Thermodynamic and economic evaluation of a solar aided sugarcane bagasse cogeneration power plant

E. Burin[a], T. Vogel[b], S. Multhaupt[b], A. Thelen[b], G. Oeljeklaus[b], K. Görner[b], E. Bazzo[a]

[a]Laboratory of Combustion and Thermal Systems Engineering (LabCET)
Federal University of Santa Catarina (UFSC), Florianópolis, Brazil
burin@labcet.ufsc.br, e.bazzo@ufsc.br
[b]Chair of Environmental Process Engineering and Plant Design (LUAT), University of Duisburg-Essen,
Leimkugelstr.10, Essen, 45141, Germany
tobias.vogel@uni-due.de, andre.thelen@stud.uni-due.de, sven.multhaupt@uni-due.de,
gerd.oeljeklaus@uni-due.de, klaus.goerner@uni-due.de

Abstract:

The objective of this work was to evaluate the integration of Concentrated Solar Power (CSP) with a typical sugarcane bagasse cogeneration power plant, located in Campo Grande in the State of Mato Grosso do Sul in Brazil, under thermodynamic and economic aspects. Of the related plantation three million tons of sugarcane are processed per harvest (April-to-December). The cogeneration cycle has two 170 t/h capacity steam generators that provide steam at 67 bar / 525 °C. Main steam is expanded in parallel in a backpressure (BPST) and a condensing-extraction (CEST) steam turbine. Three integration layouts of CSP into cogeneration cycle were evaluated in this work, namely: (1) solar feedwater pre-heating; (2) saturated steam generation with solar energy and post superheating in biomass steam generators and (3) generation of superheated steam in parallel with biomass steam generators. Linear Fresnel and parabolic trough collectors were implemented for integration layouts (1) and (2), while central tower with direct steam generation was implemented in integration (3). As main results, the gains due to integration of solar concentrators with sugarcane bagasse cogeneration power plants equipped with BPST and CEST turbines were demonstrated. Owing to the opportunity of solar-only operation layout 3 showed to be the best option, as capacity factor of solar field was maximized by its operation regardless of the availability bagasse.

Keywords:

Sugarcane; bagasse; cogeneration; concentrated solar power; hybridization.

1. Introduction

Renewable energy resources like sun or wind have the problem of inconsistent availability. In order to match the power production with the demand, storage technologies are important. A direct storage of electricity is not possible. For that reason in all existing storage technologies the electricity is transferred into another energy potential, e.g. chemical, heat or elevation. This energy could be used later again in order to produce electricity. In case of CSP, the thermal energy storage systems are commonly used for that purpose.

Instead of that, another conceivable approach could be to combine CSP with a storable energy source, like natural gas, coal or biomass. Concerning this, two ways of thinking the integration are possible: (I) add solar energy to a conventional power plant or (II) add the other energy source to the solar power plant. Hereto lots of different concepts and approaches are discussed or even implemented in applications. In case of (I) as major concepts the ISCC (Integrated Solar Combined Cycle) and the SAFWH (Solar Aided Feedwater Heating) have to be mentioned. All concepts related to (I) are strongly limited in the potential solar share, because of the limited thermal amount that can be integrated. A smart approach with a kind of energy sources equilibrium is implemented in the Termosolar Borges in Spain, where solar energy and biomass are used as fuel. From the stand point of global warming from the named energy sources biomass is the favored partner for solar energy.

Brazil has a quite interesting potential for CSP as well as for biomass, wherefore the combined use of both energy sources in one power plant could be a smart solution. Even today, the electricity generation in Brazil is based strongly on renewable resources. For example in 2011 87 % of electricity was produced by technologies using renewable energy sources [1]. Biomass has thereon a share of 6.1 % [1]. The major source of biomass and usage in power sector is bagasse. The thermal utilization of bagasse represents in 2014 80 % of the overall biomass power generation capacity [2].

Traditionally the bagasse-fueled power plants are cogeneration power plants directly located at the sugarcane factories in order to deliver therefore the on-site power and heat demand. This is underpinned by the large total amount of 386 bagasse-fueled power plants and their average installed capacity of 25.4 MW_{el} [2]. In the last decades, due to a strongly increasing Brazilian electricity demand and the Brazilian electricity sector decentralization in 2,000 the focus has changed more and more from fulfilling the on-site demand to exporting electricity to the grid. Since 2005 the electricity exportation could be raised each year by 34 %, so that in 2,013 a total amount of 15,067 GWh_{el} was produced by bagasse-fueled power plants [3]. Even for the future development there are ambitious targets, with a further increase by the factor of 13 until the year 2022 [3]. Besides increasing the sugarcane production, co-combustion of sugarcane bagasse and straw, retrofit measures or building new efficient power plants, the integration of solar energy might be an interesting lever.

2. Solar aided sugarcane bagasse plants

Bagasse is the residue, which remains after the extraction of the aqueous sugar solution out of sugarcane. The bagasse itself consists out of cellulose, hemicellulose and lignin. Due to the demand of electricity and heat for the downstream positioned process factory, the bagasse is directly used as fuel in the cogeneration power plant. The interrelationship is visualized in Fig. 1.

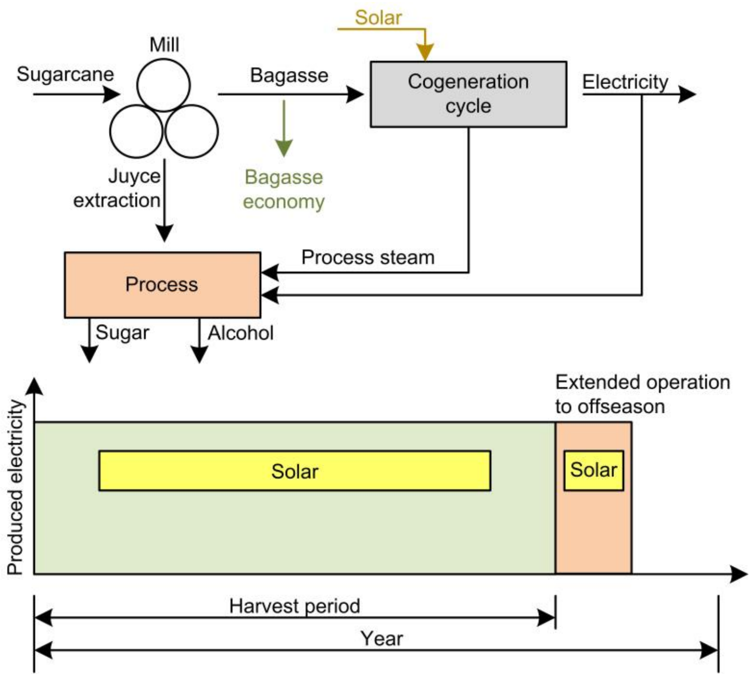

Fig. 1. Schematic of the process and illustration of the concept.

Whereas sugarcane cannot be stored, the operating time of the process factory is coupled to the sugarcane harvesting period, which typically ranges in the Center-South region of Brazil from April to December. Outside this period, the most of the cogeneration power plants are out of operation and no electricity is exported to the grid. In contrast to sugarcane, bagasse is storable. Hence, by replacing partially bagasse with solar energy during normal operating season, the overall power plant operating period could be extended, through the use of the stored bagasse.

3. Base case power plant

A hypothetical sugarcane bagasse cogeneration plant located in Campo Grande, Mato Grosso do Sul, Brazil (-20.45°; -54.62°) with configuration and operational parameters identified in cooperation with equipment suppliers was simulated to evaluate its integration with solar thermal energy. The cogeneration plant was designed to meet the operation of a sugarcane mill with main boundary conditions listed in Table 1.

Table 1. Boundary conditions of base case power plant.

Parameter	Unit	Value
Crushing capacity	t/h	600
Annual sugarcane crushing	Mt	3
Effective operation hours in harvest	h	5,000
Harvest starting day	-	01st April
Process electricity demand	kWh_{el}/t	28
Process steam demand (heat demand)	t/h	220 (2.5 bar; x=1)

The layout and main results related to the simulation of cogeneration plant at design point peak summer operation are presented at Fig. 2. The steam cycle is equipped with two 170 t/h capacity steam generators that produce superheated steam at 525 °C / 67 bar (point 1). The base case scenario is operated during harvest burning 142.5 t/h of bagasse prevenient from sugarcane crushing station. The major part of superheated steam (point 2, 220 t/h) is expanded in the back-pressure turbine (BPST) until 2.5 bar as required by process heat demand. In parallel, roughly one third of the superheated steam (point 6, 117 t/h) is expanded in the condensing-extraction turbine (CEST). Three extractions are implemented at CEST turbine (17.5 bar - point 7; 5 bar - point 8 and 1.8 bar - point 9) to preheat feedwater to 200 °C (point 20). The CEST exhaust steam (point 10) is condensed in a wet-cooled condenser.

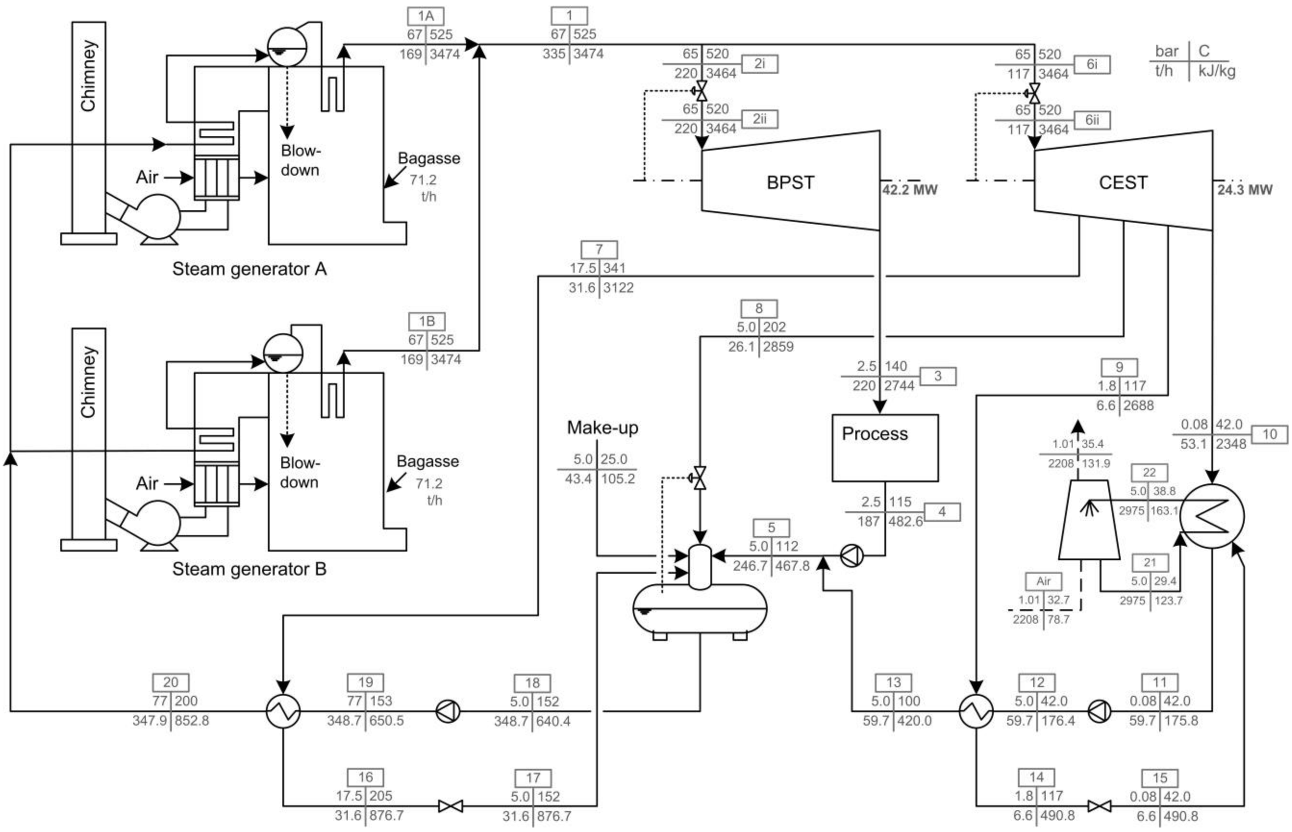

Fig. 2. Base case cogeneration power plant layout and simulation results at design point.

The properties of sugarcane bagasse considered in simulations are presented in Table 2. To calculate the amount of produced bagasse at the sugarcane crushing station output the fibers to stalk ratio of sugarcane was considered equal to 0.125 [4]. Based on this assumption, 250 kg of wet bagasse with a moisture content of 50 % was produced for each ton of crushed sugarcane. It was considered that 95 % of wet bagasse was directly burned at steam generator, while the remaining 5 % was stored as a back-up to start the plant on next coming season.

Table 2.Sugarcane bagasse properties [4].

Proximate analysis [wt %, ar]				Ultimate analysis [wt %, daf]					LHV [kJ/kg, ar]
Fixed carbon	Volatile matter	Moisture	Ash	C	H	N	O	S	
6.9	41.6	50.0	1.6	45.6	5.8	0.4	48.2	0.0	7162

wt %: percent by weight; ar: as received; daf: dry and ash free.

C: carbon; H: hydrogen; N: nitrogen; O: oxygen; S: sulfur; LHV: lower heating value.

Two identical natural circulation subcritical water tube steam generators composed of furnace, boiler (boiling occurring in water tube walls enclosing furnace), convective superheating system with main steam temperature control using a desuperheater positioned in between the sections SH1 and SH2, economizer (ECO) and tubular air heaters AH1 and AH2 with air representing the external flow have been modeled. The steam capacity of each amounts to 170 t/h.

In Table 3 the heat exchange area (in squared meters), the longitudinal (s_l, in meters) and transversal (s_t, in meters) spacing of tubes, the diameter (d, in meters) and thickness (e, in meters) of tubes as well as the arrangement of bundle of tubes are presented.

Table 3. Configuration of heat exchangers used in steam generators.

Parameter	Unit	Superheater 2 (SH2)	Superheater 1 (SH1)	Economizer (ECO)	Air heater 2 (AH2)	Air heater 1 (AH1)
Area	m²	520.5	1041.0	1307.5	3030.0	3030.0
s_l	mm	134.0	134.0	134.0	87.0	87.0
s_t	mm	102.0	102.0	100.0	100.0	100.0
d	mm	44.5	44.5	50.8	63.6	63.6
e	mm	3.8	3.8	3.8	2.3	2.3
Arrangement	-	Aligned	Aligned	Aligned	Scattered	Scattered

The results in design point operation related to the detailed modeling of steam generators are presented in Fig. 3.As it can be seen, 208 t/h of air is preheated from ambient temperature to 296 °C. Additional 23 t/h of air (10 % of total) is used as bagasse carrying air. Both streams consist in 30 % air excess as required to optimize combustion process. Feedwater (174.3 t/h) is heated in economizer from 200 to 277 °C. Blowdown consists of 3 % of main steam mass flow in order to maintain impurities concentration under specification limits. Finally, 169.1 t/h superheated steam is produced by heating saturated steam (x=1 / 72 bar) from boiler drum until required final parameters (525 °C / 67 bar). It is important to notice that 17.2 t/h of saturated water (x=0 / 72 bar) is injected in between sections SH1 and SH2 at design point operation. At part load this amount is gradually reduced to keep main steam temperature constant.

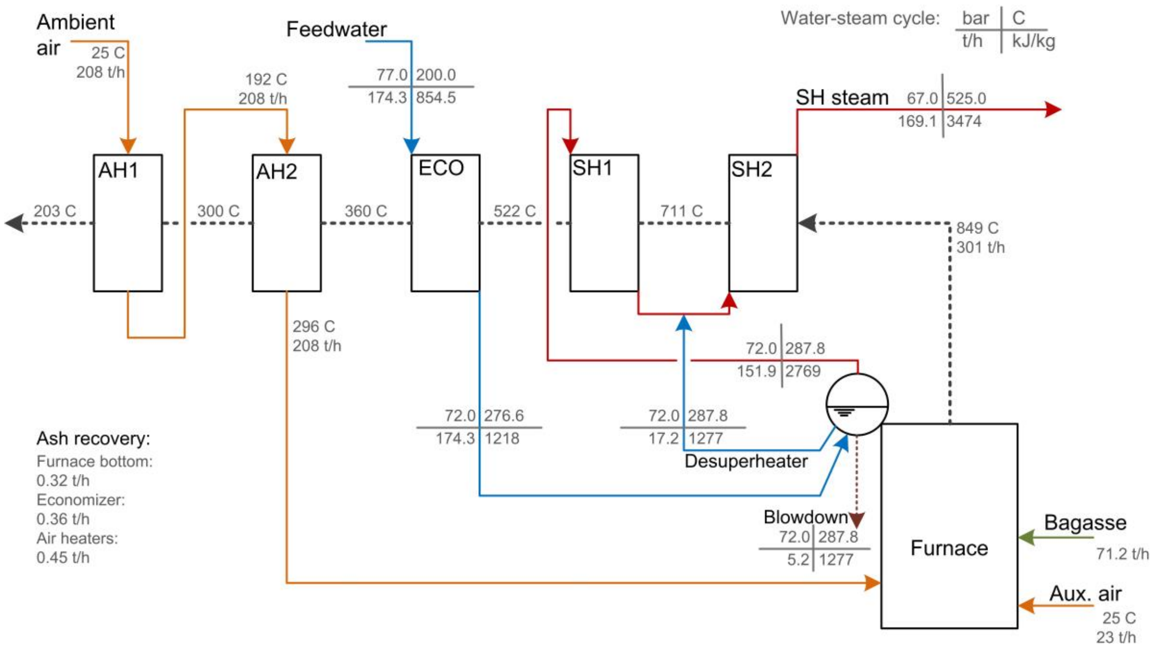

Fig. 3. Base case steam generator layout and simulation results at design point operation.

A simulation for the entire harvest period was performed, while keeping the net electricity exported to the grid equal to the reference condition (46.6 MW_{el}) and respecting the ambient weather fluctuations – results are presented in Table 4. The required time to crush 3 Mt of sugarcane was equal to 5000 hours, when 750,000 t of bagasse was produced, 710,316 t of bagasse was burned (94.7 % of total) and 233,025 MWh_{el} was exported to the grid. The plant operation started at 1st April and was finished at 3rd December. The total harvest period was 5,921 hours, what represented a capacity factor of 84.4 %. The total duration of sugarcane harvest is mainly prescribed by rainfall, as during rainy hours as well as during the necessary time for soil drying it is not possible to harvest sugarcane. This result matches with the capacity factor of sugarcane cogeneration plants located in the Centre-South region of Brazil that normally ranges from 80 % to 85 % [5] [6].

Table 4. Summary of the results for the base case cogeneration power plant over the harvest period.

Parameter	Unit	Value (5000 h of operation)
Produced bagasse	t	750,000
Burned bagasse	t	710,316
Stored bagasse	t	39,684
BPST gross output	MWh_{el}	211,255
CEST gross output	MWh_{el}	121,325
Net electricity production	MWh_{el}	317,025
Auxiliary electricity consumption	MWh_{el}	15,555
Process electricity consumption	MWh_{el}	84,000
Process heat consumption	MWh_{th}	691,097
Net electricity exported to the grid	MWh_{el}	233,025

4. Hybrid layouts

In general the ways of concentrating solar energy could be divided into linear and point focusing technologies. Parabolic trough and linear Fresnel collectors belong to the linear focusing technologies, whereas the main point focusing technologies are namely central receiver (solar tower) and parabolic reflector (Dish). From point of market availability and current state of development, for the present case-study the following three technology options have been chosen: Linear Fresnel (LF); Parabolic Trough (PT) and Solar Tower (ST). For all named CSP options there are different technology configurations possible, whose range is shown in Table 5.

Table 5. Overview to the three considered CSP-Technologies.

	Unit	LF	PT	ST	Source
Heat Transfer Fluid (HTF)	-	thermal oil water salt	thermal oil water salt	water salt air	
Concentration ratio	-	25-100	70-80	300-1.000	[7]
Temperature Range Power Cycle	°C	380-600$^{(ST)}$	380-600$^{(ST)}$	565$^{(ST)}$-1.200$^{(GT)}$	[8]
Performance	MW_{el}	10-200	10-200	10-150	[7]
Ratio of current installed capacity	%	1	88	11	[9]
Ratio of capacity under construction (2012)	%	6	75	18	[10]

$^{(ST)}$: Steam turbine $^{(GT)}$: Gas turbine

Because of the different stage of technical development of the three CSP technologies and their HTFs for the case study the following combinations were examined: PT (thermal oil); LF (water/steam) and ST (water/steam).

Regarding the integration layouts of the three chosen CSP technologies, from the thermodynamic point of view it is to strive an as high as possible temperature level for the added solar heat. For that reason the added solar heat was used here to provide heat for the high pressure feedwater preheating as well as for the parallel production of saturated steam and live steam in parallel with bagasse steam generators. The process flow diagrams of the three integration layouts are shown in Fig. 4.

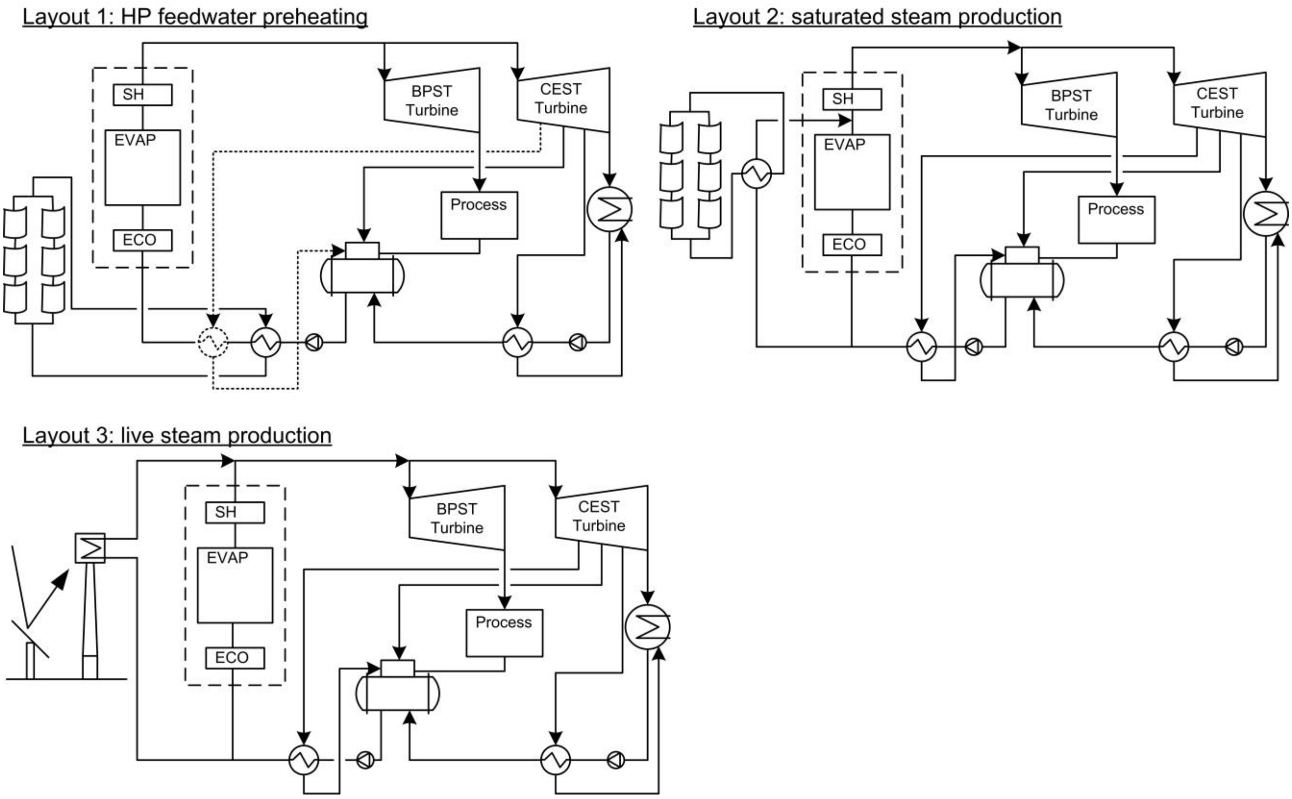

Fig. 4. Process flow diagrams of the three considered integration layouts.

In layout 1 the solar heat replaces fully the high pressure bled steam of the CEST turbine. For this purpose the solar field provides at design point a thermal output equivalent to the required heat demand in the base case power plant for the high pressure feedwater heater (17 MW_{th}). Due to the fuel saving operation mode this replacement and the reduced amount of burned bagasse (reduction of 8,3 t/h) affects the CEST turbine performance as well as the feedwater heating line. Because of the comparatively low temperature level of 200°C for the substituted high pressure bled steam the CSP technologies PT and LF were selected. It should be noted that a solar only operation is not possible.

The integration layout 2 enables a parallel production of saturated steam with solar heat in order to reduce the bagasse consumption. Therefore, part of the main feedwater mass flow going to the steam generators is diverted. This secondary mass flow passes, in case of PT, through a typical solar steam generator, whereas in case of the LF, it is directly fed to the solar field. In both cases, consistently saturated steam at 67 bar is produced, which is then joined to the main mass flow within the steam generators for superheating. Accordingly, the integration layout 2 only affects the steam generators performance, while the live steam conditions stay the same. By staying with the case study close to technical feasibility, the technical boundary conditions of the steam generators should be respected. In order to avoid strong imbalances in these components it was assumed that it is allowed to reduce both steam generators load to a minimal level of 85 %. Therefore at design point the solar field should supply for the water/steam cycle a thermal load equal to 34 MW_{th}. Likewise, this layout enables not a solar only operation.

In integration layout 3 the solar heat displaces both steam generators thermal load. A part of the feedwater is bypassed from steam generators. As it is passed through the solar tower system, superheated steam at 525 °C and 67 bar is produced. This integration affects only the steam generators thermal performance while the water/steam cycle is operated in normal mode. In comparison with integration layout 2, the steam generators operation is simplified. That means, the steam generators are operated here in normal partial load from 100% to 65% load. In respect to that, by enabling a minimal steam generator load of 65 % at solar design point the solar tower was designed to provide 79.4 MW_{th}. It should be noted, that for integration layout 3 a solar only operation is possible when sugarcane facility is out of operation.

The simulations performed for each integration layout are described in Table 6. Distinct solar multiples were simulated in order to perform a sensitive analysis related to mirrors aperture area.

Table 6. Number of simulations performed for each layout.

Simulated layouts	CSP technology	Simulated Solar Multiples (SM)	Overall number of simulations
Layout 1	PT	0.9 – 1.4	6
	LF	0.8 – 1.4	7
Layout 2	PT	0.9 – 1.3	5
	LF	0.8 – 1.4	7
Layout 3	ST	0.8 – 4.0	10

The calculation software Engineering Equation Solver (EES®) (in combination with MATLAB®) and the commercial power plant calculation program Ebsilon®Professional were used for the thermodynamic modeling and to perform the annual yield simulations. The weather data considered for the simulations (dry bulb temperature [°C], wet bulb temperature [°C], direct normal irradiation [W/m²] and rain precipitation [mm]) was obtained from Meteonorm® TMY data base considering one-hour time steps.

5. Results and discussion

In order to identify an economic optimum for each case the Levelized Cost of Electricity (LCOE) was used as criteria. This parameter was calculated for the additional electricity produced due to solar hybridization. The adopted assumptions and cost data used for economic analysis as well as the LCOE calculation procedure are presented in Appendix 1. In Fig. 5 the solar field area sensitive analysis is exemplified for layout 3.

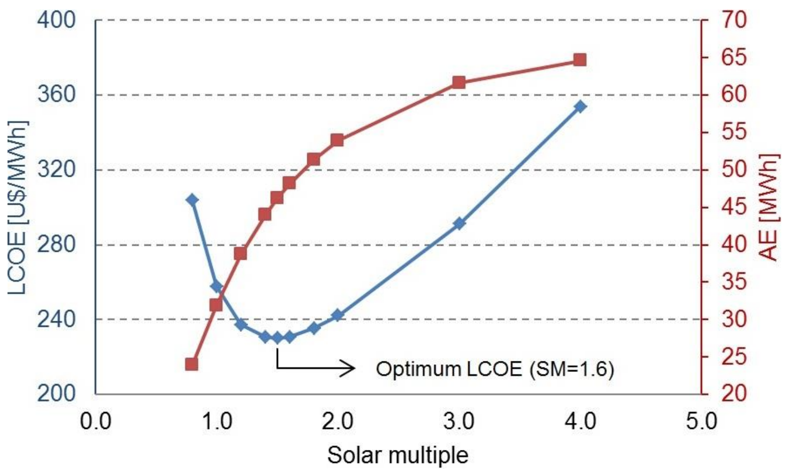

Fig. 5. Additional solar equivalent electricity and LCOE for different solar multiples.

The additional electricity produced for all evaluated integrations for the identified optimum solar multiple are presented in Fig. 6. In layouts 1 and 2 the PT technology provided a slightly higher solar electricity output compared with LF. This was related to the higher annual solar field efficiency of PT which was caused mainly by the smaller incidence angles observed in the beginning and in the end of the days when compared with LF. Layout 2 provided higher solar electricity output when compared with layout 1 mainly due to the higher thermal load required to reduce evaporator thermal load of bagasse steam generators. Finally, it is clear that layout 3 provided a significantly higher solar electricity output when compared with other evaluated cases. This was not only due to the higher thermal load associated with the reduction of steam generators load to 65 % in peak DNI hours, but also due to the possibility of solar-only operation.

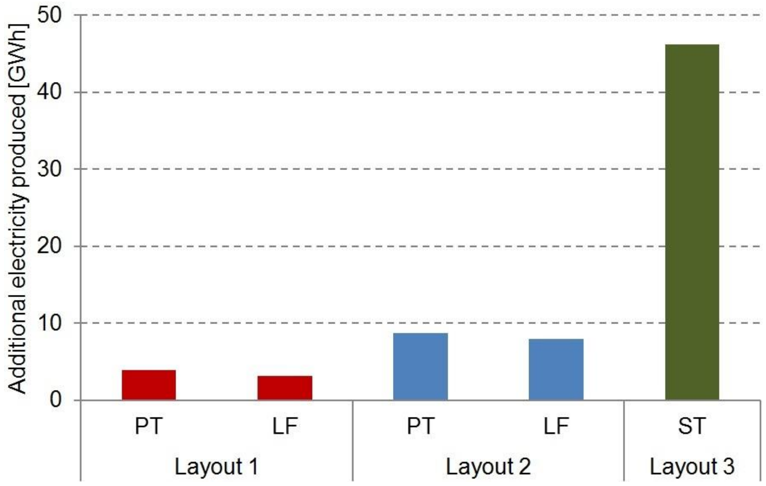

Fig. 6. Additional solar equivalent electricity generated due to solar hybridization.

The duration curves related to the bagasse steam generators and solar field energy outputs for base case and hybrid layouts 2 and 3 are exposed in Fig. 7 to clarify the advantage of solar-only operation. In layout 2 the solar energy was exclusively used to manage part of bagasse from harvest to the off-season period – the same operation strategy was adopted for PT and LF technologies as well as in layout 1. In layout 3, in the other hand, the economized bagasse during harvest was preferentially used at night or in rainy days and solar-only operation was possible during sunny hours. This is a very important aspect once the capacity factor of solar field was maximized by its operation regardless of the availability bagasse.

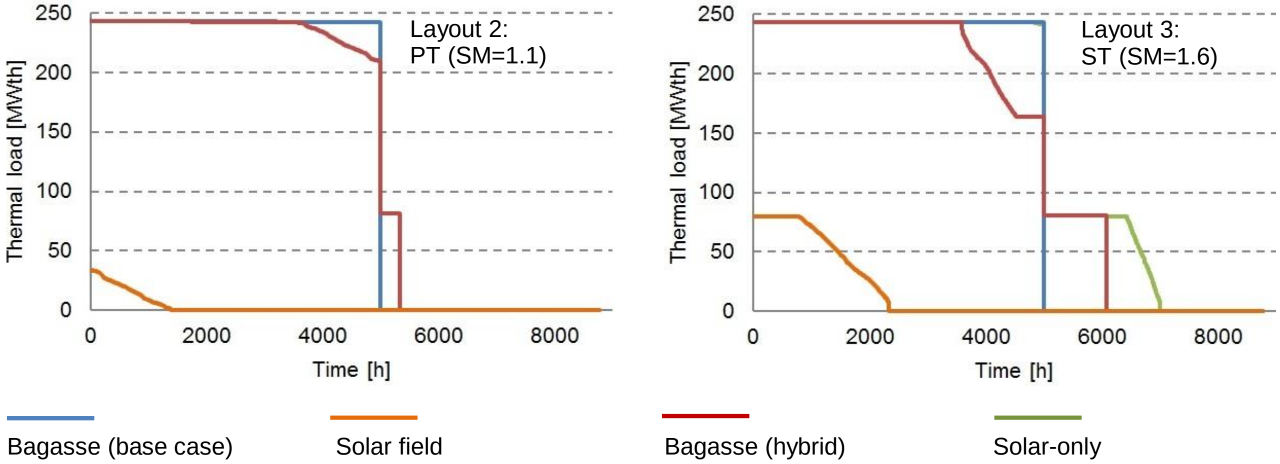

Fig. 7. Thermal energy transferred to water-steam cycle related to bagasse and solar energy inputs for base case and hybrid layouts 2 and 3 for comparison.

Another aspect evaluated in this work consists on the required mirrors aperture area and total land area for solar field installations (see Fig. 8). For layouts 1 and 2, the aperture area required by LF was higher when compared with PT due to the lower peak efficiency of LF when compared with PT technology. Regarding land area, on the other hand, LF showed a significant advantage in comparison with PT, requiring -54 % and -49 % land respectively for layouts 1 and 2. The compactness of LF might be of great importance to enable the implementation of CSP in areas where the land is used for crop plantation and, as a consequence, its cost is high. Finally, ST aperture and land areas were higher in comparison other evaluated scenarios due to the higher solar thermal load required by layout 3. The land to aperture area ratio here considered was 3.3 for ST, 4.25 for PT and 1.8 for LF.

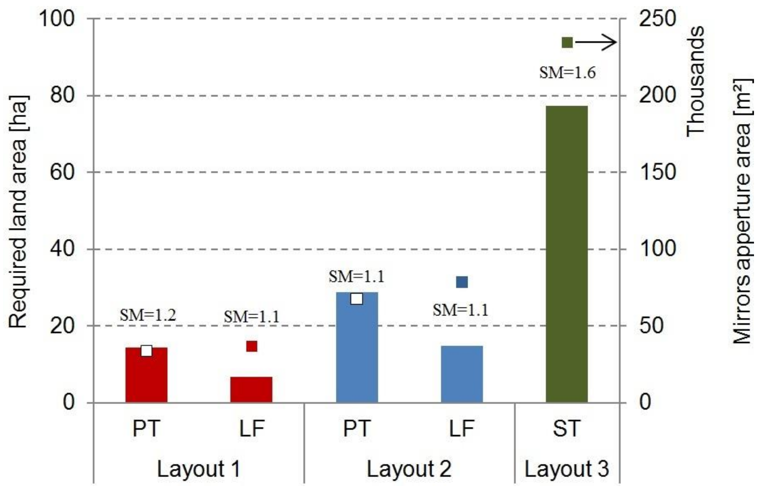

Fig. 8. Comparison of mirrors aperture area required land area for solar field installation.

Regarding economic analysis, the capital and O&M costs of studied scenarios are presented in Fig. 9-a, while in Fig. 9-b the LCOE results are showed. The adopted assumptions for equipment and O&M costs were based on consultations with equipment suppliers and literature survey. In both layouts 1 and 2 the capital and O&M costs were lower for LF in comparison with PT technology (-14 % and -11 %, respectively, for capital cost). Observing LCOE, nevertheless, LF presented similar or even higher electricity generating costs in comparison with PT due to its lower efficiency. LCOE was significantly reduced in Layout 3, reaching 220 U$/MWh$_{el}$. As exposed before, the solar-only operation maximized capacity factor of solar field is directly linked to an improved economic performance. It is important to notice, finally, that Layout 3 could also be possible with

PT or LF depending on main steam parameters of cogeneration power plant or even considering the utilization of molten salt as heat transfer fluid.

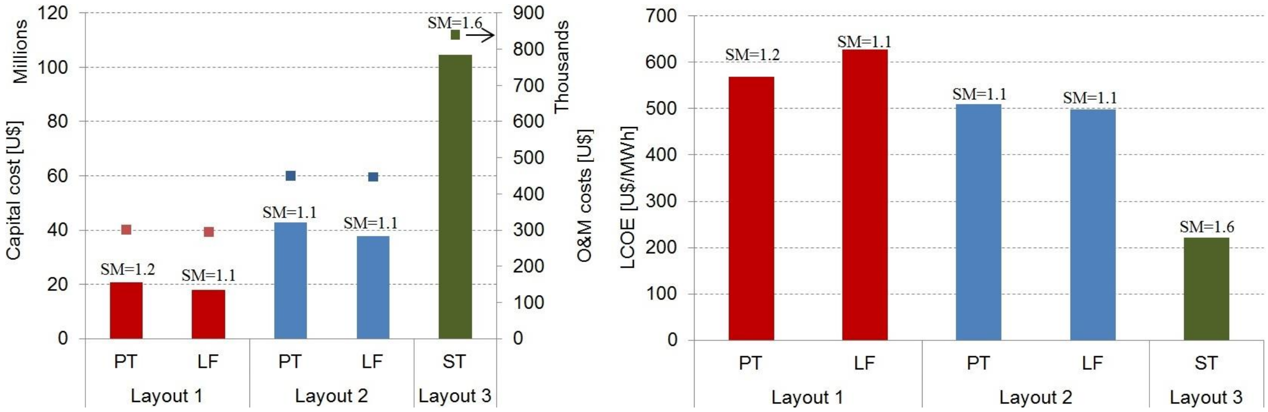

Fig. 9. a) Investment and O&M costs of solar hybridization; b)LCOE of additional solar equivalent electricity.

6. Conclusion

CSP hybridization of sugarcane bagasse cogeneration plants equipped with BPST and CEST turns possible to improve the annual electricity output of these plants by maximizing their capacity factor while providing additional off-season operation. This represents a gain due to the use of existing infrastructure that otherwise would stay out of operation part of the year when no sugarcane was available.

Solar feedwater heating has the advantage of requiring minimal modifications on the original plant and investment costs related to solar integration are reduced. Nevertheless, the small solar share and the incapability of solar-only operation limit the additional electricity output and the capacity factor of solar field. Saturated steam production in parallel with bagasse steam generators turns possible to improve the solar share. An important negative aspect resides in the complexity inherent to the retrofit and operation of biomass steam generators and heat imbalances that might be observed. This integration has also the incapability of solar-only operation. Finally, solar superheated steam generation provides the highest solar share in comparison with other layouts here considered. The power plant operation in a solar-only mode improves the solar field capacity factor and, as a consequence, the economic feasibility of investment. This layout may also not require major modifications in hosting steam cycle as biomass steam generators are operated in normal part-load.

Regarding CSP technologies, no major difference in terms of economic feasibility was obtained between PT and LF in layouts 1 and 2 for the considered economic assumptions and problem specific characteristics (e.g. plant configuration and operational parameters, site weather conditions, operation seasonality of cogeneration plants). ST provided the best result in terms of LCOE (220 U$/MWh) what can be considered competitive to the currently under operation CSP power plants as reported in [11]. Nevertheless, the results here presented clearly show the advantage inherent to year-round operation of solar field and might not be interpreted as a suggestion to exclude the LF and PT technologies of future analysis once they could be also implemented for superheated steam generation depending on main steam parameters of cogeneration power plant or even considering the utilization of molten salt as heat transfer fluid.

Acknowledgments

The authors acknowledge the funders of the program “new partnerships (iNOPA)”, namely the German Federal Ministry for Economic Cooperation and Development (BMZ) and the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES), for the financial support of the project “Cogeneration Power Plant” (project ID: 57072739) in the program part iNOPA-Solar Power 13. The authors acknowledge also the companies TGM turbines and Caldema Industrial Equipment Ltda for technical support and data input provided to the simulation models implemented in this work.

Appendix 1

In Table A1 it is presented the assumptions and cost data used for economic analysis.

Table A1. Adopted assumptions and cost data used for economic analysis.

Parameter	Unit	Adopted assumption
Parabolic trough		
Solar field[a]	U$/m^2	400
Economizer [12]	U$/kW$_{th}$	27
Boiler [12]	U$/kW$_{th}$	47
Fresnel		
Solar field[a]	U$/m^2	360
Solar Tower		
Heliostats field [13]	U$/m^2	200
Receiver [13]	U$/kW$_{th}$	250
General		
EPC and contingency[b][14]	U$	20 % of DC
Site improvements [15]	U$/ha	250,000
Land investment[c]	U$/ha	20,000
Material replacement [16]	U$/year	1 % of DC
Employee charge[b,c]	U$/year	40,000
Interest rate, r	-	8 %
Life time of plant, lt	Years	25

[a]Quoted cost; [b]Considered not dependent on solar field area; [c]Estimated cost;

The economic analysis was performed considering the Levelized Cost of Electricity (LCOE) [U$/MWh] according to the methodology proposed in [17]. The LCOE is calculated for the additional power generated due to solar hybridization (Eq. A1).

$$LCOE = \frac{\sum_{t=0}^{lt}(CC + LC + O\&M)\cdot(1+r)^{-t}}{\sum_{t=0}^{lt} AE \cdot (1+r)^{-t}} \qquad \textit{Eq. A1}$$

where CC, LC and $O\&M$ [U$] are the capital, land and annual operation and maintenance costs. The parameter r represents the interest rate and lt is the lifetime of plant.

Nomenclature

CSP	concentrated solar power
BPST	back pressure steam turbine
CEST	condensing-extraction steam turbine
ISCC	integrated solar combined cycle
SAFWH	solar aided feedwater heating
AH	air heater
ECO	economizer
SH	superheater
EVAP	evaporator
d	diameter
e	thickness
s	spacing
SM	solar multiple
EES	engineering equation solver
TMY	typical meteorological year
LCOE	levelized cost of electricity
DNI	direct normal irradiation
EPC	engineering, proc. and construction
O&M	operation and maintenance
r	interest rate
lt	life time
CC	capital cost
LC	land cost
AE	additional electricity

PT parabolic trough
LF linear Fresnel
ST solar tower
HTF heat transfer fluid

Subscripts
l longitudinal
t transversal

References

[1] International Energy Agency (IEA). Available at: <http://www.iea.org/statistics/statisticssearch/report/?year=2011&country=BRAZIL&product=ElectricityandHeat> [accessed 15.12.2015].

[2] ANEEL, Banco de informações de geração (BIG). Available at: <http://www.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm> [15.01.2015].

[3] Souza Z. (UNICA): Bioelectricity Overview, Clean Technology Seminar - CNI, Brasilia, 1. April 2014.

[4] Lamônica H., Linero F. A. B., Importância da palha na geração de excedentes de eletricidade, in: Curso de Caldeiras, Vapor e Energia (SINATUB), 2013.

[5] Filho A. B., Andrade R. A., Perfil do setor do açúcar e do álcool no Brasil: Edição para a safra 2010-2011, Tech. rep., Ministério da Agricultura, Pecuária e Abastecimento, Companhia Nacional de Abastecimento (Conab) (2013).

[6] Filho A. B., Andrade R. A., Perfil do setor do açúcar e do álcool no Brasil: Edição para a safra 2009-2010, Tech. rep., Ministério da Agricultura, Pecuária e Abastecimento, Companhia Nacional de Abastecimento (Conab) (2012).

[7] Reuß, N.: Modern Gas- & Steam Turbines in Solarthermic Applications; 14th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, 27.02.2012, Honolulu (USA).

[8] Pitz-Paal, R.; et al.: Solar thermal power plants; BINE-Themeninfo II/2013, FIZ Karlsruhe GmbH; ISSN 1610-8302.

[9] National Renewable Energy Laboratory: Concentrating Solar Power Projects by Country. Available at: <http://www.nrel.gov/csp/solarpaces/by_country.cfm> [accessed 15.02.2015]

[10] REN 21: Global Status Report 2013; Paris, 2013, ISBN 978-3-9815934-0-2.

[11] IRENA. Renewable energy technologies - cost analysis series - concentrating solar power (June 2012).

[12] Manzolini G., Giostri A., Saccilotto C., Silva P., Macchi E., Development of an innovative code for the design of thermodynamic solar power plants part B: Performance assessment of commercial and innovative technologies, Renewable Energy 36 (2011) 2465-73. doi:10.1016/j.renene.2011.02.003.

[13] Turchi C., Mehos M., Ho C., Kolb G.. Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market, in: Solarpaces, 2010.

[14] Bakos G. C., Tsechelidou C., Solar aided power generation of a 300 MW lignite fired power plant combined with line-focus parabolic trough collectors field, Renewable Energy 60 (2013) 540-47. doi:10.1016/j.renene.2013.05.024.

[15] Turchi C., Parabolic trough reference plant for cost modeling with the solar advisor model (SAM), Tech. rep., National Renewable Energy Laboratory (2010).

[16] Morin G., Dersch J., Platzer W., Eck M., Häberle A., Comparison of linear Fresnel and parabolic trough collector power plants, Solar Energy 86 (2012) 1-12. doi:10.1016/j.solener.2011.06.020.

[17] Projected costs of generating electricity, Tech. rep., International Energy Agency; Nuclear Energy Agency; Organization for Economic Cooperation and Development (2010).