar technologies integrated with the USC coal plant. The combination of these two solar technologies in the hybridization process optimized the cost of the final solution by maximizing the electricity production coming from renewable sources.

Two different scenarios were evaluated to optimize the final hybrid solution:

- **Scenario A**. PV dispatches electricity into the grid in parallel operation with Boiler. CSP also in parallel operation with Boiler

- **Scenario B**. PV covers the following two objectives: (i) Provide electricity into the grid and (ii) Provide electricity (using PV dumping) to molten salts **electrical heaters** used to charge a part of the salts in the MST storage system. CSP in parallel operation with Boiler as in the previous Scenario

Figure 12 shows the overall plant scheme for USC Hybrid Solar/Coal plant for Scenario B:

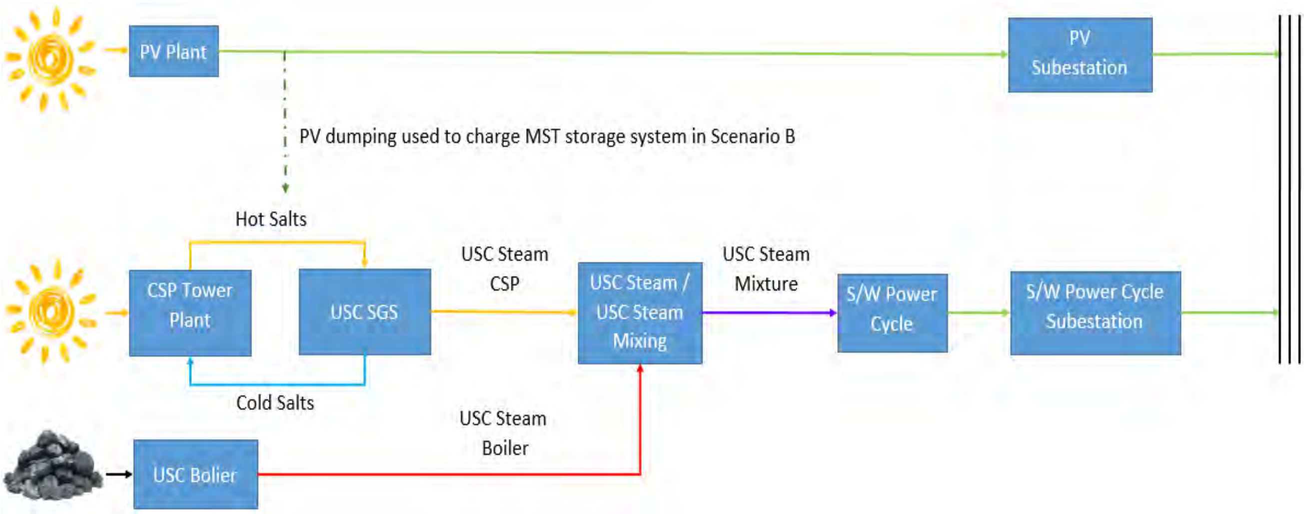


Figure 12 USC Hybrid Solar/Coal overall plant scheme

The USC hybrid Solar/Coal plant was modelled to obtain the optimum output for PV and MST capacity to assure the most competitive Production/Cost ratio and solar share. The design basis for each solar subsystem were as follow:

- **PV subsystem. The** PV plant was designed to dispatch electricity during the day while the solar resource is available. At the same time, and for Scenario B, PV dumping was to be used to cover the power consumption of the electrical heaters integrated into the storage system of the MST plant.

- **MST subsystem**. MST plant was designed to store thermal energy during the day while PV is dispatching electricity into the grid. When no solar resource is available, the MST storage system would be discharged and USC steam would be produced in the Molten salts-USC Steam Generator

System (SGS). USC steam produced by the MST plant would get mixed with USC steam coming from the USC boiler and finally circulated to the USC steam turbine to produce electricity

MST overall plant configuration is shown in Figure 13 for Scenario A and B. As previously stated, the main difference between both scenarios was the integration of electrical heaters in the TES system. Molten salts electrical heaters were to be fed by the PV dumping increasing the temperature of a part of the salts used in the storage system.

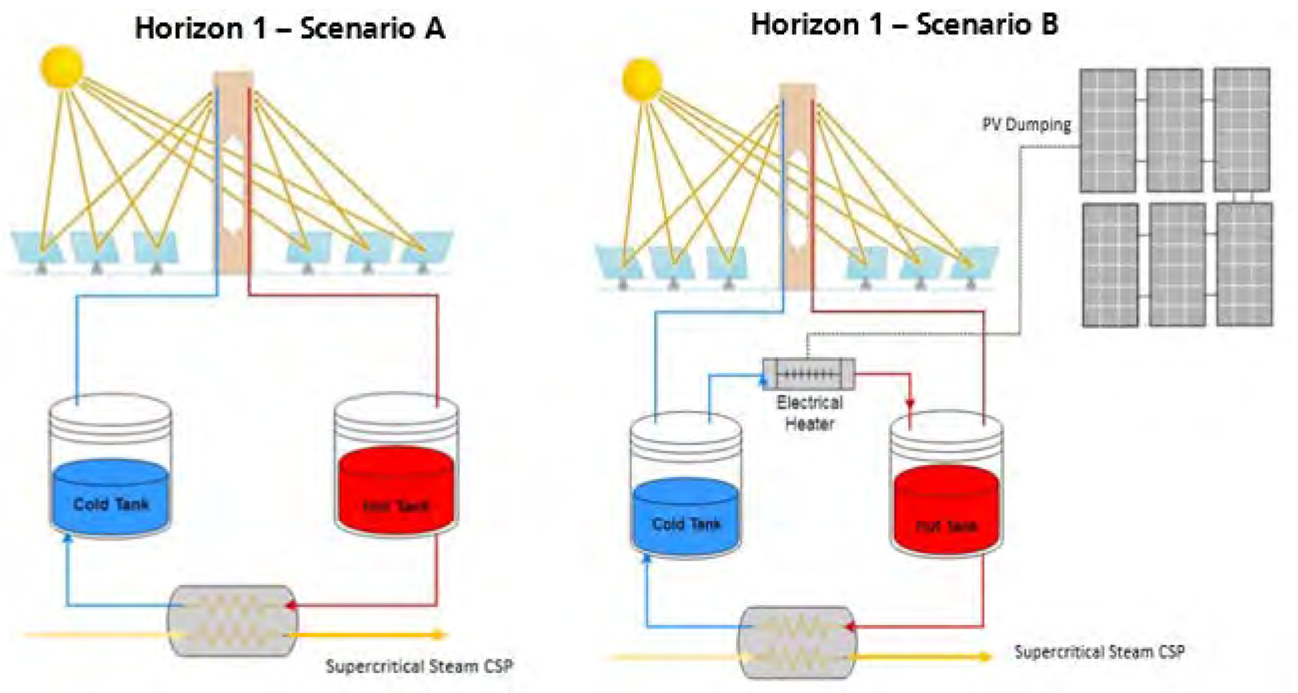


Figure 13 MST TES design for Scenario A and B

6.2 SOLAR/COAL HYBRID PLANT OPERATIONAL PRINCIPLES

In the case of parallel operation, both steam coming from CSP and the coal-fired boiler were designed to be mixed and then flow into the steam turbine. Conventional coal-fired power plants have either sliding pressure operation mode or constant pressure operation mode and the main steam pressure is the variable controlled (Figure 14). The transition point between sliding pressure and constant pressure operation modes would be around 80-100% load for a standard coal-fired plant but it had to be reduced as much as possible for the hybrid plant in order to keep the rated main steam pressure and be compatible with its solar counterpart.

This CSP plus a coal-fired system has two steam generators and each steam generator will have a different amount of feedwater. The combined total amount of steam will be enough to generate 300 MW by the steam turbine generator but the steam is generated by mixing the steam from the two different steam generators.

In the case when the CSP is in operation, it was expected that 200 MW of steam will come from the coal-fired boiler and 100 MW of steam will be produced by the CSP. The coal-fired boiler needs to be operated with rated main steam pressure but limiting the amount of steam to 2/3 of the rated flow rate. Since the boiler will have 330MW as maximum capacity in Horizon 1, the coal-fired boiler need to be operated at the rated main steam pressure from the 200MW mark to 300MW operation (66% - 100% Load) (Fig.10-b).

In summary, the new configuration of CSP + coal-fired power plant required a different control logic for the main steam pressure unlike a conventional power plant, since the feedwater flow rate may vary even if the gross output is controlled at constant.

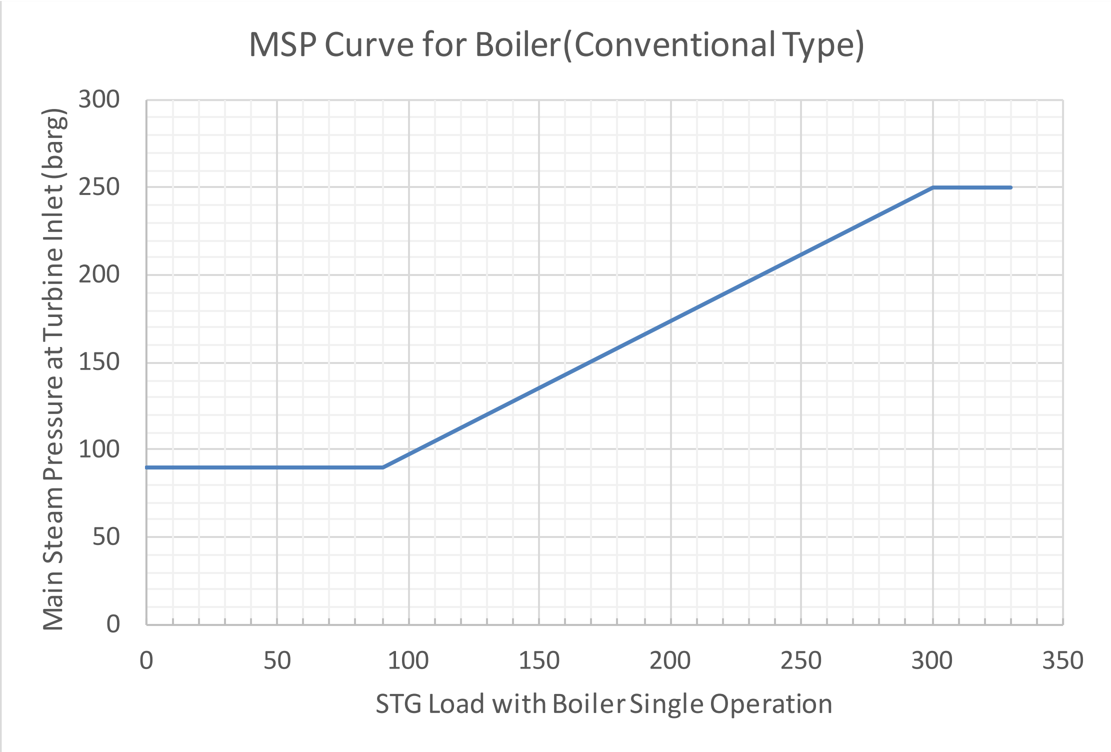


Figure 14 Main Steam Pressure Curve for Conventional Coal-fired Power Plant

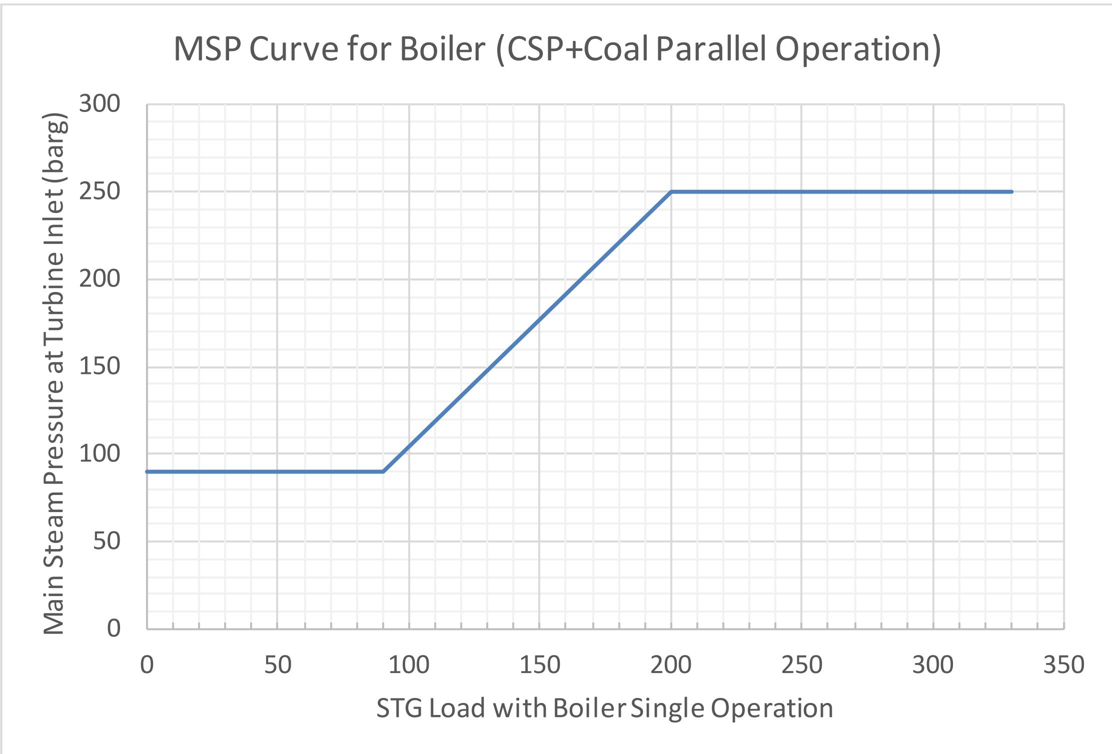


Figure 15 Main Steam Pressure Curve for Boiler with CSP Parallel Operation

6.2.1 Operating Limitation

During the study it was identified a limitation for parallel operation. The main steam pressure depends on the total amount of steam flowing into the steam turbine. As shown in Figure 15, the boiler will have its limitation at 200MW minimum load with the rated pressure output. Therefore, the parallel operation of the CSP system and coal system had its limitation on the flow ratio. For example, in a case of 200MW gross power output with 100MW from CSP boiler and 100MW from the coal-fired boiler, following a conventional pressure curve the main steam pressure from the coal-fired boiler will be assumed as 170 bar, see Figure 15. However, there will be steam coming from the CSP steam generator at fixed pressure flowing to the steam turbine in order to generate 200MW. In this case, the 200MW worth of steam will raise the turbine inlet pressure up to rated pressure (250 bar), so there will be a mismatch between boiler design and actual pressure. Since the boiler cannot accept the 250 bar with low steam flow rate (also mismatched main steam line pressure) and the CSP boiler cannot supply enough steam to the steam turbine for this rated power; it was then clear why the limitation had to be incorporated in the design.

Based on this limitation the coal fired boiler and CSP system can only be on parallel operation when the coal-fired boiler is generating more than 200MW steam flow.

Therefore, the main steam pressure curve for the power plant will be as following Figure 16, which is then the same as the boiler's operating curve.

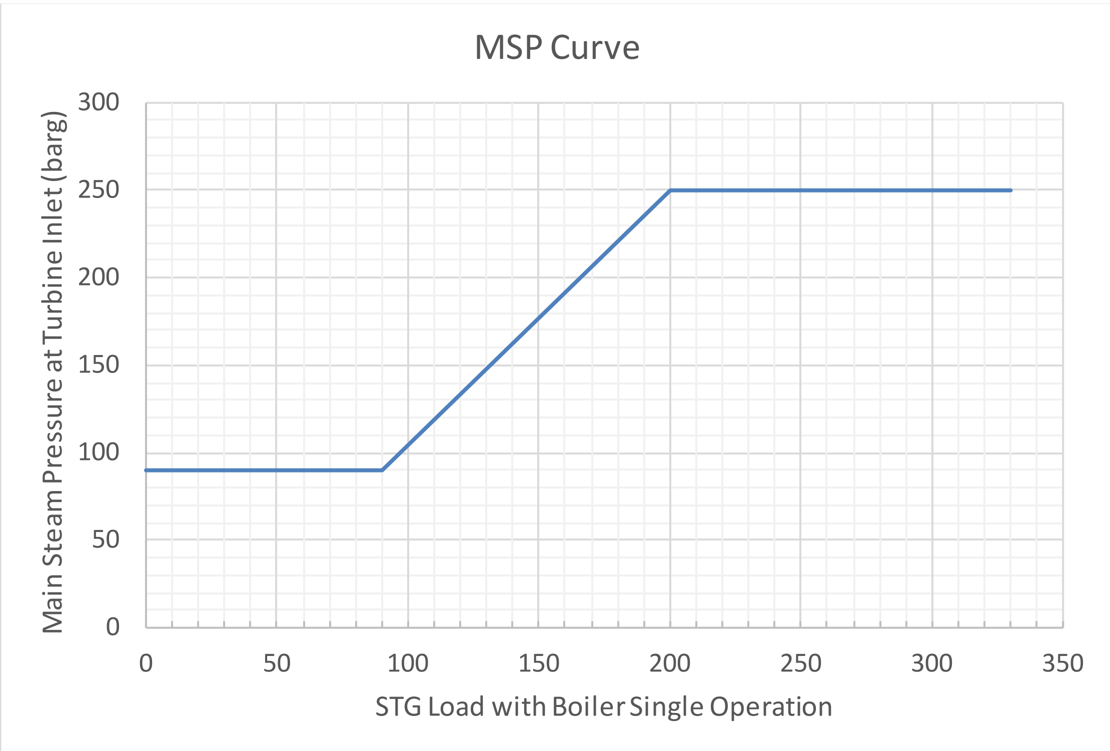


Figure 16 Main Steam Pressure Curve of Power Plant

Considering the boiler design limitation, the following operational concept shown in Table 19 was proposed.

Table 19 operational concept of Hybrid Solar/Coal operation

The STG output > 200 MW	CSP boiler and coal-fired boiler can operate at the same time, which means parallel operation.
The STG output < 200 MW	CSP boiler and coal-fired boiler cannot operate at the same time. It must be a boiler single operation or CSP single operation. However, CSP single operation would not happen because CSP has only 100MW capacity so the plant cannot get 300MW without boiler operation in the nighttime.

Considering the above limitation, the operation principles for the USC Hybrid Solar/Coal plant were summarized below for a typical clear day:

USC Hybrid Solar/Coal operation during the day

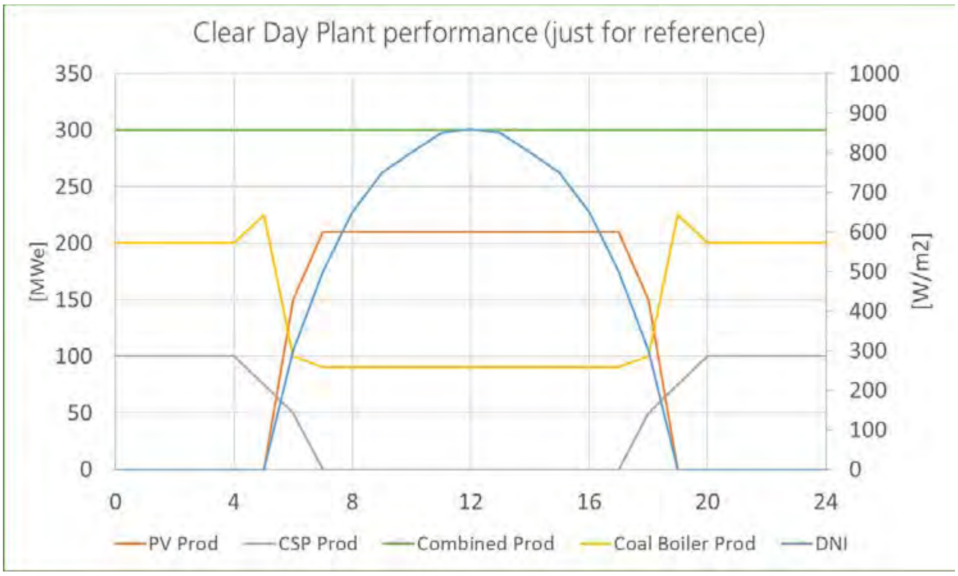
- Scenario A
  - PV generation (210MW) + Boiler generation (90 MW, minimum load)
  - CSP in charge mode storing salts in the hot tank of the installation
- Scenario B
  - PV generation (210MW) + Boiler generation (90 MW, minimum load)

    PV dumping used to cover the power consumption of molten salts electrical heaters
  - CSP in charge mode storing salts in the hot tank of the installation

USC Hybrid Solar/Coal operation during night

- Scenario A & B: Parallel production: CSP (100 MW) + Boiler (200MW)

The following figure (Figure 17) shows (just for reference) how USC Hybrid Solar/Coal plant operation would cover the required power output (300 MW) for this installation for a clear and cloudy day. USC Boiler is used to smooth the transition between PV and CSP and to cover gaps when solar resource is not available or TES system is not completely charged. If the load change rate is more rapid than the capability of change rate by the boiler, the boiler may not compensate for load change by PV and CSP.



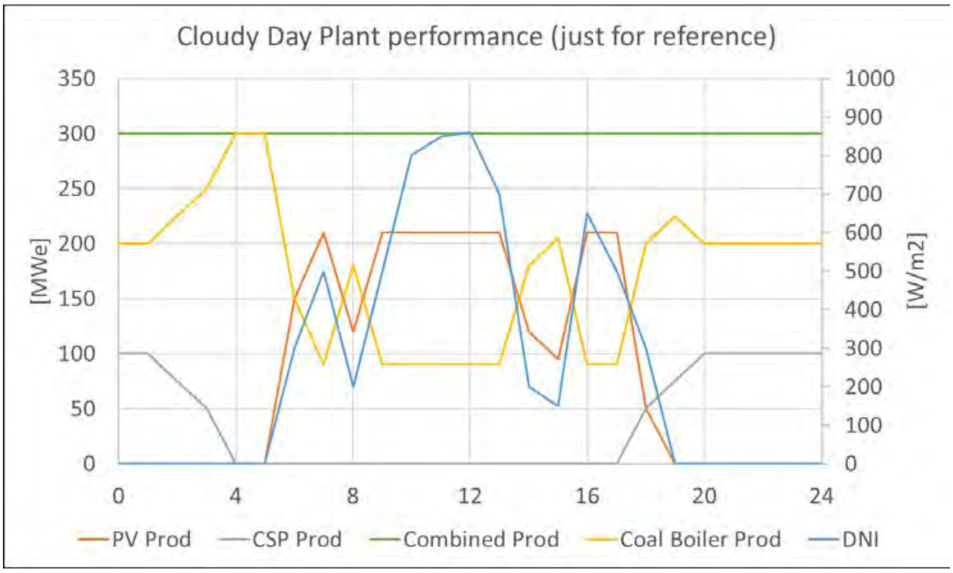


Figure 17 USC Hybrid Solar/Coal plant typical operation for clear and cloudy days

6.3 CONCEPTUAL PROCESS FLOW DIAGRAM FOR CSP/COAL HYBRID UNIT

Initially, the concept system configuration of the Hybrid Solar/Coal plant was based around 'conventional' power plant steam/water cycle, as shown in Figure 18. The features of the system configuration were;

- The feedwater line branching to the coal-fired boiler and the CSP after the final feedwater heater.
- A common SFP for coal-fired boiler and CSP.
- A single train of HP feedwater heaters
- A flow control valve (CV1) placed in the CSP side on the feedwater line, and
- A flow control valve (CV4) placed in the CRH line

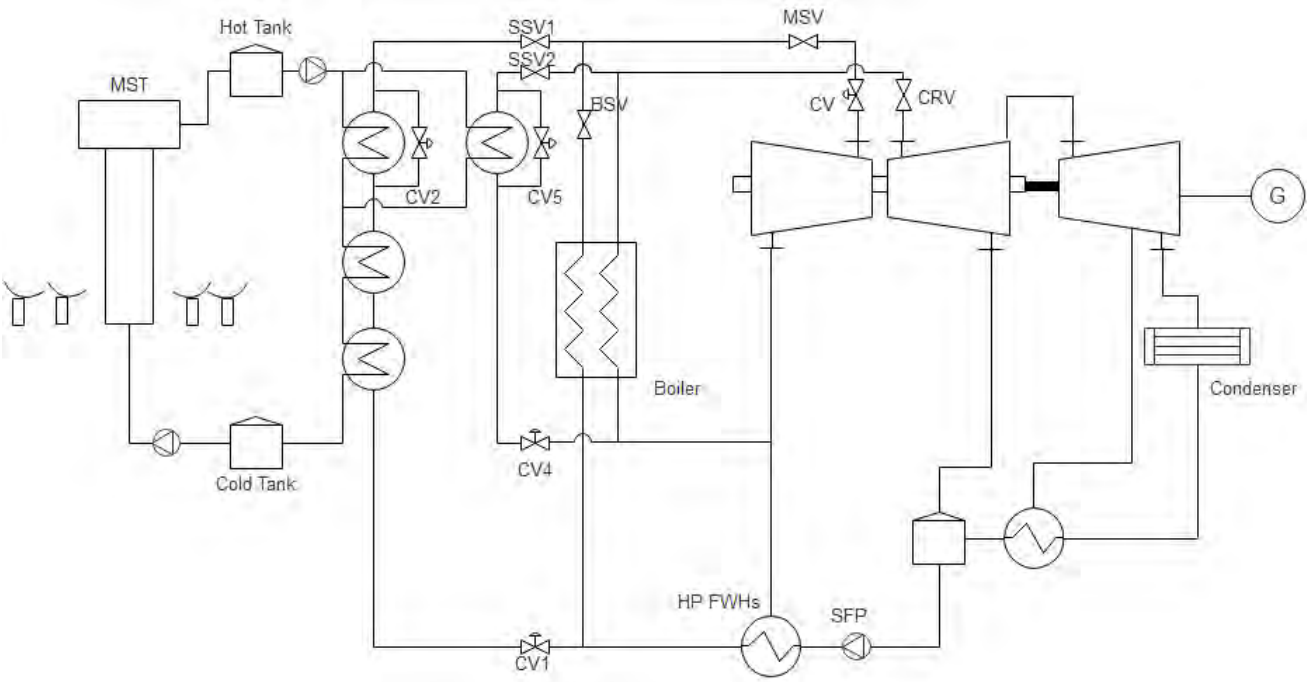


Figure 18 Initial Conceptual Process Flow Diagram

However, as the systems were further analysed it was found that it was not possible for CV1 to control the flow rate while keeping more than 25MPa steam pressure before the MSV across the range of load. This was because the operation of CV1 in hybrid operation would result in a significant pressure loss across CV1 and the main steam pressure at the CSP steam generator would be less than 25MPa.

Then the system configuration was revised as shown in Figure 19. The features of the revised system configuration are;

- Two non-identical HP FWH trains with two non-identical SFPs that are identified as B-SFP and S-SFP.
- Each pump controls the pressure and flow for the coal side and CSP side independently.
- Steam bypass lines from the CSP side and coal side to the condenser

To allow better control of the feedwater flow for the CSP side a dedicated SFP (S-SFP) was required. This was necessary to ensure that the correct steam pressure would be maintained at the MSV under all operating conditions. This resulted in the revised configuration having two SFPs that would be designed specifically for each application since the system head and maximum flow rate are different. Each pump controls the pressure and the flowrate to the boiler side and CSP side independently.

The HP FWH trains will also be non-identical for the coal boiler side and CSP steam generator side. The coal boiler side requires the FWHs to have a feedwater flow capacity equivalent to 330MW, while the CSP side only requires a feedwater flow capacity equivalent to 100MW. This difference in capacity exists due to the different operating modes available for the hybrid plant that was explained in Section 6.4.

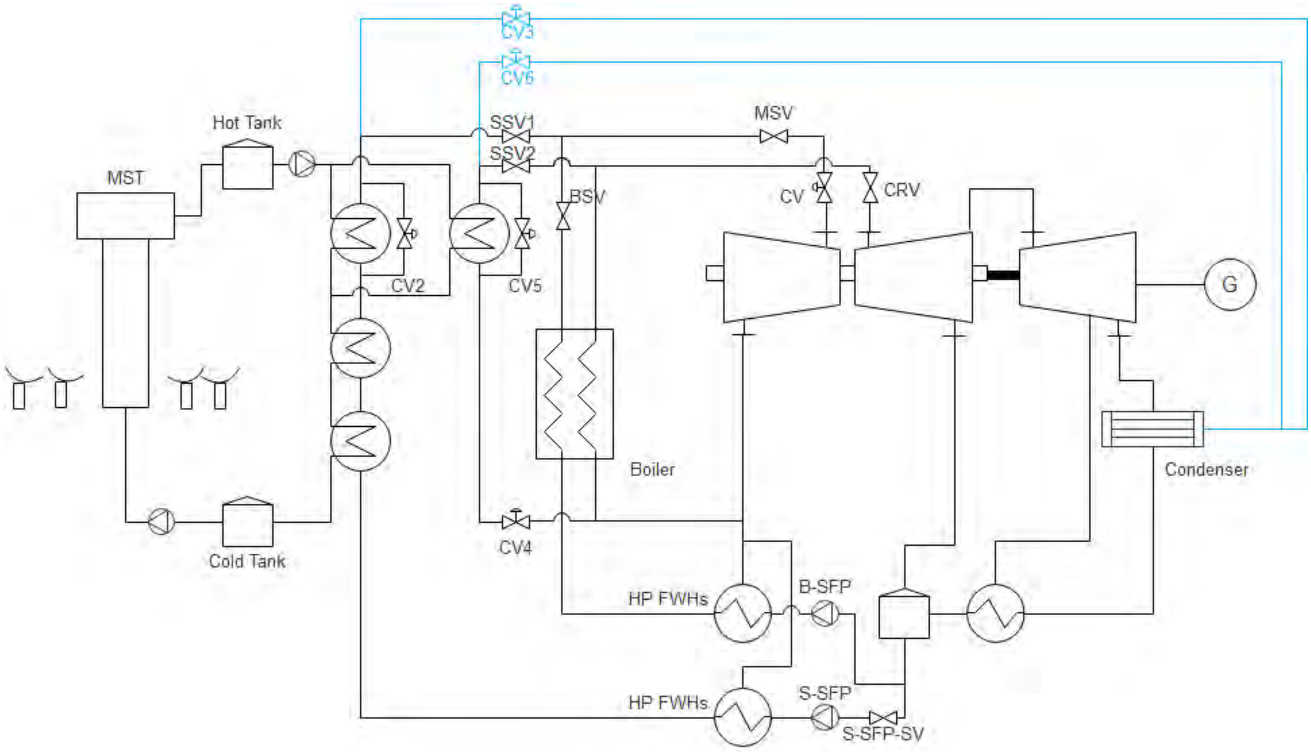


Figure 19 Revised Conceptual Process Flow Diagram

6.4 CONCEPTUAL PLANT CONTROL LOGIC

For the revised plant, there are three proposed operation modes:

1. Boiler only operation,
2. Hybrid Solar/Coal operation, and
3. Boiler plus PV operation

These different modes are shown diagrammatically in Figure 20.

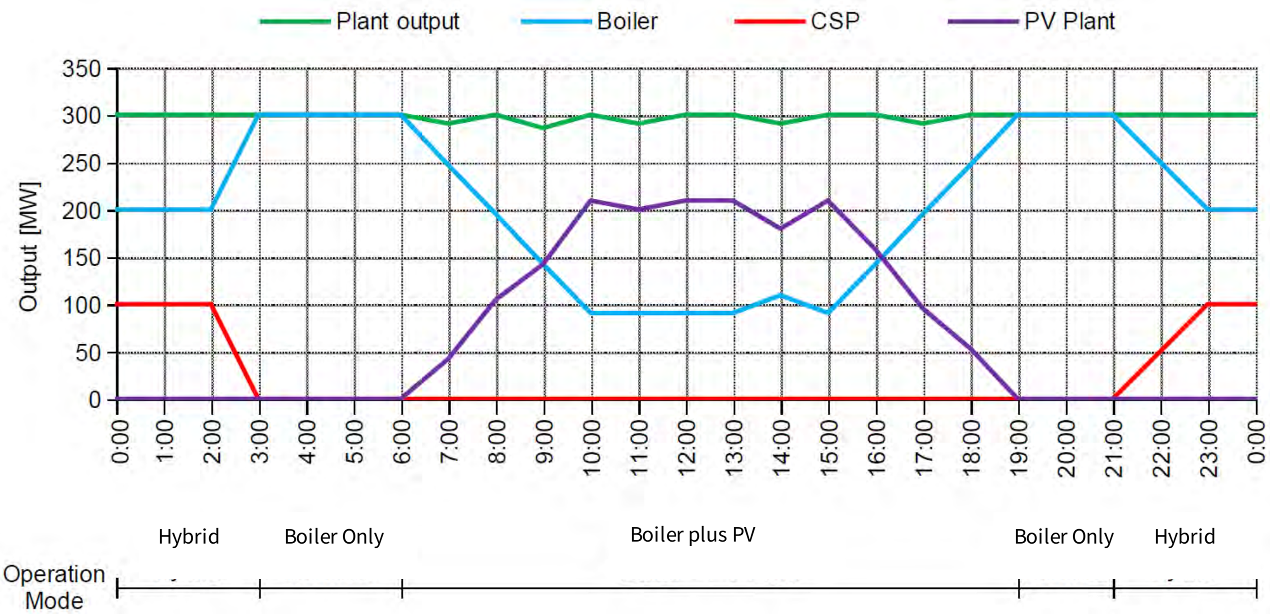


Figure 20 Typical Outline of Plant Operation on a Sunny Day

6.4.1 Boiler Only Operation Mode

When operating with just the coal boiler the Unit Master is set to use coordinated control mode. In this mode, the Unit Master controls the main steam pressure and the generator output as used in a conventional coal-fired power plant. The outline of the control configuration is shown in Figure 21.

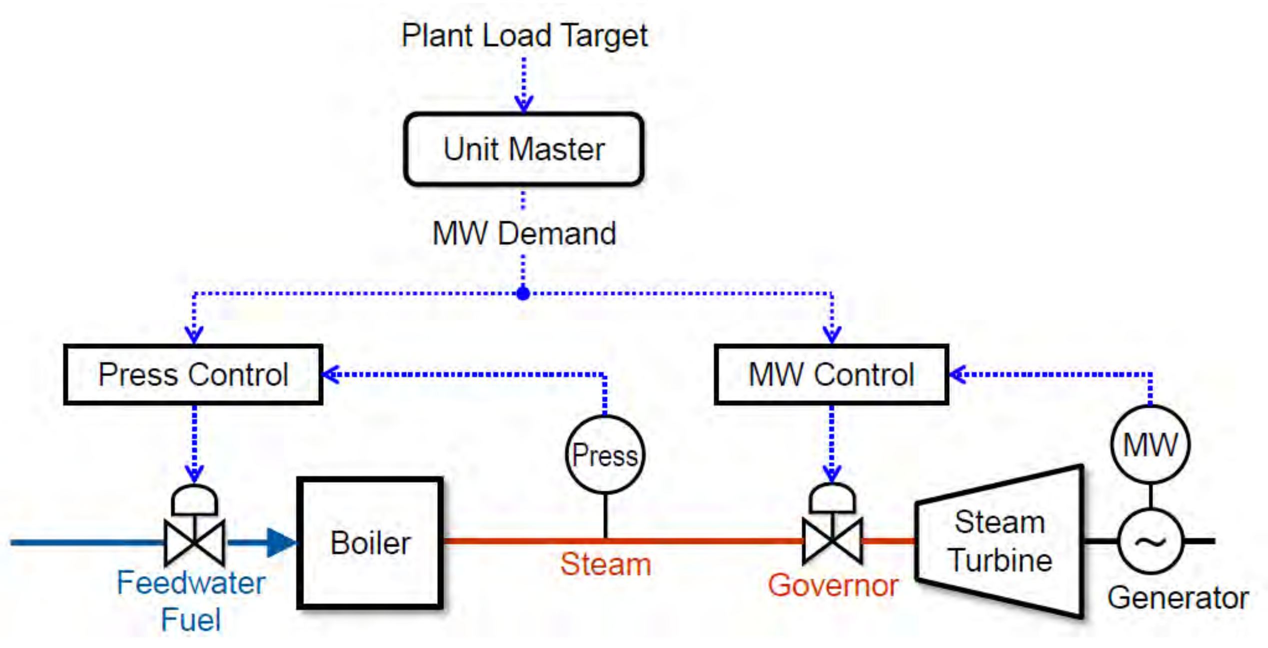


Figure 21 Unit Master Configuration in Boiler Only Operation Mode

6.4.2 Hybrid Solar/Coal Operation Mode

In this operating mode, the steam for the turbine comes from the coal side and CSP side in parallel to meet the plant load output requirement. The Unit Master signals the load demand respectively to the coal side and

CSP so that the individual steam generators output the correct steam requirements. The outline of master control in this mode is shown in Figure 22.

Since the load response of the coal boiler is slow the boiler load is fixed at approximately 200MW (feedwater and fuel input are fixed) and the main steam pressure is controlled by CV3 coming from the CSP. To make up the 300 MW total output the CSP generates the steam equivalent of 110 MW with the excess steam being dumped to the condenser via CV3. By adjusting, the steam discharged to the condenser via CV3 the main steam, pressure is controlled and generator output is controlled by the turbine governor, based on the load demand from Unit Master.

While the plant operation changes from Hybrid Operation Mode to Boiler Only Operation Mode or the other way, the rate of change of the load demand should be within the parameters stipulated by the CSP and boiler manufacturers.

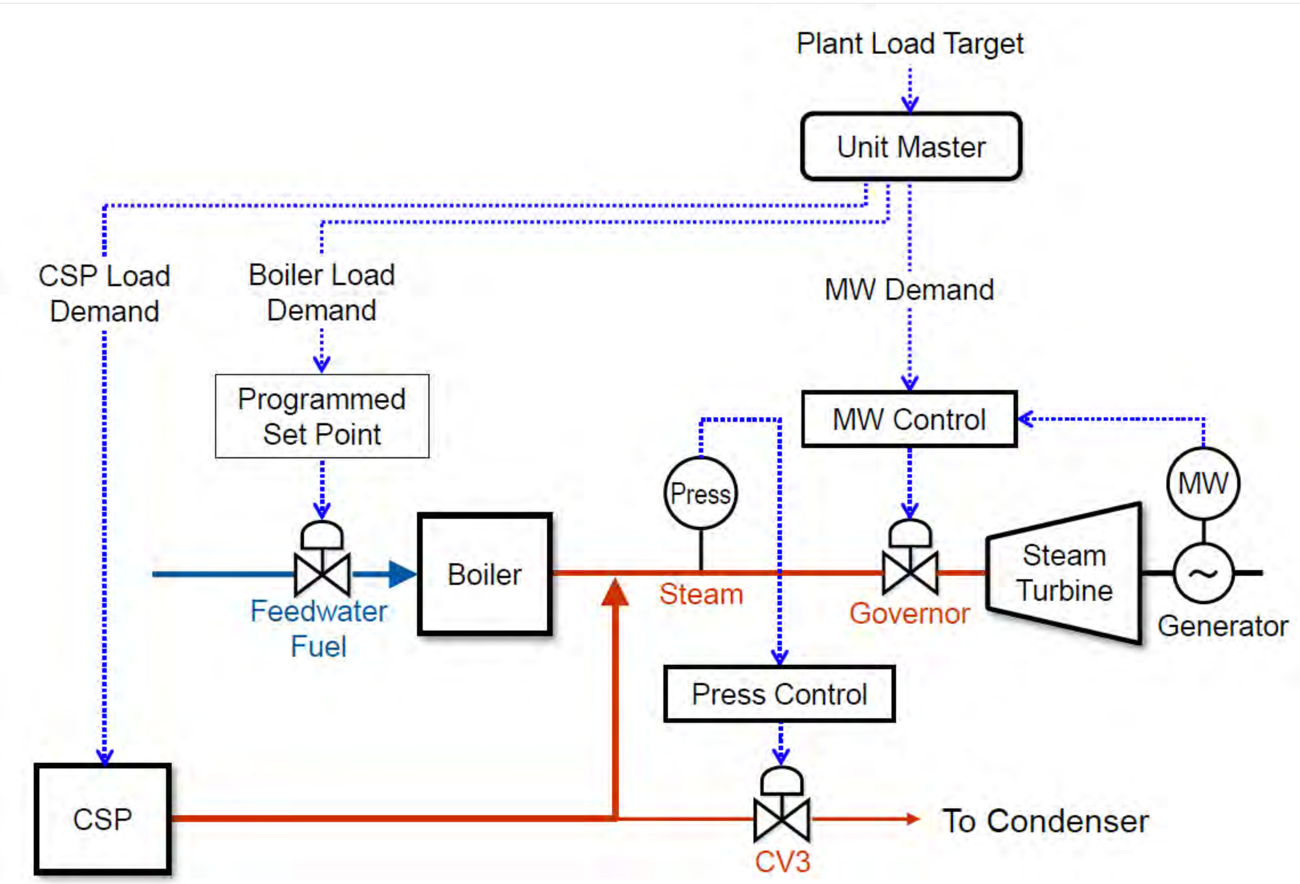


Figure 22 Unit Master Control in Hybrid Solar/Coal Operation Mode

The conceptual methodology of the transition from Boiler Only Operation Mode to Hybrid Operation Mode is as follows.

1. On Boiler Only Operation Mode;
   - 1.1. The CSP Island is isolated from the steam turbine cycle. S-SFP-SV, CV2, CV3, CV4, CV5, CV6, SSV1 and SSV2 are closed (Figure 19).
   - 1.2. The unit operates under the normal “Coordinated Control” mode like a conventional coal-fired power plant.

2. CSP steam generator start-up
    2.1. S-SFP-SV opens; CV4 slightly opens allowing feedwater and CRH steam flow into the CSP side.
    2.2. The main and HRH steam is heated to 550 deg.C by recirculating the steam in the superheater and reheater using CV2 and CV5 respectively.
    2.3. Make-up water is supplied to the condenser during the start-up process to ensure there is adequate capacity in the combined system to create enough steam to generate 300MW.
    2.4. CV3, CV6, SSV1 and SSV2 are still closed.

3. Hybrid Operation Mode starts
    3.1. SSV1 and SSV2 are opened as soon as the required steam pressure and temperature are reached.
    3.2. The steam coming from the CSP steam generator is increased by increasing the HTF flow.
    3.3. The coal side boiler heat load (fuel) is reduced so that the unit can keep 300MW.
    3.4. The main steam pressure is controlled by CV3. For this control, the CSP outputs an equivalent of approximately 110MW and any excess steam not required for generation is discharged to the condenser via CV3. In this way, the main steam pressure upstream of the turbine MSVs is controlled.
    3.5. The generator output is controlled by the turbine governor (CV) based on the load demand from Unit Master.

6.4.3 Boiler plus PV Operation Mode

In this mode all the steam required by the steam turbine is supplied only from the coal boiler so Coordinated Control is used.

The load demand signal changes as per the generated power from the PV Plant. PV output can change suddenly and unexpectedly in a short time due to the nature of the sudden changes in solar irradiation. However, the coal boiler cannot follow a rapid or large load change in a short time due to its slow response. Therefore, the load demand signal needs to be changed within the predetermined ramp rate that is generated using the PV DNI profile. It is important to mention that it is expected that the total generated power will fluctuate in this mode. The outline of the Unit Master control in this mode is shown in Figure 23.

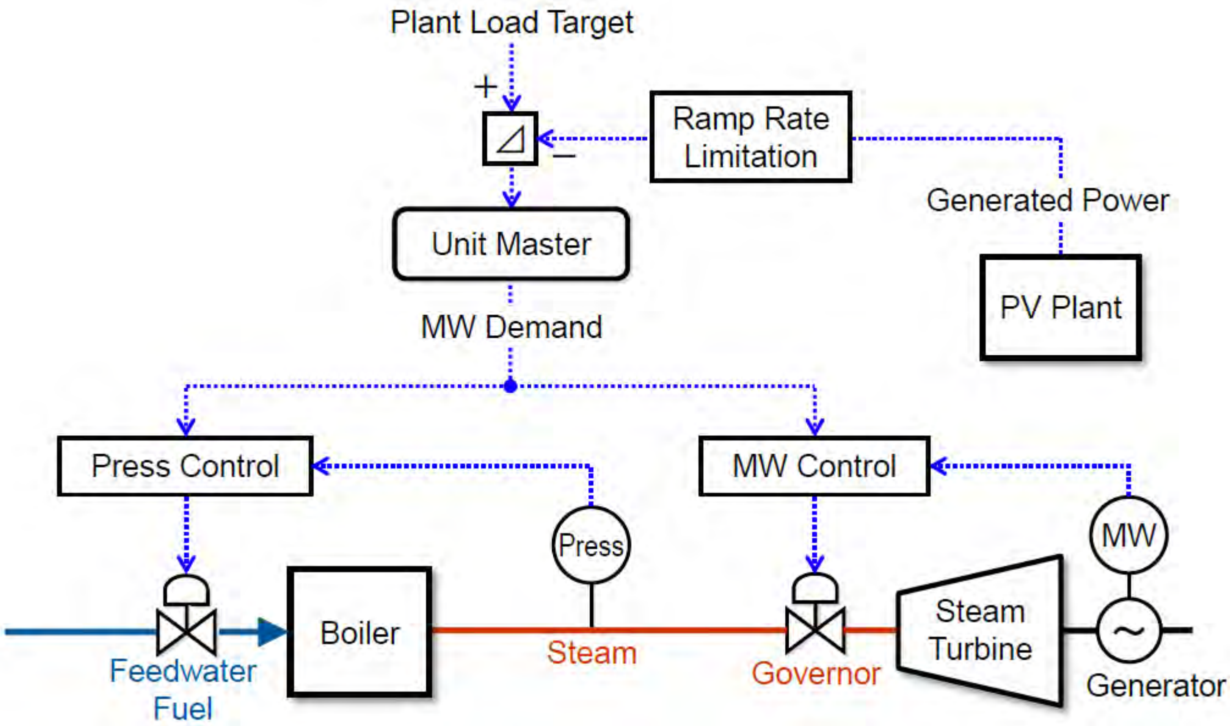


Figure 23 Master Control in Boiler plus PV Operation Mode

6.5 SOLAR/COAL HYBRID PLANT MODEL

6.5.1 Inputs Data, requirements and restrictions

For all the horizons, the scope was based on the following main inputs, requirements and restrictions, which will be considered for the hybrid plant sizing:

- Location: Liddell Area with GPS coordinates: 32° 22´ 16.9´´ S; 150° 58´ 32.0´´ E
- Meteorological Data from Liddell area. Accumulated DNI 1746.88 kW/m^2
- Turbine characteristics: 300MW gross power class turbine island with 250 Bar and operating temperature in the range of 565 °C - 590 °C
- Hybrid facility life plant: 35 years
- Facility annual gross electric power generation considering minor and major overhauls: 2234 GWhe
- Exportation limit for the hybrid plant: 300 MW Gross Power
- USC coal boiler operating range: 90 MW to 300 MW
- Dispatchability Strategy
- Solar production share: Electrical production coming from solar source will be optimized to achieve the maximum cost-effective Solar Ratio contribution

Operational restrictions coming from the existing USC Boiler technology to consider for parallel operation between CSP & Boiler are as follow:

- CSP + Boiler parallel operation constraints:
  - STG output > 200 MW: Parallel operation is allowed
  - STG output < 200 MW: Parallel operation is not allowed

6.5.2 Solar/Coal hybrid plant Performance Model description

The optimal Solar/Coal hybrid plant for Horizon 1 was obtained by using the Abengoa Power Plant Performance Model (hereafter PM). This tool is a software developed by Abengoa that models the behaviour of the main equipment involved in a Hybrid Solar Power plants (solar field, solar receiver, salt tanks, salt pumps, salt main pipes, steam generator, PV plant, Electric Heaters, power block, etc.) and generates annual productions of the configured plant.

A simplified module of a USC Boiler was modelled to integrate the non-renewable generation of the power plant. This model is an energy module that responds to the electricity demand of the power plant (considered as a flat demand of 300 MW), adjusting its electricity generation each time-step simulation as a function of the generation capacity of the renewables technologies integrated into the PM. The generation of the USC Boiler was affected by the restrictions cited in section 6.2.1 and the limits in the transitions. For the other solar components, the PV Power generation has been obtained by using a commercial software called PVsyst taking into account the meteorological data from the project location. Electrical generation calculated by PVsyst is used in the PM as an input for the whole Solar/Coal hybrid plant model. Additionally, a thermodynamic model of the water-steam cycle was built in the Thermoflex software and it was used by the PM to simulate the performance of the water-steam cycle under the different operating conditions of the power plant.

Power generation estimated by the PM will, therefore, calculated the breakdown generation between the different technologies considered; i.e. annual generation separated into generation from Coal Plant, Molten salts Tower Power Plant and PV Plant. Finally, the renewable energy share was calculated as the annual generation from the PV and CSP plants combined.

The procedure followed to determine the optimum configuration and sizing of the hybrid power plant for this project was a process aimed at finding the most cost-effective solution for the baseline (Horizon1) maximizing the renewable energy share taking into account that were not going to be substantial changes for the more complex horizons. First, the particular boundary conditions (equipment limitations, generation restrictions etc.) were defined and programmed in the software, so all the simulations performed took into account the project conditions. All the pieces of equipment were modelled and integrated into a Hybrid Power plant model that combines different technologies with the generation of each of them governed by a strategy of operation programmed to maximize the annual plant generation.

Once the plant performance model was ready, the plant optimization process started by defining the fundamental variables that needed to be studied to define the final plant configuration. These variables were identified and listed. The optimization process consisted of a parametric simulation considering all these variables and evaluating its annual generation impact compared to its costs. The result was a parametric table where the cost-effectiveness of each solution was compared allowing to select the best configuration for the project.

In this project, the critical optimization variables identified were the following:

- PV Peak power
- Solar receiver thermal power
- Solar field number of heliostats
- Thermal storage capacity
- PV-CSP-Coal Boiler interaction

6.6 SOLAR/COAL HYBRID PLANT SIZING

The optimal USC Solar/Coal Hybrid plants for Horizon 1 Scenario A and Scenario B are described within this section. The renewable solution has been designed considering the following sizing criteria:

- Selection of the most efficient power plant key components for the particular conditions of this stage
- Minimize the ratio CAPEX / Generation
- Maximize the renewables share

6.6.1 Horizon 1 – Scenario A

Horizon 1 – Scenario A solution comprehends a Photovoltaics plant and a Molten salts Tower concentrated solar power plant. The combination of these two solar technologies in the hybridization process optimised the cost of the final solution maximizing the electricity production coming from the renewable source. The simulation process started with a pre-design plant used as starting point to perform the parametric simulations. Three parametric analysis were performed to identify the (i) solar field optimum sizing, (ii) TES system optimum sizing and finally (iii) Solar Receiver optimum sizing.

Solar Field sizing

Several solar field configurations were prepared for different solar fields starting from 3000 heliostats up to 8000 heliostats. The rest of the plant parameters were kept constant to be able to compare the impact of the solar field size over the plant generation, the index CAPEX/Generation and the solar field dumping. The plant predesign considered a TES system with 14 equivalent hours and a Solar Receiver of 400 MWth, i.e. all the simulations performed in the solar field parametric analysis were done using these fixed parameters.

The following criteria were followed to decide the optimum solar field size:

- Minimize the ratio CAPEX / Generation
- Maximize the annual plant generation per heliostat installed
- Maintain the solar field annual energy dumping possible
- Maximize as much as possible the impact over the plant renewable ratio

Figure 24 shows the results of the parametric analysis. **Attending to the criteria previously mentioned, the optimum solar field size was 5000 Heliostats**. This is the compromise solution to keep the minimum CAPEX / Generation ratio, highest generation per heliostat (meaning that a further increase in the number of heliostats installed would not be cost-effective) and an annual solar field dumping below 15%.

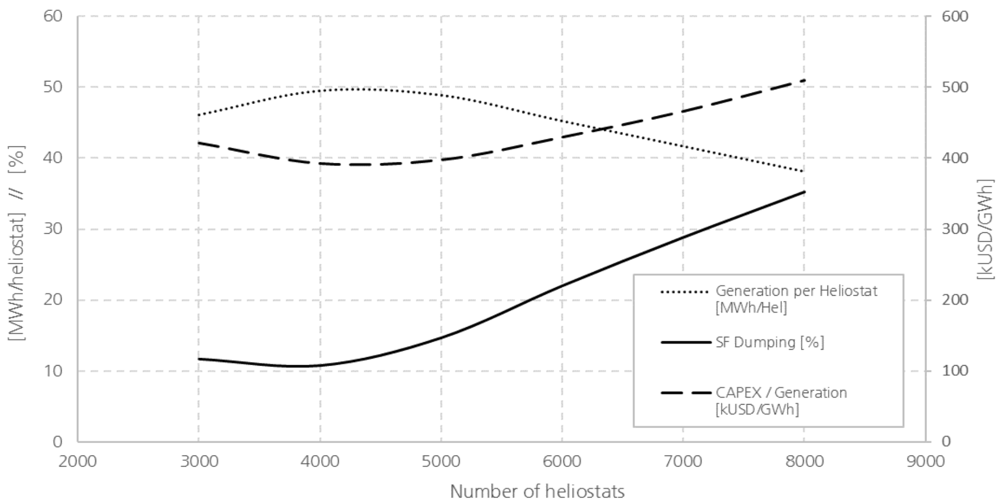


Figure 24 Solar field parametric analysis

TES system sizing

The optimization process continued with the finding of the optimum size for the TES system. Using the optimum solar field size previously studied (5000 He), and the same Solar Receiver size used in all the previous iterations, a parametric analysis was now performed varying the number of equivalent hours of molten salts storage.

The following criteria were followed to decide the optimum TES system size:

- Minimize the ratio TES CAPEX / Generation
- Maximize the annual plant generation
- Maintain the solar field annual energy dumping possible
- Maximize as much as possible the impact over the plant renewable ratio

Figure 25 presents the results of the analysis where an opposite effect appears in terms of CAPEX/Generation index and solar field dumping. On one side, the CAPEX/Generation index achieves lower values as the TES system is reduced, however on the other side the solar field dumping with less than 13 equivalent hours of storage is very high meaning a non-effective use of the solar field. The trend of the CSP Gross Generation is flattened in between 13 and 14 equivalent hours. Considering all these factors, **the optimum TES systemsize selected was 14 equivalent hours**.

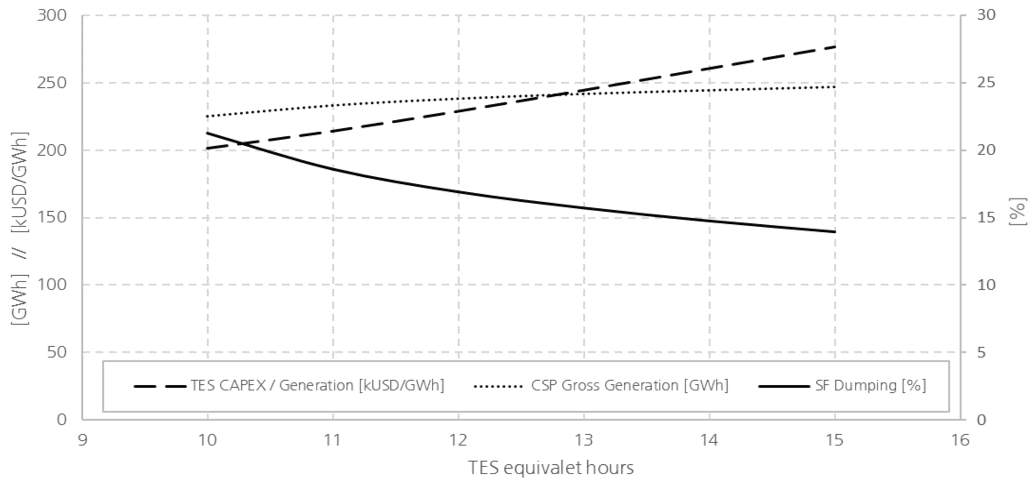


Figure 25 TES system parametric analysis

Solar Receiver Sizing

Once the solar filed size and the TES system equivalent hours were selected, choosing the correct power of the solar receiver (SR) had an important impact on the annual generation. The CSP configuration process concluded with the last parametric analysis to evaluate the impact of different SR thermal power.

Figure 26 shows the results of the Solar Receiver parametric evaluation. **The Solar receiver optimal size for the selected configuration in this project was 350 MWth**. This solar receiver thermal power optimizes the plant gross generation and minimizes the solar field dumping. The symmetric bell-shaped curve of the plant gross generation can be explained if it is considered the effect of the two restrictions of the solar receiver:

- Minimum incident thermal power: the solar receiver has a minimum incident thermal power for an operation that depends on the size of the receiver. Receiver with higher thermal powers will also have a more restrictive limit in terms of minimum thermal power for operation. This restriction introduces a disadvantage for larger receivers which need more solar energy to start the daily operation

- Maximum incident thermal power: lager solar receivers will be able to collect more solar energy at high radiation instants and take advantage of the solar field size installed.

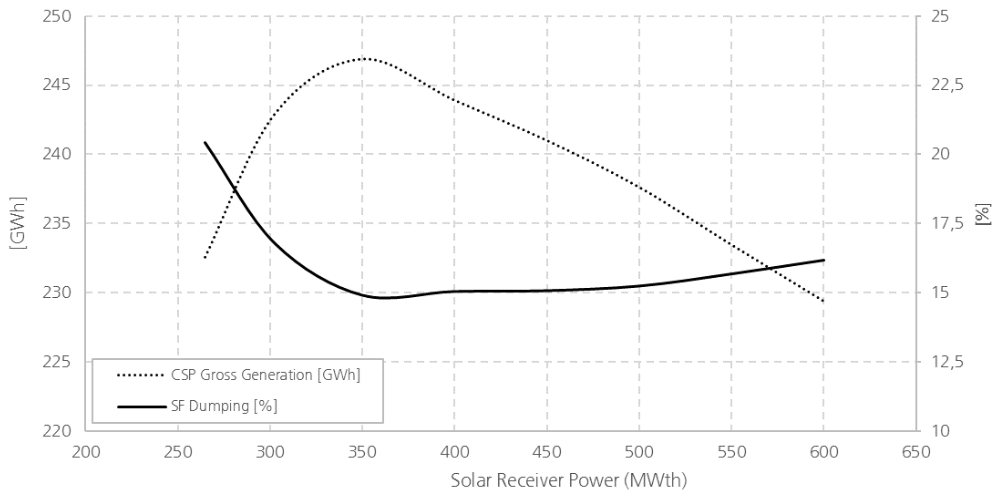


Figure 26 Solar receiver parametric analysis

PV Sizing

The sizing of the PV system is conditioned by the load of USC Boiler which cannot be reduce below 90MW; i.e. the maximum gross power that can be exported by the PV system when operating in parallel with the USC Boiler is 210 MW.

The following criteria was followed to decide the optimum PV sizing:

- Minimize the ratio TES CAPEX / Generation
- Maximize the annual plant generation
- Keep the PV annual dumping below 2%

In light of the results of the parametric analysis of the PV Peak power displayed in Figure 27, **the optimum PV size was 290 MWp which achieves a PV dumping of 1.8%** and has a CAPEX/Generation ratio almost minimum compared to the rest of scenarios analysed.

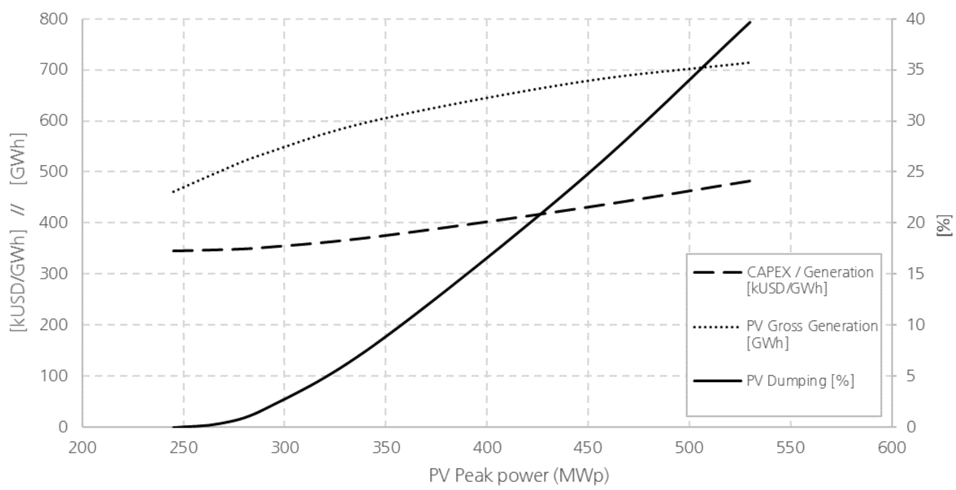


Figure 27 PV parametric analysis

6.6.2 Horizon 1 – Scenario B

Horizon 1 - Scenario B considered a further step in the hybridization of the renewable solution considered, integrating electrical heaters in the TES system. Molten salts electrical heaters, which were fed by the PV dumping increasing the temperature of part of the salts used in the storage system. Accordingly, considering the PV system configured for the Scenario A presented above, a dedicated module was used in the Abengoa Power Plant Performance Model to consider the effect of the installation of an electrical heater that benefits from the PV dumped energy to store additional energy in the TES system.

The molten salts electrical heaters optimum power depends on the PV energy that can be used to feed the heaters. According to the PV sizing selected (290 MWp) and its associated annual dumped energy, a parametric analysis varying the molten salts electrical heaters power have been performed. The results of this evaluation shown in Figure 28, indicates that **electrical heaters of 20 MWth were the optimum option for this project**. With this configuration, the PV dumping is reduced to 0.4%. It can be also observed that heaters with installed power over 30 MW do not increase the electric heater exchanged power.

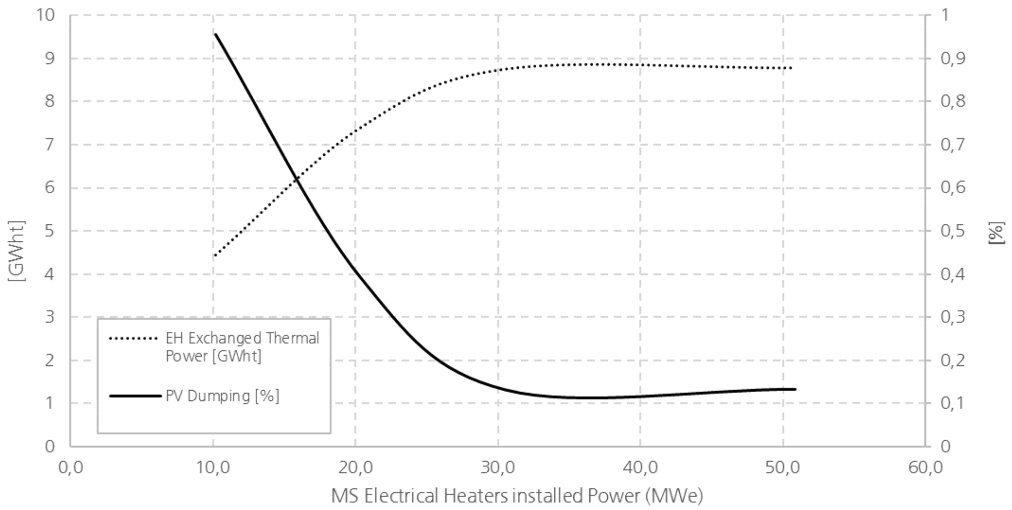


Figure 28 Molten salts electrical heater parametric analysis

6.7 SOLAR/COAL HYBRID OPTIMAL CONFIGURATIONS FOR HORIZON 1

The result of the plant sizing study for Horizon 1 and associated Renewable share is as follows.

Horizon 1 - Scenario A

- CSP solar field: 5000 Heliostats
- TES system: 14 equivalent hours
- The solar receiver 350 MWth
- PV plant Peak Power 290 MWp

Renewable Share: 29.28 %

Horizon 1 - Scenario B

- CSP solar field: 5000 Heliostats
- TES system: 14 equivalent hours

- The solar receiver 350 MWth
- PV plant Peak Power 290 MWp
- Electrical heaters 20 MWe

Renewable Share: 29.95 %

6.8 TYPICAL UNIT POWER GENERATION PROFILE

The 24-hour power generation profile was generated considering the ambient weather condition (Section 2.1.2), all of the equipment performance (Section 3, 4 and 5) and hybrid plant operational principles (Section 6.2). In fact, the result of Section 6.7 comes from the calculation result of the 24-hour power generation profile across a year.

This section introduces some of the distinctive hourly profile in a year.

Figure 29 shows the profile on a clear summer day near the summer solstice. During the daytime, from 0700 to 1600, there is enough DNI to allow the PV system to generate 210MW. In this duration, the boiler can reduce load to a minimum of 90MW and keep it around 10 hours. As the DNI decreases in the evening, the boiler ramps up so that the plant output is maintained at 300MW. At the same time, the CSP generates steam allowing the hybrid operation of the plant to starts. Due to enough stored thermal energy during the daytime, the CSP can generate steam during the whole night.

The estimation of the plant output every day for 365 days under different ambient conditions with a very high degree of accuracy would take an excessive amount of time and this was not practical for this study so an estimate of the output based on 4 different operating situations was considered and the results are shown in Figure 29 to Figure 32. In these figures, the overall accuracy of the heat balance calculations was set lower to expedite the results, so the total plant power output does not match exactly to 300 MW.

Figure 29 shows the profile depicted above of a clear summer day

Figure 30 shows the profile on a clear winter day near the winter solstice.

Figure 31 shows the profile on a clear autumn day near the equinox. The trend itself is the same as the summer case. However, the duration boiler can keep the minimum load is around 7 hours.

Figure 29 to Figure 31 show the trend on a clear day but a completely clear day is not a realistic and very rare in a year. Hence, Figure 32 shows the trend on a cloudy day in spring. The accumulated DNI in a day is equivalent to its yearly average so this trend can be stated as the typical operational trend for this plant. In the same way, the PV generation amount is dependent on DNI and its power profile changes drastically due to the changes of DNI, in other words, the changes in the weather condition. The boiler operates so that the total plant gross output keeps 300MW as described in Section 6.2.

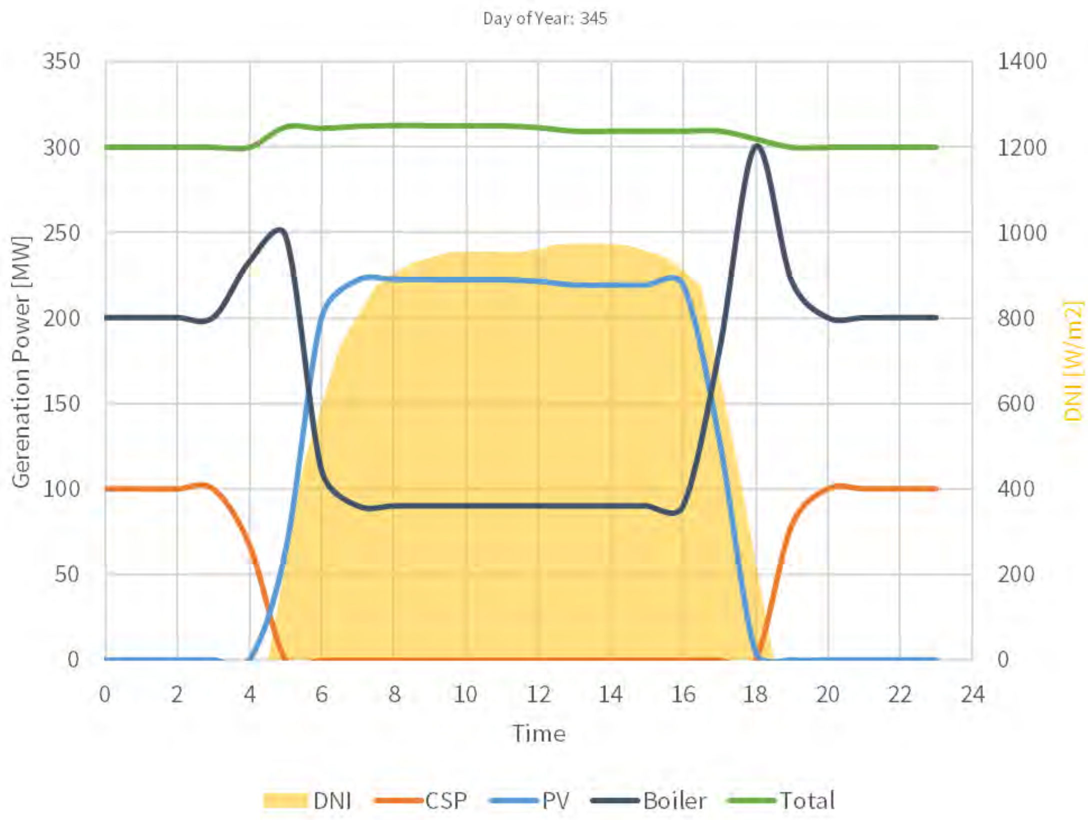


Figure 29 Plant power generation profile on a clear summer day

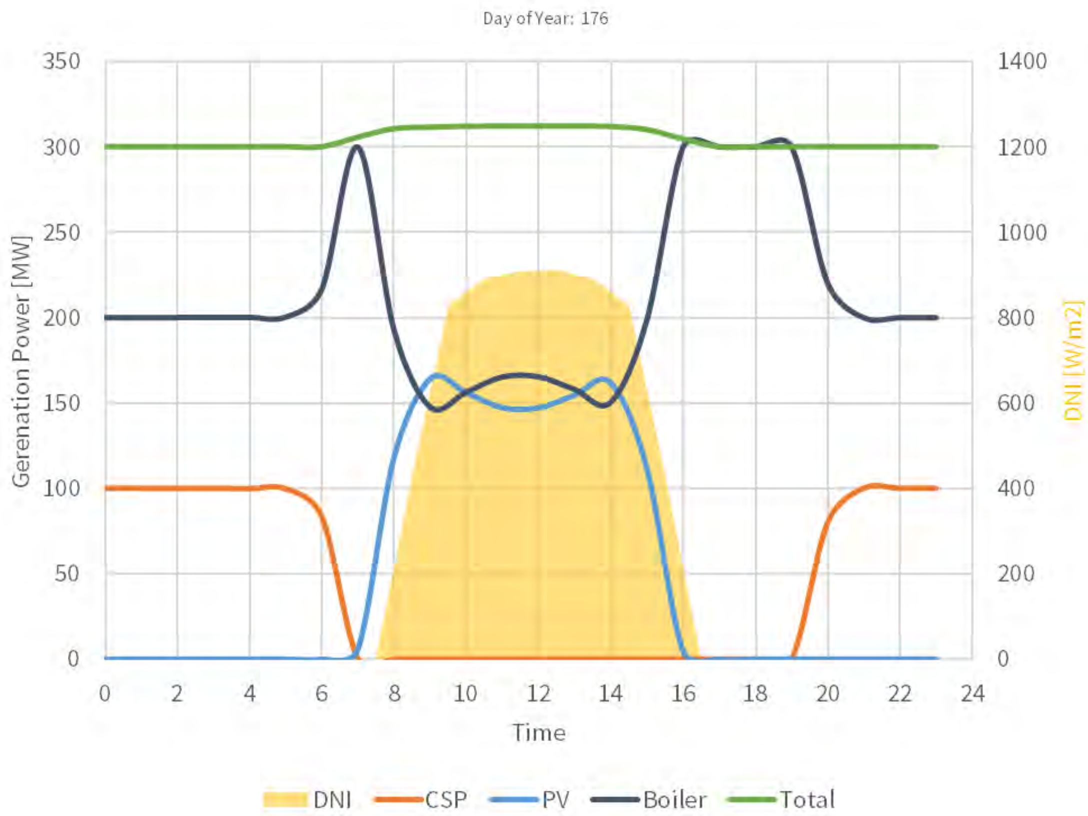


Figure 30 Plant power generation profile on a clear winter day

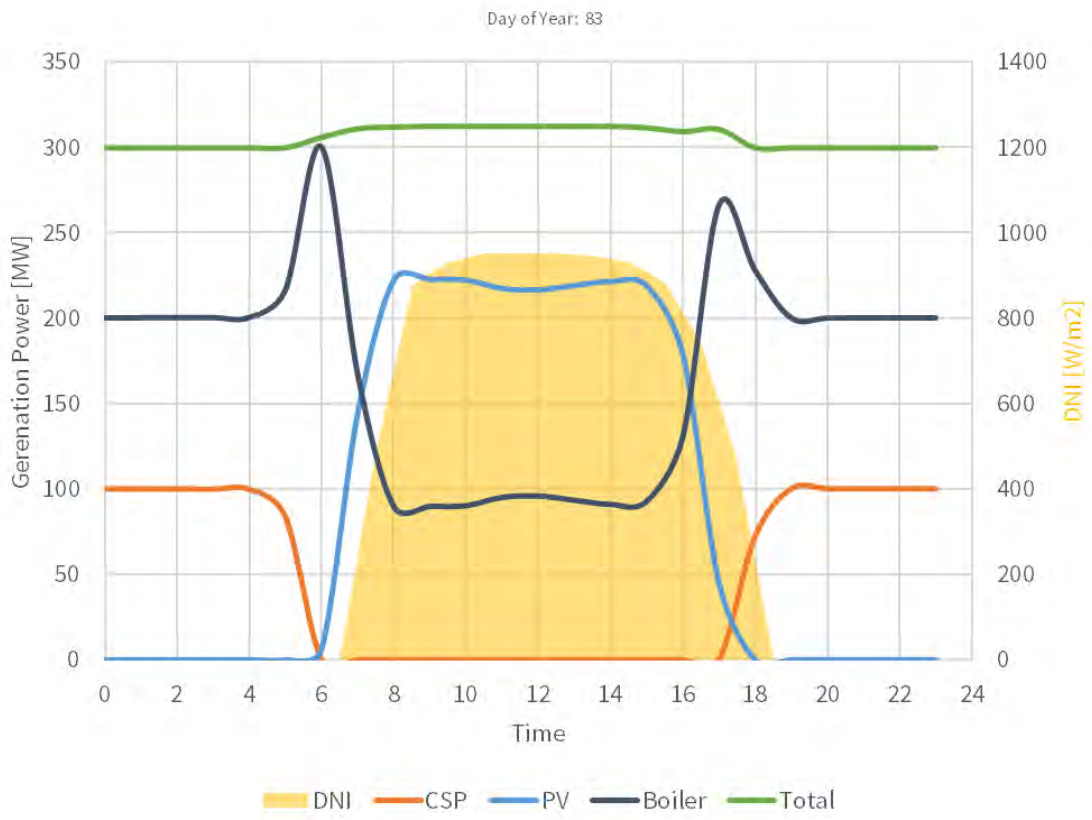


Figure 31 Plant power generation profile on a clear spring/autumn day

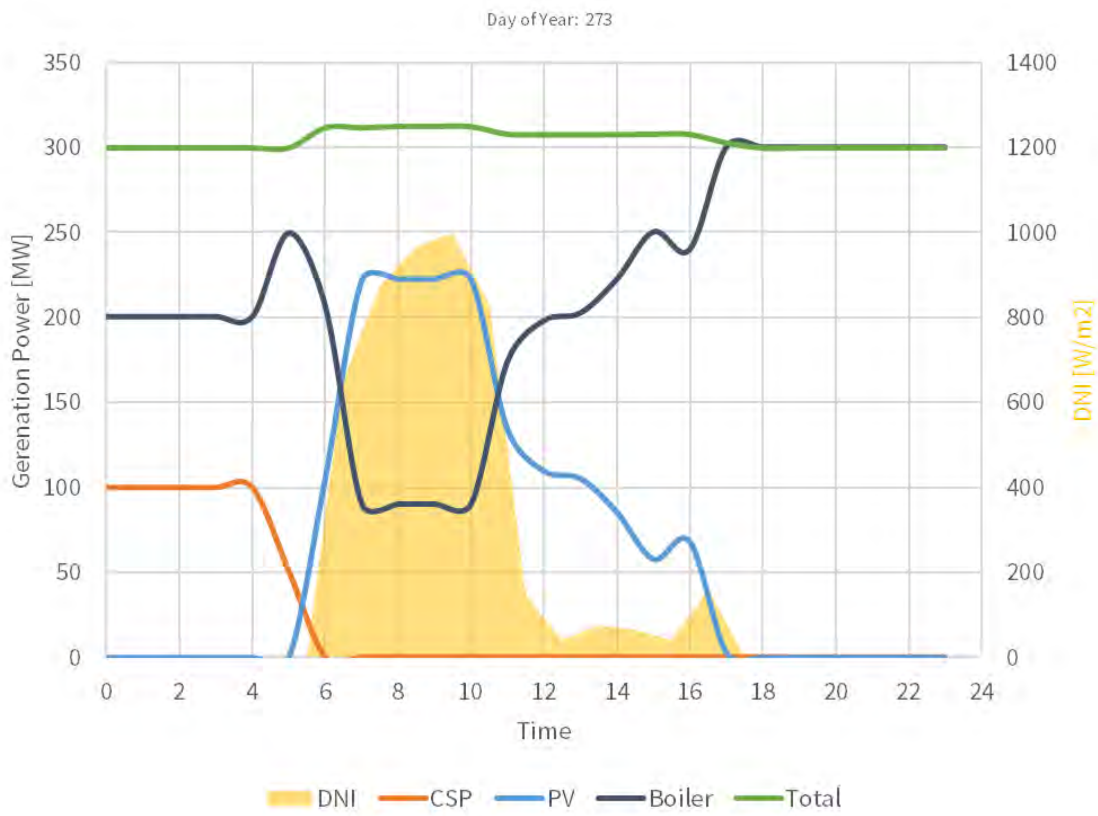


Figure 32 Plant power generation profile on an average accumulated DNI day

Table 20 shows the power generation share for PV, CSP and the boiler. The renewable share could reach almost 50% on a clear summer day. It could also be more than 40% in a clear equinox day. In average, it would be around 29% that follows the description in Section 6.7. Approximately, i**t could be concluded that this plant can reduce around 30% coal fuel and 30% CO_2 emission compared with the same capacity of the conventional coal-fired plant**. However, it can safely assumed that this reduction could be around 25% if it is considered the frequent low-efficiency operation such as the minimum load operation and the ramp-up.

Table 20 Power generation share

Climate condition	Respective figure	Accumulated DNI in a day W/m^2	PV share %	CSP share %	Boiler share %
A clear day near the Summer solstice	Figure 29	11070	36%	13%	52%
A clear day near Winter solstice	Figure 30	6126	16%	15%	69%
A clear day near Equinox day	Figure 31	9112	29%	16%	55%
An average day	Figure 32	4839	21%	8%	71%

6.9 DISCUSSIONS – HORIZON 1

The basic design for Horizon 1 was completed.

- ✓ Solar/coal hybrid plant operational principle was proposed considering the general boiler operational characteristics regarding the main steam pressure and STG load control. Only the case in which more steam flow equivalent to 200MW coming from the boiler, the parallel operation can be acceptable because of the main steam pressure can be controlled constant regardless of the amount of steam from the CSP. Controlling the boiler steam pressure freely regardless of the steam flow into the HP turbine is not practical for a supercritical boiler under the current commercialized technology.

- ✓ The conceptual plant flow diagram was proposed. The steam cycle configuration was revised from the original concept because of the necessity to control the feedwater pressure and flow for the boiler side and CSP side independently. The features of the system configuration are;
  - Two non-identical HP FWH trains with two non-identical SFPs - B-SFP and S-SFP.
  - Each pump controlling the pressure and flow for the boiler side and CSP side independently.
  - Steam bypass line from CSP side to the condenser for CSP start-up and pressure control purpose.
  - Steam bypass line from the boiler to the condenser

- ✓ The conceptual plant control logic was proposed for the following three operational modes.
  - Boiler Only Operation Mode
  - Hybrid Solar/Coal Operation Mode
  - Boiler plus PV Operation Mode

- ✓ Main equipment basic design specification was proposed. The boiler and steam turbine can be designed at the boiler single operation at rated load. Even though the operational range for the steam turbine and feedwater system were different from a conventional coal-fired plant due to the mixture of steam coming from CSP, no special design philosophy or specification was required for the boiler and steam cycle from the point of mechanical design.

- ✓ The number of Heliostat, TES capacity, solar receiver capacity and PV capacity was optimised. The following criteria was followed for optimization and to reach a final configuration (scenario B).
  - o Minimize the ratio CAPEX / Generation
  - o Minimize the solar field annual energy dumping
  - o Maximize the plant renewable ratio

- ✓ Operational profiles in typical days was proposed. The renewable share could reach almost 50% on a clear summer day. It could also be more than 40% even in a clear equinox day. In average in annual climate condition, it would be around 29% on average. Roughly speaking, it could be concluded that this plant can reduce around 30% coal fuel, which means it can reduce 30% of CO_2 emission compared with the same capacity of the conventional coal-fired plant. However, this number may vary between plus or minus 5% depending on the frequency of low-efficiency operation such as the minimum load operation and the ramp-up speed.

7 INTEGRATION FOR THE HYBRID SYSTEM FOR HORIZON 2

7.1 SOLAR PLANT CONFIGURATION AND LIMITATIONS TO BE USED FOR HORIZON 2

The proposed configuration for Horizon 1 was based on a hybrid facility using PV and MST as the main solar technologies to be integrated with the USC coal plant. MST used nitrates salts (60% NaNO3-40% KNO3) as the heat transfer fluid that is heated in the receiver up to 565 deg.C. Then, USC steam is produced in the salts-to-steam SGS at 550 deg.C. This steam is typically combined with the USC steam coming from the boiler to feed the USC turbine. The CSP configuration scheme and CSP design proposal are shown in Figure 33.

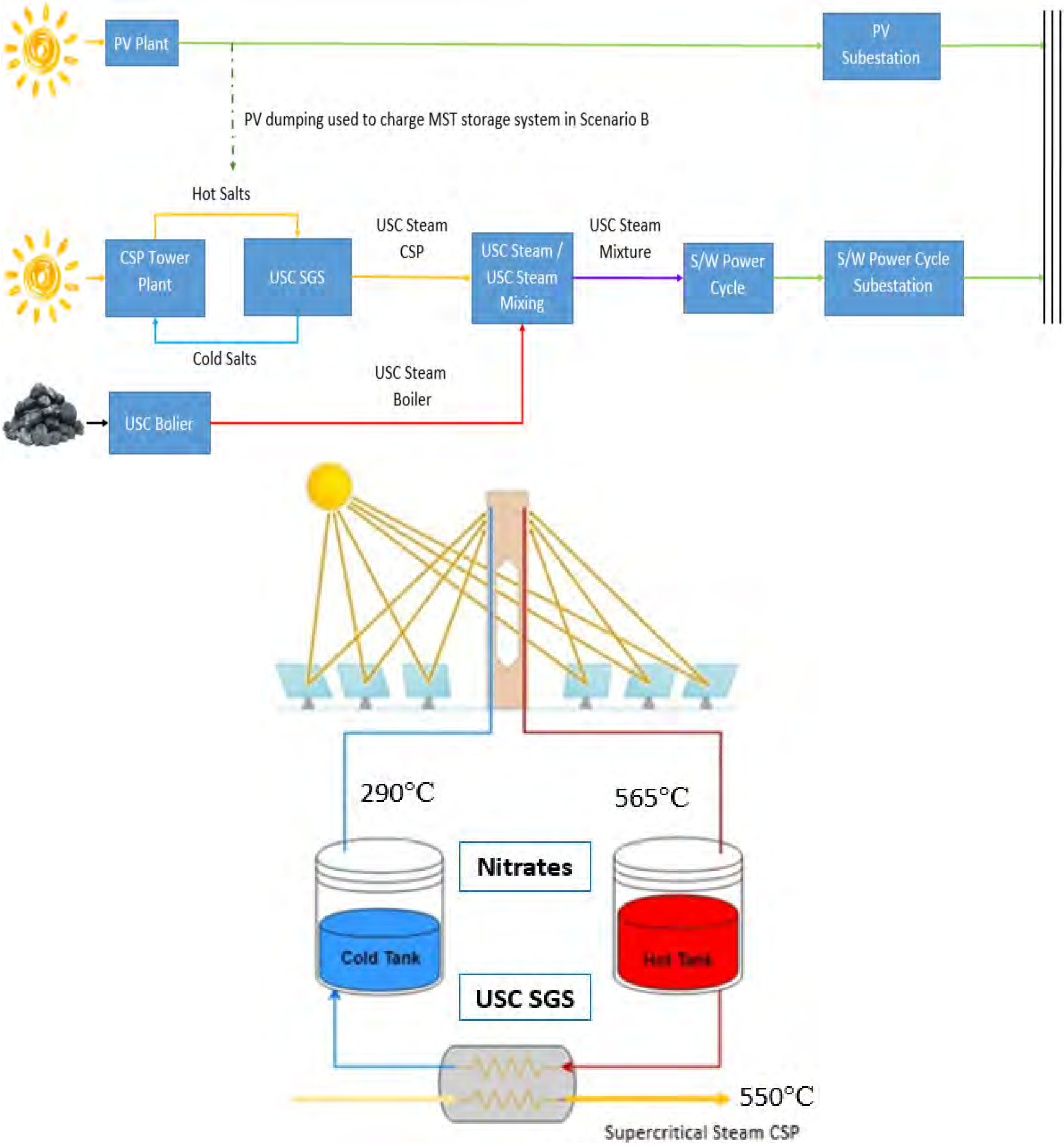


Figure 33. a) Up, Hybrid Solar/Coal plant configuration; b), Down, CSP design proposal for Horizon 1

Currently the nitrates thermal stability is the main drawback to use this fluid for more demanding CSP applications in terms of temperature. The current proposed operating temperature, 565 deg.C in the outlet of the solar receiver, was already close to the maximum operating temperature allowed for this mixture of nitrates.
Higher nitrates operating temperatures would produce two main effects (Walczak M, 2018):

- Nitrates thermal degradation generating a high content of oxidizing species
- Enhance the nitrates salt corrosiveness over the selection of the materials of the installation

Horizon 2 target would require heating the nitrates salts up to 615 deg.C to obtain the USC steam at 600 deg.C. Therefore, this temperature requirement was not feasible using nitrates salts alone under the plant configuration proposed in Horizon 1. As mentioned before several alternatives will be evaluated in the following Sections (7.2 and 7.3) to cover the inlet turbine temperature required in Horizon 2.

7.2 ALTERNATIVE HEAT TRANSFER FLUIDS TO BE USED FOR HORIZON 2&3

Attending to the previous discussion, fluids with higher thermal stability than nitrates should be used to obtain USC steam at 600 deg.C coming from the CSP plant. The new HTF should meet the following requirements to be considered as a potential candidate (Vignarooban K, 2015):

- Low melting point
- High boiling point
- High thermal stability
- Low vapour pressure at high temperature
- Low corrosion with metal alloys
- Low Viscosity
- High thermal conductivity
- High heat capacity
- Low cost

Heat transfer fluids could be classified into the following categories:

- Gases
- Water/Steam
- Thermal oils and Organics
- Molten salts
- Liquid metals

Figure 34 shows the typical operating temperature range for different HTFs:

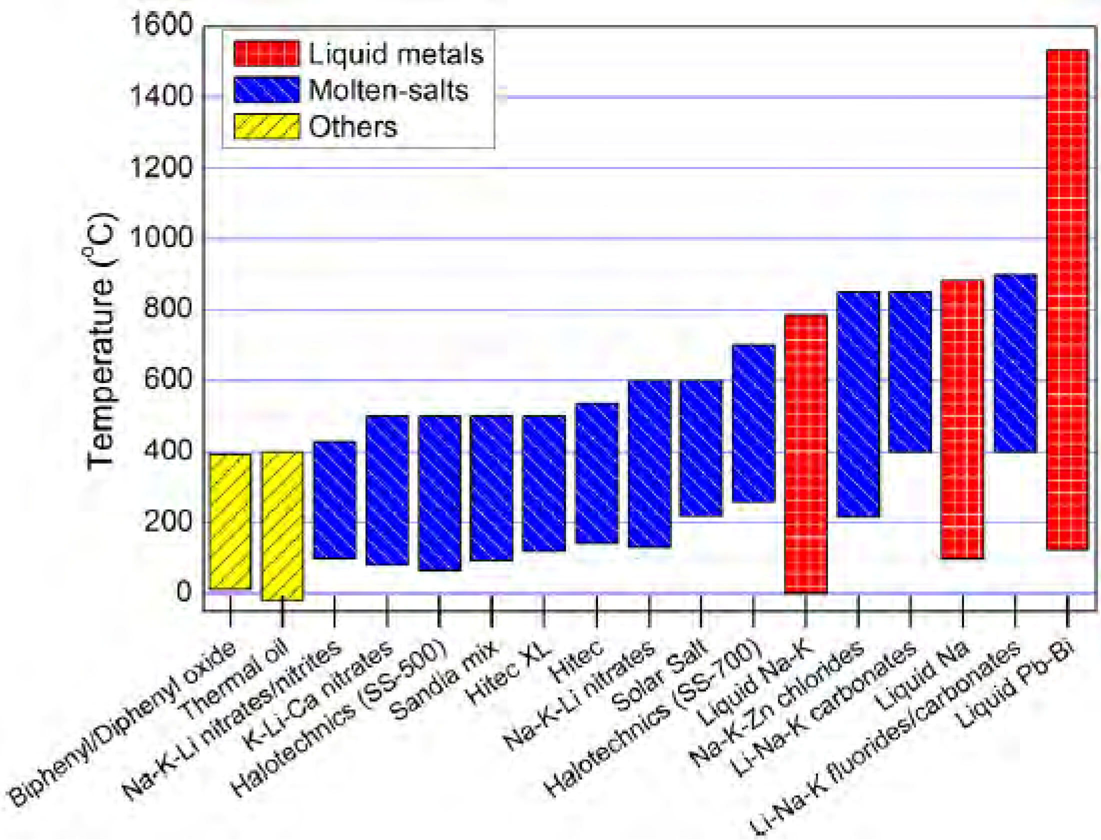


Figure 34 Operating temperature range for different heat transfer fluids

Most of the potential heat transfer fluids have limitations that restrict the usage as an HTF for Horizon 2. The main limitations for each fluid is discussed in the following points.

- Gases. Air and other gases are a relatively uncommon HTF for large CSP plants. The main reason is the lack of technical-economic feasibility for TES systems associated with CSP configurations using these types of HTF's. As the Hybrid Solar/Coal power plant under design for Horizon 2 requires a storage system providing more than 10 hours of energy without solar resource, this option as an HTF was discarded

- Water/Steam. This HTF is also discarded for the same reason explained before for Gases

- Thermal oils and other organic fluids. Most of these fluids have an operating temperature limitation associated with their thermal stability that is close to 400 deg.C as shown in Figure 34. Other drawbacks associated with thermal oil and organic fluids are the high associated cost per kg and high vapour pressure. Then, these fluids were also discarded for our application

- Liquid metals. Liquid metals have been used in nuclear industries since the mid-'90s and are currently being studied for use in solar thermal systems as HTFs and thermal energy storage media. Although liquid metals show excellent properties to be considered as HTF (extensive operating temperature range, low viscosity, high heat transfer characteristics, among others), these types of fluids are not considered as a real option in the midterm. Main reasons are as follows: lack of experience at large commercial scale, safety issues, and cost and materials compatibility.

Molten-salts, however, make excellent HTFs mainly due to their thermal stability at high temperatures (Operating temperature > 500 deg.C). Molten salts also have properties comparable to water at high temperature including similar viscosity and low vapour pressure.

Nitrates and nitrites salts have lower thermal stabilities than desired for Horizon 2. As discussed in previous sections, it is not feasible to increase the temperature of these types of fluids up to 615 deg.C due to problems associated with thermal degradation and corrosion.

Chlorides, fluorides and carbonates salts could cover the high-temperature requirement associated with Horizon 2 due to their thermal stability being in the range of 700 deg.C-800 deg.C. The main drawbacks for these three fluids are as follow:

- Chlorides:
  - Lack of experience for commercial applications using large inventories
  - High corrosiveness over metal alloys typically used for CSP applications
  - High melting point

- Fluorides:
  - Lack of experience for commercial applications using high inventories
  - High cost
  - High melting point

- Carbonates:
  - Lack of experience for commercial applications using high inventories
  - High melting point

Taking into account Abengoa's expertise in the development of new HTFs, chlorides and fluorides would be discarded for this application. In addition to this, Abengoa has developed a pilot plant using carbonates (Eutectic Na-Li-K mixture) validating the thermal stability and corrosion compatibility of this fluid for temperature up to 700 deg.C (Prieto & Fereres, 2020). Therefore, carbonates was considered as a potential candidate for high-temperature CSP applications, but a detailed technical-economical evaluation was needed to conclude the final feasibility of this fluid in a large-scale commercial plant.

Summarising, the eutectic Na-Li-K carbonates mixture would be the most promising HTF to expand the operating temperature of CSP applications up to 700 deg.C, satisfying the requirements for the Hybrid Solar/Coal power plant under the design condition for the Horizon 2. However, the use of this fluid was not feasible in the short term due to the need of additional efforts in the research and development phase that are still pending.

7.3 HYBRID SOLAR/COAL PLANT CONFIGURATIONS PROPOSAL FOR HORIZON 2&3

Two different configurations were proposed for the Hybrid Solar/Coal plant to meet the design condition for Horizon 2:

- USC Coal Power Boiler + Photovoltaics + CSP with storage using nitrates and carbonates to reach 615 deg.C (salts) and 600 deg.C (USC steam)
- USC Coal Power Boiler + Photovoltaics + Batteries + CSP with Storage System using nitrates and electrical steam heater to reach 600 deg.C (Steam)

The main difference between both configurations is focused on the CSP facility designed to provide steam to the USC turbine. Both configurations are analysed in the following sub-sections.

7.3.1 Option 1: Nitrates and carbonates

The main characteristics associated with the CSP facility are as follow (Figure 35):

- Use of two HTF's to obtain USC steam at 600 deg.C: Nitrates and carbonates
- Nitrates molten salts tower is used to heat this fluid at 565 deg.C in the same way as in Horizon 1
- A second HTF loop based on carbonates. Two-tank storage system (565 deg.C and 615 deg.C) using an electrical heater fed by PV to charge the TES module
- USC steam at 550 deg.C coming from nitrates loop is heated in a Carbonates-Steam USC steam generator system obtaining USC steam at 600 deg.C
- USC steam at 600 deg.C is finally mixed with steam coming from the USC coal boiler and introduced in the turbine to produce electricity

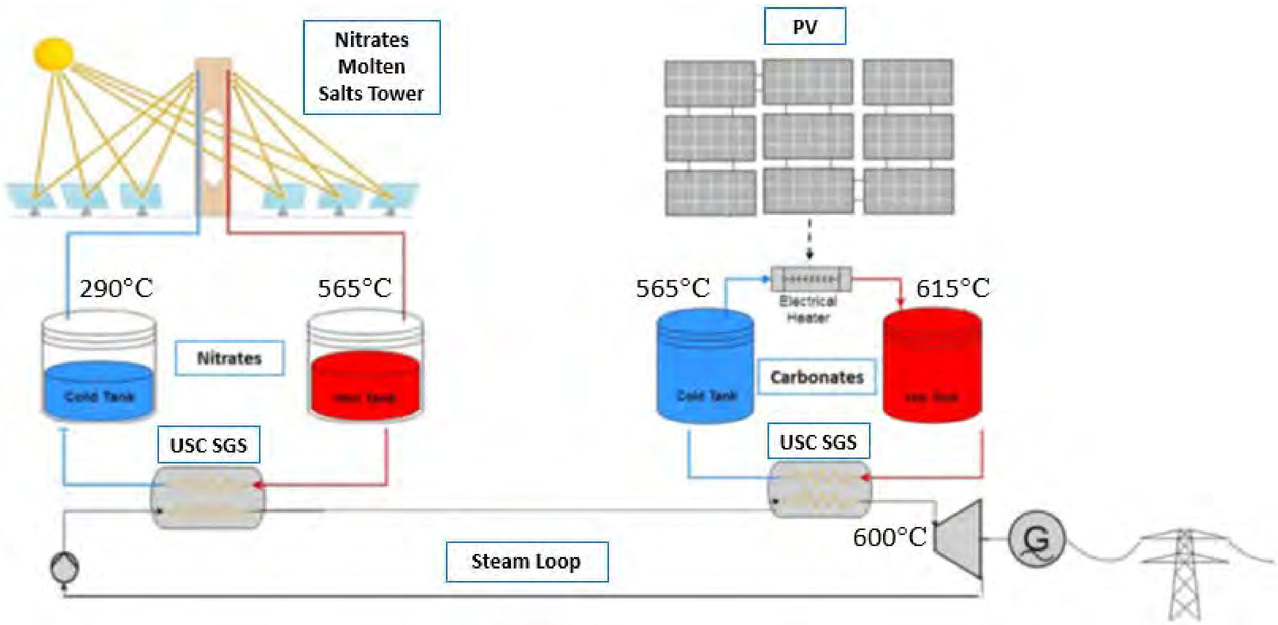


Figure 35 CSP plant configuration based on nitrates and carbonates

7.3.2 Option 2: Nitrates and electrical steam booster heater

Main characteristics associated with the CSP facility are as follow (Figure 36):

- Use of just one HTF to obtain USC steam at 600 deg.C: Nitrates
- Nitrates molten salts tower is used to heat this fluid at 565 deg.C in the same way as in Horizon 1
- USC steam at 550 deg.C coming from nitrates loop is heated in a steam booster heater to increase the temperature up to 600 deg.C
- As the steam booster heater will be typically used when no solar resource is available, **an additional energy storage system will be needed to feed this equipment**
- Lithium-ion batteries provide the electricity needed by the booster heater to increase the temperature of the USC steam. Lithium-ion batteries are charged using PV modules
- As in the previous configuration, USC steam is finally obtained at 600 deg.C downstream of the booster heater. This steam is mixed with steam coming from the USC coal boiler to produce electricity in the power block of the installation

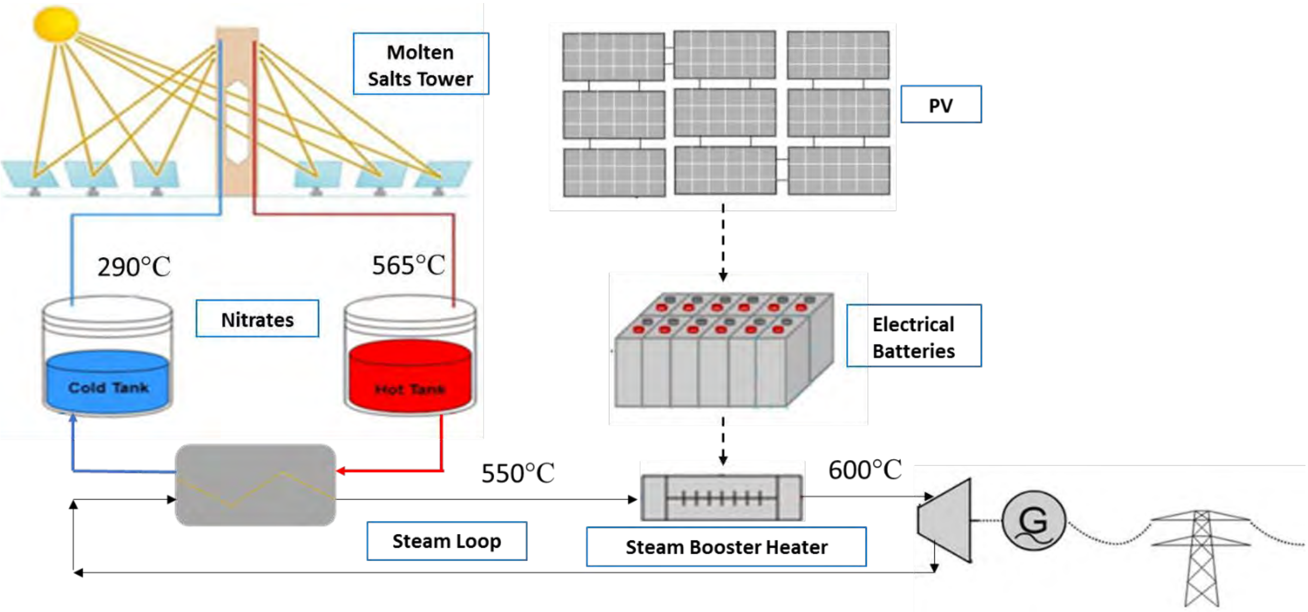


Figure 36 CSP plant configuration based on nitrates and steam booster heater

7.3.3 Hybrid Solar/Coal plant configuration selection for Horizon 2

The Hybrid Solar/Coal plant selected for Horizon 2 is shown in Figure 36 and uses a nitrates molten salt tower and a steam booster heater. The original proposal focused on nitrates and carbonates is rejected for the following reasons:

- Use of carbonates as HTF. Although there are some R&D experiences using carbonates as HTF, there are no commercial references to assure the feasibility of a large-scale carbonates TES system as required for this application
- There are no commercial references for carbonates-USC steam electrical heaters
- The construction of the hot carbonate storage tank implies a really challenging design due to the thermal-mechanical requirements and materials compatibility to assure the lifetime of the installation

Summarising, the configuration based on nitrates and carbonates has a low technological readiness level compromising the feasibility of the whole Hybrid Solar/Coal plant in the mid-term. Then, the configuration using a nitrates tower plant and steam booster heater was the choice to be further evaluated.

The configuration using a nitrates tower plant and USC steam booster heater has the following advantages:

- Use of nitrates as the HTF. Nitrates are used in a tower CSP plant at the usual operating conditions for this technology
- All components are currently available at commercial scale
- A USC steam booster heater is the most challenging component in this configuration due to the operation conditions (high pressure and temperature). However, although a detailed optimization would be required, the suppliers confirmed the feasibility of this equipment
- The Hybrid Solar/Coal plant using nitrates + booster heater configuration was the potential design for Horizon 2 thinking in a short-term implementation at commercial scale

Hybrid Solar/Coal plant layout proposed for Horizon 2 is shown in Figure 37:

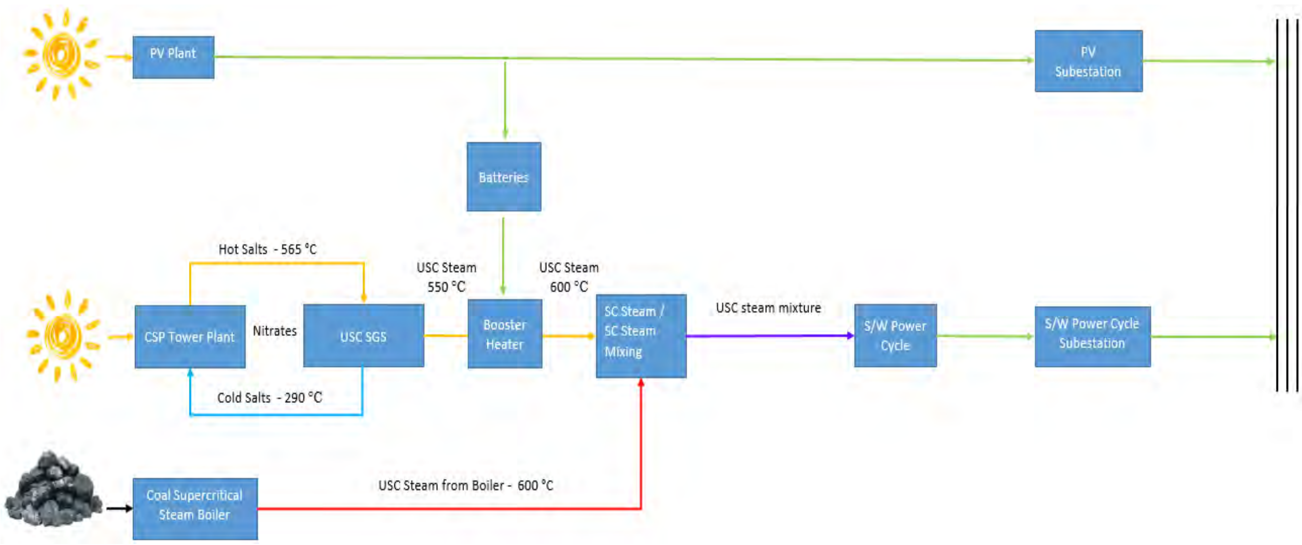


Figure 37 Horizon 2 overall plants scheme

7.4 PLANT OPERATIONAL PRINCIPLES

Operation principles for USC Hybrid Solar/Coal plant are summarised in Table 21 for typical clear days. Figure 38 shows the plant configurations used for Horizon 2.

Table 21 USC Hybrid Solar/Coal plant operation

Horizon 2 Hybrid Solar/Coal operation - day	Horizon 2 Hybrid Solar/Coal operation - night
PV generation (210MW) + Boiler generation (90 MW, minimum load): 300 MW Gross Power CSP in charge mode storing salts in the hot tank of the installation Lithium-ion batteries charged by a dedicated PV	Parallel production: CSP (100 MW) + Boiler (200MW): 300 MW Gross Power Nitrates TES module discharge to produce USC steam at 550 deg.C Lithium-ion batteries discharge to feed the booster heater. USC steam obtained at 600 deg.C
Note: Boiler will close gaps produced in the renewable generation	

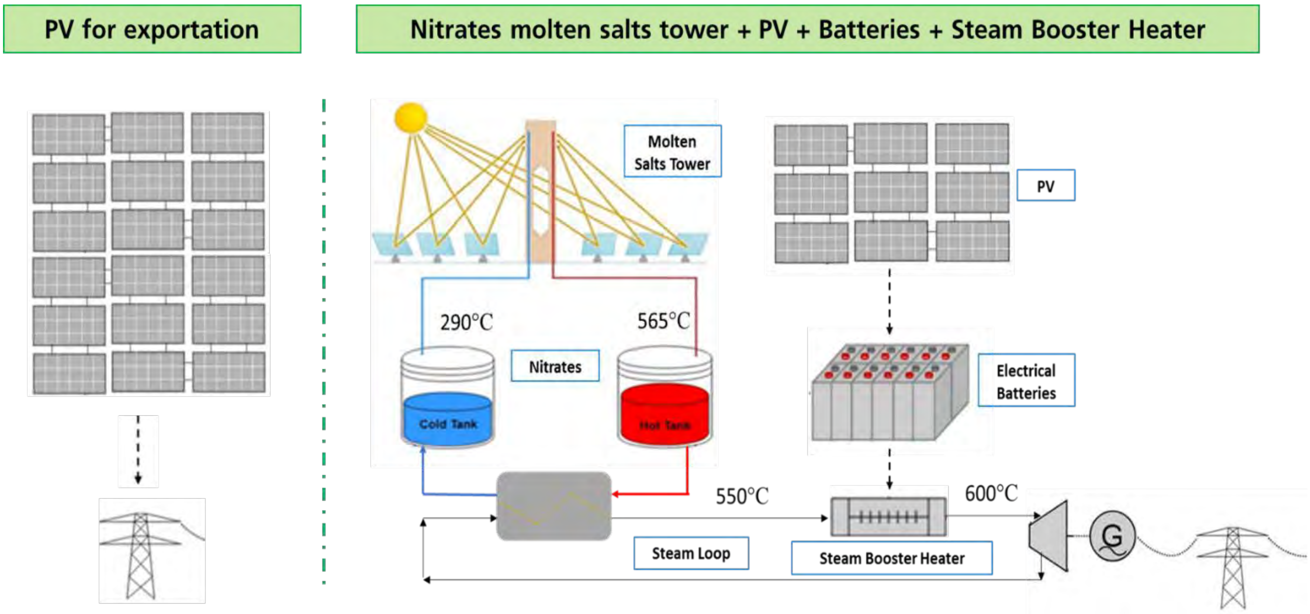


Figure 38 Plant configurations used for Horizon 2

The plant control logic proposed in Section 6.4 is also applicable for Horizon 2. For Horizon 2, Electrical batteries are charged by a dedicated PV in "Boiler Single Operation Mode" and "Boiler plus PV Operation Mode", and are discharged to feed the booster heater in "Hybrid Solar /Coal Operation Mode".

7.5 PHOTOVOLTAICS AND BATTERIES SIZING

The batteries sizing was carried out according to the Booster Heater (BH) capacity, they were sized to be able to cover 14 consecutive hours of the BH working at full capacity. This capacity is aligned with the CSP thermal storage sizing which was explained in detail in Section 6.6.1. The Booster Heater has a total thermal capacity of 18 MWth, assuming an electric to the thermal efficiency of 99%. Therefore, the batteries capacity is estimated to be 250 MWh.

Once the battery were sized, the sizing of the PV plant was carried out according to a dumping ratio and the total amount of hours that the booster heater can work with the batteries. Reaching a compromise between the two previous mentioned variables. A sensibility analysis has been done increasing the total PV peak power from 21MWp to 39MWp. Figure 39 shows the results of this analysis.

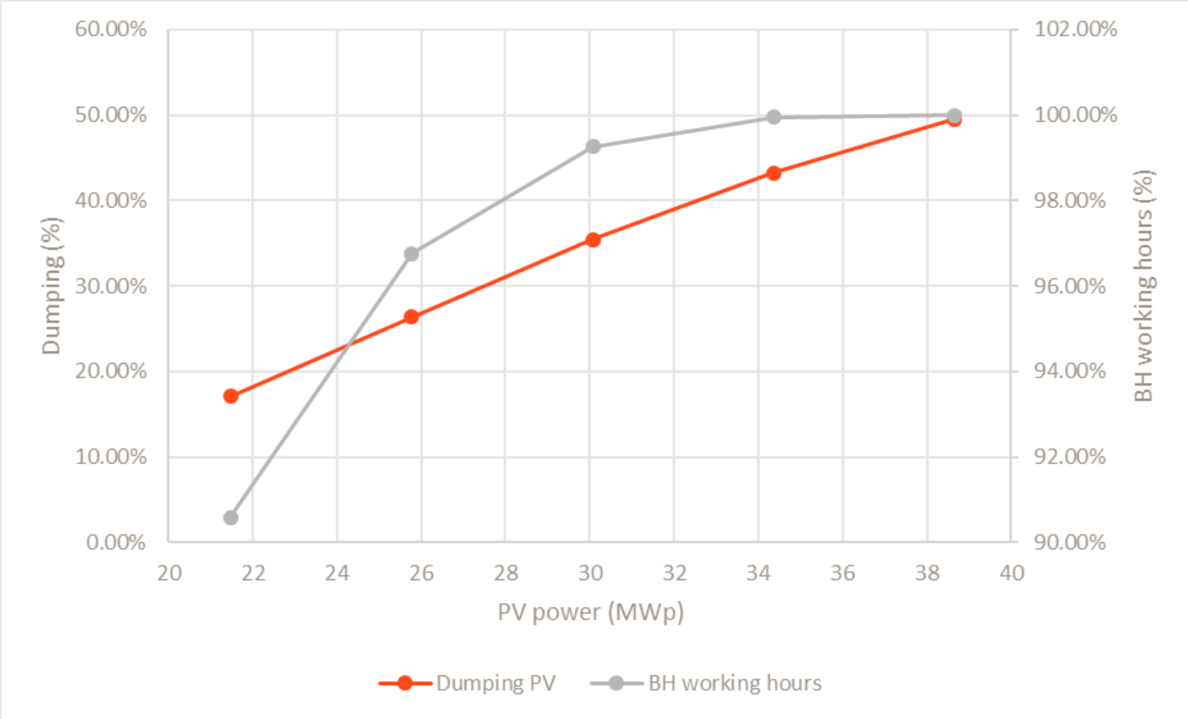


Figure 39 Dumping and BH working hours percentages

- The dumping ratio is calculated as the energy that the PV plant cannot store in the batteries over the total energy the PV plant can produce.
- The BH working hours is calculated as the total number of equivalent hours that the batteries can power the booster heater over the total hours that the CSP plant is working.

Since the main purpose of the PV plus batteries is to power the BH and raise the steam temperature, the BH working hours have been prioritized over the dumping ratio. Following this principle, the PV plant capacity was chosen to be 25.8 MWp, which can power the booster heater for a 96.8% of the total hours the CSP is working maintaining the dumping ratio on 26.4%, which is reasonable according to the objective. It is important to mention that even if the BH cannot operate due to the lack of electricity, it never causes any negative impacts on the plant operation. Hybrid Solar/Coal plant can continue to operate with the mixture steam that is 550 deg.C steam coming from CSP and 600 deg.C steam coming from the boiler.

7.6 PLANT GENERAL LAYOUT

The general plant layout was examined in accordance with the result of the plant sizing examination.

7.6.1 PV Unit General Layout

Figure 40 shows the general layout of the PV unit for exportation and charging the batteries. In this study, the plant location was in the Hunter Valley region but it assumed that there was no specific land limitation so the PV plant layout could be just rectangular. The layout can be changed due to the topography, the locational limitation and obstructions for sunlight etc. However, the layout is left in a simple form to allow an estimation of the land size that was required. The general layout of the PV unit is attached in Appendix J: PV Unit General Layout for Horizon 1 & 2 and Appendix K: PV Unit General Layout for Charging the Batteries for Horizon 2.

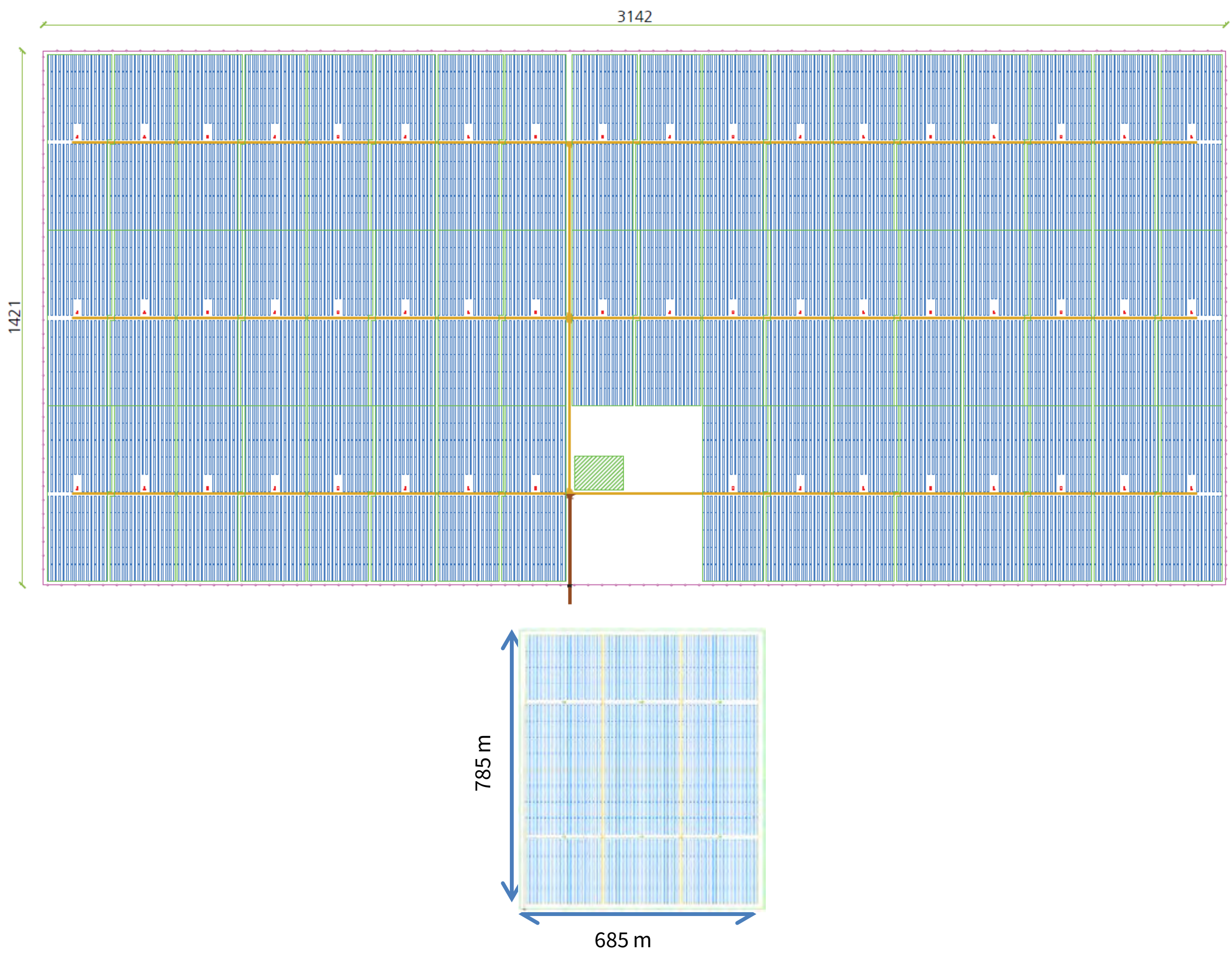


Figure 40 PV General Layout, a) UP, for Exportation; b) DOWN, for Charging Batteries

7.6.2 Hybrid Solar/Coal plant General Layout

Figure 41 shows the general layout of the CSP. It was found that the optimum solar field size was 5000 heliostats which are distributed in one heliostat field and located around one central receiver tower. The technical data of the heliostats is attached in Appendix G: Heliostat Data Sheet, and the manufacturing data sheet is attached in Appendix H: Heliostat Manufacturing Data Sheet. Most of the main equipment for the steam cycle and thermal storage cycle should be arranged in the centre circle. It is important to arrange the equipment so that the area of the centre circle can be optimised and minimised. Even though Figure 41 does not include the boiler and auxiliary equipment, the general plant layout was considered complete at a high enough level to get an overall understanding of the land size required for this configuration of the plant. This is due to being part of a pre-existing power station that already considers the space taken by the remaining equipment not shown here (boiler, stacks, and auxiliaries). A detailed layout study would be required in order to analyse the practical and optimized layout in the centre circle considering all of the equipment. However, its impact on the studied total size so far, which is 2200 m diameter circle, could be considered negligible.

The general layout of the Hybrid Solar/Coal plant is attached in Appendix I: Hybrid Solar/Coal Plant General Layout for Horizon 1 & 2.

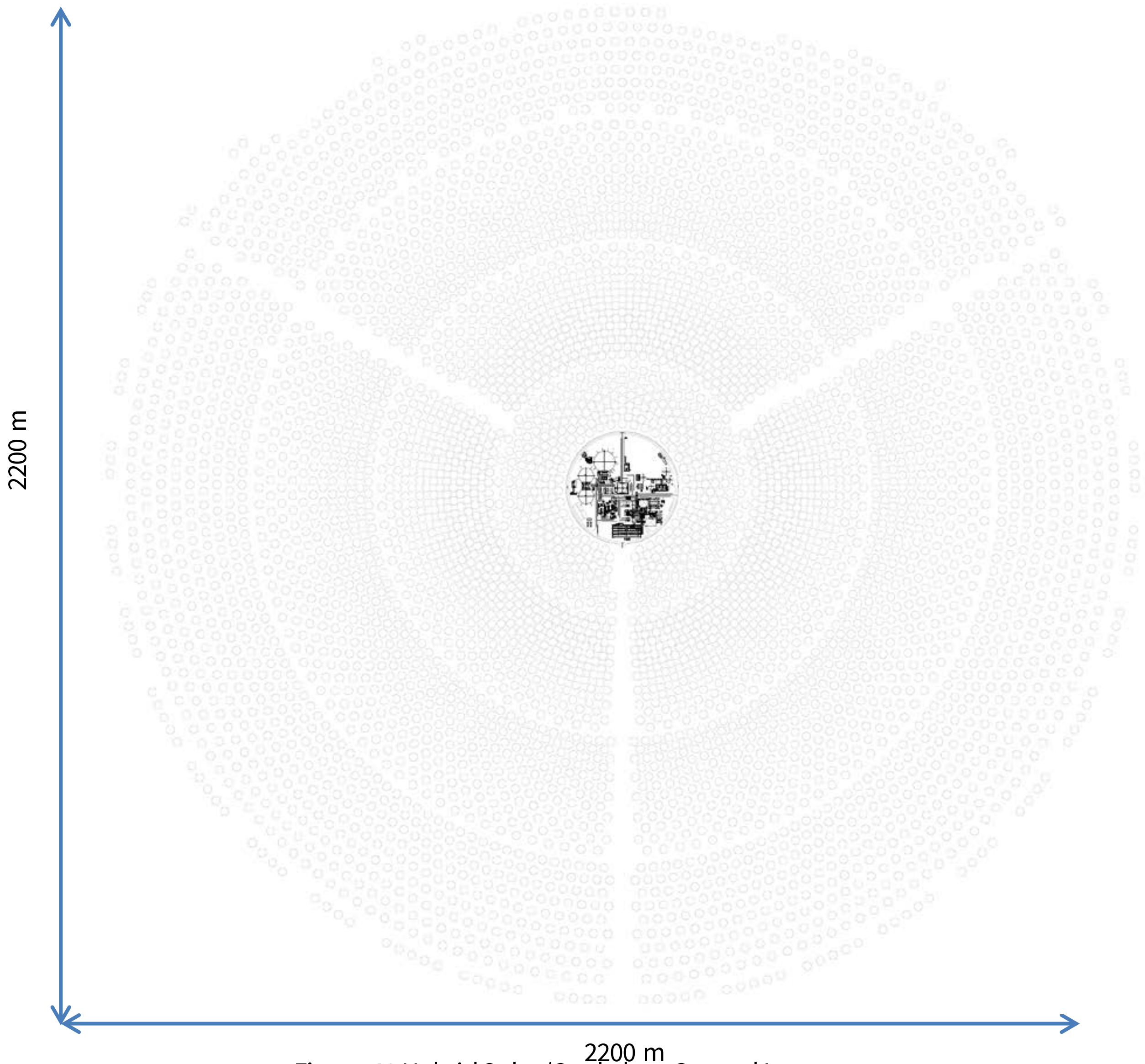


Figure 41 Hybrid Solar/Coal plant General Layout

As identified on the project any detailed study of the Hybrid Solar/Coal plant General Layout will have some challenges as follows.

- Cooling water supply

Originally, it was assumed that a suitably sized water basin was available near the plant such as Lake Liddell. However, the steam turbine and the condenser for Hybrid Solar/Coal plant cannot be located near a water basin because the main equipment should be located in the centre circle surrounded by the heliostats as seen in Figure 41. The water intake and outtake would be far way.

A cooling tower could be an alternative option for cooling the water for the condenser and auxiliary equipment. The cooling tower would need to be a mechanical draught type-cooling tower to minimise the amount of shade that would be cast over the heliostats.

An air-cooled condenser could be another alternative option since the height of an air-cooled condenser would be lower than a hyperbolic cooling tower and it does not release vapour. The plant performance could be less than if water-cooling is used because of the poorer condenser vacuum.

- Coal handling

Coal should be stored as closed to the boiler but it is not realistic to build a huge coal yard in the centre circle. A coal yard should build outside the heliostat circle but close to it.

7.6.3 Comparison with a Conventional Coal-Fired Unit

Figure 42 shows the comparison of the size for the hybrid plant, Bayswater Power Station and Liddell Power Station. Spare spaces, green spaces and coal yard are not included in the plant area. The total area of the PV unit and Hybrid Solar/Coal plant is about 50 to 70 times larger than a conventional coal-fired plant.

Considering the plant output versus plant area, the area of the Hybrid Solar/Coal plant would need to be 480 times larger than a conventional coal-fired plant.

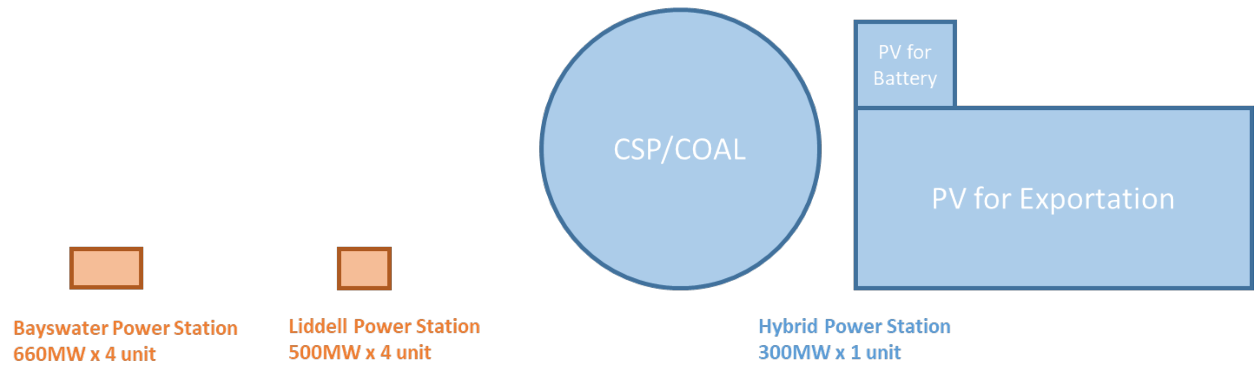


Figure 42 Comparison of Plant Size

7.7 PLANT CONFIGURATION SUMMARY AND PLANT PERFORMANCE

The final plant configuration for Horizon 2 consisted of a CSP plant with the solar receiver of 350 MWth and, as seen in the previous point, a 25.8MW PV plant with a battery system of 250 MWh to power the booster heater in order to raise the solar steam temperature from 560 deg.C to 600 deg.C. Due to this new configuration, the overall power cycle efficiency increased allowing for better use of the stored solar thermal energy.

The impact of the booster heater implementation leads to a 9.0% increase in the total annual produced CSP energy and a 1.2% decrease of the energy that needs to be produced by the boiler.

Please remember that two scenarios were presented in Horizon 1 study as shown in Figure 43.

- Scenario A, consisting of the following configuration:
  - CSP solar field: 5000 Heliostats
  - TES system: 14 equivalent hours
  - The solar receiver 350 MWth
  - PV plant Peak Power 290 MWp

- Scenario B, which additionally includes an Electric Heaters of 20 MWe which operated using PV the dumping from the PV for exportation

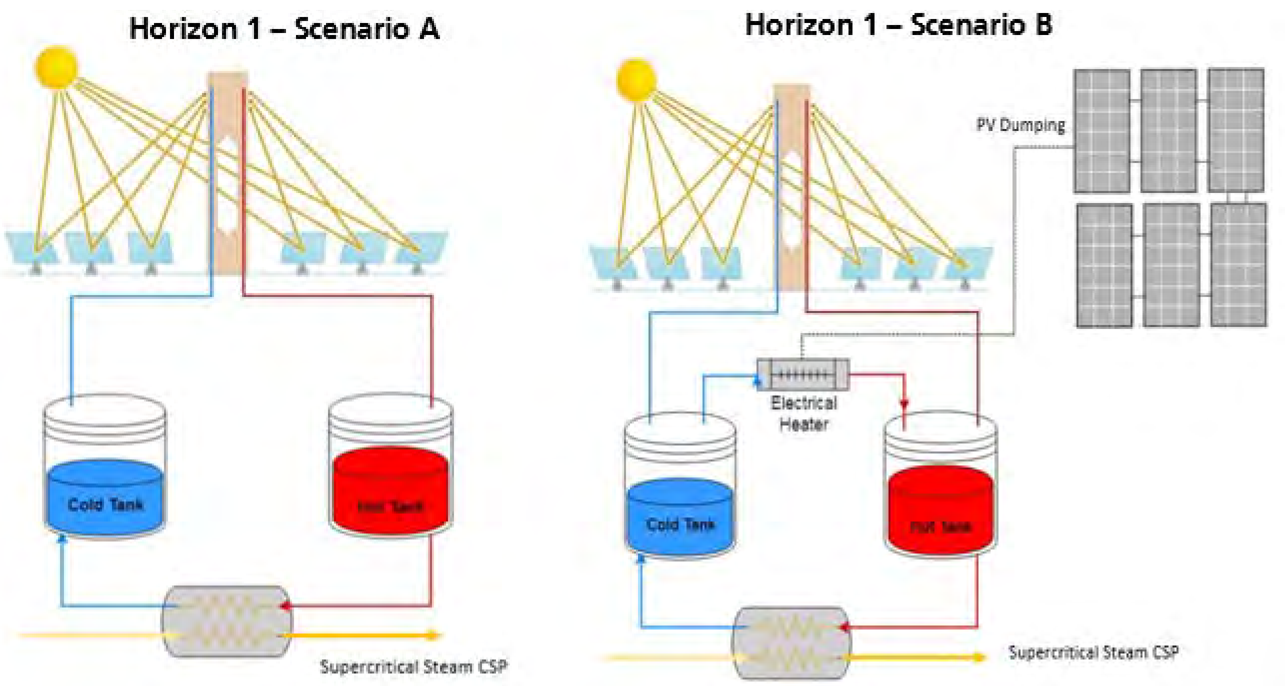


Figure 43 MST TES design for Scenario A and B in horizon 1

In Horizon 2, the results have been also detailed according to the different initial scenarios previously presented in horizon 1, as shown in Table 22.

Table 22 Renewable Share

	Horizon 1	Horizon 2
Scenario A	29.28%	30.10%
Scenario B	29.95%	30.80%

There was no significant change in renewable share between Horizon 1 and 2. This was because the main equipment capacities were not changed and the operational restrictions remained. CSP still has around one-third of the renewable share. Then the increase of the CSP energy results in a 2.8% increase of the renewable share and resulting in a 1.2% decrease of the boiler share.

From Horizon 1 to Horizon 2;

- Turbine island heat rate improved around 0.8%.
- Boiler efficiency was unchanged.
- The boiler share in a year reduced by 1.2%.

Considering these results, the further reduction of CO_2 emission in a year was estimated at around 2%.

7.8 DISCUSSIONS – HORIZON 2

The conceptual design for Horizon 2 was completed.

- ✓ Considering the plant operational restrictions and the plant optimization found through the Horizon 1 study, it was concluded that the difference between Horizon 1 and 2 was just the main and reheat steam temperature.

- ✓ The CSP configuration had the same nitrates molten salts tower as used in Horizon 1 and an electrical steam booster heater charged from a dedicated PV through Lithium-ion batteries was proposed to get 600 deg.C steam. The advantages of this configuration against applying other salts like carbonates reside in the fact that nitrates are currently available technology at a commercial scale as a HTF and it would mean a faster and reliable implementation.

- ✓ For Horizon 2, Electrical batteries are charged by a dedicated PV in "Boiler Only Operation Mode" and "Boiler plus PV Operation Mode", and are discharged to feed the booster heater in "Hybrid Solar/Coal Operation Mode".

- ✓ The battery system sizing was carried out according to the Booster Heater capacity, which is 18MW. The batteries have been sized so that it is able to cover 14 consecutive hours of the BH working at full capacity assuming an electric to the thermal efficiency of 99%. Therefore, the batteries capacity is estimated to be 250 MWh.

- ✓ There is no significant design difference between Horizon 1 and 2 in terms of the boiler, steam turbine and generator. The same material was applied to both cases. The thickness of the main pipe, main valves and steam turbine casing increased.

- ✓ Plant general layout was proposed. For Hybrid Solar/Coal plant, most of the main equipment for the steam cycle and thermal storage cycle should be arranged in the centre circle. It is important to arrange the equipment so that the area of the centre circle can be optimised and minimised. The selection and layout of the steam exhaust cooling system could be a big challenge. It is highly dependent on the actual location condition that an actual plant would be built on. A coal yard location and layout could be also another challenge.

- ✓ There is no significant change in renewable share between Horizon 1 and 2. The main reason being that the main equipment capacities are not changed and the operational restrictions remain. Even though the impact of the booster heater implementation leads to a 9.0% increase of the total annual produced, CSP energy compared with Horizon 1, the CSP still has around one-third of the renewable share. The actual impact of the increase in the CSP energy results in only 2.8% increase of the total renewable share and only 1.2% decrease of the boiler share. The reduction of CO_2 emission from Horizon 1 and Horizon 2 in a year is estimated at around 2%.

- ✓ The PV for dispatch purposes and the PV for charging the batteries for the electrical steam booster heater are separately configured. For further study, it was identified that it is possible to configure it as one PV system along with the batteries. By doing this the PV dumping can be minimized and would be possible to connect the batteries to not only the BH but also the grid. This configuration with the batteries being connected to the grid will greatly contribute to stabilizing the electrical output to the grid, especially in case of a sudden change in PV output due to an abrupt change in the weather. This is especially important because the boiler cannot follow the sudden PV output change in a short time due to its low ramp rate.

8 INTEGRATION FOR THE HYBRID SYSTEM FOR HORIZON 3

8.1 OXYFUEL COMBUSTION BOILER

For Horizon 3, a CO_2 capture system (CCS) was added to Horizon 2. For a coal-fired plant, a post-combustion capture system or **oxyfuel combustion system** is a common applicable practice as a CCS system. Both of them presented pros and cons. For this study however, the oxyfuel combustion system was applied because TIC's boiler partner for this study, IHI, has conducted fundamental research, combustion tests, and operability studies since 1989 acquiring the techniques needed to apply oxyfuel technology to an actual coal-fired. They also conducted a demonstration project on the integrated processes involved in CO_2 capture technology and applied oxyfuel technology to Callide Power Station in Queensland (Toshihiko Yamamda, 2015). At the same time, the feasibility of a 500 MWe oxyfuel power plant in Australia has also been studied, and the plant performance and costs have been evaluated in preparation for the commercialization of oxyfuel power plants. These experiences have definitely contributed to this study.

Oxyfuel is a technology in which fossil fuels like coal are burned with oxygen (O_2) separated from air using an Air Separation Unit (ASU). By combusting fuel with only oxygen, the flue gas is mainly composed of CO_2 and H_2O and the CO_2 ratio in the flue gas can theoretically be increased up to 90 % dry or higher. CO_2 capture system by oxygen combustion is a method of capturing CO_2 by removing water, oxygen, and other contaminants from flue gases in the CO_2 capture process. The captured CO_2 is pressurized and injected into underground storage layers in storage sites, or utilized for other purposes. Figure 44 shows the CO_2 capture process by oxyfuel technology.

An oxyfuel boiler system is a technology based on a combination of existing air combustion technologies and equipment. It can be a new installation or it can be adapted to existing air combustion power plants. One advantage when the technology is adapted for installation in an existing plant is that there is no need to modify boiler pressure parts and steam turbines.

The oxyfuel boiler for Horizon 3 was performed by simply replacing the conventional boiler in Horizon 2. The oxyfuel boiler will not affect the system configuration or performance for the steam cycle and the Solar Island. The oxyfuel boiler has the same thermal capacity as the boiler for Horizon 2. The gross output will not change from Horizon 2, but the net output will decrease due to the increased auxiliary power from ASU.

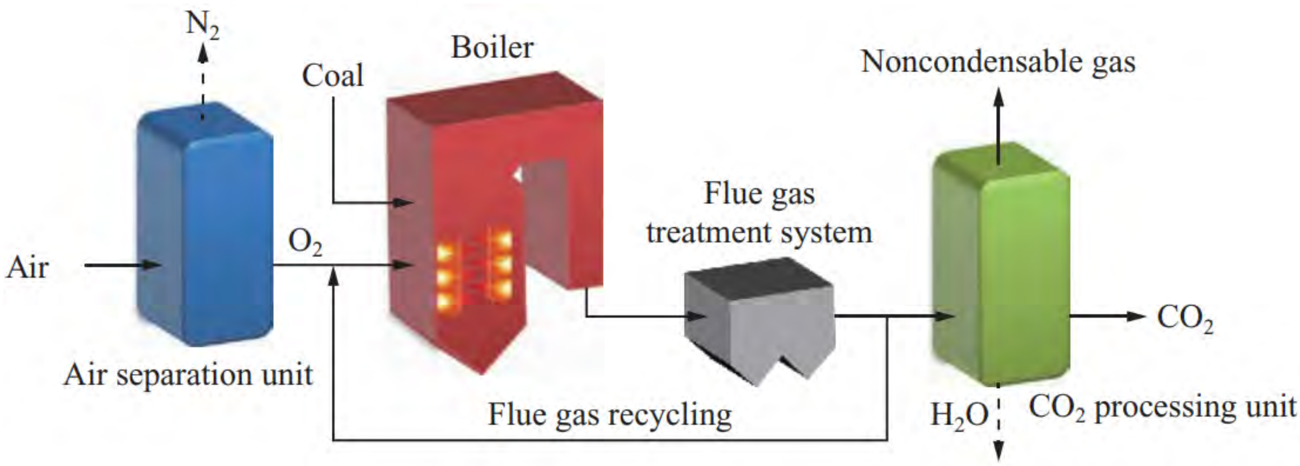


Figure 44 CO_2 capture process by oxyfuel technology (source: IHI)

8.2 PLANT CONFIGURATIONS SUMMARY AND PLANT PERFORMANCE

8.2.1 Design Concept

As described in Section 4.4, the air combustion boiler for Horizon 2 was to be replaced to an oxyfuel combustion boiler for Horizon 3 with some changes on the auxiliary systems. There were no restrictions nor negative effects arisen for the plant operation due to the replacement with the oxyfuel combustion boiler except the start-up and shutdown of the boiler. The heating surfaces of the boiler were kept the same as Horizon 2.

The main difference between Horizon2 and 3 Boiler is the air and flue gas system. Air and flue gas system are composed of the following six systems.

- Primary Air System
- Secondary Air System
- Boundary Air System
- Boiler Flue Gas System
- Gas Recirculation and Oxygen Injection System (Oxyfuel combustion only)
- CO_2 Recovery System (Oxyfuel combustion only)

Refer to Section 4.6.1. For more detailed descriptions on the common air and flue gas systems.

The following Sections describe the detail of Gas Recirculation and Oxygen Injection System and CO_2 Recovery System.

The oxyfuel boiler is capable to operate both air combustion mode and oxyfuel combustion mode. However, for the start-up and shut-down of the boiler, only Air combustion mode is applicable.

Figure 45 and Figure 46 show the difference of air and flue gas flow between air combustion mode and oxyfuel combustion mode. In oxyfuel combustion mode, a part of flue gas is recirculated from Flue Gas Desulfurization (FGD) outlet to FDF and PAF inlet, and is supplied for combustion air after mixing with O_2. The remaining flue gas is fed to the CO_2 Compression and Purification Unit (CPU) and then high concentrated CO_2 are separated and recovered. Around 75% of CO_2 is recirculated and the remained 25% is fed to CPU.

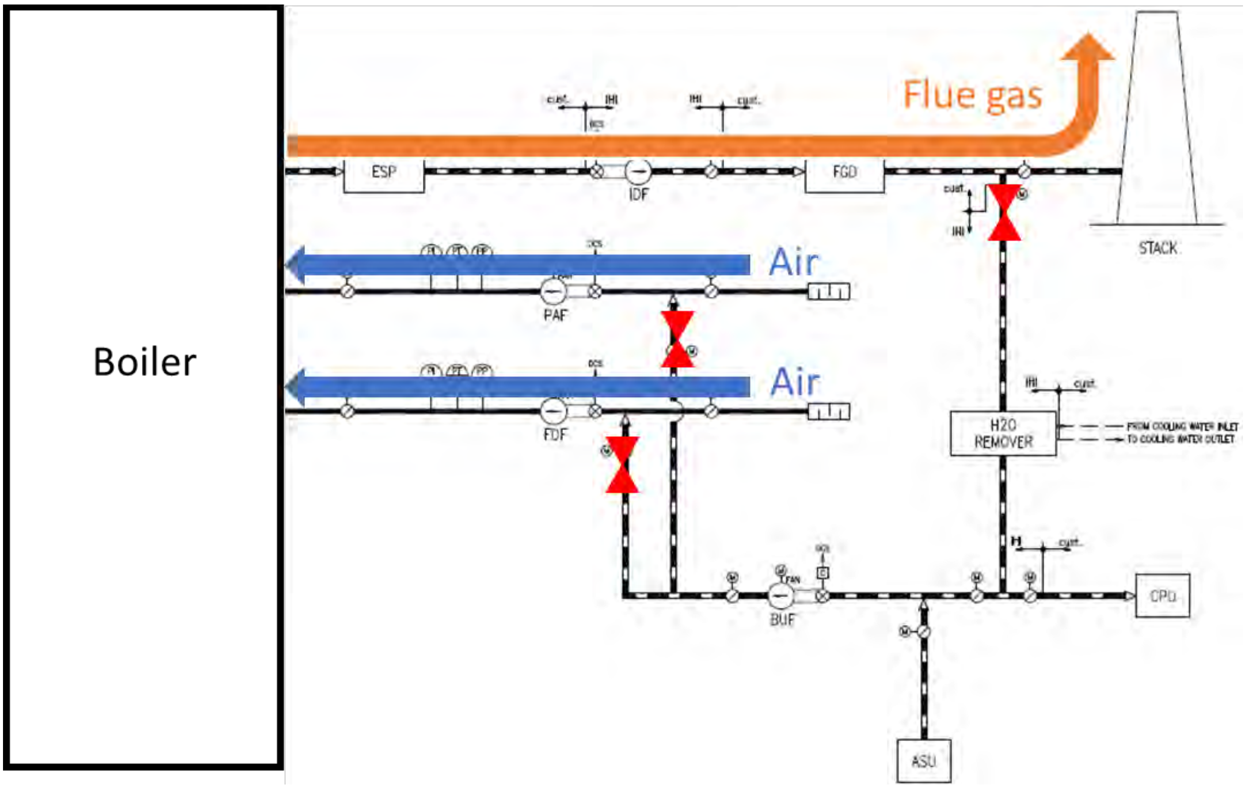


Figure 45 Air and Flue Gas Flow in Air Combustion Mode

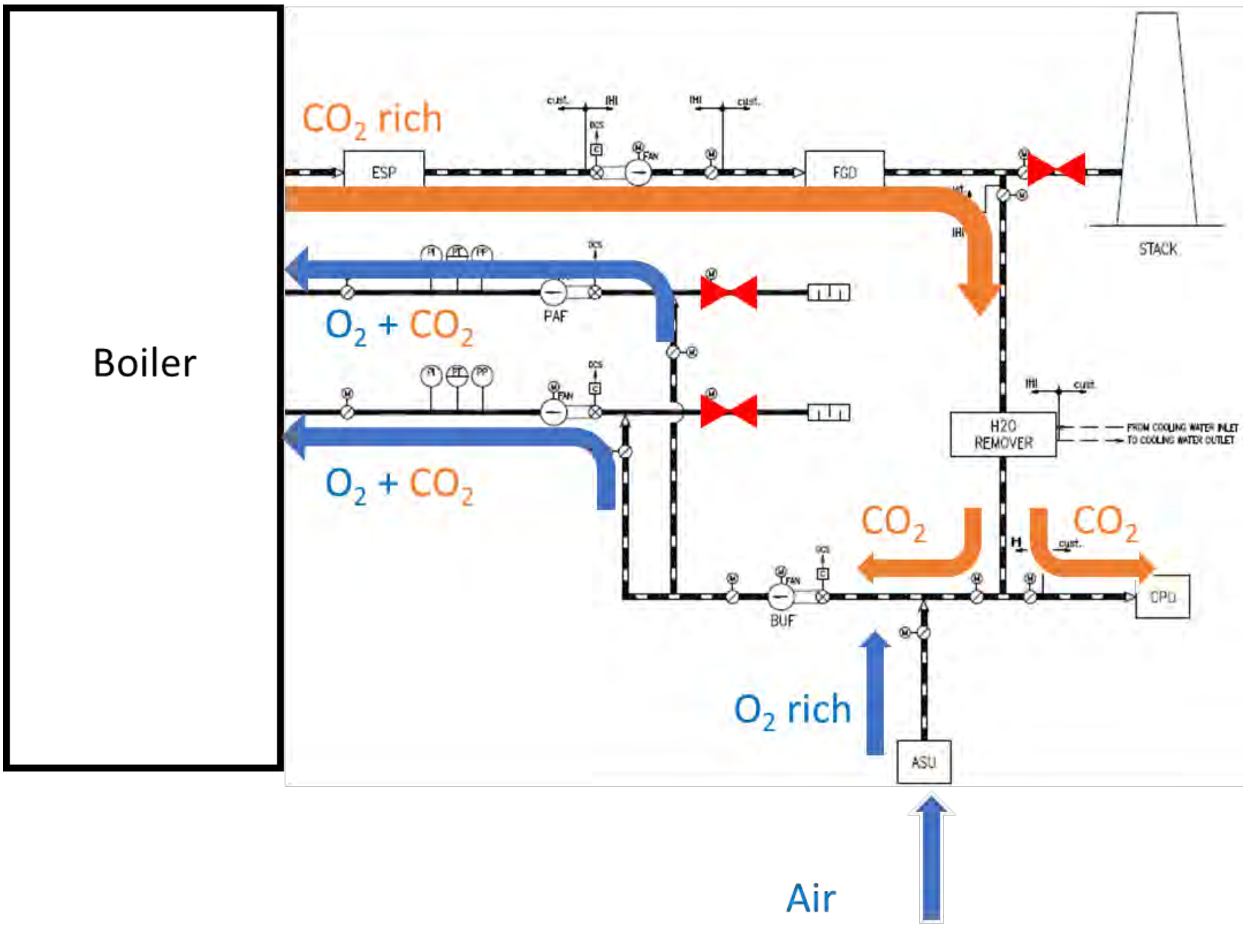


Figure 46 Air and Flue Gas Flow in Oxyfuel Combustion Mode

8.2.2 Gas Recirculation and Oxygen Injection System

The functions of the Gas Recirculation and Oxygen Injection System are;

- To reduce moisture in the flue gas by H_2O Remover.
- To supply O_2 to recirculation gas with ASU.
- To supply recirculation gas to PAF and FDF through Boost Up Fan (BUF).

The gas recirculation system is located downstream of FGD and separated from the exhaust gas system. The flue gas is dehydrated by H_2O Remover to prevent low-temperature corrosion of downstream ducts. The dehydrated flue gas is divided into the flow toward CPU and the other flow toward BUF as recirculation gas. O_2 supplied from ASU is injected into the recirculation gas. The boosted recirculation gas is supplied from PAF/FDF to the boiler.

The gas recirculation and oxygen injection system are composed of the following equipment.

(1) H_2O Remover

H_2O Remover is installed to reduce moisture in the flue gas in oxyfuel combustion. Table 23 shows its specification.

Table 23 H_2O Remover specification

Number	-		One set
Flue gas flow	Nm^3/hr (wet)	Nm^3/hr (wet)	746,000
Flue gas temperature	Inlet	deg.C	60
Flue gas temperature	Outlet	deg.C	35
Cooling water temperature	Inlet	deg.C	20
Cooling water temperature	Outlet	deg.C	30

(2) ASU

ASU is installed to produce the oxygen for oxyfuel combustion. Table 24 shows its specification.

Table 24 ASU specification

Number	-	Two sets
Oxygen purity	%	96.3
Production capacity	Nm3/hr (wet)(96.3%O_2) / set	80,000

(2) BUF

BUF is installed to boost the pressure of the recirculation gas. Table 25 shows its specification.

Table 25 BUF specification

BUF Spec		
Number	-	One set
Gas temperature (@BUF Inlet)	deg.C	33
Gas specific gravity	kg/Nm^3	1.693
Gas Flow (@BUF)	m^3/min/set	14,600
Suction static wind pressure	kPa	-8.44
Discharge static wind pressure	kPa	2.56
Plant Power	kW/set	3,500

8.2.3 CO_2 Recovery System

The CO_2 Recovery System is composed of the CPU to separate and collect CO_2 in the flue gas. The CPU system configuration or specifications should be selected in accordance with the purpose of the CO_2 capture. It could be CO_2 injection to the underground for storage or be utilization for something industrial purposes such as producing petroleum alternative fuels and chemical compounds.

The detailed examination of the CPU system configuration or specifications is not included in the scope of the study; it was assumed that the CO_2 is injected underground to estimate the plant auxiliary power. The CO_2 conditions for injection are assumed as follows.

- Pressure : around 15 MPa
- Temperature : around 40 deg.C

8.2.4 Auxiliary Power Consumption and Plant Net efficiency

Table 26 shows the comparison of the auxiliary power consumption and plant net efficiency for all Horizons. In order to have the same base line, they are compared under Boiler Only Operation Mode.

Comparing Horizon 1 and 2, the plant gross efficiency increases from Horizon 1 to Horizon 2 due to the increased steam temperature. Auxiliary power consumption is also slightly improved due to less air and flue gas flow and cooling water. Because of this, Horizon 2 gets 0.35% higher plant net efficiency than Horizon 1.

Comparing Horizon 2 and 3, the plant gross efficiency decreases in Horizon 3. The reason being that the boiler efficiency of Horizon 3 is lower than that of Horizon 2 as shown in Table 12 and Table 13 even though the heat rate of the turbine island was the same. The net plant efficiency of Horizon 3 is quite lower than that of Horizon 2 due to the hugely increased auxiliary power. As mentioned in the above sections, the following equipment is added to Horizon 3 from Horizon 2.

- ASU
- BUF
- H_2O Remover

- CPU

The ASU and CPU require a lot of power so the total auxiliary power consumption increases drastically. Particularly for this study, the gross output is small compared with a conventional USC plant so the auxiliary power rate becomes relatively high against a general USC plant. This was the crucial disadvantage of Horizon 3.

If the gross output were to increase more, the auxiliary power consumption rate could decrease and the plant net efficiency could improve. Higher gross output capacity is preferable to minimize the auxiliary power consumption rate and maximize the plant net efficiency. However, the problem will in turn be the required area for CSP. As described in Section 7.6, this Hybrid Solar/Coal unit requires a large amount of land due to the surface area required for the CSP heliostats. Bigger unit capacity results in a bigger land area requirement and it can become impractical. If the boiler capacity was increased with the same solar island capacity, the result would in decreased renewable share in the plant.

Another idea to improve the plant net efficiency is to utilize "dumped" PV power to complement the auxiliary power. As described in Section 6.6.1, around 15% of annual PV power is dumped. If this "dumped" power were utilized in the plant to offset the auxiliary power, it would improve the net plant efficiency.

All of these possibilities were identified during study and specifically during Horizon 3 but as they were not part of the original scope of the project, they were not further elaborated or pursued.

Table 26 Auxiliary Power Consumption and Plant Net efficiency at Boiler Only Operation

		Horizon 1	Horizon 2	Horizon 3
Gross output	MW	300.0	300.0	300.0
Auxiliary Power Consumption	MW	24.1	23.8	115.5
Auxiliary Power rate	%	8.0%	7.9%	38.5%
Net output	MW	275.9	276.2	184.5
Plant gross efficiency	%	43.45	43.78	43.50
Plant net efficiency	%	39.95	40.30	26.75

8.3 DISCUSSIONS – HORIZON 3

The conceptual design for Horizon 3 was completed.

- ✓ The conventional air combustion boiler for Horizon 2 was replaced to the oxyfuel combustion boiler for Horizon 3 with changes to the auxiliary system. There were no restrictions nor negative effects arisen for the plant operation due to the replacement to the oxyfuel combustion boiler except the start-up and shutdown of the boiler. The heating surface area of the boiler was the same as Horizon 2.

- ✓ The main difference between Horizon 1&2 from Horizon 3 was the added features of with or without Gas Recirculation and Oxygen Injection System and CO_2 Recovery System. The oxyfuel boiler is capable to operate both air combustion mode and oxyfuel combustion mode. In air combustion mode, the Gas Recirculation and Oxygen Injection System and CO_2 Recovery System are isolated and the plant operates in the same way as depicted in Horizon 2. In oxyfuel combustion mode, a part of flue gas is recirculated from FGD outlet to FDF and PAF inlet and is supplied for combustion air after mixing with O_2. The remaining flue gas is fed to the CPU and then high concentrated CO_2 are separated and recovered.

- ✓ For Horizon 3, the plant net efficiency is lower than Horizon 2 due to the significantly increased auxiliary power mainly from ASU and CPU. It will decrease from 40.3% of Horizon 2 to 26.8% in Horizon 3. The auxiliary power consumption rate exceeds 38% for Horizon 3. To improve the plant net efficiency, it was identified the possibility of utilizing "dumped" PV power to offset the auxiliary power needed. In this regard, there is around 15% of annual PV power dumped so it is possible to further improve the plant net efficiency if this "dumped" power can be utilized in the overall plant.

9 ECONOMIC EVALUATION

Economic performance is one of the most important factors for the commercialization of a new technology. Even though a coal-fired plant has been regarded as being on the cheap side for electric generation systems, the same cannot be said for a Hybrid Solar/Coal technology, which was expected to have a higher cost due to the additional “hybridized” equipment to the conventional coal-fired plant. Capital cost, Operation and Maintenance (O&M) cost and Levelized Cost of Electricity (LCOE) were estimated for all Horizons individually and then compared with a conventional coal-fired plant, a CSP plant and PV plant. In addition, CO2 avoided cost was examined to see comparative differences between the hybrid technology and USC with post-combustioin capture.

9.1 METHODOLOGY OF ECONOMIC EVALUATION

9.1.1 Literature review for Australian electricity generation technology costs

A series of electricity generation technology cost has been researched in Australia by CSIRO and AEMO.

The *Australian Power Generation Technology Report* (CO2CRC, 2015) is one of the milestones of the electricity generation technology cost research, which CSIRO participated in as a member of the steering committee. The report provided an unbiased, technology-neutral review of a broad range of generation technologies, current and projected capital costs, operation and maintenance costs, and detailed performance data for 2015 to 2030. CSIRO conducted its update on this and issued as *Electricity generation technology cost projections* (Graham, 2017).

Another milestone would be *AEMO costs and technical parameter review* (GHD, 2018). AEMO commissioned GHD to provide an update of electricity generation cost and performance characteristics for conventional and new electricity generation. The report provided an overview of the scope, methodology and assumptions used in its development.

Following these studies mentioned above, the GenCost project was jointly funded by CSIRO and AEMO. It is a joint initiative of CSIRO and AEMO to provide an annual process for updating electricity generation cost data for Australia. The goal is to adopt the best features of predecessor processes and deliver the required data in a more modest format, but one that allows for incremental improvement over time. *GenCost 2018* (Paul W Graham, 2018) is their first edition and was updated as *GenCost 2019-20: preliminary results for stakeholder review* (Paul Graham, 2019).

These reports mentioned an overview of the scope, methodology and assumptions used in their development. For this economical study, most of the assumptions were applied in a reasonably accurate approach so that we can compare the economic performance with the results of its predecessors as closely as possible.

9.1.2 The definition of Levelized Cost of Electricity

The levelized cost of electricity (LCOE) in electrical energy production can be defined as the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered. LCOE is a useful tool for comparing the unit costs of different technologies over their operating life. LCOE can be calculated by the following equation.

$$LCOE\ (\$/MWh) = \frac{\sum[(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^{-t}]}{\sum MWh(1+r)^{-t}}$$

MWh : The amount of electricity produced in MWh in a year, assumed constant;

r : Discount rate;

$(1+r)^{-t}$: The discount factor for year t;

$Capital_t$: Total capital construction costs in year t;

$O\&M_t$: Operation and maintenance costs in year t;

$Fuel_t$: Fuel costs in year t;

$Carbon_t$: Carbon costs in year t;

D_t : Decommissioning and waste management costs in year t;

9.1.3 The definition of CO_2 avoided cost

The CO_2 avoided cost describes the overall CCS project costs and gives a singe value from trade-off between costs and environmental benefits when CCS is added. It is calculated based on the cost and CO_2 emission intensity of the electricity generated with and without CCS as shown in the following equation and originaly defined by the IPCC (Roussanaly, 2019)

$$CO2\ avoided\ cost = \frac{(LCOE)_{CCS} - (LCOE)_{ref}}{(tonne_{\ CO2}/MWh)_{ref} - (tonne_{\ CO2}/MWh)_{CCS}}$$

Where:

$(LCOE)_{ref}$: The levelised cost of electricity of the power plant without CCS
$(LCOE)_{CCS}$: The levelised cost of electricity of the power plant with CCS
$(tonne\ CO_2/MWh)_{ref}$: The CO_2 emission intensity of electricity of the power plant without CCS
$(tonne\ CO_2/MWh)_{CCS}$: The CO_2 emission intensity of electricity of the power plant with CCS

For this study, “CCS” was interpreted as hybridisation unit (Horizon 1,2 and 3) and “ref” is interpreted as a conventional USC plant to comapare the CO_2 avoided cost across Horizons.

9.1.4 Methodological Conventions and Key Assumptions

Lifetimes
Plant lifetime was assumed to be 35 years as described in Section 2.4.

The amount of electricity produced (MWh)
The plant annual gross electric power generation was calculated in Section 2.4. However, for the LCOE calculation, the net electric power generation should be applied not the gross. The net electric power generation for each Horizon is shown in Table 27. The net output was studied in Section 8.2.4.

Table 27 Plant annual net electric power generation

		Horizon 1	Horizon 2	Horizon 3
Gross output	MW	300.0	300.0	300.0
Net output	MW	275.9	276.2	184.5
Capacity factor	-	0.85	0.85	0.85
Plant annual net electric power generation	MWh	2,054,049	2,056,294	1,373,593

Discount rate
To calculate the lifetime revenue requirement of a plant, the present value of annual charges is calculated for each year and assumed to determine the total present value. The present value is calculated based on the discount rate, which is the product of the cost of debt (or interest rate) and the percentage of debt financing plus the product of the cost of equity and the percentage of equity financing. For example, in this study, the nominal before-tax discount rate is calculated as follows. The data comes from the coal-fired generation date in Table 9 of (GHD, 2018).

$$(\%\ debt) * (cost\ of\ debt) + (\%\ equity) * (cost\ of\ equity) = discount\ rate$$

$$40\% * 5.3\% + 60\% * 13\% = 9.9\%$$

Capital cost
Capital Cost was calculated assuming costs on an “overnight” capital cost basis. The total plant engineering, procurement and construction (“EPC”) cost was organized into the following categories:

I. Specialized Equipment
II. Other Equipment
III. Civil
IV. Mechanical
V. Electrical Assembly & Wiring
VI. Buildings & Structures
VII. Engineering & Plant Start-up
VIII. Contractor's Soft & Miscellaneous Costs

“Specialized Equipment” means the main equipment of the plant such as CSP systems, PVs, boilers, steam turbines, feedwater heaters, condensers, emissions control equipment, and transformers. Especially CSP systems, PVs, boilers, steam turbines account for 90% of total Specialized Equipment and they are given by each manufacturer who is a partner of this study.

All other costs have been estimated using PEACE (Plant Engineering and Construction Estimator) function of Thermoflow 29 software. Thermoflow software comprises a range of proprietary software packages used to model performance and costs of thermal power generating plants. The software is widely recognised within the power industry. The plant database is updated several times a year to include new plant models/technologies and reflect international cost trends. For cost calculation other than Specialized Equipment, the default setting or assumption which PEACE uses was applied. Thermoflow utilises several “cost multipliers” which allowed it to adjust from default “Reference US Site” to the actual site countries or region. The applied cost multipliers are shown in Table 28.

Table 28 Cost Multipliers for Capital Cost Calculation

Cost Multipliers	Thermoflow default (Australia)	Applied for calculation	Comment
Specialised equipment	1.15	1.15	The cost of CSP systems, PVs, boilers, steam turbines were directly given by the manufacturer. The other specialized equipment cost was estimated by PEACE.
Other equipment	1	1	No change
Commodities	1	1	No change
Labour	1.485	1.485	No change

The following items are excluded in capital cost. This precondition aligns to the assumptions on the other reference reports (CO2CRC, 2015) (Paul W Graham, 2018) (Paul Graham, 2019).

- Escalation
- Owner's cost
  - Permits, Licenses, Fees, Miscellaneous
  - Land Cost
  - Utility Connection Cost
  - Legal & Financial Costs
  - Escalation and Interest During Construction
  - Project Administration & Developer's Fee
- All taxes, import duties
- Site-specific considerations
- CO_2 injection

Fixed O&M cost ($/kW/year)
Fixed O&M costs ($/kW/year) represent the costs of operation and maintenance that do not vary with output, such as wages and salaries, insurances, other overheads and periodic maintenance.

Variable O&M cost ($/kWh/year)
The additional operating and maintenance costs for an increment of electrical output depends on several factors, including the size of the increment in a generation, how wear and tear on the generation units are accrued between schedule maintenance and whether the operation is as a baseload or peaking facility. For coal, variable O&M costs include additional consumables such as water, chemicals and energy used in auxiliaries including incremental running costs for coal and ash handling etc.

Table 29 shows the O&M cost for each of the Horizons, this does not mean that one Horizon can just be upgraded from another. Each of the costs are particular for the Horizons and should be not scaled. O&M cost was considered separately between Boiler & Turbine island and Solar island. For Boiler & Turbine Island, Fixed and Variable coast were referred from the reference report (Paul Graham, 2019)[1] for Horizon 1 and 2, and (CO2CRC, 2015)[2] for Horizon 3. The reference report (CO2CRC, 2015) is shown in June 2015 Australian dollar so it was corrected to 2020 Australian dollar considering the producer price indexes (PPI) between June 2015 and March 2020 per Australian Bureau of Statistic Data Set 6427.0. For Solar island, the O&M cost was given by manufacture as a total annual cost.

[1] Appendix Table B.5, in 2020

[2] "Oxyfuel in Table 33. (escalated by PPI per Data Set 6427.0 i.e. * 112.6/104.9)

Table 29 O&M cost

		Horizon 1	Horizon 2	Horizon 3
Boiler & Turbine island	Fixed O&M cost ($/kW-year)	53.2[1]	53.2[1]	59.0[2]
Boiler & Turbine island	Variable O&M cost ($/kWh-year)	4.2[1]	4.2[1]	12.9[2]
Solar island	Total O&M cost ($/year)	6,750,000	7,087,500	7,087,500

Fuel costs
Coal price was assumed to be 2.8 AUD/GJ as the same assumption as the reference study (Paul Graham, 2019)[1].

Carbon costs
Carbon price can be included in LCOE calculation. However, at the time this report was written there was no carbon price in Australia so it was ignored in this study.

Decommissioning and waste management costs
At the end of a plant's lifetime, decommissioning costs and waste management costs are incurred. For fossil fuel plants, the residual value of equipment and materials shall normally be assumed equal to the cost of dismantling and site restoration, resulting in a zero net cost of decommissioning. In other words, it is assumed that the net salvage value is zero. The reference studies (Paul W Graham, 2018) and (Paul Graham, 2019) are seemed not mentioned about how much the decommissioning costs would be. However, the reference study (CO2CRC, 2015) says that the net salvage value is zero.

Other assumptions

- All costs are shown in $AUD
- All costs are exclusive of GST
- Exchange rate: 1.35 AUD/USD, 0.0125 AUD/JPY
- All costs are constant (real) dollars basis, i.e. net of inflation.

9.2 RESULT AND COMPARISON WITH OTHER ELECTRICAL GENERATION SYSTEM

Figure 47 shows the capital cost breakdown of Horizon 1. Specialized Equipment accounted for more than half of the total capital cost. As described above, 90% of total Specialized Equipment cost was given by each manufacturer so it should be quite reliable. Even though the other half of the capital cost was estimated by using Thermoflow 29, the total result should be reasonable considering its presence within the power industry.

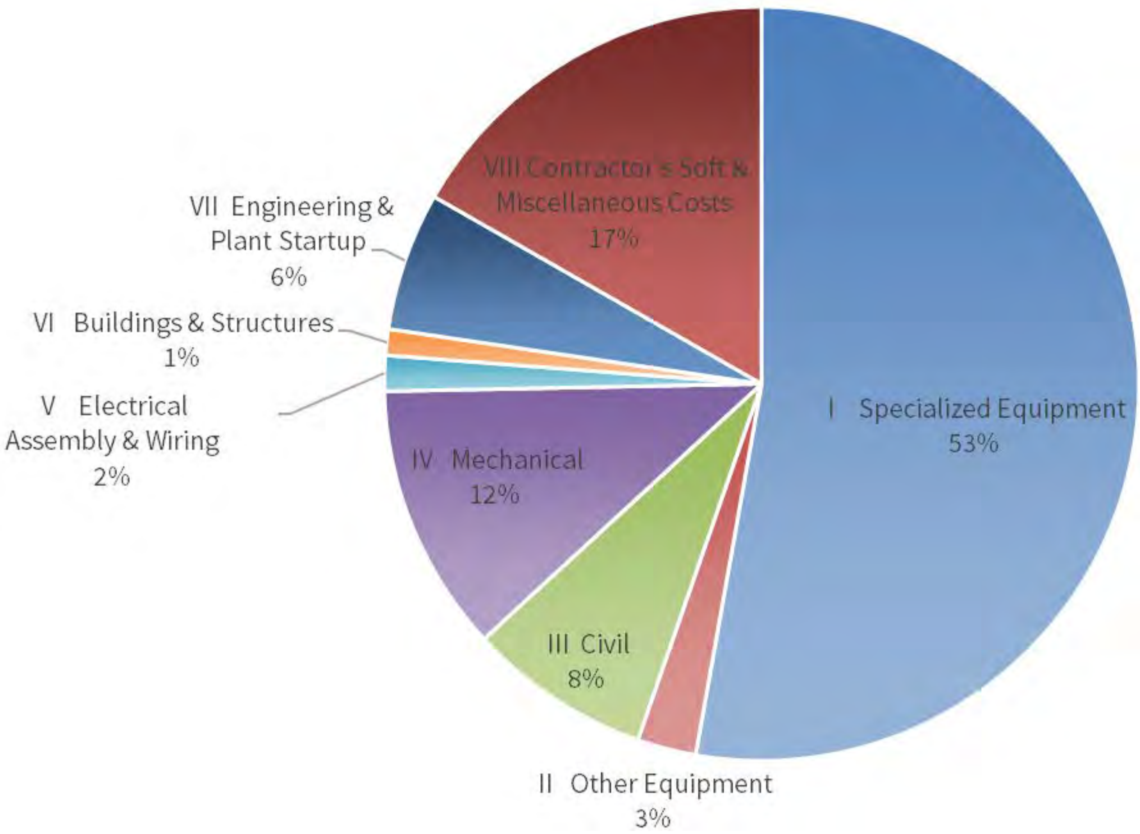


Figure 47 Capital cost breakdown of Horizon 1

Figure 48 summarizes the capital cost for all Horizons and also black coal-fired power plant, large scale solar PV, solar thermal with 8-hour thermal storage and oxyfuel coal-fired power plant. The data of black coal-fired power plant, large scale solar PV, solar thermal with 8-hour thermal storage come from the reference report (Paul Graham, 2019) 3 and they are shown in orange. The data of oxyfuel coal-fired plant also comes from the reference report (CO2CRC, 2015) 4 but the data is shown in June 2015 Australian dollar so it was escalated to 2020 by considering PPI between June 2015 and May 2020 per OECD Data 5. It is shown in yellow.

Although the cost calculations for all Horizons used the same assumptions as possible for the reference report such as the discount rate, O&M cost, fuel cost etc., other detailed assumptions were not known. In addition, the technical specifications such as steam temperature and thermal storage capacity are different between this study and the reference report. In fact, there are some deviations from the reference reports that makes a comparison not entirely adequate. However, it is considered a practical approach to approximately grasp the economic performance.

As expected, the cost increases from Horizon 1 to 3 due to the increased equipment such as the additional PVs, the batteries for Horizon 2 and the replacement to oxyfuel combustion boiler and its auxiliaries for Horizon 3.

Some confusion could arise seen that Horizon 1 and "Solar thermal" are almost at same cost level even it could be considered more of a combination of "Black coal", "Large scale solar PV" and "Solar thermal". This

[3] Appendix Table B.1, in 2020
[4] Table 32
[5] https://data.oecd.org/price/producer-price-indices-ppi.htm

approach should not be used and it shall be noted that the Horizon 1 cost cannot be close to a simple summation of its parts due to the following reasons.

i. Solar thermal has the steam cycle as "Black coal" has it as well, so it would be double-counted. Solar thermal cost except the steam cycle equipment cost would account for roughly 70% even though it is highly dependent on the thermal storage capacity.
ii. For this study, CSP has 100MW equivalent capacity but the unit itself has 300MW capacity and the capital cost ($/kW) shows the total capital cost ($) divided by 300MW (300,000kW). It means that the capital cost for CSP in ($) in Horizons is compressed roughly one-third in ($/kW).

Due to the reason above, the capital cost for the CSP portion in ($/kW) in Horizons is compressed compared with a standalone Solar thermal.

The capital cost for Horizon 3 increased drastically from Horizon 2. It was confirmed that the capital cost ($/kW) difference between Horizon 2 and 3 are similar to the difference between "Black coal" and "Oxy-fuel".

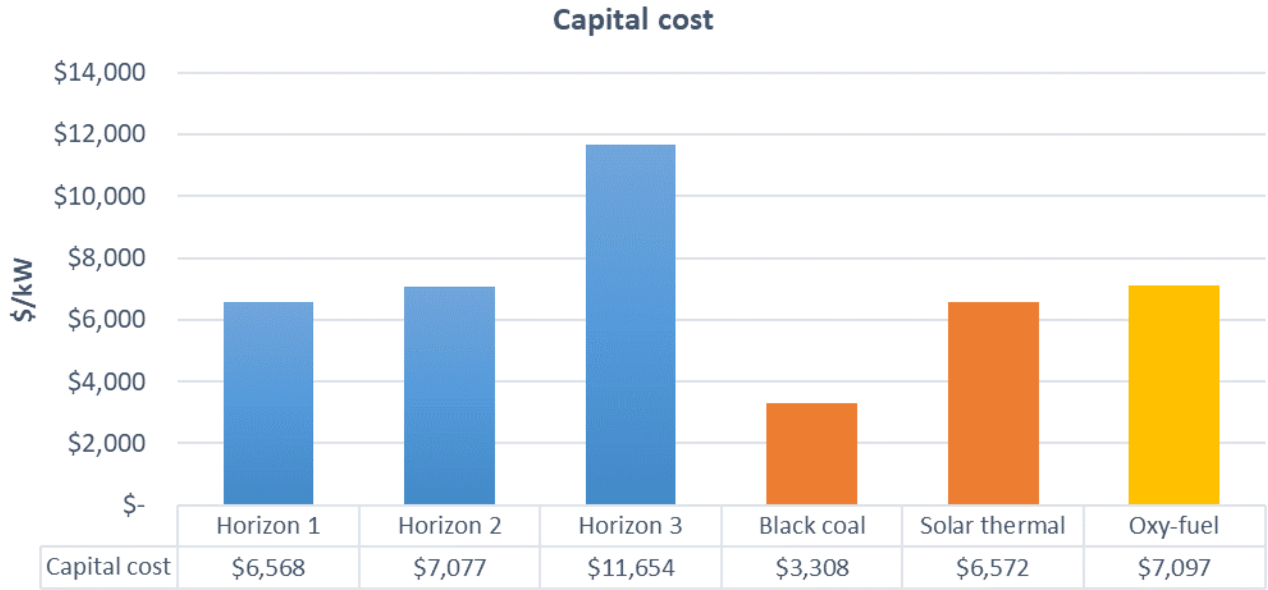


Figure 48 Capital cost comparison

It was originally considered to include in the large scale PV in the comparison but it was ultimately removed, as it is not a dispatchable or semi-dispatchable technology. Nevertheless the Capital cost value for the Large Scale value is around $1,284 $/kW

Figure 49 summarized LCOE as the same category and the colours as Figure 48. The data of black coal-fired power plant, large scale solar PV, solar thermal with 8-hour thermal storage come from the same reference report (Paul Graham, 2019)[6]. It shows "Low" and "High" scenarios so the band shows LCOE. The data of oxyfuel coal-fired plant also comes from the same reference report (CO2CRC, 2015)[7] but the data is shown in June 2015 Australian dollar so it was escalated to 2020 by considering PPI between June 2015 and May 2020 per OECD Data[5]. There were not "Low" and "High" scenarios so the band shows the ±10%. All Horizons is shown by ±10%.

Similar confusion could arise again that LCOEs for Horizon 1 and 2 are lower than Solar thermal. The reason for it is similar to the case of capital cost.

[6] Appendix Table B.6, in 2020
[7] Table 46

i. CSP in Horizons has 100MW equivalent capacity but the unit itself has 300MW capacity so the amount of electricity produced (MWh) is three times than a simple CSP with 100MW capacity and results in lowering LCOE.
ii. The capacity factor for a general CSP plant would be around 50% or less. However, the capacity factor for Hybridized plant is 85% so high capacity factor makes LCOE lower than a simple CSP.
iii. Fuel cost portion in LCOE of Horizon 1 and 2 is lower than "Black coal" due to the renewable energy assist.

Because of these, Horizon 1 and 2 are positioned in the middle of Black coal and Solar thermal.

The LCOE for Horizon 3 increased drastically from Horizon 2 as well as the capital cost. It is confirmed that the LCOE difference between Horizon 2 and 3 are similar to the difference between "Black coal" and "Oxy-fuel".

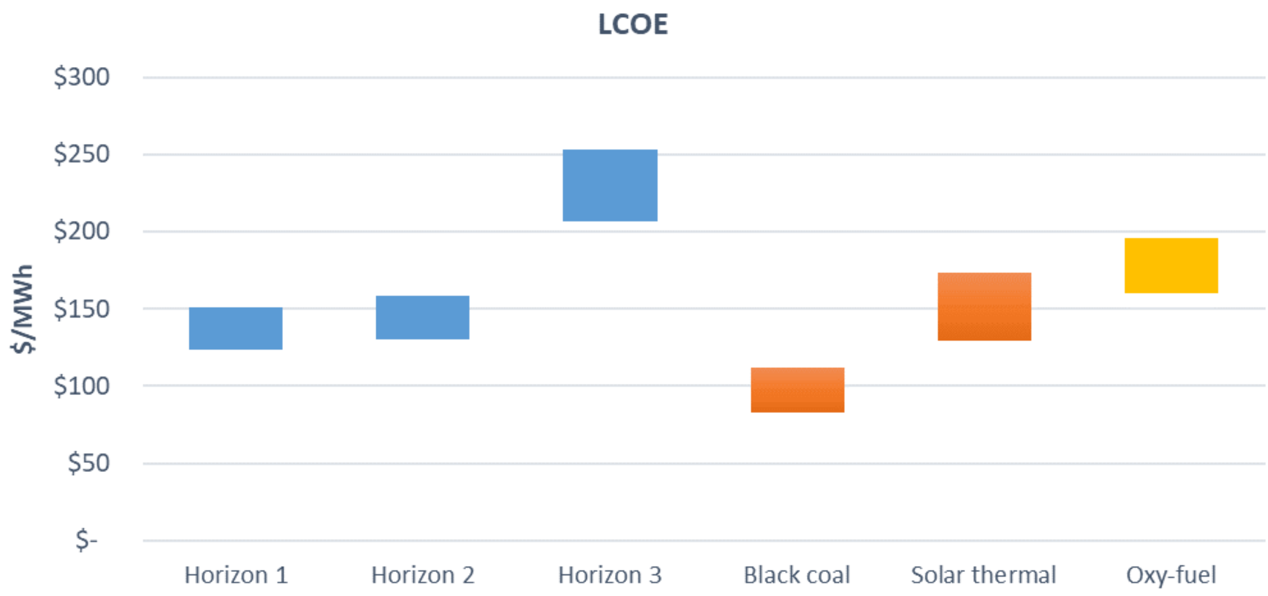


Figure 49 LCOE comparison

Similar to capital cost the values for large scale PV was left out of the comparison due to the nature of its dispatchability. Nevertheless, for reference its band is $59 $/MWh.

In general, LCOE is a useful tool for comparing the unit costs of different technologies over their operating life. As expected, low LCOE means high economic performance and in simple terms low-LCOE technology should be chosen in accordance with economic rationality. However, it is important to note that the LCOE is not a perfect indicator to show which electric generation technology should be consider. It does neither take account of the additional balancing costs associated with variable renewable electric generation technologies nor recognized that electric generation technologies have different roles such as peaking generation, dispatchable generation or non-dispatchable generation. In addition, it does not take account of the amount of CO_2 emission. Therefore, it is not adequate to simply conclude that Hybrid Solar/Coal plant is inferior to a conventional coal-fired plant and a large scale solar PV etc.

The Table 30 shows the summary of the CO_2 avoided cost. As stated in Section 9.1.3, the CO_2 avoided cost is an indicator of the cost per unit CO_2 that is incurred when CCS is added. As you can see in the equation in Section 9.1.3, the difference of the plant characteristics between "CCS" and "ref" should be only with or without CCS. In that sense, it might not be adequate to calculate the CO_2 avoided cost for Horizons against a conventional USC plant because Hybrid plants have a PV unit which a conventional USC plant does not have although the CSP unit may be interpreted as a CCS-like system that reduces CO_2 emissions. Nevertheless, the CO_2 avoided cost was studied expecting to gain some insight. In Table 30, “Black coal” means a reference plant, in other words, a conventional USC plant.

Some preconditions are;

- CO_2 emission of Black coal was calculated based on the same steam cycle and fuel condition as Horizon 1.
- CO_2 emission of Horizon 1 was calculated in accordance with the result from Section 6 showing Horizon 1 can reduce CO_2 emission by 30% compared with a Boiler Only Operation Mode.
- CO_2 emission of Horizon 2 was calculated in accordance with the net efficiency difference between Horizon 1 and 2 showing in Table 26.
- Cases where a Post-Combustion Capture (PCC) system with an amine-absorption process was added to Horizon 2 and “Black coal” was added for comparison. A LCOE increase due to adding PCC was calculated referring to (CO2CRC, 2015).
- CO_2 recovery rate for PCC applying an amine-absorption process was assumed to be 90%.
- CO_2 emission of Horizon 3 was assumed to be zero neglecting emission through the unit start-up and shut-down,
- The cost of CO_2 injection is excluded as described in Section 9.1.4.

Table 30 CO_2 avoided cost

		Horizon 1	Horizon 2	Horizon 2 with PCC	Horizon 3	Black coal	Black coal with PCC
LCOE (median)	$/MWh	137	144	240	230	98	174
CO_2 emmition	tCO_2/MWh	0.573	0.569	0.057	0.000	0.819	0.082
CO_2 avoided cost	$\$/tCO_2$	160	188	187	161	ref	104

Some insights we could get are;

- When compared to Black coal, Horizon 1 followed by Horizon 3 offers the lowest CO_2 avoided costs of all of the hybrid systems examined.
- Adding PCC to Horizon 2 significantly reduces the emissions but the CO_2 avoided costs are the highest level. Horizon 3 shows lower LCOE, CO_2 emission and CO_2 avoided cost so Horizon 3 is a better option than Horizon 2 with PCC in case more than 90% of CO_2 need to be reduced.
- The CO_2 avoided costs for all Horizons are higher than that of Black coal with PCC because an increase of LCOE from Black coal to Black coal with PCC is simply due to adding a PCC system that directly removes CO_2 emission. On the other hand, CSP and PV contribute to reducing CO_2 emission but they are not a system directly removing CO_2.
- However, Horizon 1 and 2 offer a lower LCOE than Black coal with PCC and an opportunity to reduce emissions by 30% over Black coal at a CO_2 avoided cost ranging from $160 to $188.
- For further substantial emissions reductions beyond 30%, Black coal with PCC offers a cheaper solution than Horizon 3 because Horizon 3 has CSP and PV system which enable to reduce of CO_2 emission even while CO_2 capturing system is off due to assistance from CSP and PV. On the other hand, Black coal with PCC emits 100% of CO_2 while PCC is off. This difference makes LCOE and CO_2 avoided cost for Horizon 3 higher than those of Black coal with PCC.

9.3 DISCUSSIONS – ECONOMIC EVALUATION

The economical evaluation was completed.

- ✓ Capital cost, Operation and Maintenance (O&M) cost and Levelized Cost of Electricity (LCOE) were estimated for all Horizons to examine the economic performance and then compared with those of a conventional coal-fired plant, CSP plant and PV plant. CSIRO and AEMO have been studying the electrical generation cost for years and their reports mentioned an overview of the scope, methodology and assumptions used in its development. For this economical study, most of the assumptions applied in their reports were reasonably applied so that we can compare the economic performance with their results as closely as possible.

- ✓ For the capital cost, the main equipment accounted for more than half of the total capital cost. 90% of the total main equipment cost was given by each manufacturer so it is consider quite reliable. Even though the other half of the capital cost was estimated by using Thermoflow 29, the total result should be reasonable considering its presence within the power industry.

- ✓ It seems an odd result but Horizon 1 and 2 showed almost similar capital cost as a solar thermal plant with 8-hours thermal storage. The reason is that the CSP for Horizon 1 and 2 has 100MW equivalent capacity but the unit itself has 300MW capacity and the capital cost ($/kW) shows the total capital cost ($) divided by 300MW (300,000kW). It means that the capital cost for CSP in ($) in all the Horizons is compressed roughly one-third in ($/kW) compare with a simple CSP. In addition, the steam cycle equipment cost is overlapped for a simple CSP and Hybridized unit so it can be excluded from a standalone CSP.

- ✓ Similar situation could be seen again that LCOE for Horizon 1 and 2 are lower than Solar thermal. The reason for it is similar to the case of capital cost. Firstly, CSP in all Horizons has 100MW equivalent capacity but the unit itself has 300MW capacity so the amount of electricity produced (MWh) is three times than a simple CSP with 100MW capacity and results in lowering LCOE. Secondary, the capacity factor for a general CSP plant would be around 50% or less. However, the capacity factor for Hybridized plant is 85%, so a high capacity factor makes LCOE lower than a simple standalone CSP. Thirdly, fuel cost portion in LCOE of Horizon 1 and 2 is lower than a conventional coal-fired plant due to the renewable energy assist. Because of these, Horizon 1 and 2 are positioned in the middle of Black coal and Solar thermal.

- ✓ Nevertheless, from an economic perspective comparing the Horizon 1 and 2 with a standalone Solar thermal plant, it was found that Horizon 1 and 2 are similar (or better) in economic performance than a Standalone Solar thermal plant. It is a great and promising outcome of the economic study because it could be intuitively considered that the economic performance of a Hybrid Solar/Coal plant would always be worse than a standalone CSP. The fact is different. The capital cost per kW and LCOE of Hybrid Solar/Coal plant can be lower than a CSP due to the increased kW capacity and high capacity factor. This result suggests that a new CSP plant should be hybridized with a coal-fired boiler. Hybrid Solar/Coal plant not only has better economic performance than a CSP and is dispatchable.

10 CONCLUSION

The feasibility study for Hybrid Solar/Coal plant was conducted with the aim to show that coal can remain an integral part of the future energy mix and that it can be competitive in the rapidly changing low emission market where a large focus in the future is on dispatchable generation. The methodology for this study was broken down to three Horizons and the following conclusions were obtained.

For all Horizons:

- ✓ The unit location was selected to be Hunter Valley region where there is already coalfields and thermal power stations in NSW. Ambient weather conditions have been obtained from Meteonorm database for a typical meteorological year. Hunter Valley domestic thermal coal was reasonably applied for this study.

- ✓ Solar/coal hybrid plant operational principle was proposed considering the general boiler operational characteristics regarding the main steam pressure and STG load control. Only the case in which steam flow equivalent to 200MW comes from the boiler, the parallel operation can be acceptable because the main steam pressure can be controlled constant regardless of the amount of steam flow rate from CSP. Controlling the boiler steam pressure freely regardless of the steam flow into the HP turbine should not be practical for a supercritical boiler under the current commercialized technology.

- ✓ The conceptual plant flow diagram was proposed. The steam cycle configuration was revised from the original concept because of the necessity to control the feedwater pressure and flow for the boiler side and CSP side independently. The features of the system configuration are;
  - Two non-identical HP FWH trains with two non-identical SFPs - B-SFP and S-SFP.
  - Each pump controlling the pressure and flow for the boiler side and CSP side independently.
  - Steam bypass line from CSP side to the condenser for CSP start-up and pressure control purpose.
  - Steam bypass line from the boiler to the condenser

- ✓ The conceptual plant control logic was proposed for the following three operational modes.
  - Boiler Only Operation Mode
  - Hybrid Solar/Coal Operation Mode
  - Boiler plus PV Operation Mode

- ✓ Main equipment basic design specification was proposed. The boiler and steam turbine can be designed at the boiler single operation at rated load. Even though operational range for the steam turbine and feedwater system would be expanded more than a conventional coal-fired plant due to the mixture of steam coming from CSP, any special design philosophy or specification would not be required for the boiler and steam cycle from the point of mechanical design.

- ✓ The number of Heliostat, TES capacity, solar receiver capacity and PV capacity was optimised through a parametric study. The optimization was done based on Horizon 1 but almost the same results could be obtained for Horizon 2 and 3 because main equipment capacities were not changed across Horizons and the operational restrictions remained.
  - Minimize the ratio CAPEX / Generation
  - Minimize the solar field annual energy dumping
  - Maximize the plant renewable ratio

- ✓ The operational profiles at typical day's conditions were proposed. Based on these operational profiles and conditions the renewable share could reach almost 50% on a clear summer day. It could also be more than 40% even in a clear equinox day. In an average annual climate condition, it would be around 29% on average. Approximately and according to the high-level research performed in this study, it could be concluded that this plant can reduce around 30% coal fuel, which means that it would reduce 30% of CO_2 emission compared to a conventional coal-fired plant with the same capacity. However, this number may vary between plus or minus 5% depending on the frequency of low-efficiency operation such as the minimum load operation and the ramp-up speed. Even though there is an increased steam temperature for Horizon 2&3, the ratio between renewable share and boiler share is not changed.

An average day	Renewable share	Boiler share
Horizon 1	29.28%	70.72%
Horizon 2&3	30.10%	69.90%

For Horizon 2:

- ✓ The CSP configuration combining the same molten salts nitrates tower as in Horizon 1 and an electrical steam booster heater charged from the dedicated PV through the Lithium-ion batteries was proposed to get 600 deg.C steam. The advantages of this configuration against applying other salts like carbonates reside in the fact that nitrates are currently available technology at a commercial scale as an HTF and it would mean a faster implementation.

- ✓ The battery system sizing was carried out according to the Booster Heater capacity that is 18MW. The batteries were sized so that it is able to cover 14 consecutive hours of the BH working at full capacity assuming an electric to the thermal efficiency of 99%. Therefore, the batteries capacity is estimated to be 250 MWh.

- ✓ There is no significant design difference between Horizon 1 and 2 in terms of the boiler, steam turbine and generator. The same material is applicable to both cases. The thickness of the main pipe, main valves and steam turbine casing could increase.

- ✓ Plant general layout was proposed for Horizon 2. Most of the main equipment for the steam cycle and thermal storage cycle should be arranged in the centre circle. It is important to arrange the equipment so that the area of the centre circle can be optimised and minimised. The selection and layout of the steam exhaust cooling system could be a big challenge. It is highly dependent on the actual location condition that an actual plant would be built on. A coal yard location and layout could be also another challenge.

For Horizon 3:

- ✓ The conventional air combustion boiler for Horizon 2 could be replaced to the oxyfuel combustion boiler for Horizon 3 with changes of the auxiliary system. There are no restrictions nor negative effects arisen for the plant operation due to the replacement to the oxyfuel combustion boiler except the start-up and shutdown the boiler. The heating surface area of the boiler is the same as Horizon 2.

TOSHIBA

- ✓ The main difference between them is with or without Gas Recirculation and Oxygen Injection System and CO_2 Recovery System. The oxyfuel boiler is capable to operate both air combustion mode and oxyfuel combustion mode. In air combustion mode, the Gas Recirculation and Oxygen Injection System and CO_2 Recovery System are isolated and the plant operates in the same way as Horizon 2. In oxyfuel combustion mode, a part of flue gas is recirculated from FGD outlet to FDF and PAF inlet and is supplied for combustion air after mixing with O_2. The remaining flue gas is fed to the CPU and then high concentrated CO_2 are separated and recovered.

- ✓ For Horizon 3, the plant net efficiency is quite lower than Horizon 2 due to the increased auxiliary power mainly from ASU and CPU. It will decrease from 40.3% of Horizon 2 to 26.8% of Horizon 3. The auxiliary power consumption rate exceeds 38% for Horizon 3. To improve the plant net efficiency, utilizing "dumped" PV power to complement the auxiliary power is one possible are for further research. There is around 15% of annual PV power dumped so it seems entire plausible to improve the plant net efficiency if this "dumped" power is utilized in the plant to offset the auxiliary power.

Economic evaluation:

- ✓ Nevertheless, from an economic perspective comparing the Horizon 1 and 2 with a standalone Solar thermal plant, it was found that Horizon 1 and 2 are similar (or better) in economic performance than a Standalone Solar thermal plant. It is a great and promising outcome of the economic study because it could be intuitively considered that the economic performance of a Hybrid Solar/Coal plant would always be worse than a standalone CSP. The fact is different. The capital cost per kW and LCOE of Hybrid Solar/Coal plant can be lower than a CSP due to the increased kW capacity and high capacity factor. This result suggests that a new CSP plant should be hybridized with a coal-fired boiler. Hybrid Solar/Coal plant not only has better economic performance than a CSP and also is dispatchable.

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11 RECOMMENDATIONS

The followings key points have arisen through the study and are listed as recommendations for the future investigation.

- Restriction of the USC Boiler operating in parallel with the CSP Plant

The CSP Power plant has been designed and optimized according to the restriction of the USC Boiler operating in parallel with a minimum load of 200MW at the rated pressure. More flexibility of this restriction will allow a significant increase in the power generated from the solar plant, leading to an increase in the plant renewable share.

- Rapid PV output change vs Slow ramp rate of the boiler

PV output changes suddenly and dramatically in a short time due to the sudden changes in solar irradiation. However, the boiler cannot follow a rapid or large load change in a short time, due to its slow response. Therefore, MW Demand signal needs to be changed within the predetermined ramp rate and the total generated power will fluctuate in this mode.

- PV for dispatch and PV for charging

The PV for dispatch purposes and the PV for charging the batteries for the electrical steam booster heater are separately configured. However, it can also be possible to configure it as one PV system along with the batteries. By doing this, the PV dumping can be minimized. Furthermore, with this approach it is possible to connect the batteries to not only the BH but also the grid. This configuration with the batteries being connected to the grid will greatly contribute to stabilizing the electrical output to the grid, especially in case of a sudden change in PV output due to an abrupt change in the weather. This is especially important because the boiler cannot follow the sudden PV output change in a short time due to its low ramp rate.

- Major maintenance schedule

When considering the plant lifetime generation, the difference between the scheduled annual outage required for the USC Boiler maintenance and the solar plant annual scheduled outage (significative lower) brings the opportunity to generate power exclusively from solar resources during this gap period. Therefore, it is expected to operate the plant during the boiler outage as well. It means that it is expected that the steam turbine can operate without operating the boiler. It will contribute not only to increase the plant capacity factor but also to increase the annual renewable share.

- Plant layout

All of the main equipment for the steam cycle and thermal storage cycle should be arranged in the centre circle. It is important to arrange the equipment so that the area of the centre circle can be minimized. A detailed layout study would be required in order to analyse the practical and optimized layout in the centre circle considering all of the equipment. The selection and layout of the steam exhaust cooling system could be a big challenge. It is highly dependent on the actual location condition that an actual plant would be built on. A coal yard location and layout could be also another challenge because it takes huge land space so it will conflict with minimizing the area of the centre circle.

- Site Location

The Typical Meteorological Year (TMY) used plays an important role in the solar plant optimal configuration and consequently on the expected renewable share. Different locations within Australia with a higher accumulated solar radiation will have a positive impact in the renewable share generation and its profitability. Actual plant configuration designed in the Liddell Area has been compared independently by Abengoa with a new plant location in the Alice Springs Area. The result of this evaluation is a significant increase of 26% in the renewable share ratio that increases from 29.28% to 37 % in the new location.

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APPENDICES

Appendix A: Heat Balance Diagram for Horizon 1

Appendix B: Heat Balance Diagram for Horizon 2&3

Appendix C: Conceptual Molten Salts Process Flow Diagram

Appendix D: Main Equipment Data Sheet for CSP Plant

Appendix E: PV Configuration and Data Sheet

Appendix F: ITS Data Sheet

Appendix G: Heliostat Data Sheet

Appendix H: Heliostat Manufacturing Data Sheet

Appendix I: Hybrid Solar/Coal Plant General Layout for Horizon 1 & 2

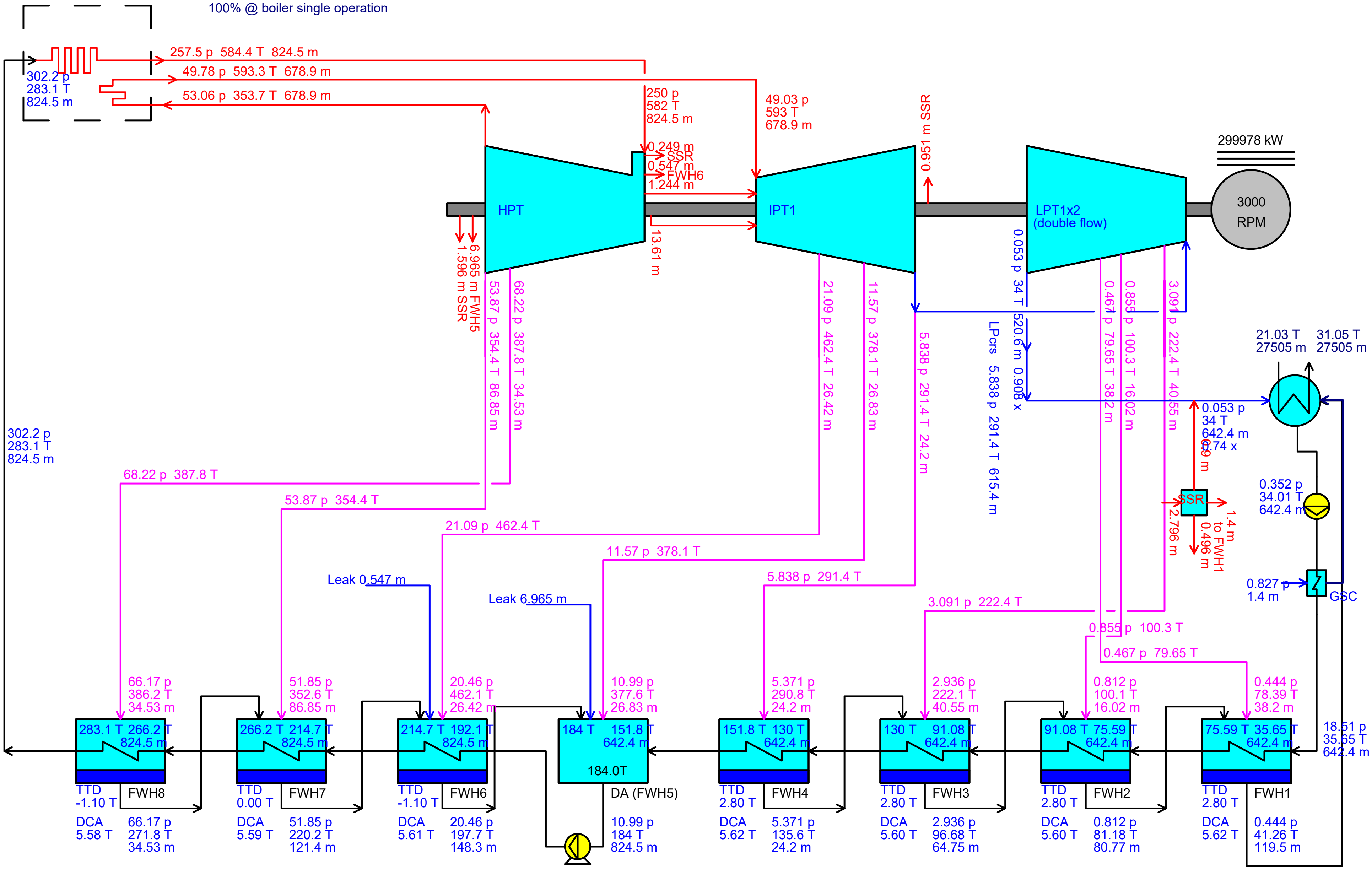
Appendix J: PV Unit General Layout for Horizon 1 & 2

Appendix K: PV Unit General Layout for Charging the Batteries for Horizon 2

Appendix A: Heat Balance Diagram for Horizon 1

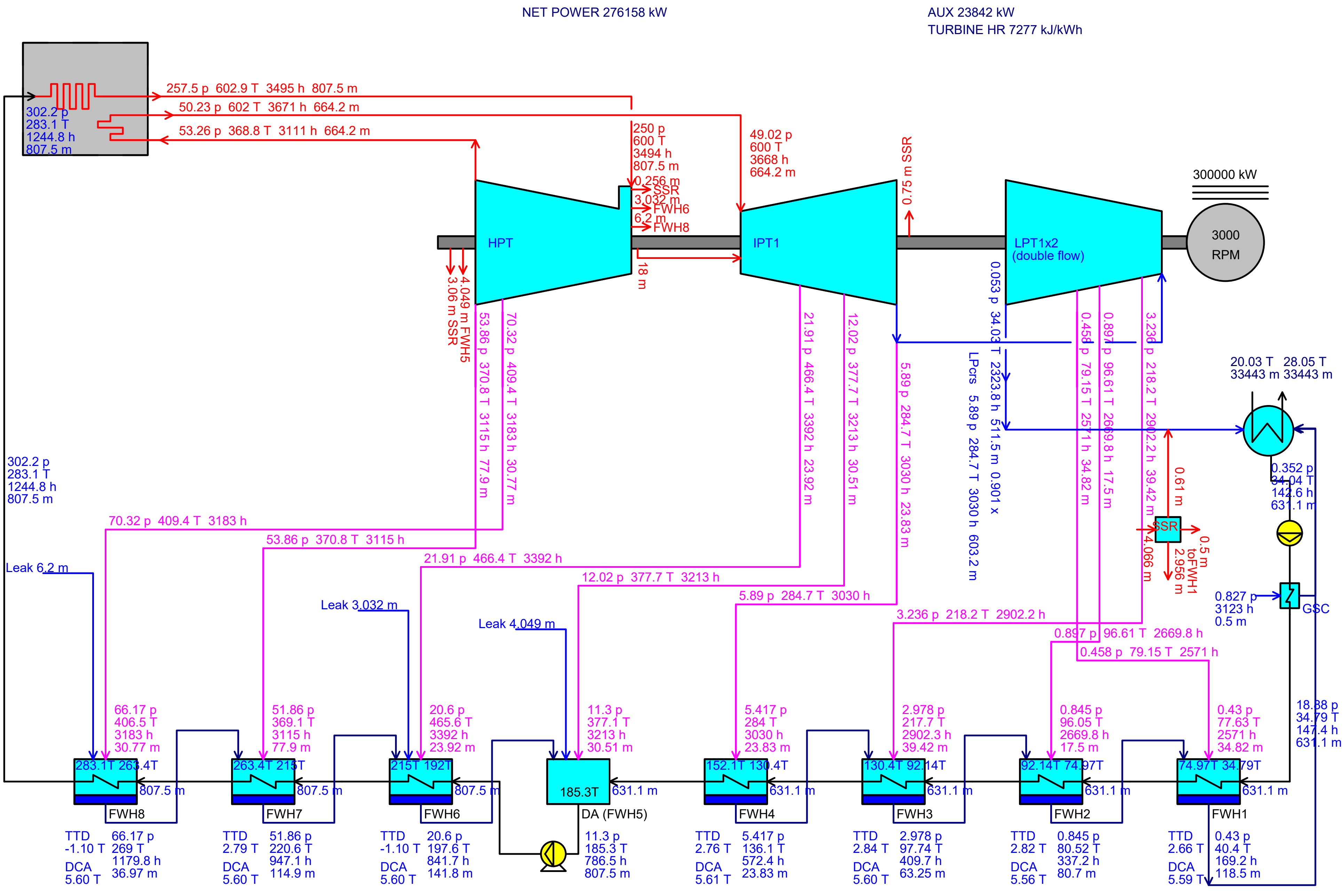
STEAM CYCLE HR 7345 kJ/kWh

Horizon 1
100% @ boiler single operation



Steam Properties: IAPWS-IF97
p[bar], T[C], h[kJ/kg], m[t/h], x[-]

Appendix B: Heat Balance Diagram for Horizon 2&3



STEAM MASTER 28.2 Admin 853 11-07-2019 11:16:58 Steam Properties: IAPWS-IF97
FILE: C:\Users\nakada\Desktop\Horizon 2\Horizon2_HB_Rev.0_300MW_Rated.STM Cycle Schematic
1 CONDENSER
p[bar], T[C], m[t/h], h[kJ/kg], x[-]

Appendix C: Conceptual Molten Salts Process Flow Diagram

Rev. nº:	Date edition:	Description:	Drawn:	Revised:	Approved:
00	2019/07/10	First Edition	EGF	ACR	JNM
			Firm	Firm	Firm

Client: TOSHIBA

Seal:

Firm:

Nº License:

Engineering: ABENGOA

Project:

300-200MW ultra supercritical hybrid solar coal R&D pathway study

Scale: S/E

Title & Subtit.: **Molten Salts process flow diagram**

Sheets: 1 Sheet nº: 1

Internal Code nº:

	Status	Date of the first edition
X	Desing Phase (IFD)	2019/07/10
	Offer Phase (IFB)	
	Purchase Phase (IFP)	
	Construction Phase (IFC)	
	Final State Built	

A1

Appendix D: Main Equipment Data Sheet for CSP Plant

Data Sheet

Title
Cold Molten Salt Tank Datasheet
Client: Toshiba
Project:300-200MW ultra supercritical hybrid solar coal R&D pathway study

Num	
Code	0202-TEC-ABE-TIC-0003
Revision	00
Date	30/06/2019

Prepared by	
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Approved by:	
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ABENGOA	USC - Hybrid TOSHIBA ABENGOA 300-200MW ultra supercritical hybrid solar/coal R&D pathway study	Cold Molten Salt Tank Datasheet						
			00	30/06/2019	FJRC/CPR	CPR	MMT	Inicial Issue
Sheet 1/3			Revision	Date	Prepared	Revised	Approved	Motivation

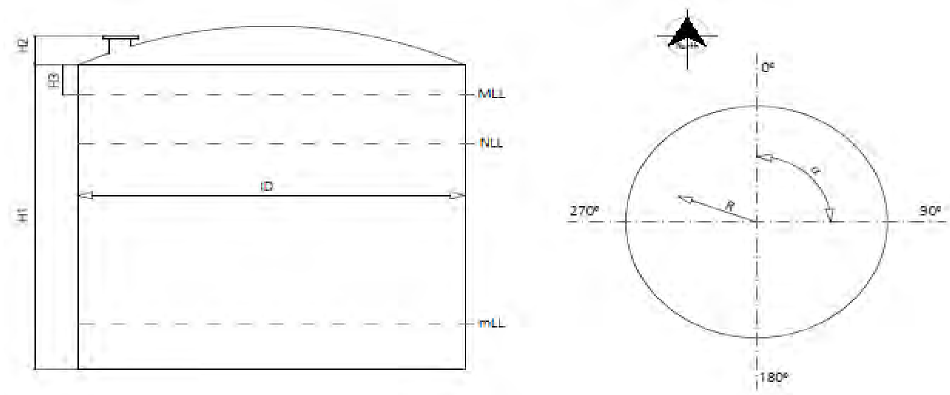
1	General				
	Codification				
	Service		Cold molten salts storage		
	Units		1		
	Maximun capacity (ton)		pending		
	Net working capacity (ton)		28894,32		
	Lenght / Height (m)		14		
	Inner Diameter (m)		40		
2	Operation Process conditions				
	Fluid		Molten salts : $NaNO_3/KNO_3$ 60/40(%w)		
	Operating Pressure (barg)		0.010-0.020		
	Op. Temperature (ºC)		290		
	Density (kg/m3)		1905		
	Viscosity (cP)		3.5		
	Blanketing (Yes/No-Gas)		Yes - Air		
3	Design information				
	Code		API 650 with maximum allowable stress found in ASME II Part D		
	Design pressure - internal (barg)		0.028		
	Design pressure - external (barg)		0.0025		
	Test pressure (barg)		Full of water	(Yes/No)	Yes
	Design temperature (ºC)		370		
	Design liquid level (m)		12		
	Maximun fill rate (Kg/s)		641,6	empty rate	1690.6
	Thermal insulation (type/density/thick.)		Rock wool		
	Max wind velocity (m/s)		*		
	Max/Min Ambient temperature (ºC)		*		
	Seismic Group			Parameters	
	Radiografic / NDT		100% / (2)	Efficiency	
	Heat Treatment				
	Type of fundation				
	Cathodic Protection System		No		
4	Material Specification				
	Component		Material	Thickness	CorrosionAllowance
	Shell		A 516 Gr 70	By supplier	By supplier
	Bottom		A 516 Gr 70	By supplier	By supplier
	Roof		A 516 Gr 70	By supplier	By supplier
	Tank supports		By supplier	By supplier	
	Internal supports		By supplier	By supplier	
	Stiffeners rings		By supplier	By supplier	
	Plates		By supplier	By supplier	
	Base rings		By supplier	By supplier	
	Gaskets (RF/RTJ)		316 SS with vermiculite filled centring / O ring SS Type 347H	By supplier	
	Nozzles	Flanges/fittings	A 105/ A234 GR.WPB (Seamless)	By supplier	
		Necks of pipes	A 106 Gr B	By supplier	
		Neck of metal sheets	A 516 Gr 70	By supplier	
	Internal elments	Profiles	By supplier	By supplier	
		Pipes	A 106 Gr B (12)	By supplier	
		Fittings	By supplier	By supplier	
		Plates	By supplier	By supplier	
		Meshes	By supplier	By supplier	
		Accesories	By supplier	By supplier	
	Bolts/Nuts	External	A 193 Gr.B7 / A 194 Grade 2H	By supplier	
		Internal	A 193 Gr.B7 / A 194 Grade 2H	By supplier	
	Shell for immersion heaters		ASTM SA-335-P11	By supplier	

ABENGOA	USC - Hybrid TOSHIBA ABENGOA 300-200MW ultra supercritical hybrid solar/coal R&D pathway study	Cold Molten Salt Tank Datasheet 0202-TEC-ABE-TIC-0003	00	30/06/2019	FJRC/CPR	CPR	MMT	Inicial Issue
Sheet 2/3			Revision	Date	Prepared	Revised	Approved	Motivation

5	Surface treatment		
	Internal	*	
	External	*	
	Cleaning	*	
	Internal painting	*	
	External painting	*	
	Post Weld Heat treatment	*	
6	Construction information (9)		
	Description	Supplied by	Assembly by
	Blind flanges,screws, ext joints and davit	Supplier	Supplier
	Handrails (with braided steel cable)	Supplier	Supplier
	Insulation clips	Supplier	Supplier
	Weight and capacity		
	Insulation Weight (kg)	*	
	Assembly Weight (kg)	*	
	Content Weight (kg)	*	
	Operting Weight (kg)	*	
	Weight full of water (kg)	*	
7	NOTES		
	* By supplier		

ABENGOA	TOSHIBA	Cold Molten Salt Tank Datasheet						
	300-200MW ultra supercritical hybrid solar/coal R&D pathway study		00	30/06/2019	FJRC/CPR	CPR	MMT	Inicial Issue
Sheet 3/3			Revision	Date	Prepared	Revised	Approved	Purpose

8 Tank Sketch



H1 (Shell Height)	pending mm
H2 (Nozzle Height)	See '9 Nozzle data'
H3 (Freeboard)	pending mm
Dint (Diameter Interior)	pending mm
MLL (maximun liquid level)	pending mm
NLL (normal liquid level)	pending mm
mLL (minimun liquid level)	pending mm

9 NOZZLE DATA

Mark number	Place	Description	Quantity	Size (NPS)	Rating	Code	Position: Height (mm) H1+H2	Position: Angle (º) α	Position: Radius (mm) R	Pipe Inside	Notes
A1	Roof	From SGS	1				pending	pending	pending		
A2	Roof	From downcomer	1				pending	pending	pending		
A3	Roof	Vent header	1				pending	pending	pending		
A4	Roof	Min. Recirculation	1				pending	pending	pending		
A6	Roof	Min. Recirculation	1				pending	pending	pending		
A7	Roof	Fist filling	1				pending	pending	pending		
J1	Roof	Receiver pump 1	1				pending	pending	pending		
J2	Roof	Receiver pump 2	1				pending	pending	pending		
J3	Roof	Receiver pump 3	1				pending	pending	pending		
J4	Roof	Receiver pump 4	1				pending	pending	pending		
J5	Roof	Attemp. pump 1	1				pending	pending	pending		
J6	Roof	Attemp. pump 2	1				pending	pending	pending		
S1	Roof	Preheating inlet	1				pending	pending	pending		
S2	Roof	Air Balance line	1				pending	pending	pending		
W1	Roof	PSV/VB	1				pending	pending	pending		
W2	Roof	PSV/VB	1				pending	pending	pending		
P1	Roof	Pressure instrument	1				pending	pending	pending		
P2	Roof	Pressure instrument	1				pending	pending	pending		
P3	Roof	Pressure instrument	1				pending	pending	pending		
L1	Roof	Spare	1				pending	pending	pending		
L2	Roof	Spare	1				pending	pending	pending		
L3	Roof	Spare	1				pending	pending	pending		
L4	Roof	Radar level instrum.	1				pending	pending	pending		
L5	Roof	Radar level instrum.	1				pending	pending	pending		
L6	Roof	Radar level instrum.	1				pending	pending	pending		
T1	Roof	Temperature instr.	1				pending	pending	pending		
T2	Roof	Temperature instr.	1				pending	pending	pending		
T3	Roof	Temperature instr.	1				pending	pending	pending		
T4	Roof	Skinpoints inlet	1				pending	pending	pending		
T5	Roof	Skinpoints inlet	1				pending	pending	pending		
T6	Roof	Skinpoints inlet	1				pending	pending	pending		
M1	Roof	Manhole/ Chimney	1				pending	pending	pending		
M2	Roof	Manhole	1				pending	pending	pending		
V1	Roof	Vent	1				pending	pending	pending		
S3	Shell	Electric heater 1	1				pending	pending	pending		
S4	Shell	Electric heater 2	1				pending	pending	pending		
S5	Shell	Electric heater 3	1				pending	pending	pending		
S6	Shell	Electric heater 4	1				pending	pending	pending		
S7	Shell	Electric heater 5	1				pending	pending	pending		
S8	Shell	Electric heater 6	1				pending	pending	pending		
S9	Shell	Electric heater 7	1				pending	pending	pending		
S10	Shell	Electric heater 8	1				pending	pending	pending		
S11	Shell	Electric heater 9	1				pending	pending	pending		
S12	Shell	Electric heater 10	1				pending	pending	pending		
S13	Shell	Electric heater 11	1				pending	pending	pending		
S14	Shell	Electric heater 12	1				pending	pending	pending		
S15	Shell	Electric heater 13	1				pending	pending	pending		
S16	Shell	Electric heater 14	1				pending	pending	pending		

USC - Hybrid

Data Sheet

Title
Hot Molten Salt Tank Datasheet
Client: Toshiba
Project:300-200MW ultra supercritical hybrid solar coal R&D pathway study

Num	
Code	0202-TEC-ABE-TIC-0004
Revision	00
Date	30/06/2019

Prepared by	
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ABENGOA	USC - Hybrid TOSHIBA ABENGOA 300-200MW Ultra Supercritical Hybrid Solar/Coal R&D pathway study	Hot Molten Salt Tank Datasheet 0202-TEC-ABE-TIC-0004						
			0	30/06/2019	FJRC/CPR	CPR	MMT	First release
			Revision	Date	Prepared	Revised	Approved	Motivation

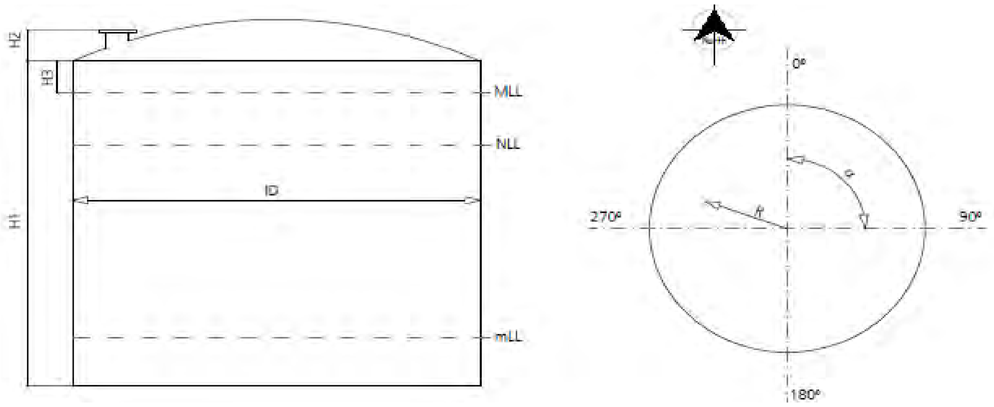
1	General				
	Codification		Hot Molten Salts Storage Tank		
	Service		Hot molten salts storage		
	Units		1		
	Maximun capacity (ton)		Pending		
	Net working capacity (ton)		28894		
	Lenght / Height (m)		14		
	Inner Diameter (m)		40		
2	Operation Process conditions				
	Fluid		Molten salts : NaNO3/KNO3 60/40(%w)		
	Operating Pressure (barg)		0,010-0,020		
	Op. Temperature (ºC)		565		
	Density (kg/m3)		1730,6		
	Viscosity (cP)		1,14		
	Blanketing (Yes/No-Gas)		Yes - Dry Air		
3	Design information				
	Code		API 650 with maximum allowable stress found in ASME II Part D		
	Design pressure - internal (barg)		0,035		
	Design pressure - external (barg)		0,0025		
	Test pressure (barg)		Full of water	Dry interior (Yes/No)	Yes
	Design temperature (ºC)		593		
	Design liquid level (m)		12,4		
	Thermal insulation		Rock wool		
	Radiografic		100%	Welding Efficiency	1
	Heat Treatment		No		
	Cathodic Protection System		No		
	Material Specification				
4	Component		Material	Thickness	Corrosion Allowance
	Shell		A 240 TP 347H	By Suplier	By Suplier
	Bottom		A 240 TP 347H	By Suplier	By Suplier
	Roof		A 240 TP 347H	By Suplier	By Suplier
	Tank supports		By Suplier	By Suplier	
	Internal supports		By Suplier	By Suplier	
	Stiffeners rings		By Suplier	By Suplier	
	Plates		By Suplier	By Suplier	
	Base rings		By Suplier	By Suplier	
	Gaskets (RF/RTJ)		316 SS with thermiculite filled centring / O ring SS Type 347H	By Suplier	
	Nozzles	Flanges/fittings	A 182 Gr.347H/ A 403 Gr.347H	By Suplier	
		Necks of pipes	A 312 TP 347H	By Suplier	
		Neck of metal sheets	A 240 TP 347H	By Suplier	
	Internal elments	Profiles	By Suplier	By Suplier	
		Pipes	A 312 TP 347H	By Suplier	
		Fittings	By Suplier	By Suplier	
		Plates	By Suplier	By Suplier	
		Meshes	By Suplier	By Suplier	
		Accesories	By Suplier	By Suplier	
	Bolts/Nuts	External	A193 GR.B8 / A194 GR.8	By Suplier	
		Internal	A193 GR.B8 / A194 GR.8	By Suplier	
	Shell for immersion heaters		ASTM A312 TP347H	By Suplier	
5	Surface treatment				
	Internal		By Supplier		
	External		By Supplier		
	Cleaning		By Supplier		
	Internal painting		By Supplier		
	External painting		By Supplier		
	Post Weld Heat treatment		By Supplier		
6	Construction information (4)				
	Description		Supplied by	Assembly by	
	Blind flanges,screws, ext joints and davit		By Supplier	By Supplier	
	Handrails (with braided steel cable)		By Supplier	By Supplier	
	Insulation clips		By Supplier	By Supplier	
	By Supplier				
	Insulation Weight (kg)		By Supplier		
	Assembly Weight (kg)		By Supplier		
	Content Weight (kg)		By Supplier		
	Operting Weight (kg)		By Supplier		
	Weight full of water (kg)		By Supplier		
	NOTES				
	NA				

ABENGOA	USC - Hybrid TOSHIBA ABENGOA	Hot Molten Salt Tank Datasheet						
	300-200MW Ultra Supercritical Hybrid Solar/Coal R&D pathway study	0202-TEC-ABE-TIC-0004	0	30/06/2019	FJRC/CPR	CPR	MMT	First release
Sheet 2/2			Revision	Date	Prepared	Revised	Approved	Motivation

7	Surface treatment		
	Internal	By Supplier	
	External	By Supplier	
	Cleaning	By Supplier	
	Internal painting	By Supplier	
	External painting	By Supplier	
	Post Weld Heat treatment	By Supplier	
8	Construction information (4)		
	Description	Supplied by	Assembly by
	Blind flanges,screws, ext joints and davit	By Supplier	By Supplier
	Handrails (with braided steel cable)	By Supplier	By Supplier
	Insulation clips	By Supplier	By Supplier
	By Supplier		
	Insulation Weight (kg)	By Supplier	
	Assembly Weight (kg)	By Supplier	
	Content Weight (kg)	By Supplier	
	Operting Weight (kg)	By Supplier	
	Weight full of water (kg)	By Supplier	
	NOTES		
	NA		

ABENGOA	TOSHIBA	Hot Molten Salt Tank Datasheet						
	300-200MW ultra supercritical hybrid solar/coal R&D pathway study	0202-TEC-ABE-TIC-0004	0	30/06/2019	FJRC/CPR	CPR	MMT	First release
Sheet 3/3			Revision	Date	Prepared	Revised	Approved	Purpose

8 Tank Sketch



H1 (Shell Height)	pending mm
H2 (Nozzle Height)	pending mm
H3 (Freeboard)	pending mm
Dint (Diameter Interior)	pending mm
MLL (maximun liquid level)	pending mm
NLL (normal liquid level)	pending mm
mLL (minimun liquid level)	pending mm

9 NOZZLE DATA

Mark number	Place	Description	Quantity	Size (NPS)	Rating	Type	Code	Position			Pipe Inside	Notes
								Height (mm)	Angle (º)	Radius (mm)		
								H1+H2	α			
A1	Roof	From downcomer	1					pending	pending	pending		
A2	Roof	Spare	1					pending	pending	pending		
A3	Roof	Vent header	1					pending	pending	pending		
A4	Roof	Min. Recirculation	1					pending	pending	pending		
A5	Roof	From SGS return line	1					pending	pending	pending		
A6	Roof	From drain tank	1					pending	pending	pending		
A7	Roof	First filling & Rack of Samples	1					pending	pending	pending		
J1	Roof	SGS pump 1	1					pending	pending	pending		
J2	Roof	SGS pump 2	1					pending	pending	pending		
S1	Roof	Preheating inlet	1					pending	pending	pending		
S2	Roof	Air Balance Line	1					pending	pending	pending		
S9	Roof	Service air Line	1					pending	pending	pending		
V1	Roof	Vent	1					pending	pending	pending		
W1	Roof	PSV/VB	1					pending	pending	pending		
W2	Roof	PSV/VB	1					pending	pending	pending		
P1	Roof	Pressure instrument	1					pending	pending	pending		
P2	Roof	Pressure instrument	1					pending	pending	pending		
P3	Roof	Pressure instrument	1					pending	pending	pending		
L1	Roof	Radar level instrum.	1					pending	pending	pending		
L2	Roof	Radar level instrum.	1					pending	pending	pending		
L3	Roof	Radar level instrum.	1					pending	pending	pending		
T1	Roof	Temperature instr.	1					pending	pending	pending		
T2	Roof	Temperature instr.	1					pending	pending	pending		
T3	Roof	Temperature instr.	1					pending	pending	pending		
T4	Roof	Skinpoints inlet	1					pending	pending	pending		
T5	Roof	Skinpoints inlet	1					pending	pending	pending		
T6	Roof	Skinpoints inlet	1					pending	pending	pending		
M1	Roof	Manhole / Chimney	1					pending	pending	pending		
M2	Roof	Manhole	1					pending	pending	pending		
S3	Shell	Electric heater 1	1					pending	pending	pending		
S4	Shell	Electric heater 2	1					pending	pending	pending		
S5	Shell	Electric heater 3	1					pending	pending	pending		
S6	Shell	Electric heater 4	1					pending	pending	pending		
S7	Shell	Electric heater 5	1					pending	pending	pending		
S8	Shell	Electric heater 6	1					pending	pending	pending		
B1	Shell	Emergency Drain	1					pending	pending	pending		

Data Sheet

Title
Tower Datasheet
Client: Toshiba
Project:300-200MW ultra supercritical hybrid solar coal R&D pathway study

Num	
Code	0202-TEC-ABE-TIC-0005
Revision	00
Date	30/06/2019

Prepared by	
Francisco Javier Ruiz Cabañas Cristina Prieto Ríos	Firma electrónica

Revised by	
Cristina Prieto Ríos	Firma electrónica

Approved by:	
Miguel Méndez Trigo	Firma electrónica

ABENGOA	USC - Hybrid TOSHIBA ABENGOA	Tower Datasheet						
	300-200MW ultra supercritical hybrid solar/coal R&D pathway study	0202-TEC-ABE-TIC-0005	00	30/06/2019	FJRC/CPR	CPR	MMT	Inicial Issue
Sheet 1/1			Revision	Date	Prepared	Revised	Approved	Motivation

1	**General**			Notes
2	Tower Heigth (Foundation to Bottom of Receiver)	m	180	
3	Tower Diameter (Top)	m		
4	Tower Foundation Diameter	m		
5	Elevator	set	2	
6	Structure		Reinforced Concrete	
7	The Thickness of shaft	m	0.5~0.9	
8	Loads		Dead,Live,Seismic,Wind, MSCR load etc.	
9	Design software		Staad Pro and Sap2000	
10	Codes and standards		OTS	
11	Erection method for tower		Slip-formas per OTS	
12	Steel Protections		Painting Or Galvanized	
13	Testing Process		Finalized At The Execution Stage	

USC - Hybrid
TOSHIBA ABENGOA

ABENGOA

Datasheet

Title:
Heat transfer fluid
Client: Toshiba
Project: 300-200MW ultra supercritical hybrid solar coal R&D pathway study

Document No.:	0202-TEC-ABE-TIC-0006
Revision:	00
Date:	30/06/2019

Issued by:	
Francisco Javier Ruiz Cabañas Cristina Prieto Ríos	Electronic Signature

Checked by:	
Cristina Prieto Ríos	Electronic Signature

Reviewed by:	
Miguel Méndez Trigo	Electronic Signature

Heat transfer fluid datasheet

The fluid used for the thermal energy storage consists of a molten salt mixture with a weight composition of 60% of sodium nitrate and 40% of potassium nitrate. The most important features are:

- High specific heat
- High thermal conductivity
- High chemical stability (up to 600ºC)
- Non-flammable
- Non-toxic

The mixture is stable in air and has a low vapour pressure. Molten salts can be used over a temperature range of 260ºC to approximately 621ºC. As temperature decreases, they start to crystallize at 238ºC and solidify at 221 ºC.

- Heat fusion: 161 kJ/kg
- Change in density upon melting: $\Delta V/\Delta V_{solid}$ =4.6%

The physical properties for the fluid mixture nitrate salt, 60% $NaNO_3$ and 40% KNO_3, as a function of temperature between 300 to 600 °C (570 to 1110 °F) are the following:

- Density (kg/m3) =ρ=2090-0.640* T (ºC)
- Specific heat (J/kg ºC)=Cp= 1.450+0.0001646*T(ºC)
- Absolute viscosity (mPa s) =μ=-1.24E-7*T^3 (ºC)+2.05E-4*T^2-0.11*T(ºC)+21.89
- Thermal conductivity (W/m ºC) = k= 0.385+ 1.9E-4*T(ºC)

The maximum contamination from all sources in sodium nitrate composition shall be:

- Chloride ion 0.1 w% (Including perchlorates and chlorides)

- Halide Content (Cl+Br+I)	0.12 w%
- Nitrites	0.02 w%
- Carbonates	0.1 w%
- Sulfates	0.1 w%
- Hydroxyl alkalinity	0.05 w%
- Magnesium	0.02 w%
- Total Insoluble Materials	0.05 w%
- Moisture	0.1 w%

The total content of impurities shall be that the purity of the sodium nitrate salts is equal or higher than 99.5%.

The maximum contamination from all sources in potassium nitrate composition shall be:

- Chloride ion	0.1 w% (Including perchlorates and chlorides)
- Halide Content (Cl+Br+I)	0.12 w%
- Nitrites	0.02 w%
- Carbonates	0.02 w%
- Sulfates	0.05 w%
- Hydroxyl alkalinity	0.01 w%
- Magnesium	0.01 w%
- Total Insoluble Materials	0.05 w%
- Moisture	0.1 w%

The total content of impurities shall be that the purity of the potassium nitrate salts is equal or higher than 99.6%.

Regarding the granule size, 95% of particles shall be between 0.05 and 6 mm and particles greater than 6 mm shall be removed prior to transport at site.

During salt melting, part of the salt mixture will naturally decompose. This is considered as losses and is 1 % maximum estimated over the total. This is considered for salt purchasing.

Regarding the quality assurance, the products to be supplied shall conform to the requirements of the Salt Specification, to the best accepted international practice and to the requirements imposed by the service conditions. As a means of ensuring these objectives, the Supplier shall apply a documented quality assurance system that shall be certified to ISO 9001 standard. The Supplier shall ensure that the same requirements are applied to products, systems, and services supplied by sub-contractors and sub-suppliers.

The purchaser has the right to review and evaluate at any time the effectiveness of the quality assurance system related with the products of this document including the Supplier's subcontracts. This right is extended to the final customer or his representatives. This right get access to documentation and the workshops or places where related with the equipment supply.

In the case of deviations on the application of the quality system leading to doubts about quality product, the purchaser shall reserve the right to have additional random tests to be done by the Supplier and/or subcontractors.

Acceptance by the Purchaser of any document or activity related with the product shall not relieve the Supplier of his obligation to supply and install plant fully capable of meeting the specification and service requirements.

Once the nitrate salt reaches the jobsite, it will be unloaded from the trucks, placed on dunnage for isolation from the moisture in the soil, and covered with tarps for protection from precipitation and condensation.

ABENGOA

USC - Hybrid
TOSHIBA ABENGOA

Datasheet

Title:
Solar receiver datasheet
Client: Toshiba
Project: 300-200MW ultra supercritical hybrid solar coal R&D pathway study

Document No.:	0202-TEC-ABE-TIC-0007
Revision:	00
Purpose:	
Date:	30/06/2019

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Reviewed by:	
Cristina Prieto Ríos	Electronic Signature

Approved by:	
Miguel Méndez Trigo	Electronic Signature

Revision Control Sheet

Revision	Date	Reason for revision	Issued by	Checked by	Reviewed by	Approved by
00	30/06/2019	First edition in official formats	FJRC/CPR	CPR	CPR	MMT

Datasheet

Ambient conditions

- Location: Liddell Area with GPS coordinates: 32º 22´ 16.9´´ S ; 150º 58´ 32.0´´ E

Molten Salt Solar Receiver Datasheet		
Client: Toshiba		
Project: 300-200MW ultra supercritical hybrid solar coal R&D pathway study		
Parameter	**Units**	**Value**
Nominal absorbed power	MWt	350
Nominal efficiency	-	0,8803
Overload	-	0,00
Max absorbed power	MWt	
Max incident power	MWt	
Required area	m2	*
Height	m	*
Diameter	m	*
H/D Ratio	-	*
Outlet temperature	ºC	565,00
Inlet temperature	ºC	303,69
Max mass flow	kg/s	
Nominal mass flow	kg/s	802,62
Tubes outer diameter	mm	*
Tubes thickness	mm	*
Distance between tubes	mm	*
Max volumetric flow	m3/s	
Tubes inner area	m2	*
Max velocity 1 tube	m/s	*
Max velocity per tube	m/s	*
Number of tubes	-	*
Panel width	mm	*
Number of panels	-	*

* All the values pending to be defined "By supplier", shall be provided by Supplier for EPC Contractor to check and validate. Once an initial design is provided by Supplier, an iterative process will be done between Supplier and EPC Contractor to optimize both the final Molten Salt Solar Receiver and Solar Field designs.

ABENGOA

USC - Hybrid

TOSHIBA ABENGOA

Data Sheet

Title
Molten Salt Pump Datasheet
Client: Toshiba
Project:300-200MW ultra supercritical hybrid solar coal R&D pathway study

Num	
Code	0202-TEC-ABE-TIC-0008
Revision	01
Date	30/06/2019

Prepared by	
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Revised by	
Cristina Prieto Ríos	Firma electrónica

Approved by:	
Miguel Méndez Trigo	Firma electrónica

ABENGOA	USC - Hybrid TOSHIBA ABENGOA	Steam Generator pumps datasheet						
	1/1		0	30/06/2019	CPR/FJRC	CPR	MMT	First edition
	Sheet		Revision	Date	Prepared	Revised	Approved	Purpose

1	**Supply**	Nº Pumps 2x100%	Manufacturer: *	Model: *	

2	**General description**					
	Type:	Vertical	Suspended	Multistage	Open lineshaft	Tag No:
	P&ID / sheet / zone			Main inlet/outlet li		
	Site Location: Outdoors					

Enviromental Conditions	Site : Outdoors						Site : Indoors	
	Height above	Temperature	Relative humidi	Wind	Snow load	Barometric pressure	Relative humidity	Temperature
	*	Max. ** ºC	* %	* m/s	N/A kg/m^2	* mbar,a	N/A %	Max. N/A ºC
	1550 m	Min. * ºC						Min. N/A ºC

Seismic qualification: Seismic Zone 3, Occupancy category IV					
Noise level 1 m away from the pump-motor assembly:	85 dBA	Vibration:	Not exceed limits of Zone A of ISO 7919 or ISO 10816 and ISO 1940 or 11342 (as applicable)		
Atex Category	Not qualified :	Category	Category 2 :	Category 3 :	
Remarks :					

3	**Relevant documents, codes and standards**			
	Codes:	Reference Documents	Local / Country Regulations	USA / International Codes
				API 610
				HIS
	Remarks :			

4	**Service conditions**					
	Fluid :	Molten Salts (40% KNO3 - 60% NaNO3)				
	Temperature (max / operating / min) (ºC) :	593 / 565 / 270	System design temperature (ºC) :	Inlet : 593	Outlet:	593
	Viscosity (cP) :	1,03 / 1,14 / 4,04	System design gauge pressure (barg):	Inlet : N/A	Outlet:	15
	Density (kg/m^3) :	1712,8 / 1730,6 / 1918,2	Service (continuous/intermittent)	Continuous (6)		
	Vapor absolute pressure (bara) :	N/A	Parallel operation (Yes/No) :	No		
	Remarks :					

5 Performance requirements

	Specifications				Supplier			
Operating conditions	Continuous Minimum flow	Operating	Design Point	Runout	Continuous Minimum flow	Operating point	Design Point	Runout
Flow (kg/s)	≤ 30% Qdesign	573,3	630,0	> 120% design flow	*	*	*	*
Total Head (TDH) (m)		52,3	64,1		*	*	*	*
Temperature at suction flange (ºC)		565	565		*	*	*	*
Pressure at suction flange (barg)		0,10	0,10		*	*	*	*
Pressure at discharge flange (barg)		6,15	8,14		*	*	*	*
Pump efficiency (%)		>80%			*	*	*	*
NPSH available (m)	-	-	-	-	-	-	-	-
NPSH required (m)	-	-	-	-	-	-	-	-
Brake horsepower (kW)		410,49	*		*	*	*	*
BEP Flow					*			
Special point					*			
Total head at shutoff condition (m)	The shutoff head should not be less than 110% and should not exceed 125% of the head at design capacity. Maximum Allowable Pump Head Rise to Shut Off: 50% (Pump Design Requirement)				*			
Shutoff pressure (bar)					*			
Pump Run out greater than					*			
Speed (rpm)					*			
First critical speed (rpm)	At least >130% operating nominal speed				*			
Maximum allowable reverse speed (rpm)					*			
Maximum achievable reverse speed in case of valve failure (rpm)					*			
Specificic speed of the first impeller (USA units)					*			
Suction specificic speed of the first impeller (USA units)	Not to exceed maximum recommended value indicated at HIS				*			
Maximum operation time at cavitation condition (s)					*			
Maximum operation time at shutoff condition (s)					*			
Pump rotation	CW				*			
Pump and driver								

Remarks

*** By supplier**

ABENGOA	USC - Hybrid TOSHIBA ABENGOA	Receiver pumps datasheet						
	1/1		0	30/06/2019	CPR/FJRC	CPR	MMT	First edition
	Sheet		**Revision**	**Date**	**Prepared**	**Revised**	**Approved**	**Purpose**

1	**Supply**	Nº Pumps	4x33%	Manufacturer: *	Model:	*

2 General description

Type:	Vertical	Suspended Multistage		Open lineshaft	Tag No:				
P&ID / sheet / zone				Main inlet/outlet lines					
Site Location: Outdoors									
Enviromental Conditions	Site : Outdoors							Site : Indoors	
	Height above Sea level	Temperature	ative humi	Wind	Snow load	Barometric pressure		Relative humidity	Temperature
	* m	Max. * ºC Min. * ºC	* %	* m/s	* g/m	* mbar,a		* %	Max. N/A ºC Min. N/A ºC
Seismic qualification: *									
Noise level 1 m away from the pump-motor assembly:		85 dBA	Vibration:	Not exceed limits of Zone A of ISO 7919 or ISO 10816 and ISO 1940 or 11342 (as					
Atex Category	NOT QUALIFIED :	Category 1 :		Category 2 :			Category 3 :		
Remarks :									

3 Relevant documents, codes and standards

Codes:	Reference Documents	Local / Country Regulations	USA / International Codes
		*	API 610
			HIS
Remarks :			

4 Service conditions

Fluid :	Molten Salts (40% KNO3 - 60% NaNO3)					
Temperature (max / operating / min) (ºC) :	370 / 290 / 270	System design temperature (ºC) :	Inlet :	370	Outlet:	370
Viscosity (cP) :	2,08 / 3,49 / 4,04	System design gauge pressure (barg):	Inlet :	N/A	Outlet:	90
Density (kg/m^3) :	1854,6 / 1905,5 / 1918,2	Service (continuous/intermittent)	Continuous (6)			
Vapor absolute pressure (bara) :	N/A	Parallel operation (Yes/No) :	Yes			
Remarks :						

5 Performance requirements

	Specification				Supplier			
Operating conditions **(1)**	Continuous Minimum flow	Operating poi	Design Point	Runout	Continuous Minimum flow	Operating point	Design Point	Runout
Flow (kg/s)	≤ 30% Qdesign	240,6	264,0	> 120% design flow	*	*	*	*
Total Head (TDH) (m)		321,7	373,8		*	*	*	*
Temperature at suction flange (ºC)		290	290		*	*	*	*
Pressure at suction flange (barg)		0,09	0,08		*	*	*	*
Pressure at discharge flange (barg)		57	66,8		*	*	*	*
Pump efficiency (%)		>80%			*	*	*	*
NPSH available (m)	-	-	-	-	-	-	-	-
NPSH required (m)	-	-	-	-	-	-	-	-
Brake horsepower (kW)		2222,13	*		*	*	*	*
BEP Flow					*			
Special point					*			
Total head at shutoff condition (m)	The shutoff head should not be less than 110% and should not exceed 115% of the head at design capacity. Maximum Allowable Pump Head Rise to Shut Off: 50% (Pump Design Requirement)				*			
Shutoff pressure (bar)					*			
Pump Run out greater than					*			
Speed (rpm)					*			
First critical speed (rpm)	At least >130% operating nominal speed				*			
Maximum allowable reverse speed (rpm)					*			
Maximum achievable reverse speed in case of valve failure (rpm)					*			
Specificic speed of the first impeller (USA units)					*			
Suction specificic speed of the first impeller (USA units)	Not to exceed maximum recommended value indicated at HIS				*			
Maximum operation time at cavitation condition (s)					*			
Maximum operation time at shutoff condition (s)					*			
Pump rotation	CW				*			
Pump and driver								

Remarks

*** By supplier**

Title:
PV configuration and data sheets
Client: Toshiba
Project: 300-200MW ultra supercritical hybrid solar coal R&D pathway study

Document No.:	0202-TEC-ABE-TIC-0009
Revision:	00
Date:	25/07/2019

Issued by:	
Francisco Javier Ruiz Cabañas Cristina Prieto Ríos	FJRC CPR

Reviewed by:	
Cristina Prieto Ríos	CPR

Approved by:	
Miguel Méndez Trigo	MMT

Revision Control Sheet

Revision	Date	Reason for revision	Issued by	Checked by	Reviewed by	Approved by
00	25/07/2019	First edition in official formats	FJRC/CPR	CPR	CPR	MMT

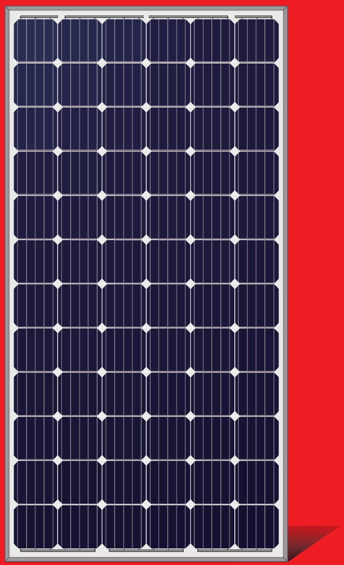
PV configuration

PV Plant General Design	Unit	
PV Blocks	Units	52
DC rated peak power	MWp	289,88
AC rated power @ RSC (25ºC, 1000m)	MVA	255,37
AC rated power @50ºC, 1000m	MVA	223,38
Number of modules	Units	762840
Number of strings	Units	25428
Number of trackers	Units	8476
Number of inverters	Units	156
Number of transformers	Units	52
Number of Inverter Transformer Stations	Units	52

PV Block	Unit	Value
PV Module		
Module model	-	Longi LR6-72PH-380M or similar
Module power	Wp	380
Number of modules	Units	14670
Number of modules/string	Units	30
Number of strings	Units	489
DC Power	MWp	5,57
Inverter Transfomer Station		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
AC rated power @ RSC (25ºC, 1360m)	MVA	4,911
Power Station AC size @ 50ºC, 1360m	MVA	4,296
Tracker		
Tracker Model	-	Soltec SF7 or similar
Mounting system	-	1-axis tracking system, decentralized
Tilt/Tracking range	º	+/-55º range
Pitch	m	10.5 m between rows
Tracker width	m	3.95 m
Trackers/ PV Block	Units	163
Electrical distribution		
DC Configuration (single circuits, DC buses)	-	DC buses
LV protection type (Combiner, switching boxes)	-	Switching boxes
Conductor Material	Cu/Al	

Inverter Transformer Station	Unit	Value
Inverter		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
Inverter rated AC power @RSC (25ºC, 1360m)	MVA	1637
Inverter rated AC power @50ºC, 1360m	MVA	1431,9
Number of inverters	Units	3
ITS AC size @ RSC (25ºC, 1360m)	MVA	4,911
ITS AC size @ 50ºC, 1360m	MVA	4,296
Transformer		
Transformer Type	-	Outdoor Oil Transformer 0.63/33 kV
Transformer Power @40ºC	MVA	4,92
Number of transformers	Units	1

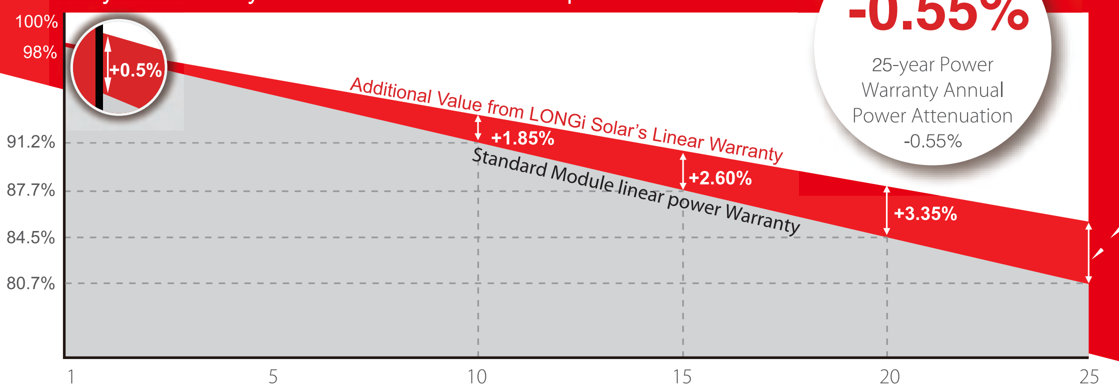
LR6-72PH
360~380M



Hi-MO1 High Efficiency Low LID Mono PERC Technology (1500V Compatible)

New

10-year Warranty for Materials and Processing;
25-year Warranty for Extra Linear Power Output



Complete System and Product Certifications

IEC 61215, IEC61730, UL1703

ISO 9001:2008: ISO Quality Management System

ISO 14001: 2004: ISO Environment Management System

TS62941: Guideline for module design qualification and type approval

OHSAS 18001: 2007 Occupational Health and Safety

* Specifications subject to technical changes and tests. LONGi Solar reserves the right of interpretation.

Positive power tolerance (0 ~ +5W) guaranteed

High module conversion efficiency (up to 19.6%)

Slower power degradation enabled by Low LID Mono PERC technology: first year <2%, 0.55% year 2-25

Better energy yield with excellent low irradiance performance and temperature coefficient

Solid PID resistance ensured by solar cell process optimization and careful module BOM selection

Adaptable to harsh environment: passed rigorous salt mist and ammonia tests

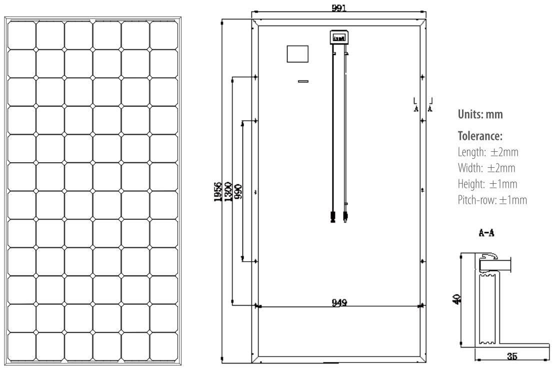
LONGi Solar

Room 201, Building 8, Sandhill Plaza, Lane 2290, Zuchongzhi Road, Pudong District, Shanghai, 201203
Tel: + 86-21-61047332 Fax: +86-21-61047377 E-mail: module@longi-silicon.com
Facebook: www.facebook.com/LONGi Solar

20180701

LR6-72PH 360~380M

Design（mm）



Mechanical Parameters

Cell Orientation: 72（6×12）

Junction Box: IP67, three diodes

Output Cable: 4mm², 1200mm in length

Weight: 22.5kg

Dimension: 1956×991×40mm

Packaging: 26pcs per pallet

Operating Parameters

Operational Temperature: -40℃ ~ +85℃

Power Output Tolerance: 0 ~ +5 W

Maximum System Voltage: DC1500V (IEC&UL)

Maximum Series Fuse Rating: 20A

Nominal Operating Cell Temperature: 45±2℃

Application Class: Class A

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR6-72PH-360M		LR6-72PH-365M		LR6-72PH-370M		LR6-72PH-375M		LR6-72PH-380M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	360	266.7	365	270.4	370	274.1	375	277.8	380	281.5
Open Circuit Voltage (Voc/V)	47.9	44.7	48.0	44.8	48.3	45.1	48.5	45.3	48.7	45.5
Short Circuit Current (Isc/A)	9.70	7.82	9.74	7.85	9.84	7.93	9.90	7.98	9.99	8.05
Voltage at Maximum Power (Vmp/V)	39.2	36.2	39.3	36.3	39.4	36.4	39.6	36.6	39.8	36.8
Current at Maximum Power (Imp/A)	9.18	7.36	9.29	7.45	9.39	7.53	9.47	7.59	9.55	7.66
Module Efficiency(%)	18.6		18.8		19.1		19.3		19.6	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Temperature Ratings（STC）

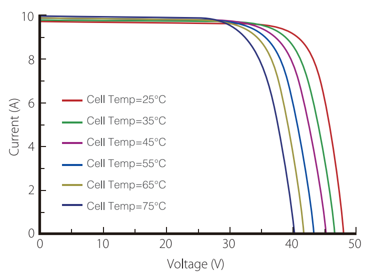
Temperature Coefficient of Isc	+0.057%/℃
Temperature Coefficient of Voc	-0.286%/℃
Temperature Coefficient of Pmax	-0.370%/℃

Mechanical Loading

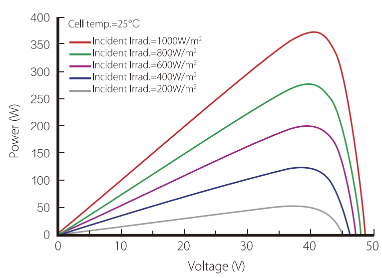
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

I-V Curve

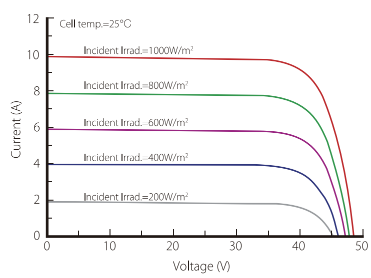
Current-Voltage Curve (LR6-72PH-370M)



Power-Voltage Curve (LR6-72PH-370M)



Current-Voltage Curve (LR6-72PH-370M)



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Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi Solar have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

20180701

TECHNICAL DATASHEET

SF7
Single-Axis Tracker

MAIN FEATURES

Tracking System	Horizontal Single-Axis with independent rows
Tracking Range	120° +
Drive System	Enclosed Slewing Drive, DC Motor
Power Supply	Self-Powered PV Series
	Optional: AC/DC Universal Input
Tracking Algorithm	Astronomical with TeamTrack Backtracking
Communication	
Wireless	Hybrid Radio + RS-485 Cable
Optional: Wire	RS-485 Full Wired
Wind Resistance	Per Local Codes
Land Use Features	
Independent Rows	YES
Slope North-South	17%
Slope East-West	Unlimited
Ground Coverage Ratio	Configurable. Typical range: 28-50%
Foundation	Driven Pile | Ground Screw | Concrete
Temperature Range	
Standard	- 4°F to +131°F | -20°C to +55°C
Extended	-40°F to +131°F | -40°C to +55°C
Availability	>99%
Modules	Standard: 72 cells | Optional: 60 Cells; Crystalline, Thin Film (Solar Frontier, First Solar and others); Bifacial

MODULE CONFIGURATIONS

1000V	Length	Height	Width
2x38	38.1 m (124' 12")	3.95 m (12' 12")	3.92 m (12' 12")
2x40	40.1 m (131' 7")		

1500V	Length	Height	Width
2x42	42.1 m (138' 12")		
2x43.5	44.1 m (144' 8")	3.95 m (12' 12")	3.92 m (12' 10")
2x45	45.1 m (147' 12")		

SERVICES

Tracker Advisory Services	Tracker Turnkey Contracting
Technical Support	Commissioning
Pull Out Test	Maintenance

MAINTENANCE ADVANTAGES

Self-lubricating Bearings
Face to Face Cleaning Mode
2x Wider Aisles

WARRANTY

Structure	10 years (extendable)
Motor	5 years (extendable)
Electronics	5 years (extendable)

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UL LISTED [PV SOLAR TRACKER] E476688

DNV GL Technology Review available
Bankability report
WIND TUNNEL TESTED

Soltec

www.soltec.com


Soltec
SF7
One Track
Zero Gap
The latest generation of the horizontal single-axis tracker
UL LISTED
[PV SOLAR TRACKER]
E476688
SYSTEM CERTIFICATION ISO 9001 SGS
SYSTEM CERTIFICATION ISO 14001 SGS
SYSTEM CERTIFICATION OHSAS 18001 SGS

Appendix E: PV Configuration and Data Sheet

PV configuration for exportation

PV Plant General Design	Unit	
PV Blocks (*)	Units	52,00
DC rated peak power	MWp	289,88
AC rated power @RSC (25ºC, 1000m)	MVA	255,37
AC rated power @50ºC, 1000m	MVA	223,38
Number of modules	Units	762840,00
Number of strings	Units	25428,00
Number of trackers	Units	8476,00
Number of inverters	Units	156,00
Number of transformers	Units	52,00
Number of Inverter Transformer Stations (**)	Units	52,00
PV Module Area	ha	148,32

(*) PV Block	Unit	Value
PV Module		
Module model	-	Longi LR6-72PH-380M or similar
Module power	Wp	380
Number of modules	Units	14670
Number of modules/string	Units	30
Number of strings	Units	489
DC Power	MWp	5,57
Inverter Transfomer Station (**)		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
AC rated power @RSC (25ºC, 1360m)	MVA	4,911
Power Station AC size @50ºC, 1360m	MVA	4,296
Tracker		
Tracker Model	-	Soltec SF7 or similar
Mounting system	-	1-axis tracking system, decentralized
Tilt/Tracking range	º	+/-55º range
Pitch	m	10.5 m between rows
Tracker width	m	3.95 m
Trackers/ PV Block	Units	163
Electrical distribution		
DC Configuration (single circuits, DC buses)	-	DC buses
LV protection type (Combiner, switching boxes)	-	Switching boxes
Conductor Material	Cu/Al	

(**) Inverter Transformer Station	Unit	Value
Inverter		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
Inverter rated AC power @RSC (25ºC, 1360m)	MVA	1637
Inverter rated AC power @50ºC, 1360m	MVA	1431,9
Number of inverters	Units	3
ITS AC size @RSC (25ºC, 1360m)	MVA	4,911
ITS AC size @50ºC, 1360m	MVA	4,296
Transformer		
Transformer Type	-	Outdoor Oil Transformer 0.63/33 kV
Transformer Power @40ºC	MVA	4,92
Number of transformers	Units	1

PV configuration used to charge the Lithium-ion batteries

PV Plant General Design	Unit	
PV Blocks (*)	Units	6,00
DC rated peak power	MWp	33,32
AC rated power @RSC (25ºC, 1000m)	MVA	29,47
AC rated power @50ºC, 1000m	MVA	25,77
Number of modules	Units	87696,00
Number of strings	Units	3024,00
Number of trackers	Units	1008,00
Number of inverters	Units	18,00
Number of transformers	Units	6,00
Number of Inverter Transformer Stations (**)	Units	6,00
PV Module Area	ha	17,05

(*) PV Block	Unit	Value
PV Module		
Module model	-	Longi LR6-72PH-380M or similar
Module power	Wp	380
Number of modules	Units	14616
Number of modules/string	Units	29
Number of strings	Units	504
DC Power	MWp	5,55
Number of strings/inverter	Units	168,00
Inverter Transfomer Station (**)		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
AC rated power @RSC (25ºC, 1360m)	MVA	4,911
Power Station AC size @50ºC, 1360m	MVA	4,296
Tracker		
Tracker Model	-	Soltec SF7 or similar
Mounting system	-	1-axis tracking system, decentralized
Tilt/Tracking range	º	+/-55º range
Pitch	m	10.5 m between rows
Tracker width	m	3.95 m
Trackers/ PV Block	Units	168
Number of files/tracker	Units	2
Number of strings/tracker	Units	3
Electrical distribution		
DC Configuration (single circuits, DC buses)	-	DC buses
LV protection type (Combiner, switching boxes)	-	Switching boxes
Conductor Material	Cu/Al	

(**) Inverter Transformer Station	Unit	Value
Inverter		
Inverter model	-	Ingeteam_Ingecon SUN 1640TL B630 Outdoor or similar
Inverter rated AC power @RSC (25ºC, 1360m)	MVA	1637
Inverter rated AC power @50ºC, 1360m	MVA	1431,9
Number of inverters	Units	3
ITS AC size @RSC (25ºC, 1360m)	MVA	4,911
ITS AC size @50ºC, 1360m	MVA	4,296
Transformer		
Transformer Type	-	Outdoor Oil Transformer 0.63/33 kV
Transformer Power @40ºC	MVA	4,92
Number of transformers	Units	1

Appendix F: ITS Data Sheet

MEDIUM VOLTAGE INVERTER STATION, CUSTOMIZED UP TO 7.2 MVA

From 2340 to 7200 kVA

This brand new medium voltage solution integrates all the devices required for a multi-megawatt system.

Maximize your investment with a minimal effort
Ingeteam's Inverter Station is a compact, customizable and flexible solution that can be configured to suit each customer's requirements. It is supplied together with up to four photovoltaic inverters (two dual inverters). All the equipment is suitable for outdoor installation, so there is no need of any kind of housing.

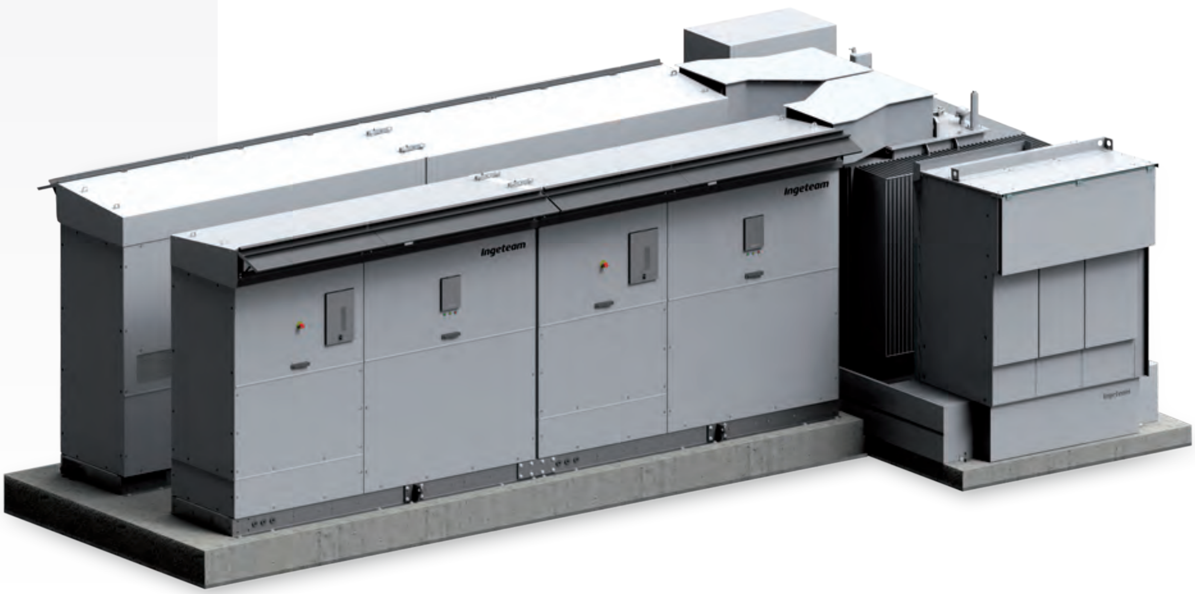
Higher adaptability and power density
This PowerStation is now more versatile, as it presents the MV transformer integrated into a steel base frame together with the MV switchgear. Moreover, it features the greatest power density on the market: 358 kW/m^3.

Plug & Play technology
This MV solution integrates power conversion equipment –up to 7.2 MVA-, liquid-filled hermetically sealed transformer up to 34.5 kV and provision for low voltage equipment. The MV Skid is delivered pre-assembled for a fast on-site connection with up to two dual PV inverters from Ingeteam's B Series central inverter family.

Complete accessibility
Thanks to the lack of housing, the inverters, the switchgear and the transformer can have immediate access. Furthermore, the design of the B Series central inverters has been conceived to facilitate maintenance and repair works.

Maximum protection
Ingeteam's B Series central inverters integrate the latest generation electronics and a much more efficient electronic protection. Apart from that, they feature the main electrical protections and they deploy grid support functionalities, such as low voltage ride-through capability, reactive power deliverance and active power injection control.

Furthermore, the electrical connection between the inverters and the transformer is fully protected from direct contact.



Medium voltage inverter station, customized up to 7.2 MVA

CONSTRUCTION

- Steel base frame.
- Suitable for slab or piers mounting.
- Compact design, minimizing freight costs.

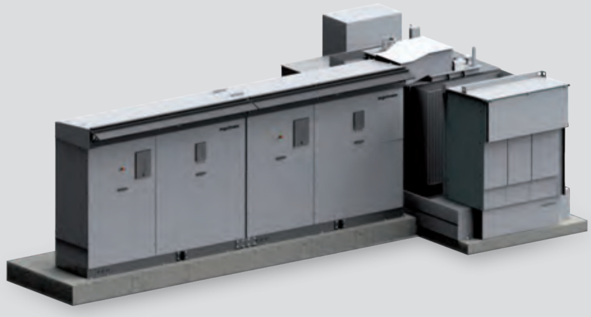
STANDARD EQUIPMENT

- Up to four inverters with an output power of 7.2 MVA.
- Liquid-filled hermetically sealed transformer up to 34.5 kV.
- Oil-retention tank.
- Frame for installation of LV equipment.
- Minimum installation at project site.

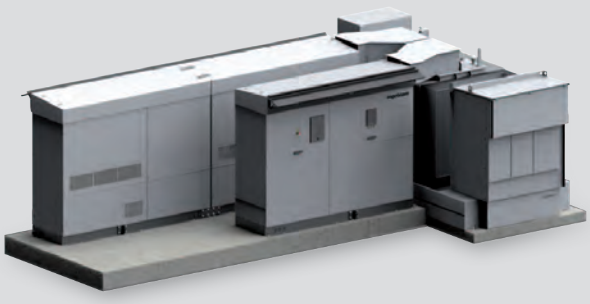
OPTIONS UPON REQUEST

- Electrical gear as per customer necessities: low voltage distribution panels, auxiliary transformers, SCADA panels, and integration on metal frame.
- Metering equipment.
- Remote communications.
- Start-up at the system site.

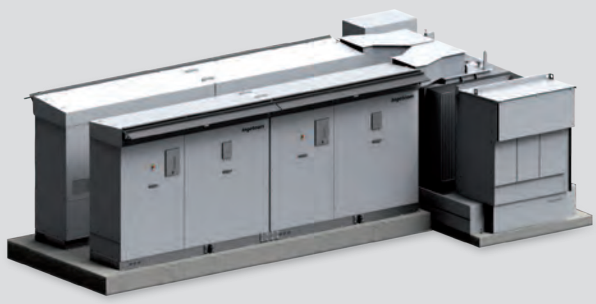
Three possible configurations



Dual Inverter Station
From 2,340 up to 3,600 kVA.



Single Inverter + Dual Inverter Station
From 3,510 up to 5,400 kVA.



Double Dual Inverter Station (*)
From 4,680 up to 7,200 kVA.

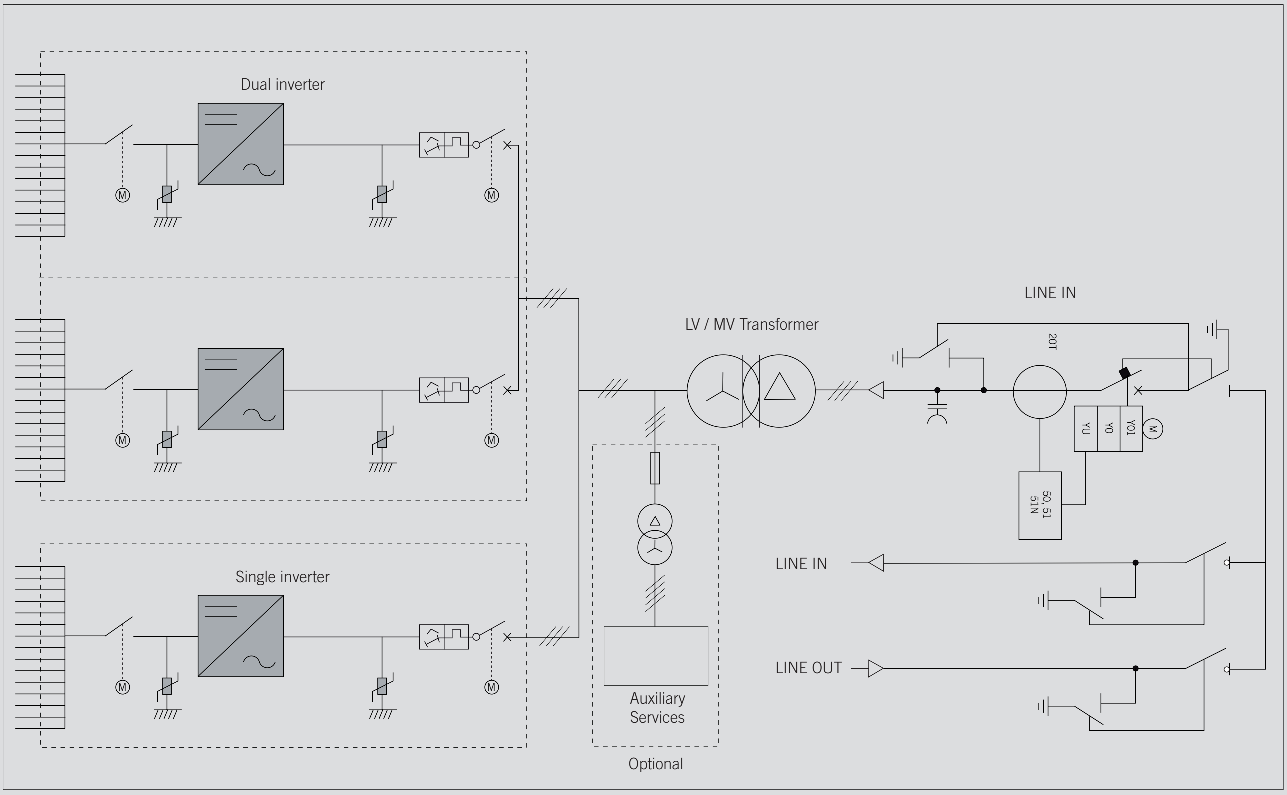
(*) This configuration should be developed with two MV transformers.

Medium voltage inverter station, customized up to 7.2 MVA

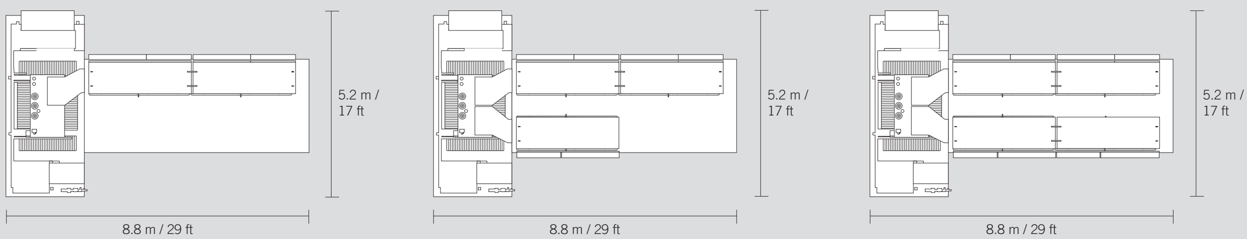
	MSK17 - Dual Inverter	MSK17 - Single + Dual Inverter	MSK17 - Double Dual Inverter
Number of inverters	2	3	4
Rated power @50 °C / 122 °F	3,227 kVA	4,840 kVA	6,454 kVA
Max. power @30 °C / 86 °F	3,586 kVA	5,379 kVA	7,172 kVA
Skid Size	5,200 x 2,100 mm / 17 x 7 ft	5,200 x 2,100 mm / 17 x 7 ft	5,200 x 2,100 mm / 17 x 7 ft
Max. estimated skid weight (without inverters)	12 tons	16 tons	21 tons
Voltage class	24 - 36 kV	24 - 36 kV	24 - 36 kV
Installation altitude[1]	Up to 4,500 m (14,765 ft)	Up to 4,500 m (14,765 ft)	Up to 4,500 m (14,765 ft)
Operating temperature range	-20 °C to +60 °C / -4 °F to +140 °F	-20 °C to +60 °C / -4 °F to +140 °F	-20 °C to +60 °C / -4 °F to +140 °F

Notes: [1] For installations beyond 1,000 m (3,280 ft), please contact Ingeteam's solar sales department.

Configuration with three B Series PV inverters



Footprint and layout



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Appendix G: Heliostat Data Sheet

Data Sheet

Title
Heliostat Datasheet
Client: Toshiba
Project:300-200MW ultra supercritical hybrid solar coal R&D pathway study

Num	
Code	0202-TEC-ABE-TIC-0011
Revision	00
Date	27/12/2019

Prepared by	
Francisco Javier Ruiz Cabañas Cristina Prieto Ríos	Firma electrónica

Revised by	
Cristina Prieto Ríos	Firma electrónica

Approved by:	
Miguel Méndez Trigo	Firma electrónica

	Value	Units
Heliostat ASUP140 v 2.5		
General		
Heliostat Manufacturer / Model	Abengoa / ASUP140 v 2.5	-
Heliostat Width	12.960	m
Heliostat Height	10.940	m
Heliostat Gross Area	141,78	m^2
Heliostat Solar Effective Aperture Area	138.672 reflective area	m^2
Mirror Elements per Heliostat	32	-
Mirror dimensions	3210 x 1350	mm
Heliostat Structure Material (i.e. ASTM class and coating)	Carbol Steel: S-275-S355 -JR Galvanized	-
Heliostat Stow Angle	0º	degrees
Heliostat Control System Description	PLC in control box	-
Heliostat Drive / Actuator		
Drive Type (Hydraulic vs. Geared Motor)	Hydraulic mechanism	-
Hydraulic Fluid (if applicable)	Mineral Oil	-
Drive Motor Characteristics (Rated Power, Voltage, Phase, Freq)	0.37/380-400/3/10-50	kW / V / Ph / Hz
Drive Connected Power Load	0.61	kWe
Drive Tracking Power Load	0.24 - 0.61	kWe
Non-Powered Drive Fail-Safe Method and Emergency Power Load (if any, in loss-of-power events)	Defocusing with Solar field UPS	-
Sensor Type	2 axis: Azimuth / Absolute encoder + Elevation/ inclinometer	-
Mirror		
Glass Material	Float glass	-
Mirror Specular Reflectivity	94,8 (average)	%

Appendix H: Heliostat Manufacturing Data Sheet

Title:
Heliostat manufacturing guidelines and workforce estimation
Project: 300-200MW Ultra Supercritical Hybrid Solar/Coal R&D pathway study (USC Solar/Coal Hybrid)

Document No.:	0202-TEC-ABE-TIC-0012
Revision:	01
Date (dd/mm/yyyy):	10/07/2019

Issued by:
Francisco Carrillo Romero Francisco Javier Ruiz Cabañas

Checked by:
Francisco Carrillo Romero Francisco Javier Ruiz Cabañas

Reviewed by:
Cristina Prieto Rios

Approved by:
Miguel Méndez Trigo

Revision Control Sheet

Revision	Date	Reason for revision	Issued by	Checked by	Reviewed by	Approved by
01	27/12/2019	First document revision	FCR FJRC	FCR FJRC	CPR	MMT

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4 Workforce 10

1 Objective

Heliostat manufacturing guidelines is the aim of this procedure explaining requirements, jigs equipment, and all the rest of auxiliary resources which are necessary in the Heliostat assembly process. It will also indicate as a reference the workforce needed in the manufacturing process for a determined production cycle.

2 Scope

This document is developed to make understanding easier about mechanical assembly; transport, process, requirements and resources needed, as well as the tasks to be performed by each operator during each operation, getting to regularize the quality standards in the final product for Abengoa Heliostat structures Asup 2.5.

3 Heliostat manufacturing building

The heliostat manufacturing building workplaces must be assembled setting a production line based in lean manufacturing work philosophy. The lay out and distribution of jigs is set in a month a half and is based at the next scheme:

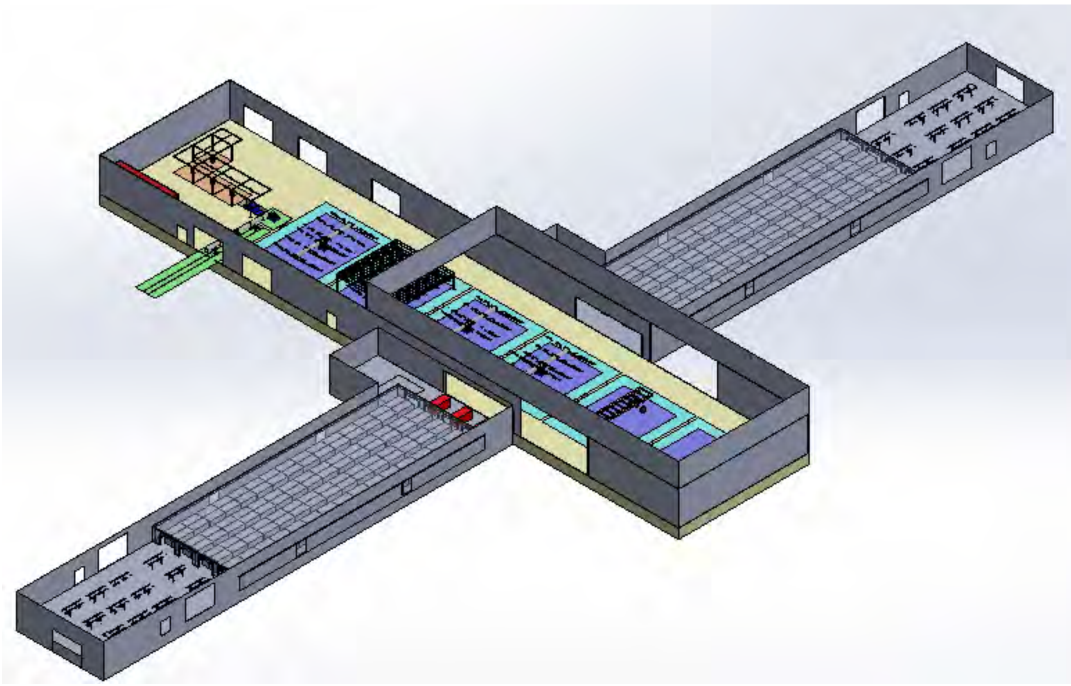


Figure 1. Heliostat manufacturing building Lay Out Production Line

3.1 Heliostat Assembly Building

Heliostat assembly building surface has a minimum of 3240 m^2. Pneumatic and electrical installation services are based in warehouse for carrying the process out. Generator and compressor are required. Line production warehouse facilities height should be no less than seven meters over the 46% of the surface and no less than 12 meters over the remainder surface for heliostat testing area and heliostat loaded on the truck. Three different overhead cranes are using on it. The first one with 2 hoist 1,5 Tn each one and the other two on the highest part of the building with two hoist 2,5 Tn both overhead crane.

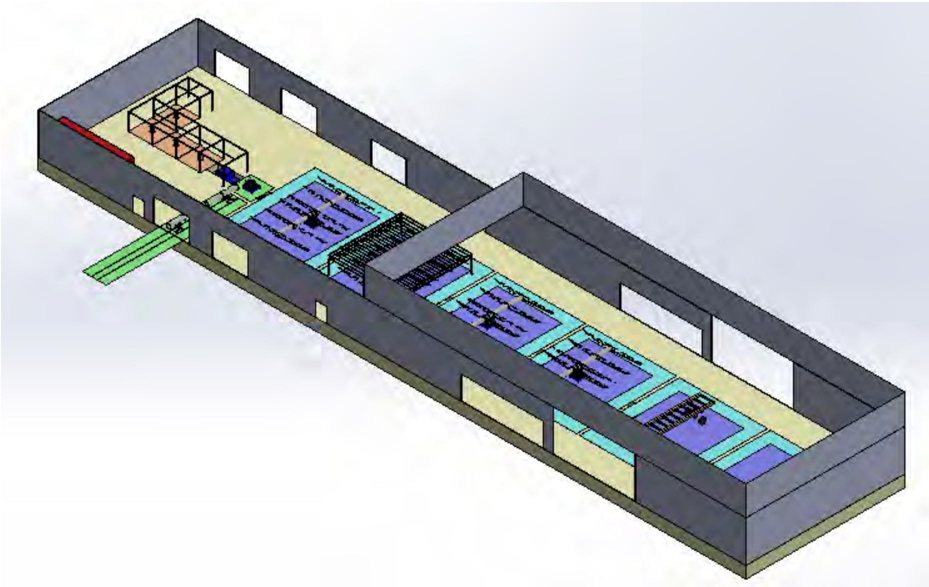


Figure 2. Heliostat Assembly Building

3.1.1 Heliostat Assembly Process Description

Heliostat assembly process is performed in a warehouse and a few operations at the solar field using different reference jigs and tools for each operation. Assembly sequence is divided in several steps each one with the same production cycle, 30 minutes. Heliostat position construction is always up side.

Figure 3. Heliostat assembly sequence

3.1.2 Assembly building Operations

- OP50 Movement Assembly

In this station the heliostat movement parts are assembled. In a first stage the support structure is mounted and secondly the hydraulics elements are placed. (Piston & mechanism). Workbench in relation with Pedestal measurements will be needed.

- OP10 Frame connection

In this operation, frames and torque tube are assembled. The structure is placed like the other operation on the cart in a lower position. Below them different carts with parts to be supplied to line will be placed. In the center area several stop sign are placed to receive the torque tube cart position.

- OP30 Mirror bracket placement

In this station, the brackets that support the mirrors are placed. The jig used in this operation is the most accuracy along the assembly line. Focal data is reached by a structure square movement based in lineal actuator and a PLC control that set the heliostat bracket position according to focal assembled data. Pneumatic installation is required setting fix and right brackets position. In this station there will be needed 4 scaffolding to reach brackets position.

- OP40 Test Station

In the Photogrammetry station the quality control has to be performed. Several targets will be placed on the mirror supports and one photo will be taken to check the deviation angles and final position of the referenced elements. In this station there will be needed the Q photo devices. Photogrammetry must be set above the overhead crane. So overhead crane can be moved without any crack with this equipment.

- OP60 Mirrors Placement

Once heliostats have mirrors support torque and looking up position, mirrors are placed on these brackets. Overhead travelling crane are used to lift the mirrors on the heliostat. Mirrors area placed from supplier bundle on sawhorse, vacuum jigs are placed on the mirrors and these jigs are lifted by the cranes moving mirror till heliostat specific position. The mirror racks are placed in the proper way to facilitate the mounting.

Once mirrors are assembled, heliostat should be drive to field transport truck lifting the heliostat and leaving on the truck.

- Mirrors Assembly Buildings

Heliostat Mirrors are assembled on site in a production line next to the main one. Mirrors assembled line is divided in 6 different operations and mirrors will be tested with deflectometry optical system

3.2 Mirror Assembly Building A and B

Mirrors assembly building surface has a minimum of 1530 m^2 each. Pneumatic and electrical installation services are based in warehouse for carrying the process out. Generator and compressor are required. Line production warehouse facilities height should be no less than six meters over the 100% of the surface.

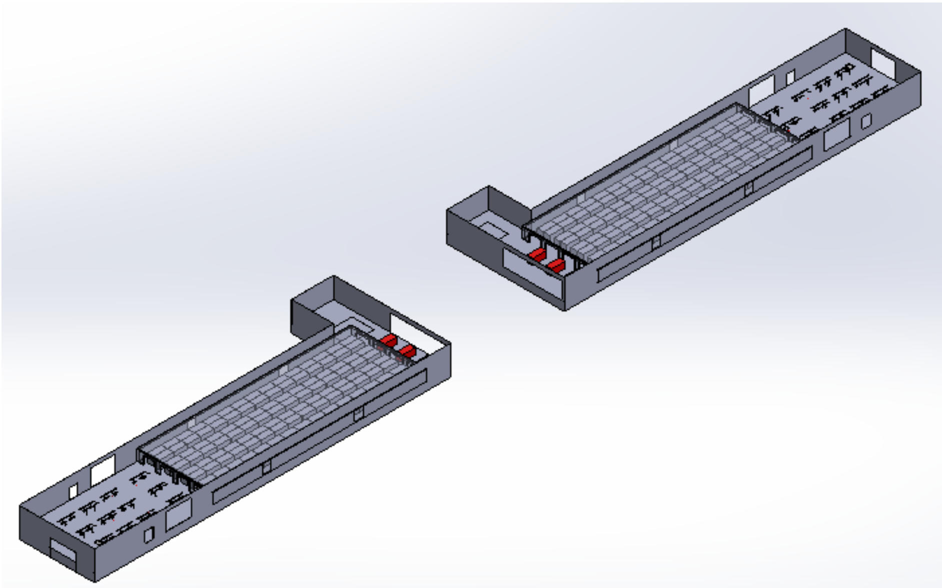


Figure 4. Mirror Assembly Building A and B

3.2.1 Mirror Assembly Process Description

Mirror assembly process is performed in a warehouse using different reference jigs and tools for each operation. Assembly sequence is divided in several steps each one with the same production cycle, 4 minutes.

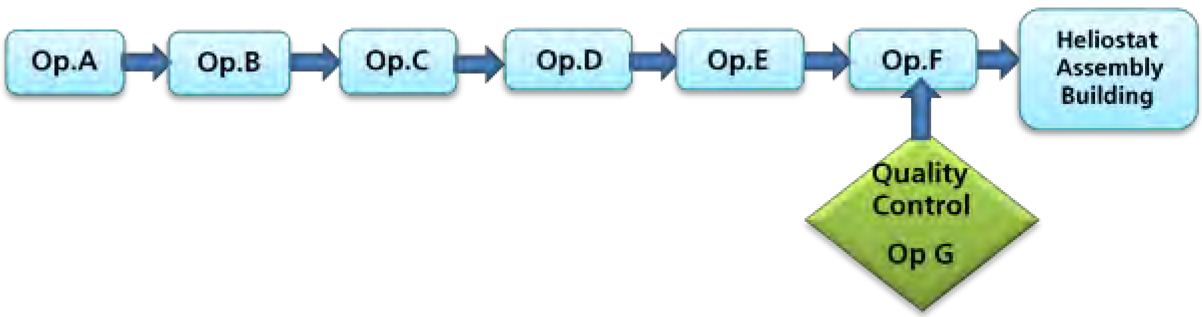


Figure 5. Mirror Assembly Building A and B Sequence

3.2.2 Assembly building Operations

- OP A Rivet Nut

In this station the mirror supported frame is assembled with rivet nut using a rivet pneumatic gun

- OP B Mirror Support

In this operation frames and brackets support are assembled. The structure is placed like the other operation on a regular workbench

- OP C Silicone Workbench

In this station silicone is set on the brackets that support the mirrors.

- OP D Mirror Placement

Using and extra material supported mirrors are placing on the workbench and frame coming from last operation is placed on the mirrors.

- OP E Dry Area

Assembled elements must be 24 hours waiting for silicone cured. Temperature must be more than 5º for a good cured result. This area must have a false ceiling with 2.5 meters height and from and rear must be wall. Air conditioned area surface 50x18x2.5 m. Industrial unit walls and false ceiling in this area must be at least 40Kg/m^3 thermal isolated density with wall thickness no least than 180 mm and air conditioning equipment must be set in order to get a design temperature silicone cured.

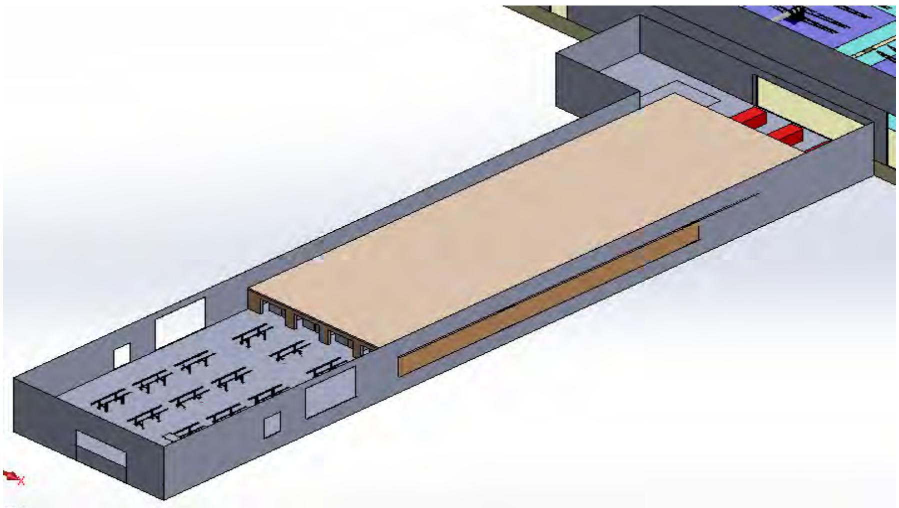


Figure 6. Silicone Cured Building air Conditioning Area

- OP F Mirror Set Workbench

Mirrors are set on site in a production line next to the main one. Mirrors assembled line is divided in 6 different operations and mirrors will be tested with deflectometry optical system.

- OP G Deflectometry

Mirrors assembled are testing in a workshop area following deflectometry criteria

Following figure shows a heliostat ready to be assembled in the solar field

Figure 7. Manufactured heliostat being transported to solar field

3.3 Solar Field Operations

- Op 70 Tower pedestal Placement

Tower pedestal from storage area is moved to solar field by a truck to specific position on site. Crane truck gives possibilities to save time using a single equipment placing and collecting tower pedestal.

- Op 80 Tower pedestal Levelling

Heliostat rotation base surface is set by tower pedestal position. With a digital level elements are adjusted according to design data in order to a specific solar field position.

- Op 90 Heliostat Placement

Once heliostat leave the manufacturing assembly building is place on site. Focal area is done by a determined heliostat number (solar field construction requirement) and each heliostat has one tower pedestal. Heliostat is placed on them helped with lifting crane.

Following figure shows a heliostat installed in the Solar field:

Figure 8. Heliostat installed in the solar field

4 Workforce

Workforce estimation for heliostat manufacturing is as follows:

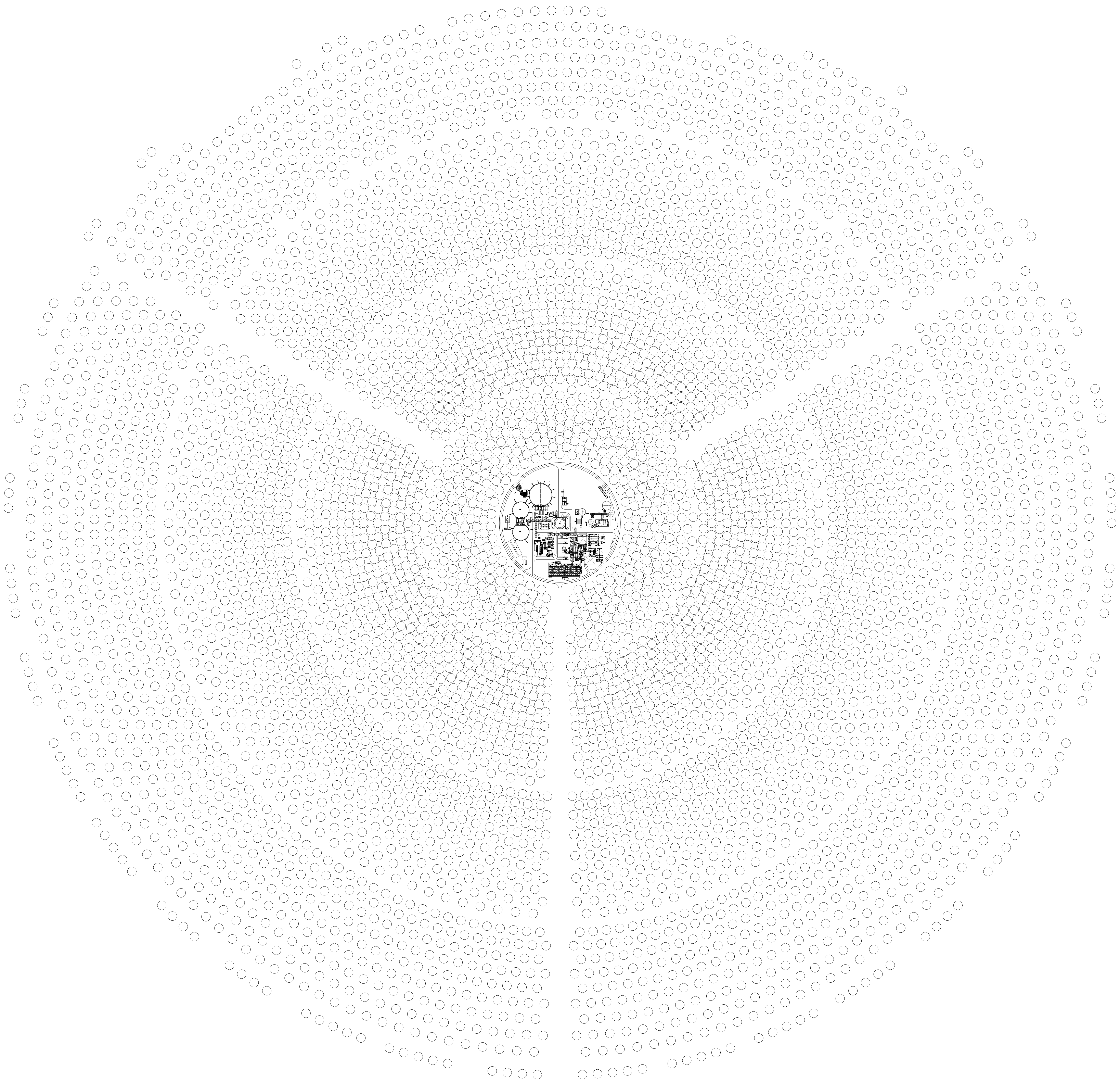
	Area	Workers	Heliostat + facets
Direct workers	Manufacturing assembly building + Solar Field	Assembly workers	200
Indirect workers	Manufacturing assembly building + Solar Field	Supervisor, Driver, Maintenance, among others	35

Table 1. Workforce estimation for heliostat manufacturing

Production data:

- Shift working time: 8 Hours
- Productive cycle: 30 min
- Number of Heliostat per shift: 16

Appendix I: Hybrid Solar/Coal Plant General Layout for Horizon 1 & 2



Rev. nº:	Date edition:	Description:	Drawn:	Revised:	Approved:
00	2019/09/26	First Edition	EGF	ACR	JNM
			Firm	Firm	Firm

Client: TOSHIBA

Seal:

Firm:

Nº License: Nombre

Engineering: ABENGOA

Project:

300-200MV ultra supercritical hybrid solar coal R&D pathway study

Scale: 1/4000

Title & Subtit.: **Molten salts tower plant layout**

Sheets:

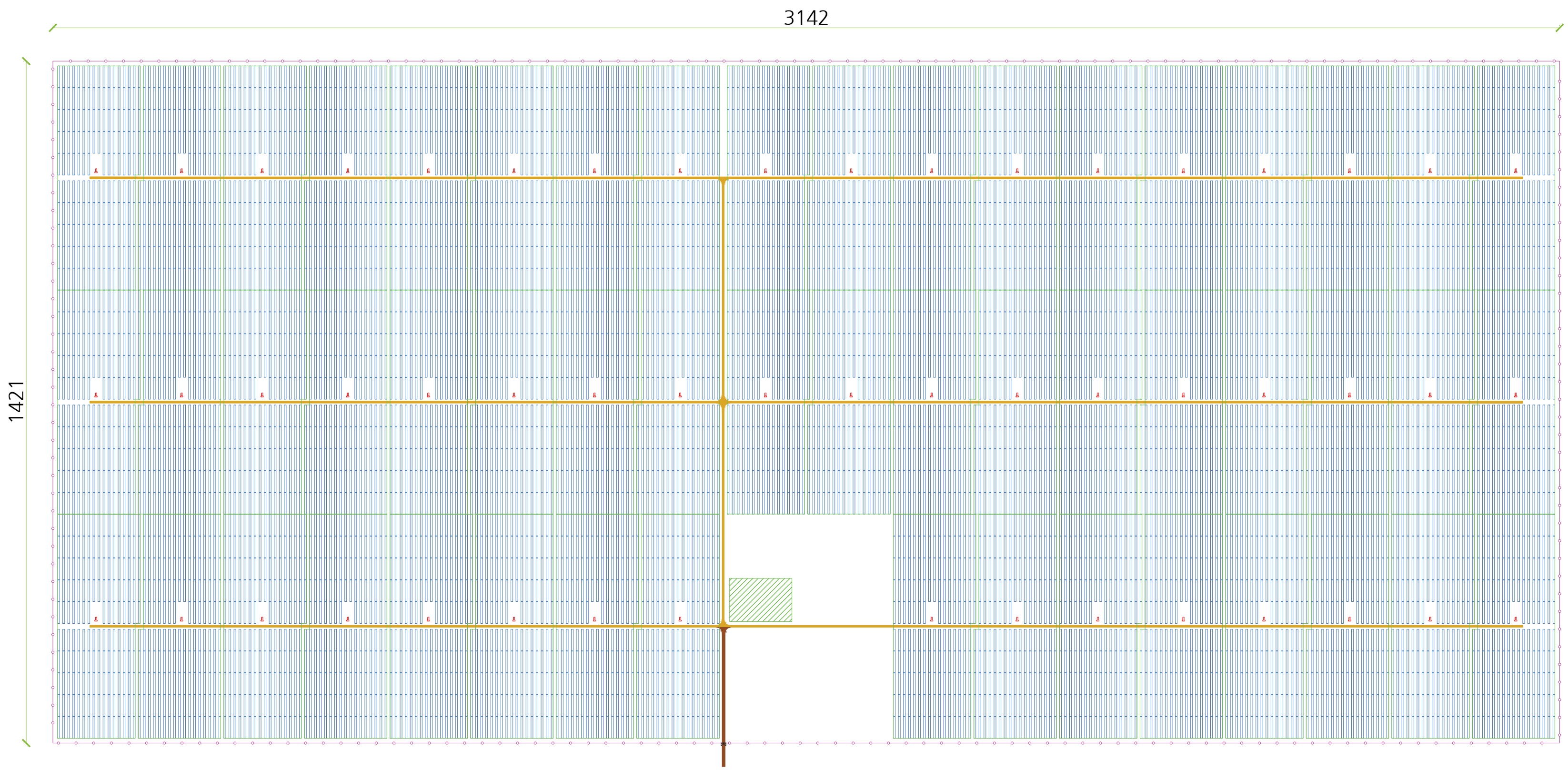
Sheet nº:

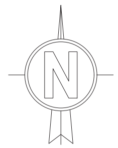
Internal Code nº:

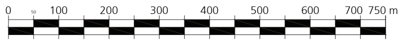
	Status	Date of the first edition
X	Desing Phase (IFD)	2014/05/15
	Offer Phase (IFB)	
	Purchase Phase (IFP)	
	Construction Phase (IFC)	
	Final State Built	

A1

Appendix J: PV Unit General Layout for Horizon 1 & 2







Legend

- Security fence
- Photovoltaic tracker 2Vx45 (8476 ea)
- Internal Roads, 4 meters-wide
- Access Roads, 6 meters-wide
- 4.92 MVA Inverter Transformer Station (ITS) 52 ea
- Access door
- MV/HV Step-Up Substation

Project Details

AC Nameplate:	255.37 MVA (@25ºC)
DC Nameplate:	289.88 MWp (STC)
Racking Type:	1-Axis tracker 2Vx45
System Voltage:	1500 V
Module Power:	380 Wp

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FECHA / DATE — FIRMADO / SIGNED

Informational Note.- All dimensions are indicated in meters

Review	Date	Description	Signature Drawing	Signature Check	Signature Approved
00	19-08-14	Initial Issue			

300-200MW ultra supercritical hybrid solar/coal R&D pathway study

290 MWp PVSP Liddell (Australia)

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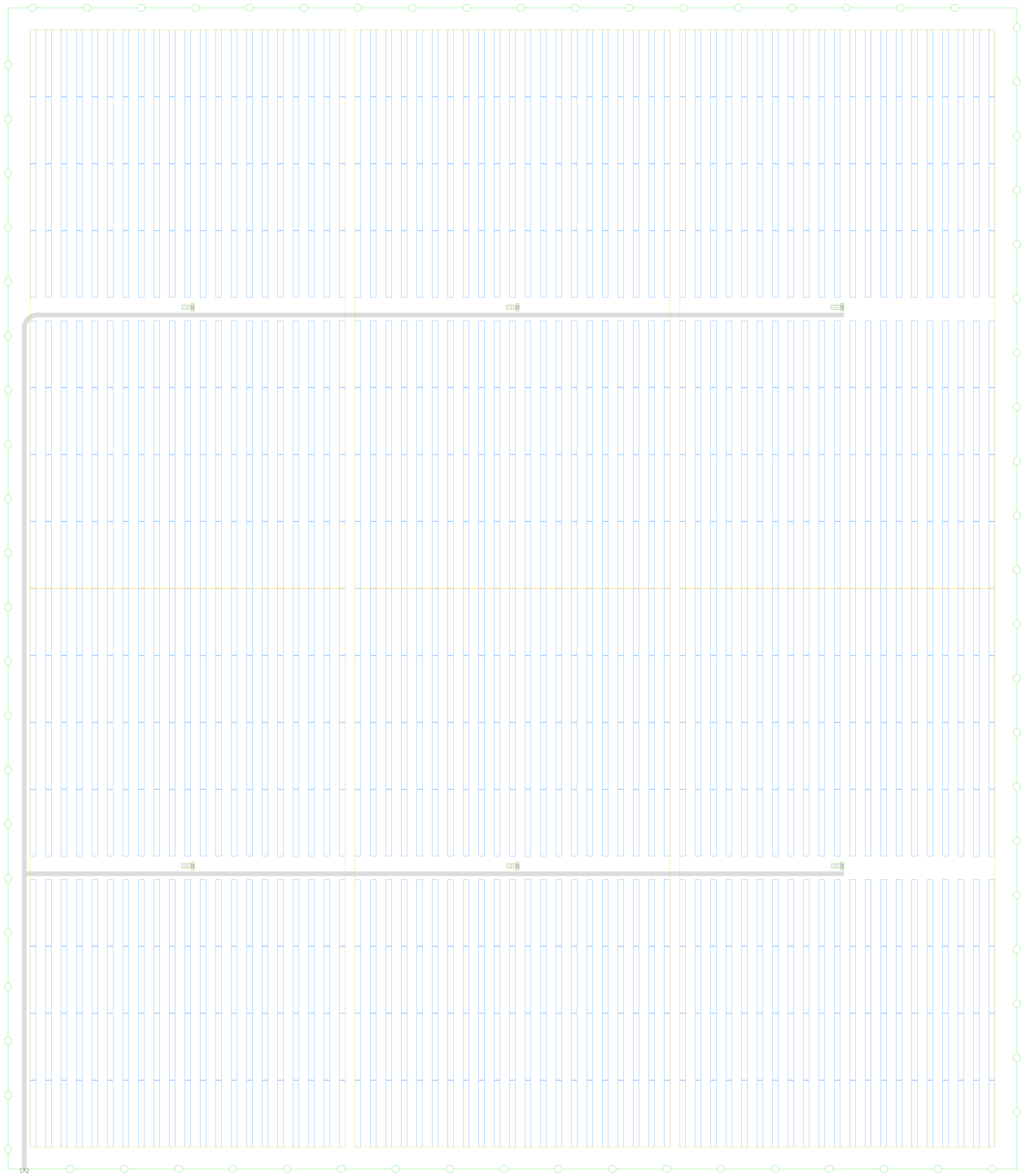
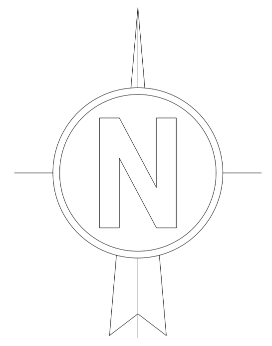
Scale: 1:7500	General Layout	Drawing Nº: 00000-DRA-ENE-000-000-0000
		Sheets: / Sheet Nº:

DIN A-2

Appendix K: PV Unit General Layout for Charging the Batteries for Horizon 2





Legend

- Security fence
- Photovoltaic tracker 2Vx45 (8476 ea)
- Internal Roads, 3 meters-wide
- 4.92 MVA Inverter Transformer Station (ITS) 52 ea
- Access door

Project Details

AC Nameplate:	29.47 MVA (@25ºC)
DC Nameplate:	33.32 MWp (STC)
Racking Type:	1-Axis tracker 2Vx45
System Voltage:	1500 V
Module Power:	380 Wp

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INFORMATION ONLY

FECHA DATE

FIRMADO SIGNED

Review	Date	Description	Signature Drawing	Signature Check	Signature Approved
00	21-01-20	Initial Issue			

300-200MV ultra supercritical hybrid solar coal R&D pathway study

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Scale 1:2500	PV - Booster Heater - General Layout	Drawing Nº: 00000-DRA-ENE-000-000-0000
		Sheets: / Sheet Nº:

DIN A-2