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Optimal start-up operating strategies for gas-boosted parabolic trough solar power plants

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Abstract

Concentrating solar power plants are taking an increasing share in the renewable energy generation market. Parabolic trough is one of such technologies and the most commercially mature. However, this technology still suffers from technical challenges that need to be addressed. As these power plants experience daily start-up procedures, the optimal performance in transient operation needs to be considered. This paper presents a performance based modelling tool for a gas-boosted parabolic trough power plant. The objective of the paper is to define an optimal operational strategy of the power plant start-up procedure with the aim of minimizing its fuel consumption while at the same time maximizing its electric energy output, taking into account all the thermo-mechanical constraints involved in the procedure. Heating rate constraints of the steam generator and the booster heater, and the steam turbine start-up schedule were considered. The simulation model was developed based on a power plant located near Abu Dhabi, and was validated against real operational data with a maximum integral relative deviation of 4.3 % for gross electric energy production. A multi-objective optimization was performed for a typical operating week during winter and spring weather conditions. The results suggest that in order to minimize the fuel consumption and at the same time maximize the electric energy production, an evaporator heating rate of 6 K/min is an optimal value both for winter and spring conditions.

24   **Key words:** *Solar energy, Concentrating solar power, Parabolic trough power plant; Steam generator;*
25   *Steam turbine; Start-up; Hybridization; Operation strategy; Flexibility; Optimization;*

26   **Nomenclature**

27   ACC   Air cooled condenser

28   BH   Booster heater

29   CSPP   Concentrating solar power plant

30   CT   Cold tank

31   D   Deaerator

32   DNI   Direct normal irradiation

33   DSG   Direct steam generator

34   ECO   Economizer

35   EVA   Evaporator

36   HT   Hot tank

37   HTF   Heat transfer fluid

38   HTFH   Heat transfer fluid heater

39   HX   Heat exchanger

40   LCOE   Levelised cost of electricity

41   PB   Power block

42   PSA   Plataforma Solar de Almería

43   PT   Parabolic trough

44	PI	Proportionate integrative	
45	PTPP	Parabolic trough power plant	
46	RD	Ramp delay	
47	SAM	System model advisor	
48	SD	Synchronization delay	
49	SF	Solar field	
50	SGS	Steam generator system	
51	SH	Super-heater	
52	SM	Solar multiple	
53	Symbols		
54	A	Area	[m ²]
55	m	Mass flow	[kg/s]
56	p	Pressure	[bar]
57	Q	Thermal energy	[GWh]
58	T	Temperature	[°C]
59	t	Time	[s]
60	U	Overall heat transfer coefficient	[W/(m ² K)]
61	ν_T	Allowable ramp-up rate/heating rate	[K/min]
62	W	Electric energy	[GWh]
63	Subscripts		

64 f fluid
65 max maximum
66 min minimum

67

68 **1. Introduction.**

69 The concentrating solar power (CSP) technology shows an increasing trend in capacity installations
70 around the globe. One of the key reasons for this, is the possibility to integrate such technology with
71 relatively cheap ways of storing thermal energy, hence allowing it to decouple the electric energy
72 production from the solar input (International Energy Agency, 2014). Parabolic trough power plants
73 (PTPPs) are the most mature and economically viable plants among the CSP technologies. They account
74 for 85 % of the current capacity installed (Groupe Reaction Inc., 2014; Khetarpal, 2016) and 80 %
75 considering the power plants currently planned to be installed (Estela et al., 2016). However, they still
76 face problems both at technical and economic levels. From a technical stand-point, the intrinsic
77 fluctuating nature of the solar irradiation causes operating challenges such as daily start-up procedures
78 and frequent variations in loads, which some components of the plant are not fully designed to endure.
79 From an economic perspective, CSP technologies are still not fully competitive with respect to traditional
80 technologies such as gas or coal power plants. A way to improve the operating flexibility and the
81 economic feasibility of PTPPs is to optimize the power block operation by maximizing its flexibility
82 towards fluctuating loads and cyclic daily start-up procedures (Mancini et al., 2011). By doing so, it is
83 possible to harvest as quickly as possible the solar irradiation, hence maximizing its electric energy
84 production and profitability.

85 One of the key aspects to improve the technical performance of CSP plants is to increase the rate at which
86 the plant can load-up in order to harness the solar energy quickly. On the other hand, in order to preserve
87 the lifetime of certain components, the ramp-up rate is limited by thermo-mechanical constraints
88 (Ferruzza et al., 2017). With regards to the power block this is especially true for the steam generator
89 system (SGS) and the steam turbine (Ferruzza et al., 2017). For the former, the heating rate at which it
90 can experience a temperature increase is limited by the thermo-mechanical stresses on the thick walled
91 components and junctions such as the steam drum, super-heater headers and T or Y junctions in the steam

pipelines (Dzierwa et al., 2016; Dzierwa and Taler, 2014; Taler et al., 2015b). Generally, the component limiting the ramp-up rate in the evaporator is the steam drum, which is designed as a high-pressure vessel, with a large diameter and consequently thick walls. The start-up procedure of the component is intended to reach as rapidly as possible nominal conditions for mass flow rates, pressure and temperature. In the case of the steam turbine, the shaft thickness is the main limiting aspect regarding thermal stresses. Therefore, in order to avoid excessive thermal stresses it is desirable to keep the temperature difference between the steam and the turbine metal as low as possible (Topel et al., 2015; Topel et al., 2017).

In order to achieve maximum responsiveness of the power plant towards a change in power load or insolation it is essential that all the components are able to start quickly thus enabling the CSP plants to start harvesting the incoming solar energy as soon as possible. However, there might be limiting factors for one component, which might reduce the required heating rate for another. For example, if the receiver or solar field are the limiting factors, there is no need for the SGS to be able to start up at a faster rate than that of the solar field. From a yearly perspective and optimization point of view, it might happen that a lower constraint is actually needed either for the steam turbine or the SGS. On the other hand, having for instance components like the SGS exceeding such optimal point might allow for more flexibility in the operational strategies of the power plant.

Considering previous work available in literature, research has been performed on modelling and evaluation of the performance of PTPPs with both oil and molten salts as heat transfer fluid, with and without gas-fired backup. For instance, Boukelia et al. (2017, 2015) investigated this by modelling specifically the power block in Ebsilon professional (STEAG, 2012) and evaluated the optimal levelised cost of electricity (LCOE) by means of artificial neural network algorithms implemented in Matlab. This, however, was done without considering detailed start-up constraints or different operating strategies. Biencinto et al. (2016) performed modelling of PTPPs both with nitrogen and Therminol-VP as heat transfer fluids. The model of the solar field was validated in detail against real plant data, while the overall model was compared with SAM (System advisor model) (Biencinto et al., 2014). In this case, the model was used to compare the annual yield of the two configurations. Bonilla and Jose (2012) modelled a direct solar steam generator PTPP using object-oriented modelling and calibrated it by comparing the model results with plant data from CIEMAT-PSA (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas – Plataforma Solar de Almería) by means of genetic algorithm based

multi-objective optimization. The model focused mainly on the solar field detailed modelling and not on the overall power plant. Blanco et al. (2011) developed a model in the Wolfram mathematical software and compared the results to available power plant data. In this case, the power block was not modelled in detail, but used thermal efficiency correlations as function of the thermal input. Another example can be found in the work performed by Al-Hanaei et al. (2016), in which the authors developed a model of the Shams I power plant. The model did not consider the details of the power block and a validation was not presented in the paper. Detailed models can be also found in the research works presented by Sun et al. (2015) and Li et al. (2017b, 2017a, 2017c), in which the authors developed a multi-dimensional model to address optical, hydraulic and thermo-elastic issues during the operation of a direct steam generator (DSG) parabolic trough collector. Even though the authors addressed the thermo-elastic problems and monitoring, they did not integrate the findings in the definition of an optimal start-up strategy.

In general, it may be claimed that many simulation tools are available to perform CSP plants design and performance evaluations. System Model Advisor (SAM) from NREL (National Renewable Energy Laboratories, USA) (Blair et al., 2008; Gilman et al., 2008; Price, 2003), Greenius (Dersch et al., 2011) from DLR (Deutschen Zentrums für Luft- und Raumfahrt) and Solergy from Sandia National laboratories (Stoddard et al., 1987) are commonly known tools in the CSP community. However, papers including detailed comparisons of simulation results with operational data of existing power plants are scarce. Concerning the start-up limitations, studies have been performed at component level. As for steam turbines, Topel et al. (2015, 2017) studied the thermo-mechanical limitations on steam turbines due to thermal stresses and start-up procedures. Concerning the steam generator system, Gomez et al. (2017) analysed such constraints for the heat exchangers and employed dynamic models for the stress evaluation. At system performance level, Topel et al. (2015) and Spelling et al. (2012) considered the impact of increasing the turbine flexibility with regards to the power plant performance. In a previous study, the authors of this paper analysed the mutual interdependencies between the turbine and steam generator and the impact of their constraints on a parabolic trough power plant performance (Ferruzza et al., 2017). However, no previous study addressed the optimization of the start-up operational strategy of a parabolic trough solar power plant considering thermo-mechanical constraints related to the steam generator, heat exchangers and steam turbine. Specifically, there are no studies available in literature that aim at lowering the fuel consumption of such plants by optimizing the start-up operating strategy.

In this paper, a hybridized PTPP with a gas-fired booster located near Abu Dhabi is considered. The plant is also integrated with an additional heat transfer fluid heaters. The objective of the paper is to define an optimal operational start-up strategy of the power plant start-up procedure with the aim of minimizing its fuel consumption while at the same time maximizing its electric energy output, taking into account all the thermo-mechanical constraints involved in the procedure. This was done by taking into consideration the evaporator and booster heater heating rate constraints to verify how a dynamic performance oriented design for such components could lead to a higher flexibility from an operational standpoint. The optimal range for these constraints in order to satisfy the aforementioned objective were determined. The numerical model was thoroughly validated considering the steady state and transient performances using two sets of operational data of a power plant located near Abu Dhabi.

In section 2 the paper presents the methods used to model the plant and validate it against operational data. It summarizes the constraints taken into account in the start-up strategy and dynamic operation and the implementation of the operation of the power plant in the control logic. Lastly, it presents the multi-objective optimization routine implemented. Section 3 presents the results of the validation, and afterwards the results and discussion of the multi-objective optimization performed for two different weather conditions. Section 4 outlines the conclusions and final remarks.

2. Methods

The modelling of the PTPP was carried out in DYESOPT, a tool able to perform power plant steady state nominal design, performance evaluation and techno-economic calculations. The tool has been previously developed and validated at KTH, Royal Institute of Technology, Stockholm (Guédez, 2016; Spelling, 2013). Figure 1 illustrates the logic flow of information and calculations within the tool, where the grey and black boxes represent the inputs and outputs of the model respectively. In order to perform the power plant design, meteorological data and an operating strategy are the required inputs together with price data if economic calculations are required. The results of the design serve for the time-dependent performance evaluation, which is carried in TRNSYS (University of Wisconsin Madison., 1975). Lastly, the results are post-processed in Matlab to obtain the required performance indicators. If these involve economic indicators, cost functions and economics of the plant location are taken into consideration. The whole procedure can be coupled with a multi-objective optimizer.

Figure 1: DYESOPT workflow diagram. Solid lines represent a YES logic while dashed lines represent a NO logic.

The steady state design and modelling of the power plant were developed and added to the tool. The sizing was performed in Matlab, while the dynamic modelling was performed in TRNSYS, and it was integrated with a control strategy to take into account the heating rate constraints during the start-up procedure. More details are provided in the following sections. DYESOPT incorporates a modified version of a queueing multi-objective optimizer (QMOO) based on a genetic algorithm developed at the Industrial Energy Systems Laboratory in Lausanne (Leyland and Favrat, 2002). Figure 1 shows the flow of information required for an optimization study. At the start of the optimization, it is possible to set conflicting objectives with regards to whether to maximize or minimize their quantities. Both design parameters and operation parameters can be set to allow for variation within the limits chosen for the study. The algorithm performs then as many iterations as needed to finalize the optimization and obtain an optimal trade-off curve or Pareto front.

2.1 Heat exchangers heating rate constraints

The details of the steam generator, heat transfer fluid heater and booster heater constraints are explained in the current section. As noted above, the rate at which each of them can start-up or heat-up is limited by

material and geometrical constraints. As for the SGS start-up, previous studies (Basaran, 2015; Taler et al., 2015b) have shown that the main limiting components in this regard are the super-heater and the evaporator, hence these two were considered in detail in the current work. From a system perspective, the limit on the maximum allowable temperature difference for the heat exchangers is implemented in a control logic for the morning start-up procedures and daily transients. The minimum and maximum heating rates may be calculated based on the geometrical configuration and material specifications according to the norm DIN EN 12952-3 (CEN, 2012). However, the objective of this paper is to determine the optimal range of constraints from a system perspective, specifically tailored for start-up strategies. Such heating rates can be used to calculate the permitted fluid temperature change using the following equations (Taler et al., 2015b):

$$\frac{dT_f}{dt} = \frac{p_{\max} v_{T_{\min}} - p_{\min} v_{T_{\max}}}{p_{\max} - p_{\min}} + \frac{v_{T_{\max}} - v_{T_{\min}}}{p_{\max} - p_{\min}} p(T_f) \quad (1)$$

These equations express the rate at which the fluid temperature (T_f) can change depending on the pressure of the fluid (minimum ($p_{\min}$) and maximum ($p_{\max}$)) and the minimum and maximum heating rates ($v_{T_{\min}}$ and $v_{T_{\max}}$) which are dependent on the geometry, material properties and operating temperature and pressure. In an evaporator, the water is at saturation point so the pressure and temperature are related. As a consequence, the temperature of the fluid will be dependent on the pressure, and Equation (1) can be solved using a Runge-Kutta method, assuming $T_f(t = 0) = T_0$. In the case of the super-heater, the fluid is not at saturation conditions, the pressure is a function of time and determined by the evaporator conditions. The same considerations are applicable to both the HTF heater and the booster heater. In these cases as the two fluids considered (oil and super-heated steam) are not at saturation point.

2.2 Steam turbine start-up schedule

In order to capture a thorough start-up operation of the power plant, the TRNSYS model was implemented with a control strategy for the start-up of the steam turbine. The rate at which this component can increase its load is determined by the metal temperature at the beginning of the procedure. The warmer the turbine, the faster a start-up procedure will be. The turbine metal cool-down was modelled according to a lumped capacitance method (Bergman et al., 2011). Depending on the metal

temperature, the appropriate start-up schedule curve was chosen in order to minimize the difference between the steam and metal temperatures. Once these are selected, the appropriate synchronization delay (SD) and the time for the turbine to reach full load (or ramp delay (RD)) are defined. Depending on the metal temperature, the start-ups can be generally classified as hot, warm and cold. A hot start-up typically takes only 8-10 % of the time it takes for a cold start-up, while a warm start-up requires between 45-50 % of the time it takes for a cold start-up. Figure 2 illustrates the three main different start-up curves implemented in the transient model, with the A-B and B-C lines representing the synchronization delay and ramp delay, respectively for the cold case (Topel et al., 2015). Figure 3 illustrates the turbine start parameters such as pressure and temperature for a typical start-up schedule of the considered turbine.

Figure 2: Cold, warm and hot steam turbine start-ups (adapted from Topel et al., (2015)).

Figure 3: Turbine start parameters within a start-up schedule (Topel et al., 2015).

2.3 Power plant modelling

Figure 4 illustrates the power plant layout considered. The schematic layout of the plant is based on the configuration of a power plant located near Abu Dhabi (Alobaidli et al., 2017). The thick lines represent the heat transfer fluid loop. The oil is heated up by the parabolic trough (PT) collectors and pumped to the steam generator system, which comprises a super-heater (SH), an evaporator (EVA) and an economizer (ECO). In the morning when there is not high direct normal irradiation (DNI) a gas-fired heat transfer fluid heater (HTFH) can be turned on to raise the temperature of the recirculating oil to the desired set point. The other cycle represents a conventional regenerative Rankine cycle with the only exception of the booster heater (BH). The super-heater outlet steam temperature is raised to the turbine inlet

temperature (TIT) by the booster heater. The power block layout comprises a steam turbine (ST) with extractions to a deaerator (D) and closed feed-water heaters. The outlet steam from the turbine is condensed by an air-cooled condenser (ACC). The main design parameters of the power plant are summarized in Table 1.

Figure 4: Layout of the considered parabolic trough power plant integrated with an oil heater and a booster heater (Alobaidli et al., 2017; Vogel et al., 2014).

Table 1: Design parameters of the power plant (Alobaidli et al., 2017; Vogel et al., 2014).

Start-up parameter	Units	Value
Location	[-]	Abu Dhabi
Solar multiple	[-]	1
Gross power	[MWe]	124
Power block nominal efficiency	[-]	0.35
Solar field aperture	[m ²]	627840
Solar field nominal efficiency	[-]	0.75
Parabolic trough collector type	[-]	Astro
Solar field outlet temperature	[°C]	393
Steam generator steam outlet temperature	[°C]	380
Turbine inlet pressure	[bar]	100
Condensation pressure	[bar]	0.17
Turbine inlet temperature	[°C]	540
Nominal condensing pressure	[bar]	0.13
Operating strategy	[-]	Solar-driven

The equations of the zero-dimensional physical models governing the components are based on the STEC library (DLR, 2006) for the power block. The inertia and response time of the components was taken into account by means of a lumped capacitance method (Bergman et al., 2011; DLR, 2006). The heat exchanger off-design models are based on scaling functions of the UA (overall heat transfer coefficient times area) value, which depends on the ratio of the actual cold side mass flow rate to that at the nominal point, while the turbine off-design performance was modelled according to the Stodola equations. The parabolic trough solar field was modelled taking into account optical efficiencies depending on the position of the sun, geometry of the collectors and weather conditions as well as thermal losses due to

249 piping and expansion vessels (Dudley, 1994; Gilman et al., 2008; Lippke, 1995). The booster heater
250 model is based on an efficiency map which depends on the steam inlet temperature according to the
251 ASHRAE handbook (ASHRAE, 2000). Properties of the HTF were computed by linear interpolation in a
252 data sheet from the oil manufacturer (Solutia, 2014).

253 The transient model of the plant was implemented with a logic controller to take into account the morning
254 start-up strategies and hybridization with the HTF heater as well as the heating constraints for the
255 abovementioned components. A summary of the morning start-up strategy is presented in Figure 5.
256 Figure 6 presents a summary of the operating modes during the start-up. In the morning (as indicated by
257 (1) in Figure 5) the main factors to account for, are the time at which the HTF heater is set to operate and
258 when the PT can actually start to operate. These are choices usually set by the plant operator. In presence
259 of DNI, the latter is allowed to operate after a certain time constraint, and more importantly, if the wind is
260 below the maximum allowable threshold. Before that, the fluid is heated up by the HTFH (OM1). The
261 start time of the HTFH is a variable which can be set in the plant operating parameters (see Figure 1).
262 Once the HTF is heated up and reaches the minimum allowable temperature (as indicated by (2) in Figure
263 5) for the SGS, the HTF mass flow rate is calculated and the start-up procedure takes place (OM2). The
264 oil temperature is raised according to the SGS heating-rate constraints. Lastly, the needed flow rate is
265 pumped to the SGS. The same can happen if the DNI is high enough to start the solar field. In this case,
266 the HTFH is turned off and the procedure is carried on in a solar only mode (OM3).

267 The steam coming from the SGS is heated up by the booster heater, which as well needs to comply with
268 thermal stress constraints. In the meanwhile, the metal temperature of the steam turbine is checked, and if
269 the steam has allowable conditions, the turbine start-up can begin, according to the corresponding start-up
270 curve, which is dependent on the metal temperature. The steam temperature and pressure are raised
271 according to the heating constraints and the mass flow rate is kept at a constant value during the rolling up
272 phase (5 % of the nominal value (Schenk et al., 2015)) before the steam turbine can actually start to load
273 up. The water mass flow rate raises and the nominal values can be reached (OM4) (as indicated by (3) in
274 Figure 5). Once the procedure is terminated the plant enters into daily operation, taking into account both
275 steady state performance and part-load performance when the DNI is not high enough according to DLR
276 (2006). During the daily transient operation a similar procedure is performed, always checking the
277 governing thermal stress constraints.

Figure 5: Morning start-up strategy control logic. Solid lines represent a YES logic while dashed lines represent a NO logic. Adapted from (Al-Hanaei et al., 2016; Ferruzza et al., 2018; Schenk et al., 2015).

Figure 6: Operating modes (OM) during the start-up of the steam generator.

2.4 Multi-objective optimization

The performance of the power plant can be measured by means of different indicators. For instance, when considering maximizing the electric energy generation of the considered power plant it is an intrinsic consequence to increase the fuel consumption. However, if the other objective is to minimize the fuel consumption, these two objectives will be in conflict. Hence, no single optimum solution exists but instead, for a given fuel consumption, a maximum electric energy production can be found, thus obtaining a trade-off of best operating designs considering fuel consumption and energy production. The optimization results can be used to choose an optimal start-up strategy for a particular requirement (Leyland and Favrat, 2002; Spelling, 2013). The objectives of the optimization were to minimize the fuel thermal energy consumption (Q_{fuel}) and maximize the electric gross energy production (W_{gross}). The decision variables chosen for the optimization studies are summarized in Table 2.

The optimization was performed for two seasons, winter and spring weather conditions, illustrating the operational flexibility of the plant throughout the year. The two periods chosen correspond to the data available for validation in order to show how the operation of the plant can be improved with the

proposed operating strategies. Using two different sets of weather conditions allows to see how the optimal operation strategy changes throughout the seasons considered. The minimum and maximum values of the decision variables were chosen to allow the possibility of radically different operating strategies. Having a higher pre-heating temperature would put less strain on the steam generator as it would need to cover a lower temperature difference to reach the nominal condition, which may result in lower optimal heating rates. Minimum and maximum heating rate constraint values were chosen as reference, and potential improvements were selected to reflect the best technologies commercially available. The ramp rate range of 3 K/min to 9 K/min represents a practically achievable range for commercially available steam generators (Aalborg CSP, 2015; Taler et al., 2015a). An intermediate value of 6 K/min was chosen as the maximum value for the decision variables considered.

Table 2: Decision variables and constraints (Almasabi et al., 2015; Moya, 2012).

Parameter	Unit	Minimum value	Maximum Value
EVA heating rate	[K/min]	1	6
BH heating rate	[K/min]	1	6
HTFH operating time	[h]	0	2.5
HTFH T	[°C]	200	310

2.5 Validation

In order to check the reliability and accuracy of the developed model, a validation was carried out both for the steady-state design and for the transient performance evaluation. The steady state validation was performed by comparing the sizing of all power plant components in DYESOPT in terms of rated thermal load and mass flow rates with the available data of the power plant in Abu Dhabi. After the model was implemented in TRNSYS, the transient performance was validated against operational data of the power plant. It was tested against available data sets of 16th – 28th February and 6th – 16th May, representing winter and spring weather conditions, respectively.

As the purpose of the model is to represent properly the power plant electric power production, the following six main parameters were chosen for the validation: Turbine inlet temperature (TIT), evaporator steam inlet pressure, steam mass flow rate, HTF outlet temperature at the SF, HTF mass flow

314 rate and gross electric power. In order to quantify the reliability and accuracy of the model the following
 315 indicators were used (Blanco et al., 2011):

$$\text{Integral relative error: } IRE = \frac{\left(\int_0^{time} (y_{model} - y_{data}) dt \right)}{\left(\int_0^{time} (y_{data}) dt \right)} \quad (2)$$

$$\text{Root Mean Square Error: } RMSE = \left(\frac{\sum (y_{model} - y_{data})^2}{N} \right)^{\frac{1}{2}} \quad (3)$$

$$\text{Normalized RMSE: } NRMSE = \frac{RMSE}{y_{max} - y_{min}} \quad (4)$$

316 The Integral Relative Error (IRE) gives an overall measure throughout the simulation time considered of
 317 the accuracy of the model. It quantifies the deviation of the integral result over the time period considered
 318 between the model results and the available data. For example, if the gross power is considered, it will
 319 give an estimation of the error of the electric energy produced throughout the time considered. The Root
 320 Mean Square Error (RMSE) and normalized RMSE (NRMSE) give a measure of the instantaneous
 321 accuracy of the model both in absolute and relative terms. The y values refer to the model and data sets
 322 for a certain number of available data points (N).

323

3 Results and discussion

3.1 Validation of the model

This section presents the validation both for steady state at design point/nominal load and for the dynamic performance. Table 3 and Table 4 present the result of the validation of the main parameters and mass flow rates, respectively, at steady state nominal load. As the values are confidential, the validation is presented in terms of normalized parameters. The mass flow rates and power were normalized with the nominal values of steam mass flow rate and gross power (see Table 1, section 2.3).

Table 3: Results of the validation of the main parameters (normalized values).

	Model	Data	Relative deviation
Steam Generator Nominal thermal load	207.3%	207.5%	-0.12%
Booster heater nominal thermal load	45.6%	47.0%	-2.90%
Condenser nominal thermal load	152.9%	153.4%	-0.36%
Power block net electric power output	89.4%	89.1%	+0.39%
Parasitic consumption	10.6%	11.2%	-5.13%
Solar + fuel to electricity efficiency	28.34%	28.57%	-0.81%

Table 4: Results of the validation of mass flow rates (normalized values).

	Model	Data	Relative deviation
SGS HTF mass flow rate	869.66%	931.67%	-6.66%
SGS steam mass flow rate	98.62%	100.00%	-1.38%
BH exhaust gas mass flow rate	20.92%	21.38%	-2.13%
Condenser water mass flow rate	72.71%	72.67%	+0.06%

The maximum deviation is found for the HTF mass flow rate at the inlet of the SGS (-6.7 %) which is attributed to the approximations made in the property calculations of the HTF (see Section 2.3). As the steam mass flow rate nominal value was used as normalization parameter for all the mass flow rate results, the HTF related results are higher than 100 %. This means that the required HTF mass flow rate is higher than the nominal turbine inlet mass flow rate. Lower deviations are found in the validation of the main parameters with a maximum error in absolute term of -5.1 % for the parasitic consumption. This deviation can be directly related to the lower nominal mass flow rate of the HTF which is required by the SGS in the model and which would affect the parasitic consumption of the solar field. Based on the results shown in the tables, it may be concluded that the plant sizing model provides reasonable results, which are sufficiently accurate in the context of the paper.

The model was also validated for transient operation; Figure 7 illustrates the validation of the model for the data available between 16th and 28th of February, showing the common input for both the model and the operational data as summarized by Table 5. Temperature and pressure values were normalized with nominal turbine inlet temperature and pressure. The figure illustrates that the model is able to predict properly the trends of the main thermodynamic points and relative mass flow rates as well as produced electric power. The major deviations for each quantity, which may be observed in Figure 7, may be noticed at the end of the day (between 17.00-19.00), as (due to the high inertia of the parabolic trough solar field) the mass flow of the HTF is recirculated through the PT even though there is no DNI. This is done to exploit the remaining thermal inertia of the SF; however, the model is not able to fully capture this possibility. Another major deviation for each quantity may be observed on day 9. In this case, the DNI is low but high enough to allow the operation of the solar field according to the constraints set in the model. However, the plant was not operated in that day, due to a decision of the operator. A similar consideration may be applied to the last day of the simulation.

Table 5 summarizes the relative error indicators as presented in section 2.5 and the RMSE values are normalized to the nominal reference values. The table illustrates that as an overall result (as integral over the days of the simulation) the model is accurate in predicting the performance of the power plant, with a maximum relative error of 3.9 % for the flow rate of the HTF at the inlet of the SGS. Even though at nominal point the HTF mass flow is underestimated as noted in Table 4, the integral area is overestimated. This is mainly related to the days in which the power plant was not operated. The gross energy production validation resulted in 2.4 % overestimation as compared to the operational data. Higher relative errors may be observed for the instantaneous validation. In this case the NRMSE goes up to +12 % for the HTF outlet temperature and +8.6 % for the gross electric power. Also in this case this can be related to a different operational decision of the operator.

Figure 7: Validation for the winter case; A) DNI for the case considered (input), B) Normalized turbine inlet temperature, C) Normalized evaporator inlet water pressure, D) Normalized steam mass flow rate, E) Normalized solar field HTF outlet temperature, F) Normalized SGS HTF mass flow rate G) Normalized gross electric power. The solid and dotted lines represent the result of the model and operational data, respectively.

Table 5: Validation results for the winter case.

Parameter	IRE [%]	RMSE [% of nominal reference values]	NRMSE [%]
TIT	2.25	7.35	9.66
p_{inEVA}	2.11	7.74	8.49
FR_{steam}	-2.57	8.56	8.34
T_{HTF}	3.19	7.62	12.00
FR_{HTF}	3.86	119.49	11.39
Gross power	2.37	8.45	8.60

In order to test further the validity of the model, its performance has been validated against the available operation data for the period 6-16 May in which a less irregular DNI was measured (even though with lower values), being a representative case for the spring. The time variant results are shown in Figure 8 and Table 6 for the error estimation. Similar considerations as those of the winter case can be drawn for the spring case from Figure 9 and Table 6, resulting in deviations of similar magnitudes. However, in the spring case the gross electric power production is overestimated to a higher extent (+4.3 %), primarily because of day 4 when the plant was not operated due to a planned outage, whereas the model allowed for electric power production. In this case, the highest error is observed for the flow rate, both for the integral and instantaneous errors due to the same reasons as those of the winter validation.

Table 6: Validation results for the spring case.

Parameter	IRE [%]	RMSE [% of nominal reference values]	NRMSE [%]
TIT	2.97	6.41	7.71
p_{inEVA}	1.02	7.98	9.12
FR_{steam}	-4.12	9.93	9.72
T_{HTF}	1.67	5.63	8.28
FR_{HTF}	4.76	139.17	13.54
Gross Power	4.32	10.23	10.32

Figure 8: Validation for the spring case; A) DNI for the case considered (input), B) Normalized turbine inlet temperature, C) Normalized evaporator inlet water pressure, D) Normalized steam mass flow rate, E) Normalized solar field HTF outlet temperature, F) Normalized SGS HTF mass flow rate G) Normalized gross electric power. The solid and dotted lines represent the result of the model and operational data, respectively.

Moreover, a validation of the time delay until reaching experimental power output was carried out. Table 7 illustrates the results for such validation on a daily basis for both weather conditions. An average value of the absolute term of the deviations is also presented. It may be noticed that a significant deviation is observed for day 10 in the winter case. This is mainly due to lower HTF mass flow rates caused by additional defocusing set by the plant operator, which is not reflected in the model. This is also why lower values are observable in Figure 7. Days 9, 11 and 13 were excluded from the winter related calculations as in those days the plant was not operated. The same reasoning applies for day 4 in the spring data set. Excluding these outliers, the highest deviation (+11.1 %) in rising time is observed for day 7 for winter conditions, which is illustrated in Figure 9 B. The lowest deviation is obtained in day 4 (-0.46 %) and the corresponding daily validation is depicted in Figure 9 A. Higher deviations (in absolute terms) are observed for the spring case with values up to -15.6 % in the case of day 8 (represented in Figure 9 D). A lower value, -8.7 %, is observed for day 7 (represented in Figure 9 C). These deviations are mainly due to a more conservative approach employed by the operator in starting up the power plant during these periods. As an overall result, the absolute average deviation on the rise time is 7.9 % and 11.8 % for winter and spring weather conditions, respectively.

Table 7: Deviation results for rise time for gross power.

Day	Deviation on rise time	
	Winter	Spring
1	-6.8%	-13.2%
2	-13.2%	-11.9%
3	-10.2%	-11.7%
4	-0.5%	-
5	5.3%	-10.3%
6	5.0%	-8.8%
7	11.1%	-8.7%
8	10.0%	-15.6%
9	-	-15.4%
10	-25.9%	-10.5%
11	-	
12	-9.1%	
13	-	
Average (absolute value)	7.9%	11.8%

Figure 9: Close-ups on the transient daily validation results for the winter and spring data resulting in lowest (A, C) and highest deviations (B, D), respectively. The solid and dotted lines represent the result of the model and operational data, respectively.

The last step of the validation consists in comparing the estimated results of the model for the daily gross energy production with the equivalent operational data. Figure 10 illustrates such comparison in percentage form (the data were normalized against the maximum integral value obtained from the operational data sets). Figures 9 A and 9 B refer respectively to the winter and spring weather conditions. The dots represent the operational data points, while the dashed lines represent $\pm 10\%$ and $\pm 5\%$ deviation in the winter and spring case, respectively. For the spring case the results indicate that 80 % of the values are within a 5 % deviation while the two worst days are overestimated. In the winter weather conditions, the deviation slopes raise to $\pm 10\%$ and in this case 85 % of the points are within this margin. The other two points correspond to day 9 and 13 when the plant did not operate. In case of day 11 (on the (0,0) coordinate in Figure 10 A) both the plant and the model predicts little to no electricity output and that is why even though the plant did not operate, no major discrepancies are observed.

Figure 10: Comparison of the model results in terms of daily electric energy production for the days available in the data sets; A) February, B) May.

These observations support the aforementioned considerations on how the model differs more significantly only when the plant decision makers decided to change the normal operating routines. Overall, the results of Figure 10 suggest that the model is more accurate from an integral perspective in spring conditions as the deviations are essentially lower. On the other hand, the errors for the winter case compensate for each other making the IRE lower in this case. In conclusion, the results of the validation indicate that the model is able to predict the dynamic behavior of a gas-boosted parabolic trough solar power plant with reasonable accuracy, which is sufficient for the purpose of the study.

3.2 Optimization of the start-up strategy

This section summarizes the results obtained for the optimization studies both for the winter and spring weather conditions. Figure 11 illustrates the results of the optimization for the winter case; the normalized objective variables (normalized with respect to the base case) are shown on the x-y-axes with one of the four decision variables (see Table 3) in each figure.

Figure 11 highlights four different points, respectively:

- i. Minimum fuel consumption
- ii. Maximum electricity production

iii. Trade-off between the two objectives in the form of minimizing the fuel to electricity ratio

$$\frac{Q_{\text{fuel}}}{W_{\text{gross}}}$$

bc. Base Case (bc): Case used for the validation of the model.

Their operational parameters and results are summarized in Table 8. In general, the results shown in Figure 11 demonstrate that it is not possible to define a single optimal point for the start-up constraints both for the evaporator and the booster heater. However, it is possible to identify a range values maximizing the performance of the plant. For the evaporator, a range between 2.5 and 4.5 K/min can be selected, including 47 % of the points in Figure 11, and an optimal value of 5.7 K/min is obtained in order to have a high electricity production without at the same time increasing significantly the fuel consumption. In case (iii), having a sufficiently high start-up constraint both for the evaporator and the super-heater allows for setting the temperature of the HTF heater to a low value of 200 °C, minimizing significantly the fuel consumption. Case (ii) shows that in order to maximize the electricity production, not only it is necessary to have a higher set point for the HTF heater temperature (with the maximum operating time), but also it is required to have higher start-up constraints. This mainly relates to the operating choices, which would allow for more electric production by increasing significantly the fuel consumption. Table 8 and Figure 11 also indicate that the base case (bc) has a slightly higher fuel/electricity ratio than the optimal cases (i.e. cases close to point (iii)). By employing the start-up strategy depicted in case (iii) it is possible to lower the fuel/electricity ratio by 1.5 % and increase the electricity production by 7.7 %, compared with the base case.

Table 8: winter case optimization results

Cases	EVA v [K/min]	BH v [K/min]	HTFH time [h]	HTFH T [°C]	Normalized W_{gross} [-]	Normalized Q_{fuel} [-]
bc	1	4	2.5	310	1	1
i	1	1	1.58	238	0.836	0.845
ii	4.4	5.2	2.6	310	1.229	1.654
iii	5.7	5.6	2.4	200	1.077	1.067

Figure 11: Optimization results for the winter case considering the different decision variables. Values normalized towards the base case results. A) Evaporator start-up rate constraints. B) Booster heater start-up rate. C) HTF heat Temperature D) HTF heater operating time.

443

444 These results indicate that it is not always necessary to have a SGS designed with high thermo-
 445 mechanical constraints. However, having such possibility can further increase the operational flexibility
 446 of the power plant. In this regard an analysis of the fuel efficient solution is performed. Figure 12
 447 illustrates a close-up on case (iii), showing the fuel/electricity ratio as a function of the evaporator heating
 448 rate constraint. On the z-axis color bar the booster heater heating rate constraints is shown. Table 9
 449 summarizes the decision variables and objective functions of case (iii) and case (iv) and (v).

Figure 12: Analysis of evaporator constraints on the Fuel/Electricity ratio – Close-up on the optimal ratio $Q_{\text{fuel}}/W_{\text{gross}}$.

Table 9: Optimal efficiency points comparison

Cases	EVA v [K/min]	BH v [K/min]	HTFH time [h]	HTFH T [°C]	Normalized W_{gross} [-]	Normalized Q_{fuel} [-]
iii	5.7	5.6	2.43	200	1.077	1.067
iv	2.6	6.0	2.12	220	1.082	1.069
v	1	1.8	0.9	242	0.932	0.921

These cases give very similar results, but employ different operating strategies. The results shown in Table 9 and Figure 12 suggest that it is possible to obtain a slightly higher (0.45 %) gross electricity production at the cost of increasing (by 0.22 %) the fuel consumption. However in this case, even though lower constraints on the evaporator might be obtained, it would be required to increase the set-point temperature of the HTFH and increasing the constraint of the booster heater. It is then preferable to choose option (iii), as the heater would only be used to pre-heat the oil to a maximum temperature of 200 °C. In case it is not possible to employ a steam generator, which allows for such constraints as its design might not allow for it, it is still possible to operate of the power plant in the optimal region at the cost of employing the HTF heater for more time and at a higher temperature. In terms of fuel to electricity ratio, a similar result can be obtained, see case (v), which represents a limit case for a very slow evaporator in terms of heating rates. However, if the heating rates of the evaporator are constrained to the lower limit, in order to have a similar fuel to electricity ratio (0.522) a much lower (-13.5 %) electric energy production is achieved.

The results of the multi-objective optimization for the spring season are summarized in Figure 13; the aforementioned four cases are also indicated in the figure. The base case is again below the Pareto front, meaning a non-optimal operating point. The detailed results of the different cases are presented in Table 10.

Table 10: spring case optimization results

Cases	EVA $\dot{v}$ [K/min]	BH $\dot{v}$ [K/min]	HTFH time [h]	HTFH T [°C]	Normalized W_{gross} [-]	Normalized Q_{fuel} [-]
bc	1.00	1.00	2.5	310.00	1	1
i	1	1	0.62	263	0.947	0.930
ii	4.3	4.3	1.83	281	1.134	1.211
iii	6	6	0.78	290	1.062	1.057

In the spring case, higher optimal values (towards the upper boundary of the constraints) are obtained for the evaporator heating rates, especially for case (iii). As the heater is operated at a lower temperature, it is necessary to increase the start-up speed of the steam generator. Compared to the base case (bc), in case (iii), by increasing the fuel consumption (+5.6 %) it is possible to increase the electricity production by 6.2 %, decreasing the fuel to energy ratio. The results indicate that if the fuel consumption is set as a constraint, a higher electricity production (+1.9 %) can be achieved by increasing the heating rates to the maximum limits and at the same time decreasing the HTF heater utilization.

One of the main differences between Figure 11 and Figure 13 is the narrower range of solutions for the spring case. This can be directly linked to the lower fluctuations in the DNI and therefore a lower impact of the constraints on the electricity production, explaining why a lower value of the maximum heating rate constraint is obtained for case (ii). This would mean that having components designed for higher heating rates would enable a larger degree of flexibility in operating the power plant. In conclusion, the results suggest that there are no clear range of optimal values for the heating rates of the evaporator and booster heater. However, by being able to operate them at a faster rate it is possible to reduce the operating time of the HTF heater and maximize the electricity to fuel ratio.

Figure 13: Optimization results for the spring case considering the different decision variables. Values normalized towards the base case results. A) Evaporator start-up rate constraints. B) Booster heater start-up rate. C) HTF heat Temperature D) HTF heater operating time.

5. Conclusions

A detailed model was used to find the optimal start-up operational strategy of a gas-boosted parabolic trough power plant. The model was developed in DYESOPT – a techno-economic tool for dynamic performance evaluation of power plants. The power block part of the model was developed accounting for the heating rate constraints of the steam generator system, booster heater and the steam turbine start-up control strategy. The model was validated both at steady-state and dynamic operating conditions, and subsequently used to optimize the start-up strategy by minimizing the fuel consumption and maximizing the electric energy production by means of a genetic algorithm based multi-objective optimizer. Both the validation and optimization were performed for two different time series corresponding to a winter and a spring case, respectively.

The results of the validation indicate that the model is able to predict with a reasonable accuracy the behavior of a gas-boosted parabolic trough solar power plant, both at steady state and dynamic operating

conditions. The validation at steady-state condition shows a maximum relative error of -6.7 % for the SGS HTF mass flow rate and -5.1 % for the total electric parasitic consumption. For dynamic operating conditions, the validation results in a maximum NRMSE of +13.5 % for the solar field HTF mass flow rate, 11.8 % on gross power rise time and a maximum integral relative error of +4.3 % for gross electric energy production in the case of the spring case. Considering the daily electric energy production, the validation indicates that 85% of the values are within a ± 10 % confidence range.

The result of the multi-objective optimization indicates that it is not possible to define a range of optimal heating rates for evaporator constraints. However, different optimal start-up strategies can be identified. If minimum fuel consumption is desirable, the heating rates would result optimal around the lower threshold of 1 K/min together with low utilization of the heat transfer fluid heater. An opposite conclusion can be drawn if maximum electric production is desirable, resulting in a higher utilization of the heat transfer fluid heater both in terms of higher set point temperature and in time of activation. If however the operating strategy is to maximize the plant performance with regards to the electricity production to fuel consumption ratio, higher evaporator heating rates are desirable, namely, 5.7 K/min and 6 K/min for the winter and spring cases, respectively. These values are representative for steam generators that are commercially available. As a general conclusion, it can be stated that even though an optimal value for the operation of the power plant can be lower than the maximum constraints stated by the manufacturer, it may be desirable to design the evaporator for higher constraints, enabling more flexibility regarding operating strategies. It is therefore clear that it is critical to take into consideration the heating rates constraints when finding the optimal start-up strategies of CSP plants.

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