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OPEN-SOURCE MODELING OF THERMAL HYBRIDIZATION IN CSP-BIOMASS COGENERATION: A BRAZILIAN SUGARCANE PLANT CASE STUDY

Summary

This study analyzes the integration of parabolic trough solar collectors into a sugarcane bagasse cogeneration plant under three configurations: (i) feedwater preheating, (ii) saturated steam generation, and (iii) superheated steam generation in parallel with a steam generator. The hybrid system was modeled hourly over a typical meteorological year using Python. Solar-to-electricity efficiency was evaluated under varying thermal loads. Results show that feedwater preheating minimizes thermal losses and yields fuel savings of up to 1.07%. Superheated steam generation reaches higher solar-to-electricity efficiency (10.12%) but demands greater collector area and results in higher losses. The baseline thermal efficiency (17.34%) increases to 22.11% with off-season solar-assisted operation. Overall, solar integration reduces bagasse consumption by up to 10.12% and enhances plant performance.

Keywords: Sugarcane bagasse, Parabolic trough collectors, Direct steam generation, Cogeneration.

1. Introduction

The global energy transition has driven the adoption of renewable sources to address challenges such as climate change, energy security, and economic sustainability. In Brazil, despite the historical predominance of hydroelectric generation, prolonged drought events have increased the pressure to diversify the electricity matrix. In this context, biomass—particularly sugarcane bagasse—plays a strategic role due to its wide availability, established infrastructure, and capacity for thermal and electrical cogeneration. In 2023, around 345 plants in the country utilized this feedstock, totaling 12 GW of installed capacity (UNICA, 2024). However, the operation of bagasse cogeneration plants is seasonal, limited to the harvest period (about 7 to 8 months per year), which leads to underutilization of infrastructure and reduces the annual contribution to the national electricity system. Simultaneously, photovoltaic solar energy is experiencing accelerated growth in Brazil, reaching 38 GW of installed capacity in 2023 (ABSOLAR, 2024). Nevertheless, the intermittency of generation and instances of energy curtailment due to grid constraints (such as the 8% cut in solar generation in July 2024) highlight the need for more dispatchable and integrated solutions (Souto, 2024).

The integration of concentrated solar power (CSP) technologies—especially parabolic trough collectors (PTC)—with biomass plants emerges as a promising alternative. This hybridization enables the use of the complementarity between daytime solar availability and the thermal flexibility of biomass, allowing for continuous operation, reduced fuel consumption, improved efficiency, and lower levelized cost of energy (Burin et al., 2016). Additionally, systems with direct steam generation (DSG) enable the production of high-temperature steam directly in the solar field, simplifying the system and improving the thermal efficiency of the cycle (Montes Pita, 2008). Importantly, these configurations preserve the inertia of steam turbines, contributing to grid frequency stability even without storage.

2. Methodology

Baseline Cogeneration Cycle – A 40 MW sugarcane-based cogeneration plant was modeled using mass and energy balance calculations. The model is based on a real facility located in Cosmópolis, São Paulo, with operational characteristics derived from actual data provided by staff at Usina Açucareira Ester S.A.

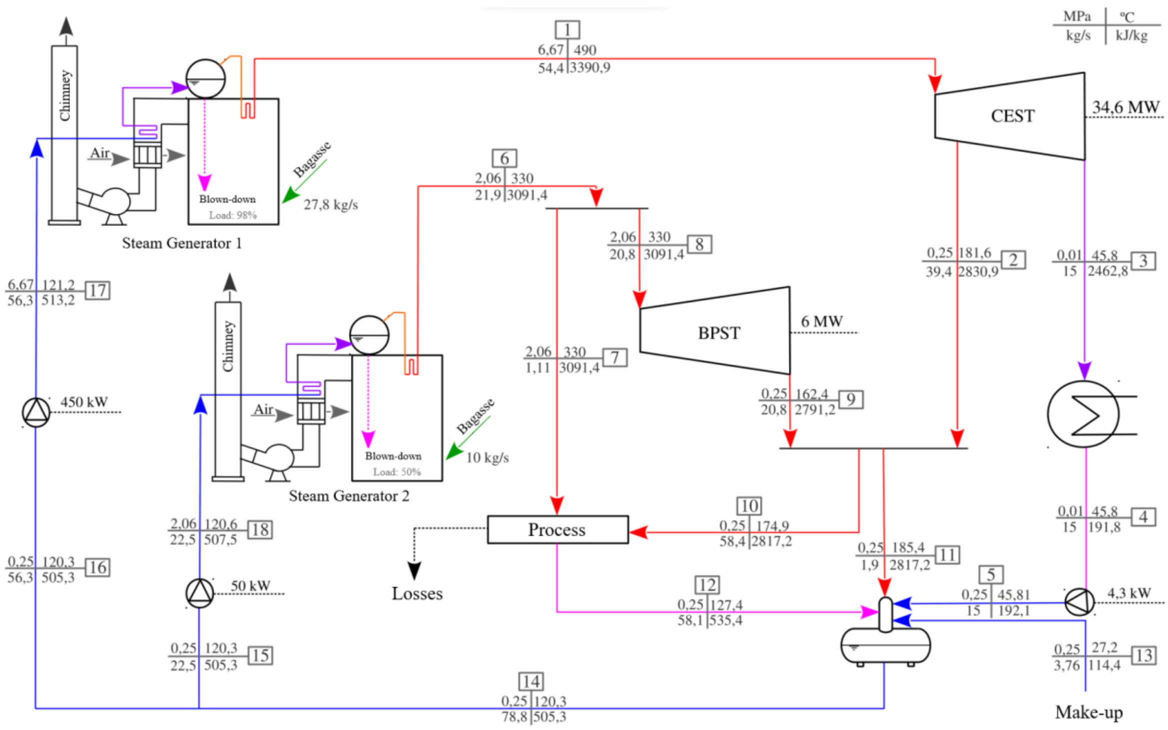

Fig. 1: Thermodynamic cycle of the cogeneration plant

The solar field with PTCs was modeled using the framework proposed by Montes Pita (2008), incorporating optical, thermal, and geometric parameters to estimate useful thermal power. Based on EuroTrough specifications, the model adopts a quasi-steady-state thermodynamic approach, solving steady-state energy and heat transfer equations. It accounts for optical, geometric, and thermal losses, and computes output using integrated equations that include solar irradiance (DNI), incidence angle modifiers, and system efficiencies.

All simulations and performance calculations were carried out over a Typical Meteorological Year (TMY) dataset, ensuring that the hourly DNI inputs represent a standardised annual irradiance profile for the site. The model was implemented in Python 2.7.10 (IPython terminal) within the Spyder 2.3.5.2 IDE and relies on external libraries including numpy, scipy, matplotlib (with pylab), IAPWS, and xlrd.

Three isolated solar-assistance configurations—each coupled to Steam Generator 1—were assessed under a fuel-saving strategy whereby, during harvest, solar heat displaces bagasse and the saved biomass is stockpiled to extend off-season operation:

- **Proposal A (Feedwater Preheating):** A 9.33 ha EuroTrough field (27 collectors) heats feedwater from 513.2 to 766.1 kJ/kg (180 °C, 6.67 MPa) at 56.3 kg/s, requiring 14 238 kW of solar heat;
- **Proposal B (Saturated Steam):** Half the boiler flow (27.2 kg/s) is evaporated to saturated steam at 6.67 MPa (h = 2 776.7 kJ/kg), cutting boiler load to ~50% with a 61 612 kW solar demand; and
- **Proposal C (Superheated Steam):** The same half-flow is superheated to 490 °C (h = 3 390.9 kJ/kg) in a single-pass solar superheater, totaling 78 331 kW of solar input.

3. Results and discussion

The performance of all three hybrid schemes across Solar Multiples (SM) from 0.8 to 1.2 (Proposals A & B) and 0.8 to 1.5 (Proposal C) is summarized in Table 1. Focusing on SM = 1.2, Proposal A (feedwater preheating) achieves 105 h of off-season operation, 3.3 GWh of additional exports, η_{STE} = 9.4 %, and 1.53 % bagasse savings. Under the same SM, Proposal B (50 % saturated-steam) extends operation by 430 h, adds 13.5 GWh, records η_{STE} = 8.2 %, and saves 5.9 % of fuel. Proposal C (superheated steam) reaches 560 h, 17.6 GWh, η_{STE} = 8.6 %, and 7.5 % savings (peaking at 20.8 GWh and 10.1 % bagasse savings at SM = 1.5). Despite its higher thermal input, Proposal C incurs greater collector losses at elevated temperatures, resulting in slightly lower overall collector efficiency.

Tab. 1: Performance Indicators for Three CSP–Biomass Integration Proposals at Various Solar Multiples

Proposal	SM [–]	Extra Hours [h]	Extra Generation [GWh]	η_{STE} [%]	Bagasse Saved [t / %]
A: Feedwater Preheating	0.8	73	2.28	6.53	6,484 / 1.07
	0.9	82	2.57	7.34	7,278 / 1.20
	1	89	2.8	8	7,919 / 1.30
	1.1	98	3.07	8.78	8,682 / 1.43
	1.2	105	3.3	9.42	9,300 / 1.53
B: Saturated Steam Generation	0.8	296	9.31	6.02	25,304 / 4.16
	0.9	334	10.48	6.78	28,297 / 4.65
	1	368	11.57	7.48	31,027 / 5.10
	1.1	400	12.56	8.13	33,517 / 5.51
	1.2	430	13.5	8.17	35,793 / 5.88
C: Superheated Steam Generation	0.8	381	11.96	5.81	32,006 / 5.26
	0.9	430	13.53	6.57	35,868 / 5.90
	1	477	14.99	7.28	39,401 / 6.48
	1.1	520	16.34	7.93	42,629 / 7.01
	1.2	560	17.6	8.55	45,583 / 7.49
	1.3	597	18.77	9.11	48,286 / 7.94
	1.4	631	19.85	9.64	50,742 / 8.34
	1.5	663	20.84	10.1	52,997 / 8.71

In summary, the technical results confirm that integrating parabolic-trough solar fields into a bagasse-fired cogeneration plant is feasible across all three hybrid schemes. Solar-to-electricity efficiency declines as operating temperature rises, so for a given Solar Multiple, feedwater preheating (Proposal A) outperforms the steam-generation options by minimizing thermal losses. Sensitivity to the Solar Multiple is critical: while higher multiples boost annual solar-to-electricity yield, they introduce midday power curtailment via defocusing and diminish instantaneous efficiency near the design point. Key operational benefits include displaced bagasse consumption—stockpiled during harvest to extend off-season running—higher capacity factors, and reduced incremental investment by leveraging existing boiler and turbine infrastructure. Also, by retaining steam turbines' rotating mass, the biomass–solar hybrid delivers real kinetic inertia—unlike inverter-based photovoltaic and wind—allowing heat input modulation to smooth power ramps and support frequency stability.

4. References

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