Particle tower technology applied to metallurgic plants and peak-time boosting of steam power plants

Lars Amsbeck, Reiner Buck, and Tobias Prosin

Citation: AIP Conference Proceedings **1734**, 070001 (2016); doi: 10.1063/1.4949148
View online: http://dx.doi.org/10.1063/1.4949148
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1734?ver=pdfcov
Published by the AIP Publishing

Particle Tower Technology Applied to Metallurgic Plants and Peak-Time Boosting of Steam Power Plants

Lars Amsbeck[1,a)], Reiner Buck[1,b)] and Tobias Prosin[2,c)]

[1] *Institute of Solar Research, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany,*
[2] *Murdoch University, 90 South Street, 6150 Perth, WA, Australia*

[a)] Lars.Amsbeck@dlr.de
[b)] Reiner.Buck@dlr.de
[c)] T.Prosin@murdoch.edu.au

Abstract. Using solar tower technology with ceramic particles as heat transfer and storage medium to preheat scrap for induction furnaces in foundries provides solar generated heat to save electricity. With such a system an unsubsidized payback time of only 4 years is achieved for a 70000t/a foundry in Brazil. The same system can be also used for heat treatment of metals. If electricity is used to heat inert atmospheres a favorable economic performance is also achievable for the particle system. The storage in a particle system enables solar boosting to be restricted to only peak times, enabling an interesting business case opportunity.

INTRODUCTION

At DLR, a particle based solar tower system with storage for temperatures up to 1000 °C is currently under development. Particle exit temperatures up to 900 °C have been demonstrated experimentally with a small receiver of about 10 kWth. Manufacturing of a 500 kWth prototype is complete, non-solar commissioning of this receiver is under way.

Previous economic analysis for such solar process heat systems [1] has shown that heat generation cost are expected to be in the range of 0.05-0.075 €/kWh$_{th}$ for the industrial demonstration (for a DNI range of 1700-2700 kWh/m^{2}a) and 0.03-0.04 €/kWh$_{th}$ within some years of deployment (assumed lifetime of 25 years, 8% interest rate on capital).

Profitability as the major investment criterion can not only be improved by reducing costs but also through higher selling prices. This paper focuses on three potential market introduction options where the technology can take advantage of high electricity prices. This is achieved either by replacing electricity used for process heat to melt or heat-treat metals or by producing additional electricity in peak hours. Actual average industrial electricity prices in countries with reasonable solar resources can be quite high:

- Brazil: 0.157 \$/kWh$_{el}$ [2] = 0.143 €/kWh$_{el}$ (\$1 = 0.914 €)
- Italy: 0.168 €/kWh$_{el}$ [3]
- Spain: 0.122 €/kWh$_{el}$ [3]

Furthermore, with regard to peak power, the lowest winning bid in the South African REIIIP program with a base tariff of 0.124 \$/kWh$_{el}$ [4] for the first year corresponds with the 270% premium paid from 16:30-21:30 to a peak electricity price of 0.335 \$/kWh$_{el}$.

SolarPACES 2015
AIP Conf. Proc. 1734, 070001-1–070001-8; doi: 10.1063/1.4949148
Published by AIP Publishing. 978-0-7354-1386-3/$30.00

For the economic analysis of the proposed concepts, the main cost assumptions are summarized in Table 1. The receiver cost estimate is based on information obtained from the manufacturing of a prototype with $1m^2$ aperture size.

TABLE 1. Main system cost assumptions

Heliostats	166 €/m^2 installed
Receiver	300 000 € for $2.5MW_{th}$
Particle/air heat exchanger	150 €/kW_{th}

PRE-HEATING FOR INDUCTION FURNACES

Annual worldwide production of iron/steel in foundries is in the order of 100 Mt, at approximately 1 MWh/t energy consumption the market size is in the order of 100 TWh/a. Some of these foundries are located in regions with good solar resources, so a potential for a cost efficient market introduction for the particle based tower system exists.

Induction furnaces are widely used in foundries to melt metals like iron and aluminum with electricity due to their low emissions compared to coke fired cupolas as well as operational simplicity and flexibility. Some alloys like ductile iron even require electric heating to avoid contamination with sulfur. Commercially available systems use fossil fuels to pre-heat the educts, like scrap or pig-iron to ~600 °C, saving about 1/3 of the electricity and raising melting capacity of the furnace correspondingly. But these systems are not commonly used potentially due to low economic benefits, higher operational complexity and slow adaption. In electric arc furnaces for steel recycling charge preheating is an established process as much larger capacities allow lower specific component costs, equipment with higher efficiencies and availability of cheap gas is more probable.

In foundries where fossil fuels are very expensive or even not available solar energy can be used instead for material pre-heating. A commercially available hot air generator and a pre-heating system can be used to integrate solar heat from ceramic particles into the system as seen in Fig. 1.

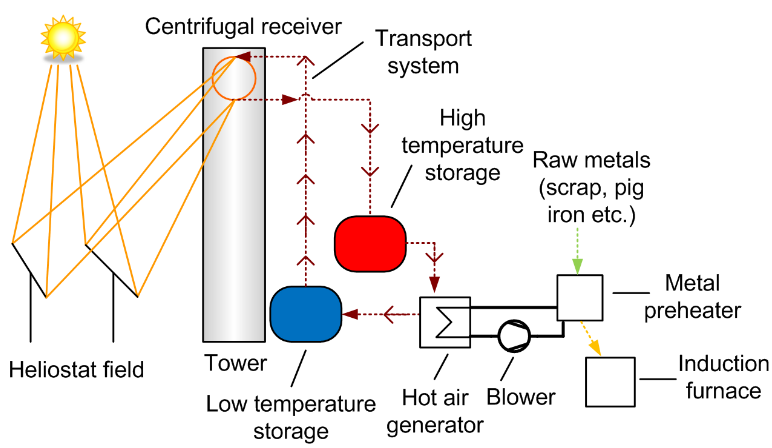

FIGURE 1. Solarized metal pre-heating system for foundry plants

A batch pre-heating system conventionally used for electric arc furnaces as shown in Fig. 2 is chosen for the foundry application. The inlet temperature to the preheat system is set to 750 °C to avoid oxidation of small pieces of scrap. Typical average heat efficiency coefficients in batch pre-heating systems are 0.6-0.7 [5].

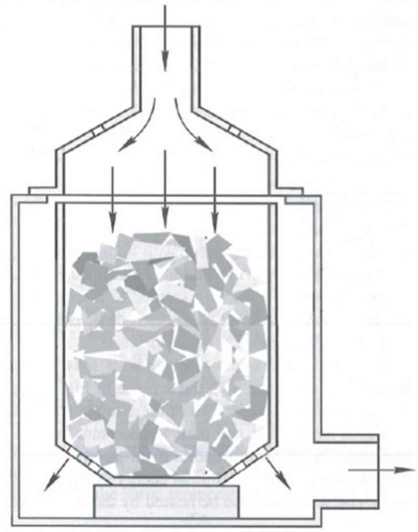

FIGURE 2. Electric arc furnace batch pre-heating system [5]

An average efficiency of 0.6 gives an average air outlet temperature of 300 °C at 750 °C inlet temperature. Since no oxygen is needed to burn fuel, the air loop can be built as closed cycle, i. e. the air is recirculated in the system. Thus, no exhaust losses reduce the system efficiency. However, higher air outlet temperatures lower the heat capacity in the storage and the receiver efficiency compared to the plasterboard configuration with 200 °C lower particle temperature presented in [1]. A serial connection of two or more vessels can decrease the air outlet temperature further, especially as the outlet temperature of the first vessel rises in the batch operation until the complete charge is pre-heated. With a driving temperature difference of 150 °C in the particle air heat exchanger the lower particle temperature in the particle cycle rises to 450 °C at an average outlet temperature of 300 °C from the charge pre-heater.

Preheating the scrap can take place either next to the furnace or further away. In the first option the pre-heated material can be discharged directly into the furnace charging system. In the second option the scrap was transported already preheated to the induction furnace and placed into the furnace with an insulated charge feeder. This needs insulated crane vessels which can be also used to preheat the scrap inside. The foundry crane system can be used for the transport. Insulated high temperature piping gives some flexibility in the location of the hot air generator, especially when the pre-heater is located close to the furnace in a space-restricted situation.

A 70 000 t/a capacity foundry with a $12MW_{el}$ induction furnace in Sao Paulo State, Brazil, with a DNI of 2175 kWh/m^2a, could incorporate a 4 MW_{th} baseload pre-heat system. To supply this pre-heat system 5 particle tower modules with a peak capacity of 2.5 MW_{th} each and a 15 h storage would be needed. 511 8 m^2 heliostats per module are used, resulting in a total plant mirror area of 20 440 m^2. The system was optimized using HFLCAL for the heliostat field and an exel-sheet based annual performance analysis. More details about the optimization method can be found in [1].

Detailed performance and cost numbers are given in Table 2. Due to replacing electricity at a very high system efficiency of 44.2% a payback time of 4 years is achieved without subsidies and loans. Compared to a receiver with 200 °C inlet temperature and 900 °C outlet temperature the peak efficiency is only reduced by 1.5% points at 450 °C inlet temperature. Due to the reduced temperature spread, storage costs increase to 17.6 €/kWh_{th} from 12 €/kWh_{th}, but are strongly overcompensated by the high value of electricity saving.

TABLE 2: Performance of a $4MW_{th}$ baseload solar plant for induction furnace pre-heating

		Unit	Value
Optical	Energy available for system (total possible DNI to mirror)	GWh	45.0
	Energy loss due to overhaul and system downtime	GWh	0.65
	Energy loss due to wind speed to high	GWh	0.92
	Energy available for system during available plant operation	GWh	43.5
	Field optical losses (attenuation, blocking & shading, intercept, cos)	GWh	18.5
	Energy incident on receiver opening before defocusing and dumping	GWh	25.9
	Defocusing losses on field	GWh	1.5
	Dumping losses on field	GWh	0.8
	Energy incident on receiver opening	GWh	23.5
Heat	Receiver losses (reflection, thermal radiation, convection, conduction)	GWh	2.5
	Thermal Energy from receiver	GWh	21.0
	Storage, transport and heat exchangers heat loss	GWh	1.1
	Blower parasitics recovered as heat	GWh	0.8
	Total solar heat to metal preheater replacing furnace electricity consumption	GWh	20.7
Electrical	Electricity consumption transport system and receivers	GWh	0.05
	Electricity consumption blower	GWh	1.3
	Electricity consumption field parasitics	GWh	0.23
	Total parasitic electricity consumption	GWh	1.60
	Net electricity consumption reduction	GWh	19.1
Annual efficiencies	Field performance efficiency (attenuation, blocking & shading, intercept, cos)	%	0.575
	Receiver performance efficiency	%	0.892
	Storage, transport and heat exchangers heat performance efficiency	%	0.949
	System efficiency (net electricity reduction/ total possible DNI to mirror)	%	0.422
Performance indicators	Pre-heater full load hours	h/a	5157
	Capacity factor	-	0.589
Financial	Solar field	M€	3.4
	Receivers	M€	1.5
	Tower	M€	0.25
	Storage	M€	1.1
	Particle-air heat exchanger	M€	0.6
	Lift system + buffer tanks	M€	1.0
	Metal pre-heater	M€	0.4
	Horizontal particle transport	M€	0.18
	Project Development	M€	0.84
	EPC Profit	M€	0.84
	Total investment cost	M€	10.1

	Income due to saved electricity at 143 €/MW_{el}	M€/a	2.73
	Annual O&M costs	M€/a	0.16
	Annual insurance costs	M€/a	0.08
	Payback time	a	4.1

HEAT TREATMENT FURNACES

Heat treatment furnaces which need to avoid oxidation of the products use sometimes electricity as a heat source. Especially aluminum furnaces are suited for solarization due to the lower temperatures needed compared to iron based alloys. The heat treatment consumes about 1/3 of the total energy demand of an aluminum cast house. The temperatures used in heat treatment of aluminum range from ~100 °C for age hardening to about 600 °C in the preparation of hot forming [6]. A direct contact particle-gas heat exchanger enables integration of solar heat stored in the ceramic particles and integration into the heat treatment furnace can be done similar to the pre-heating for the induction furnace as shown in Fig. 3.

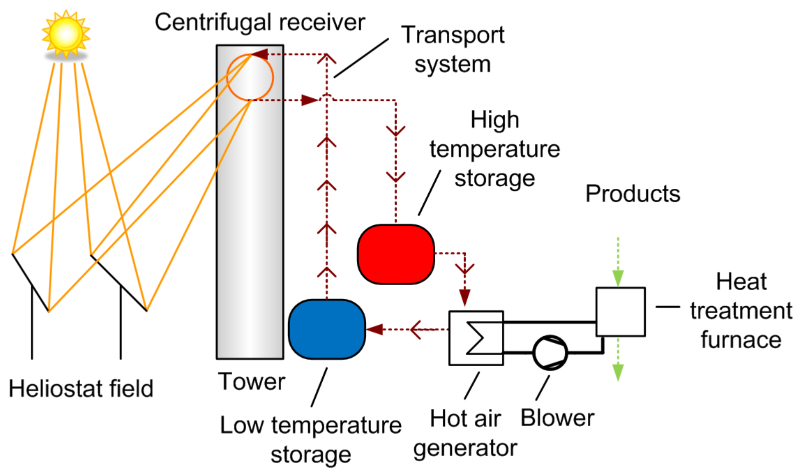

FIGURE 3. Solarized metal heat treatment system

SOLAR BOOSTING OF STEAM POWER PLANTS

Fuel saving by air-based integration in steam power plants can achieve high solar shares up to 20% [6], but is at the moment economically only attractive if expensive liquid fuels are used. The boosting of steam-based power plants only at peak demand times is much more profitable, as the additional electricity produced with boosting competes with very expensive peaker plants (e.g. simple cycle gas turbines). A thermal storage system is a prerequisite for collection of solar energy over the whole day and boosting only during the evening peak. This is particularly interesting for capacity-limited markets with strong growth, such as South Africa, India, China and some Middle Eastern nations. A particle-based system using the currently designed receiver module size and a commercially available pressurized particle-water heater optimized for the South African market is presented in the paper.

While turbine bleed steam integration is not the most efficient conversion of solar energy to electricity in a steam power plant, the benefit of increasing the power plant output without modifications to the boiler combined with the limited technical risk make this method a worthwhile option in some circumstances. In this case integration of solar steam could be accomplished in an efficient way by injecting solar produced steam at the high pressure turbine exhaust (cold re-heat) bleed line as depicted in Fig. 4.

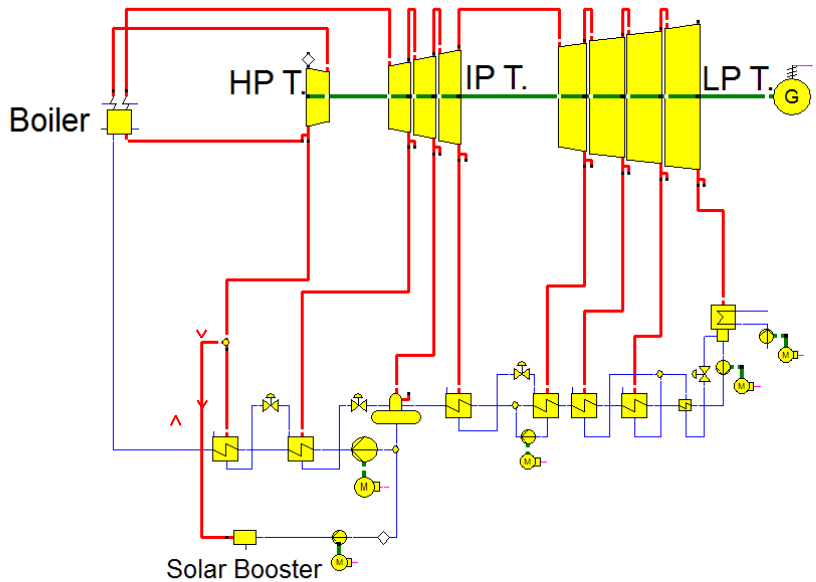

FIGURE 4. Heat balance diagram of a solar boosted re-heat steam power plant

For example, South Africa's peak power incentive [4] which pays a premium for power produced between 16:30-21:30 of 270% of the market price for electricity makes increasing the output of an existing plant during these hours particularly attractive. The situation of using a multi-tower particle receiver based system with the currently designed receiver module size and a commercially available pressurized particle-water heater only producing solar steam for power output boosting during times when a premium tariff is paid was modelled using available simulations tools previously developed [7,8]. The peak solar steam integration was set to 95 MW_{th}, replacing bleed steam from the high pressure turbine with the solar booster. This solar booster, a particle based steam generator, heats feedwater from the de-aeration tank before the boiler. The replaced bleedsteam adds to the mass flow through the high pressure turbine and therefore adds to the actual power generation. The integration potential of bleed steam solarisation at this integration point of a 744 MWel (gross) power plant [8] and annual output was calculated using the solar resource of Cape Town, with annual DNI of 2000 kWh/m².

The peak hours from 16:30-21:30 result in a solar system with 31 tower modules with 2.5 MW_{th} each and 6 h of storage, a solar multiple of only 0.8. Detailed performance and cost numbers are given in Table 3. When boosting is active during this time period, the plant output is increased by 30.5 MW_{el} or 4.1% without combustion of any additional fuel (increased output of 0.5% annually), providing additional capacity to the grid. Using a capital cost of 8.2% a levelized electricity cost of 240 €/MWh_{el} or $262.5 $/MW h_{el} is achieved ($1 = 0.914€). This is only a bit more expensive than diesel fired open gas turbines providing peak electricity at about 200 $/$MWh_{el}$ in South Africa. Under the conditions of the South African REIIIP program with the 270% CSP peak electricity tariff 96 $/MWh could be bid, lower than the actual lowest bid for CSP in the program. The absence of a long lead time for turbine procurement in this application and therefore quicker project realization adds to the benefits in a land with load shedding.

It should be clear that limiting the solar plant to operation to only 5 hours results in a suboptimal design of the solar plant, however it could provide a positive business case given the appropriate economic incentives and a turbine capable of the higher steam flows.

TABLE 3: Performance of a 95MW_{th} solar peak-boosting system

		Unit	Value
Optical	Energy available for system (total possible DNI to mirror)	GWh	255.3
	Energy loss due to overhaul and system downtime	GWh	24.7
	Energy loss due to wind speed to high	GWh	0.4

	Energy available for system during available plant operation	GWh	230.2
	Field optical losses (attenuation, blocking & shading, intercept, cos)	GWh	100.8
	Energy incident on receiver opening before defocusing and dumping	GWh	129.8
	Defocusing losses on field	GWh	2.0
	Dumping losses on field	GWh	11.8
	Energy incident on receiver opening	GWh	115.9
Heat	Receiver losses (reflection, thermal radiation, convection, conduction)	GWh	10.1
	Thermal Energy from receiver	GWh	105.8
	Storage, transport and heat exchangers heat loss	GWh	4.9
	Total solar heat to steam generator	GWh	102.5
Electrical	Electricity consumption transport system	GWh	0.23
	Electricity consumption pumps	GWh	0.4
	Electricity consumption field parasitics	GWh	1.0
	Total parasitic electricity consumption	GWh	1.66
	Net additional electricity production at 32.1% conversion efficiency of the replaced bleed steam	GWh	30.4
Annual efficiencies	Field performance efficiency (attenuation, blocking & shading, intercept, cos)	%	0.562
	Receiver performance efficiency	%	0.912
	Storage, transport and heat exchangers heat performance efficiency	%	0.954
	System efficiency (net electricity reduction/ total possible DNI to mirror)	%	0.119
Performance indicators	Boosting full load hours	h/a	1053
	Capacity factor	-	0.118
Financial	Solar field	M€	12.7
	Receiver	M€	9.3
	Tower	M€	1.55
	Storage	M€	6.8
	Particle steam generator	M€	11.4
	Lift system + buffer tanks	M€	6.6
	Horizontal particle transport	M€	0.69
	Project Development	M€	9.8
	Total investment cost	M€	59
	Annual O&M costs	M€/a	1.19
	Annual insurance costs	M€/a	1.0
	LCOE at 8.2% interest rate	€/MWh_{el}	240

CONCLUSIONS

Economics of CSP plants can be significantly enhanced not only by reducing costs and enhancing yield but by providing higher value energy in specific applications. The high temperatures of up to 1000 °C of solar tower technology with ceramic particles as heat transfer and storage medium allow the preheating of scrap for induction furnaces in foundries. 1/3 of the electricity consumption of the induction furnace can be replaced with solar generated heat with this technology. As the solar generated heat directly replaces electricity in this application a very high system efficiency of 44.2% from solar to electricity is achieved for a foundry in Brazil with 70000 t/a production capacity of cast metal products. This results in a payback time of only 4 years without the use of subsidies or bank loans. This indicates a robust business case for the market introduction of particle tower technology.

Similar economics can be expected if electricity is used for the heat treatment of metals. The low melting temperatures of aluminium even allow a solar share of up to 100%.

The particle tower technology can be also applied to solar boosting, but restricted to only the peak times using the inherent storage. A relative large storage capacity is filled over the day and discharged to a particle steam generator to replace bleedsteam when the additional produced electricity has the highest value. Under the conditions of the South African REIIIP program with the 270% CSP peak electricity tariff 96 $/MWh could be bid, lower than the actual lowest bid for CSP in the program.

REFERENCES

1. L. Amsbeck," Particle tower system with direct absorption centrifugal receiver for high temperature process heat," in *Proceedings of the SolarPACES conference 2014*, (Beijing).
2. Brazilian Ministry of Mines and Energy , "Brazilian Energy Balance, " Year 2013, Brazil.
3. Eurostat Energy Price Statistics, http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
4. http://social.csptoday.com/markets/south-africa-overview-csp-market-2015
5. Y.N. Toulouevski, I.Y. Zinurov, *Innovation in Electric Arc Furnace*, Springer Verlag Berlin 2013, p.111-112.
6. "Heat treatment of aluminium alloys," in *Materials World* (The Institute of Materials, Minerals and Mining, London, 2004), Vol. **12**, No. 3, pp. 37-38.
7. T. Prosin, et al., "Hybrid Solar and Coal-Fired Steam Power Plant with Air Preheating Using a Solid Particle Receiver ," in *Proc. Solar 2014* (Australian Solar Council, Melbourne, Australia,2014).
8. T. Prosin, et al. "Hybrid solar and coal-fired steam power plant with air preheating using a centrifugal solid particle receiver," in *Proceedings of the SolarPACES conference 2014* (Beijing).