QUICK START-UP AUXILIARY BOILER / HEATER – OPTIMIZING SOLAR THERMAL PERFORMANCE

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Abstract

Power output variations during the day caused by solar irradiance fluctuations are a common issue in concentrating solar power (CSP) plants. Changing steam parameters not only affect the steam turbine's performance and lifetime but also reduce the plants annual output and pose challenges to grid operators. Currently capital intensive thermal storage systems [1] are one option to overcome this problem but a lower cost option are back-up boilers and heaters which all CSP plants require anyway, mostly for start-up purposes. Changing the design of these back-up systems to allow quick start-up and frequent load changes is essential to use these systems for balancing the CSP plant's output.

Firing natural gas in a back-up system is not as efficient as using this fuel in a combined cycle gas turbine (CCGT) plant. Therefore the back-up boiler should not operate constantly but only in periods when the direct normal irradiance (DNI) is decreasing due to cloud coverage. Well designed quick start-up boiler can start from 0-100% load in less than 5 minutes and several references exist, e.g. quick start-up boilers in Cottbus, Germany. Even shorter times, less than 3 minutes, are possible when the water circulation is already active.

Options to minimize back-up fuel consumption include the back-up boiler integration into the CSP plant. In addition to the conventional boiler/heater design providing identical CSP field parameters steam storage, drum integration and external superheating system could be considered.

This paper briefly investigates different options to optimize back-up boiler and heater systems for CSP plants, outlines the design challenges and provides an example that outlines the effect of an optimized quick start-up back-up system on the power generation during one afternoon. The case study provided shows the benefits on the plants power output as well as the environmental impact of the back-up boiler operation.

Keywords: back-up boiler/heater, auxiliary boiler/heater, concentrated solar power, energy dispatchability.

1. Introduction

To maximize the economic availability of CSP installations it is essential to maximize annual power generation. Plants without thermal storage have limited annual hours of operation and strong DNI transients can force the plant to shut down during the day, therewith further reducing its output. Well designed back-up boilers can mitigate this problem as they can quickly offset a potential steam shortfall to the steam turbine.

The traditional boiler industry has many references where quick start-up boilers and heaters ensure the constant supply of steam/heat to important processes, e.g. chemical plants or refineries. This expertise can be applied to the requirements of CSP plants but would require the cooperation of companies that have not been working closely together in the past. The use of expertise already available would reduce risks related to untested design ideas and accelerate the successful implementation of highly flexible back-up systems.

2. Current back-up boiler and heater systems

Current gas fired back-up boilers in parabolic trough plants are integrated into the thermal oil and not the water-steam cycle. Similarly, the first biomass system hybridized with a CSP plant is also located in the thermal oil cycle [2]. This is not ideal in terms of fuel conversion efficiency due to the temperature approach in the thermal oil/water-steam heat exchanger.

Operating direct steam generation (DSG) solar tower and Fresnel plants in Spain use back-up boilers for start-up purposes. These systems are integrated in the water-steam cycle.

Due to the comparatively low peak efficiency of parabolic trough plants, 28% [3], the extensive use of natural gas, such as required for night operation, is not recommended as the same amount of fuel could be converted significantly more efficient in a CCGT plant, 50-60% conversion efficiency. Therefore conventional back-up systems should only be used for start-up and plant stability purposes.

3. Enhanced back-up boiler integration

Enhanced back-up boiler systems stabilize the power output of a CSP facility significantly by providing steam quickly to the steam turbine or stabilizing the steam condition required. Different concepts exist to fulfill these criteria, ranging from quick start-up to external superheater systems.

3.1. Water-steam cycle integration

As mentioned earlier the integration of the back-up boiler into the thermal oil cycle of a parabolic trough plant is not ideal. Therefore back-up systems should be integrated into the water-steam cycle. To ensure that the back-up system can preheat the solar field before sunrise a thermal oil tube bundle can be integrated into the boiler's flue gas pass. Boiler systems providing steam and high temperature thermal oil simultaneously have been successfully realised in industrial plants.

3.2 Fuel conversion efficiency

To minimize the environmental impact of back-up systems their efficiency should be maximized. Conventional gas fired back-up systems could use flue gas condensers to further reduce the flue gas exit temperature. Flue gas condensers are common in smaller boiler installations, some utility scale references exist too, and could be adapted to capacities required in CSP plants.

The other option is not using a gas fired back-up boiler but a small CCGT plant. The conversion efficiency of such a system could be >50%, compared to <30% of current back-up systems, and the quick start-up capabilities of the gas turbine could compensate CSP power output reductions almost immediately. Many industrial CCGT and cogeneration facilities exist worldwide and the adoption to CSP plant requirements is possible. The downside of the concept is the higher complexity and capital requirement.

3.3. Quick start-up

Quick start-up capabilities require a special boiler/heater design, see chapter 4, and operating philosophy. To minimise thermal stress and subsequently equipment lifetime reductions the boiler should be kept in warm stand-by. Options to achieve this include natural gas firing an external steam injection, see chapter 4.2. From warm stand-by the boiler can change from 0-100% load in less than 5 minutes. A boiler operating at only 10% load could ramp up to full capacity in 2-3 minutes. References proving these capabilities exist.

Another option to better integrate solar field and back-up boiler is the joint use of the drum, example see Figure 1. Both systems could keep each other in warm stand-by and steam generation reductions in the solar field could be offset quickly by the back-up unit. The boiler drum and downcomers need to be adapted to accommodate the additional water-steam quantity but current design software and engineering expertise is available to realise such a concept. The ideal CSP technologies for such a concept would be DSG systems operating in recirculation mode, such as Fresnel and parabolic trough.

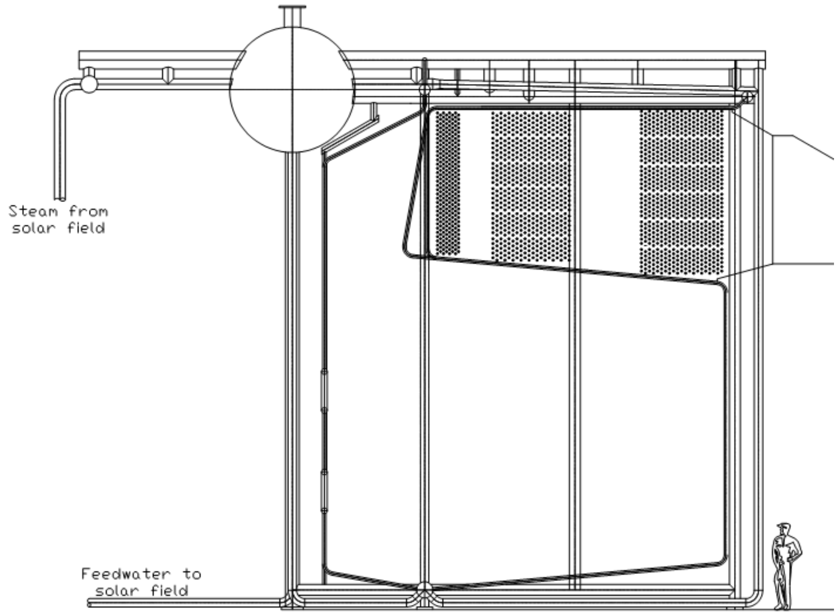

Figure 1: Back-up boiler integration into the water steam cycle of a solar field

3.4. Steam storage

To allow the CSP plant to ride through short and very sharp DNI transients the boiler drum could be designed with a larger than usual capacity to act as a steam buffer. Obviously, the steam capacity would be limited to a few minutes only as a significantly larger boiler drum has a negative impact on the boiler's quick start-up capabilities, higher wall thickness related to larger drum diameter. The use of this short-term steam buffer is expected to work best when CSP and back-up boiler system share a drum, see Figure 1.

Another benefit of the concept is its low additional investment as the boiler drum is a low cost item compared to the overall investment of a CSP plant.

3.5. External superheating

Studies show that DNI fluctuations can cause steam temperate gradients that exceed the recommended limits for steam turbine operation [4]. An external superheater can avoid low steam temperatures levels and ensure stable inlet conditions to the steam turbine, therewith avoiding turbine trips and extending the steam turbine's lifetime, see Figure 2. The concept has already been realised in Energy from Waste plants to raise the efficiency of these units, e.g. 28MWe Mabjerg, Denmark [5]. An external superheater for a CSP plant would have to be designed for more flexible operation than a system for an Energy from Waste plant but this would be only a minor design adaptation.

The external superheater could be integrated into the back-up boiler or be a separate unit between the steam outlet of the solar field and the inlet of the steam turbine, see Figure 2. The fuel consumption to operate the external superheater is very low as the external superheater is typically raising the steam temperature by not more than 50-100°C and would not operate continuously.

An external superheater could also be used to continuously raise the steam temperature of the CSP field to above 500°C therewith raising the overall plant efficiency but also natural gas consumption. This might be an option for parabolic trough plants suing thermal oil.

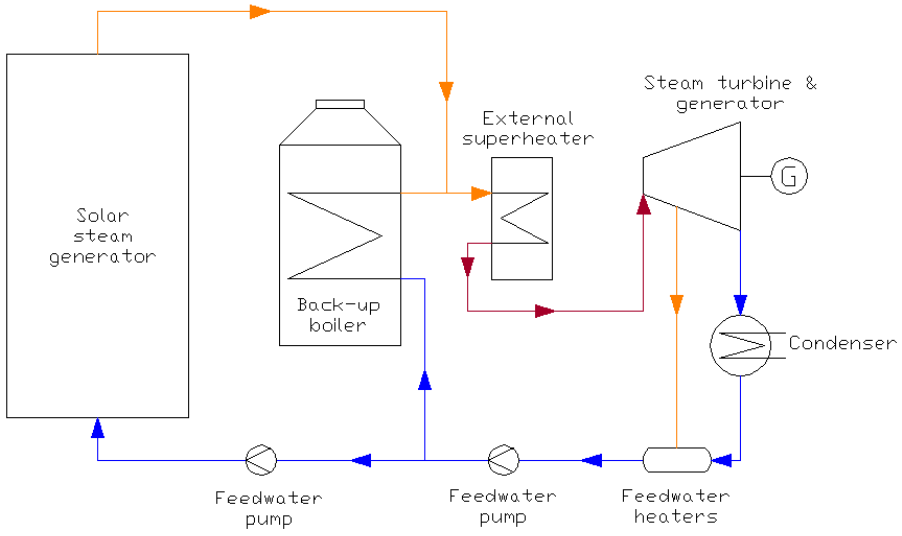

Figure 2: Simplified concept of an integrated external superheater

4. Design considerations of back-up systems

When designing back-up systems for regular and quick start-up several criteria have to be considered to avoid damages and ensure a maximum lifetime, e.g. safe water (working fluid) circulation and thermal stress. This chapter briefly discusses the relevant issues and provides guidance to avoid them.

4.1. Water circulation

A stable working fluid circulation is essential for the safe operation of any boiler/heater system. Sufficient downcomer tubes, ideally unheated, are essential to ensure sufficient working fluid supply to all tube banks and avoid fluid less zones. When starting the burners quickly the working fluid circulation has to begin as soon as possible to cool the tubes and avoid material fatigue. Therefore the riser and downcomer tubes need to be sufficiently sized to enable the appropriate flow through the system. Typically, quick start-up boilers require a very lively water circulation which can be achieved by high velocities in smaller than usual downcomer tubes as well as additional riser tubes to ensure low frictional resistance and a better circulation ratio.

Another very important aspect for quick start-up boilers is avoiding an overflowing of the drum. Higher than designed water levels in the drum trigger the control systems to shut down the system. Even if the water level does not reach a critical level a lower steam quality can cause water droplets to enter the superheater. In this event the water droplets evaporate violently and damage the superheater tubes from the inside, through scaling. This in turn lowers the heat transfer in the superheaters, leads to higher metal temperatures and earlier than normal material fatigue. To avoid these problems the drum should have a larger than normally required volume, sufficient downcomer tubes, a water steam pre-separation outside the drum and an effective steam separation system inside the drum, e.g. demister.

4.2. Thermal stress

When starting boiler and heater systems from cold stand-by thermal stress in the system is a major constraint limiting the start-up time. Thermal stress issues can be addressed to a certain degree during the design process of a boiler/heater but constantly starting the boiler/heater from cold conditions does reduce the lifetime of the unit significantly. Design options to minimise thermal stress include the tube bank arrangement, furnace desing and working fluid circulation in the system. However, the homogeneous heating of boiler mass does require time and can not be eliminated with design measures.

The boiler drum is a major bottleneck for quick start-up as the wall thickness of the drum is higher than any other heating surfaces. For the same internal pressure the bigger diameter corresponds to a higher wall thickness. Based on the strength calculation the wall thickness can increase depending on the number and distance between wall penetrations, such as riser and downcomer tube gaps. Hence reducing drum diameter and wall thickness are beneficial to reduce start-up times. One option is to pre-separate the steam-water mixture outside the drum. The use of mixture and overflow tubes is a very suitable option to achieve this, see Figure 1 & Figure 3, and several throusand references exist for this concept [6]. Other options include minimising the number of penetrations into the drum, such as reduced number of riser and downwcomer tubes.

To avoid lifetime reductions of the back-up system it is recommended to keep the boiler in warm stand-by and only take the unit offline for maintenance work. Keeping the back-up boiler in warm stand-by does require energy but not a significant amount, as the system should be well insulated and the stack closed to minimise convective heat losses. Options to keep the back-up system in warm stand-by include the use of the natural gas start-up burners or the injection of steam from the solar field into the bottom headers of the boiler. Using the natural gas burners and steam injection from another boiler are very well proven concepts, while the injection of steam from solar field has not been realised yet. However, technical risks are minimal as the steam injection concept is well understood and has many references in conventional power generation and industrial facilities.

4.3. Operational lifetime

Constant load changes, up to 20%/min, do affects the lifetime of a back-up system only to a small degree when avoiding cold starts. Units frequently starting from cold condition can encounter lifetime reductions of 4,000 or more cycles compared to standard boiler/heater systems. Therefore cold starts should be minimised. The best environmental option to keep the boiler in warm stand-by is the injection of steam from the solar field as it avoids the use of natural gas.

Pumps, fans and other auxiliary equipment is affected by frequent load changes as wellas start-ups from warm and cold conditions. Maintenance and redundancy is important to keep the auxiliary equipment readily available and minimise parasitic losses.

5. Case study

This case study refers to the integration of a back-up boiler into a 50MWe DSG parabolic trough plant as modeled by Birnbaum et al (2011) for the afternoon of the 27 February 2002 in Tabernas, Spain. The back-up boiler considered is based on two gas fired quick start-up reference systems in Cottbus, Germany. The results show that the back-up boiler can stabilize the steam flow/power output and minimize steam turbine outages as well as lifetime reduction.

Similar back-up units could also be integrated in other DSG systems as well as parabolic trough plants with thermal oil and solar towers with molten salt.

5.1. Quick start-up boiler in Cottbus, Germany

In 1996 two natural gas fired back-up boilers were installed in a combined heat and power plant in Cottbus, Germany to ensure constant steam supply. The operator requested quick start-up capabilities to be able to accommodate steam losses from the main coal fired boiler or quickly provide peak capacity. Both units have a capacity of 130t/h at 540°C and 36bar each.

The boilers are natural circulation systems and were designed for quick start-up using water-steam pre-separation outside the drum, downcomer tubes on all boiler sides, a special tube bank arrangement and other design features, see Figure 3.

Both boiler systems exceeded the 5 minute start-up requirement, see Figure 4, and operate successfully since commissioning.

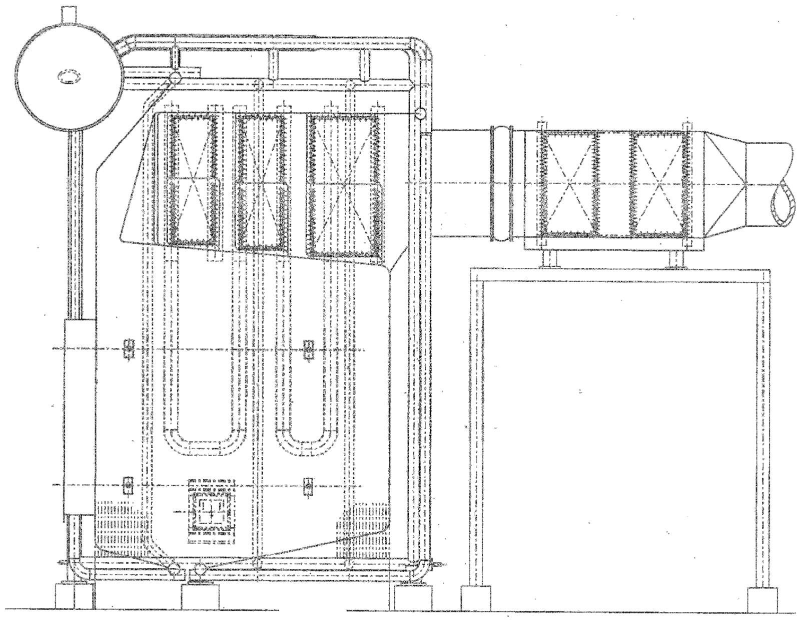

Figure 3: Quick start-up boiler design for Cottbus units, Germany

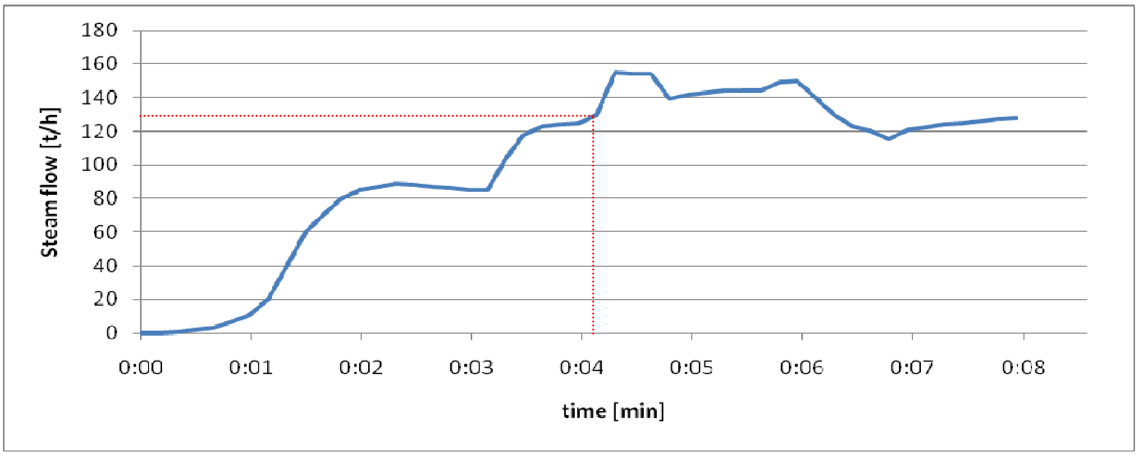

Figure 4: Start up curve for quick start-up boiler in Cottbus, Germany

5.2. Back-up boiler contribution to a CSP facility

A recent modeling of the effect of DNI fluctuations on a 50MWe DSG parabolic trough plant, 400°C at 110bar, shows that the recommended steam turbine parameters, steam flow and temperature, would be exceeded several times during the afternoon operation [4]. The effect of the DNI fluctuation, Figure 5, on the plants steam flow can be seen in Figure 6. The fluctuating steam flow not only affects the steam turbine's lifetime but also the commercial viability of the complete CSP through reduced power generation.

A back-up boiler with the capabilities as described in 5.1. can offset the steam flow reduction during this afternoon, see Figure 6, therewith increasing and smoothening the CSP plant output. Assuming a 25% plant efficiency the steam turbine would generate an additional 35MWh during this particular afternoon, which is an increase of 10.5% compared to the 335MWh in CSP only operation, see Table 1. Furthermore the steam turbine would not be negatively affected by the steam parameter variations and could expect a longer lifetime and lower maintenance costs.

The back-up systems could start automatically based on DNI data measured on site. Coupled to a database containing relevant plant data, such as thermal inertia etc, the boiler would generate the expected steam shortfall within minutes. With increasing DNI data the boiler would reduce its load and shut-down when the design DNI is reached. The process could be highly automated to minimize labor costs.

The fuel costs, 13,300Nm^3 natural gas required for the afternoon operation on 27 February 2002, to operate the boiler would be offset through typically higher electricity prices during the day [7]. The stable power output of the plant would be beneficial for grid operators, which currently encounter increasing grid stability problems through intermittent power generation sources, such as photovoltaic, wind and CSP without storage.

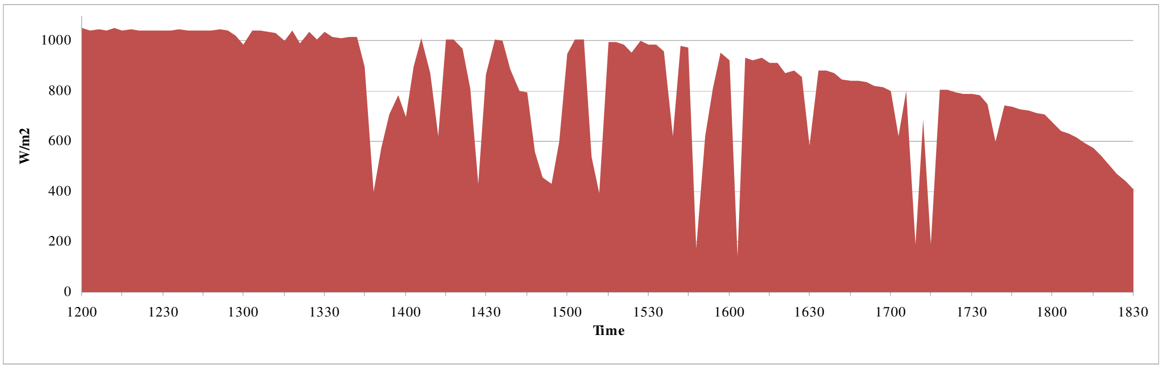

Figure 5: DNI modelling for Tabernas, Spain on the 27 February 2002, reproduced from [4]

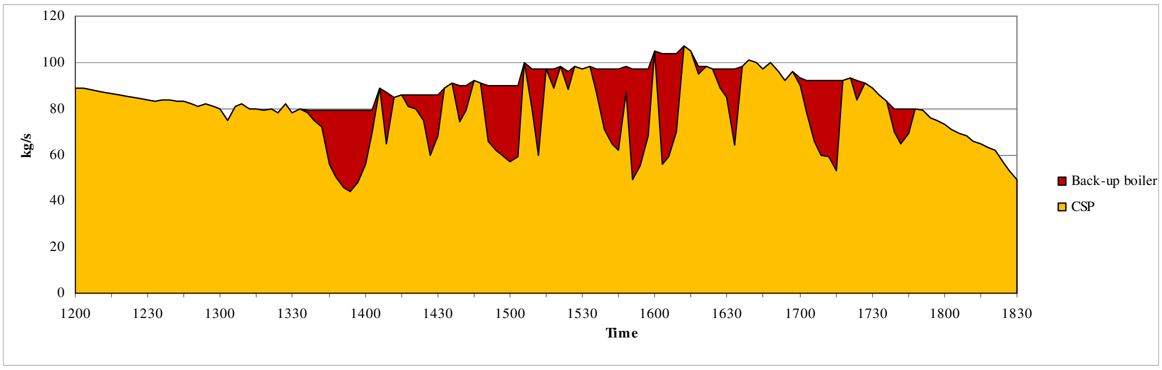

Figure 6: Steam flow changes caused by DNI variations (yellow) and back-up boiler contribution (red)

Criteria	Unit
Generated steam quantity during the afternoon	204t
Additional power generation during the afternoon	35MWh
Additional power compared to standard CSP plant	10.5%
Required natural gas quantity	13,300Nm3
CO2 emissions from back-up sysems	19.4t

Table 1: Back-up boiler contribution to afternoon CSP plant operation

6. Conclusion

Optimized back-up/auxiliary boiler and heater systems have the potential to stabilize the electricity output of CSP plants, with minimal fossil fuel usage, as they can smoothen steam flow and temperature variations caused by DNI fluctuations. Stabilizing steam parameters is not only beneficial in regards to overall power generation and grid stability but also equipment lifetime, particularly the steam turbine, as steep temperature and pressure gradients accelerate wear and tear.

Additional fuel costs could be offset by typically higher electricity prices during the day and the expertise required to design enhanced back-up systems is available from established boiler companies, thus minimizing technical and commercial risk.

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