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Research paper

Exploiting exergy and exergoeconomic analysis as decisional tool for cogeneration plant optimal operating mode: A sugar factory case study

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ABSTRACT

Due to the energy transition scenario, the efficient use of energy and operations flexibility to deal with the market volatility have become the major concerns of the industrial sector. In particular, in those contexts and countries where the grid supply cannot be continuously ensured, the selection of the best operation set up is of critical importance for both stability and profitability of the system. Based on the available data of the Wonji-Shoa sugar factory in Ethiopia, the digital twin of the related Combined Heat and Power generation plant was reproduced by means of ProSimPlus[®] process simulator. Thanks to the software dedicated tools, the exergy and exergoeconomic analysis were carried out to compare the performances of three possible functioning modes. The study revealed that the highest profitability for the power plant is achieved when it serves both the sugar factory and the electricity grid. With regard to the energy efficiency, the prevention of exergy losses up to 9.63 MW is possible and a 15% heat recovery potential could be viable by implementing a better integration between utility streams. Based on these results, the optimal combined scheduling of power plant and sugar factory will be the object of future studies.

1. Introduction

Due to the increasing concern towards the environment and the recent sharp rise in energy costs (International Energy Agency, 2022), energy efficiency has become one of the topic of major interest for both research and industrial domain. In particular, the common purpose is to design production and energy systems with the fewest losses and the highest energy efficiency within the acceptable economic margin. A well-established and sustainable solution to improve the efficiency in energy production is represented by cogeneration. In particular, when dealing with process systems, cogeneration is commonly used both to provide the thermal duty required by the process and to supply the electricity needed by the equipment such as pumps, compressors etc. (Costa and Balestieri, 2001). Moreover, in order to further increase the profitability of the system, the surplus of produced electricity can be sent to the grid based on “give and take” agreement between stakeholders (Heuninckx et al., 2022).

Although the optimal energy use and the surplus electricity sale is usually considered an opportunity for income maximization and emission reduction, in those countries where the grid stability cannot always be ensured and where the impact of a single power plant represents a relevant fraction of the overall electricity production the decision of

preferentially splitting the produced energy towards the power side, at the expenses of the process productivity, can be of crucial importance for the profitability of the entire system. In these cases, a quantitative knowledge concerning the most effective use of energy according to the system functioning mode represents not only an opportunity to improve the process efficiency but also a game-changing tool to be exploited at a strategic level for the feasible and optimal operation management.

In the analysis of Combined Heat and Power (CHP) plant performances, the most relevant indicator along with the energy consumption is the effectiveness of its use that can be quantified the irreversibilities of each transformation. This second aspect is measured in terms of exergy and, thus, exergy analysis is acknowledged as the most efficient technique for assessing the quality of energy carriers, energy conversion processes and its effective utilization (Lazzaretto and Tsatsaronis, 2006). In particular, it is frequently used to quantify thermodynamic irreversibilities and to assist analysts for the resources reduction in under-study energy conversion systems (Keshavarzian et al., 2017). In general, the combination of energetic and exergetic analysis allows a sufficient degree of detail to provide a satisfactory overview of the overall system efficiency (Morosuk and Tsatsaronis, 2019). Furthermore,

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due to the correspondence between exergy destruction and potential work losses, it can be used as a for economic worth (Ray et al., 2010).

In scientific literature, the exergy and exergoeconomic analyses represent well-established tools whose versatility has been exploited for decades with multiple purposes. A considerable amount of studies focusing on the modeling and optimal operation of efficient energy systems are constantly published over the years. However, it can be noted that the design of thermodynamically efficient and flexible CHP (Abusoglu and Kanoglu, 2009) or CHCP systems (Cardona and Piacentino, 2006) is progressively being replaced by more innovative case studies addressing the current challenges of the industry. For instance, the application interest has shifted towards the field of renewable energy sources and sustainable molecules production. In particular, it serves as a tool to quantify the eventual benefits of coupling established technologies with recent ones, such as integrated solar combined cycles (Cavalcanti, 2017; Baghernejad and Yaghoubi, 2011), polygeneration coupled with desalination (Esmailion et al., 2023; Al-Fadhli et al., 2023) and combined power and hydrogen production (Pankhedkar et al., 2023). Interesting examples concerning recycling processes (Hosseinnjad et al., 2023) and waste heat recovery (Fierro et al., 2022) can be found as well.

An additional case when the extended use of exergy based methodologies can be pointed out is that of comparative studies. A wide set of articles present the comparison between power generation systems in terms of energy efficiency and profitability according to specific design and operational choices. Significant examples can be easily found with regard to the use of different fuels (Rosen and Dincer, 2003) for power generation, different refrigerants for cooling (Zhao et al., 2024) or different technologies for molecules (Tzanetis et al., 2012) and biomolecules (Meramo-Hurtado et al., 2021) production.

Finally, a limited but not irrelevant number of publications derive from studies carried out on existing industrial plants. Applications range from conventional gas turbine (Oyedepo et al., 2015) or geothermal power plants (Yildirim and Ozgener, 2012). Among them, a set of works related to developing countries and related bio-production from agricultural wastes can be detected. In particular, quantitative examples on sugar facilities can be found for Turkey (Taner and Sivrioglu, 2015), Asia (Kumar et al., 2023) and Africa (Abuelnuor et al., 2023) while bio-alcohols are a typical subject of feasibility assessment or technology improvement studies in South America (Ensinas et al., 2009; Cortes-Rodríguez et al., 2018). Since exergoeconomic analysis is highly useful to deal with inefficiencies mitigation strategies, this approach is particularly interesting for developing countries where non-ideal functioning conditions could occur on daily basis. On the contrary, these underperformances are mainly treated as anomalies when western countries process systems are the object of the study.

Starting from these premises, in this research work, the exergoeconomic assessment of the Wonji-Shoa facility in Ethiopia is addressed. In particular, the analysis focuses on the bagasse fired cogeneration plant aiming at the simultaneous heat and power production for both the sugar factory and the electricity grid. The first step of the study is based on the generation of the digital twin reproducing the exact functioning of the steam turbine CHP plant by means of the actual operational data provided by the Head of the Wonji Research center (Wonji-Shoa factory, 2013). In the second step, the plant efficiency is evaluated for the three different functioning modes with a unit-wise approach by exploiting the exergy balance built-in tool of ProSimPlus® process simulator in order to detect the most critical operations in terms of exergy losses. Finally, the exergoeconomic assessment is carried out in order to determine the most profitable operational compromise in terms of heat and power distribution between the sugar factory and the electricity grid as well as to detect the main cost items of the utility section. Conversely, all other aspects concerning thermal analysis and possible improvements in terms of energy integration for the Wonji-Shoa facility are addressed by the authors in a separate work (Sharew et al., 2024).

In the light of the above, the added value of this research with respect to the already available literature can be resumed in three main points:

- This study provides an *a posteriori* overview of the exergoeconomic indicators for an existing plant, which is already running since more than 10 years, based on the real plant operational data;
- While a relevant number of comparative studies addresses the use of different fuels or different technologies, the outcome of this research allows the comparison of different functioning modes, based on the same industrial system. With respect to those scenarios where the grid connection is taken for granted, the exergoeconomic assessment for the Wonji-Shoa facility provides a relevant decision tool for the optimal scheduling of the plant;
- Compared with studies carried out at the design phase, the detection of system criticalities along with the corresponding suggested solution are constrained by the existing system layout. Thus, the analysis results are reported from a revamping perspective, that can seldom be found in CHP related scientific literature works.

Accurate details concerning both the layout of the Wonji-Shoa CHP plant and the possible operating scenarios are provided in the next section.

2. The Wonji-Shoa sugar factory case study

As previously mentioned, the analysis presented in this research addresses the operation and management efficiency of the actual cogeneration plant serving the Wonji-Shoa sugar factory in Ethiopia. This facility, located near Adama city, is the result of the combination, restoration, and expansion of the Wonji and Shoa sugar factories that started their activity in 1954 and 1962 but stopped their production in 2012 and 2013, respectively. The modern Wonji-Shoa sugar factory is designed to crush up to 6250 tons of sugarcane per day and producing 174,946 tons of sugar per year but the expected capacity after completing the expansion is goes up to 220,700 tons. Beside the process plant, a CHP steam turbine facility is present in order to provide the required heat and power to the sugar factory. The thermal duty for the boiler of the cogeneration plant is provided by direct combustion of sugarcane bagasse, that is a side-product of the factory itself. In terms of electricity, the sugar factory demand corresponds to 11 MW out of 31 MW totally generated by the power unit, while its steam consumption is less than 1% of the steam flowrate that is sent to the turbine. Therefore, the primary user of the generated electricity is represented by the national grid, that retrieves the remaining 20 MW power. For a better visualization of the sugar production material balance, the Sankey diagram (Kennedy and Sankey, 1898) is reported in Fig. 1.

Based on these fluxes, it appears evident that the cogeneration section plays the most critical role for the entire system. As discussed in the introduction, although the sugar factory should meet some productivity targets on the process side, energy supply and distribution in Ethiopia is a really fast developing sector, especially for electricity (International Energy Agency, 2021), and agricultural waste represents by far the primary source of electricity for the grid (International Trade Administration - Department of Commerce (USA), 2022). For this reason, the electricity production target can often override the productivity one according to the needs of the grid and, more importantly, for the economic efficiency and profitability of the entire factory. Therefore, the optimal cogeneration cycle management and efficiency becomes a matter of prior relevance for the entire facility.

Thus, in order to better understand how to apply the exergoeconomic assessment methodology, details concerning the CHP system layout, the operating parameters and the functioning modes are accurately described here below.

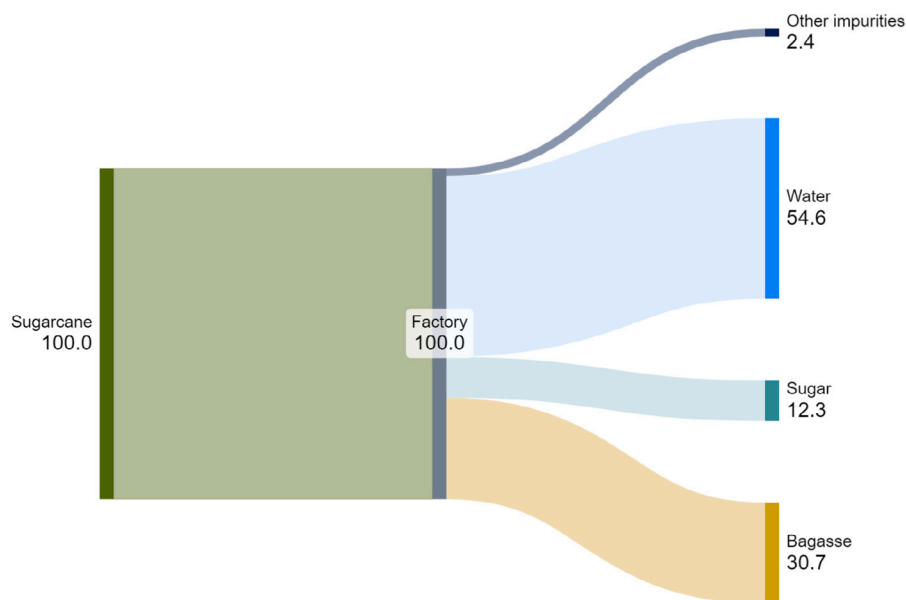


Fig. 1. Sankey diagram for the Wonji-Shoa sugar factory [%].

2.1. Steam turbine cogeneration plant layout

The Wonji-Shoa factory's cogeneration plant was designed for the supply 9 bar steam thermal duty at the outlet of the desuperheater and 3 bar steam at the extraction as well as for the transfer of the electricity surplus to the grid. For this purpose, a double condensing type turbo-alternator steam turbine generator is installed. This cogeneration system is intended to fulfill both the sugar processing facility's needs for thermal energy and electricity. In particular, with regards to the latter, the overall amount overcomes the factory requirement by allowing the electricity surplus sale to the grid system to considerably improve the facility's profitability.

The process flow diagram, issued from the simulation, is reported in Fig. 2. In particular, it represents the operating mode "GRID: ON & FACTORY: ON", hereafter referred to as "Scenario I". The reason why the plant description focuses on this layout first is that the two alternative operating modes, that will be explained in the next subsection, can be obtained by closing valves and cutting out selected modules of the cogeneration system. It is worth remarking that, along the year, the plant switches from one operating mode to another according to the grid and process conditions and demands for time intervals with variable duration.

The ON/ON operating mode applies to a factory that runs normally and covers about 4398 h per year. When the cogeneration plant operates under its default mode, the turbo-generator steam turbine is able to generate 31 MW of electricity by using extra bagasse as fuel for the live steam production.

Since the purpose of this study is to perform the energy and exergy analysis of the system, the thermodynamic parameters and specifications of the steam circuit need to be accurately collected in order to create a digital twin reproducing the real system with high reliability. First of all, two steam extractions, at 9 and 3 bar respectively, can be noticed in the circuit at the outlet of the high-pressure (HP) and low-pressure (LP) turbine section; part of their heat is recovered at the highest temperature and the residual streams, after a partial removal for the process side, are mixed with the condensate flowrate coming from the vacuum condenser, whose operating pressure is 0.1 bar. The recirculating stream is equal to about the 78% of the total flowrate that corresponds to 165 ton/h under nominal operating conditions, i.e. the conditions related to the plant full capacity at its peak hour. The remaining 22% is then integrated by a make-up water feed (MFW).

Table 1

Technical data of Wonji-Shoa turbo-alternator power plant - fixed (Wonji-Shoa factory, 2013).

Section	Unit	Parameter	Value
Combustion	Boiler	Pressure	65 bar
		Temperature	684 °C
Turbines	T-1	Inlet temperature	515 °C
		Outlet pressure	9 bar
	T-2	Extraction temperature	180 °C
		Outlet pressure	3 bar
Condensate	Condenser	Extraction temperature	130 °C
		Pressure	0.14 bar
		Temperature	32 °C
Pumps	P-1	Outlet pressure	5 bar
	P-2	Outlet pressure	70 bar

Before the inlet to the main pump, a deaerator is present to facilitate the streams mixing but, more importantly, to remove dissolved gases that would reduce the steam generation efficiency and, thus, the turbine expansion work.

To be really accurate in the facility description, it is finally worth precising that in the real plant two boilers are present whose overall capacity is compliant with the simulated boiler one while the three turbines simulated in ProSimPlus® correspond to a three stage turbine with double extraction. The main operating parameters that are kept unchanged, no matter the running functioning mode, are resumed in Table 1.

2.2. Alternative operating scenarios

As already discussed, two additional alternative operating modes exist and they correspond to the factory shutdown and to the grid that is temporary off. Based on the reference case scenario, the main operating differences are thoroughly described here below.

2.2.1. Scenario II - GRID: ON & FACTORY: OFF

The equivalent process simulation layout of the second scenario is reported in Fig. 3. On average, the plant runs in this mode for 776 h per year. Since the factory is on shutdown mode, no partial stream splitting towards the process is present. In this case, the steam production rate is 130 ton/h at the same operating conditions of Scenario I and the reduction in power production is due to the absence of equipment to

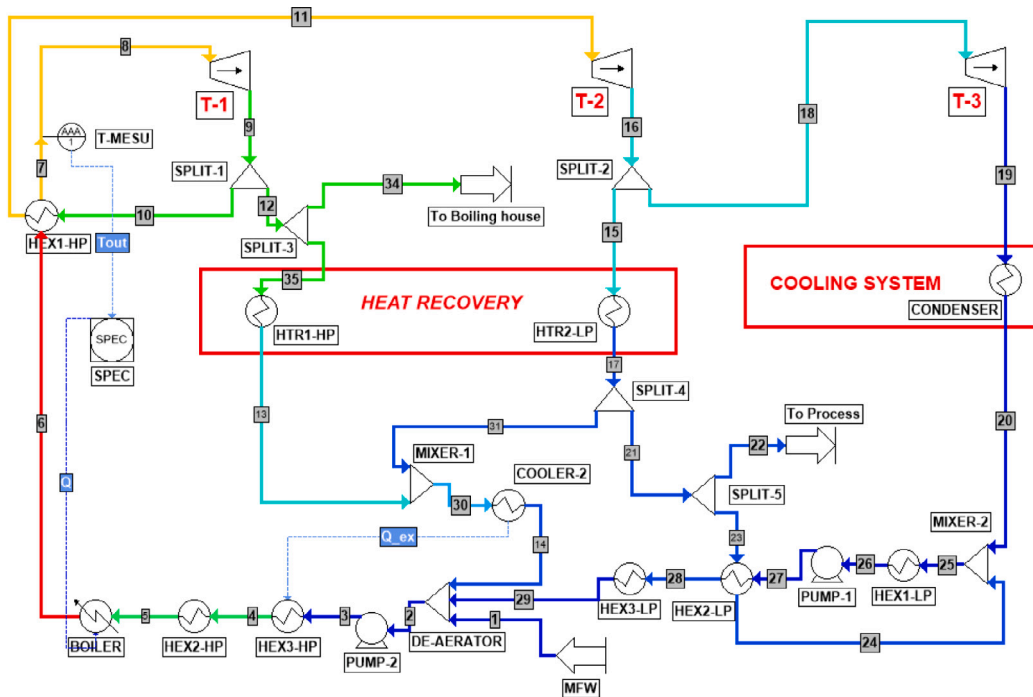


Fig. 2. Process flow diagram of Wonji-Shoa cogeneration facility (Scenario I).

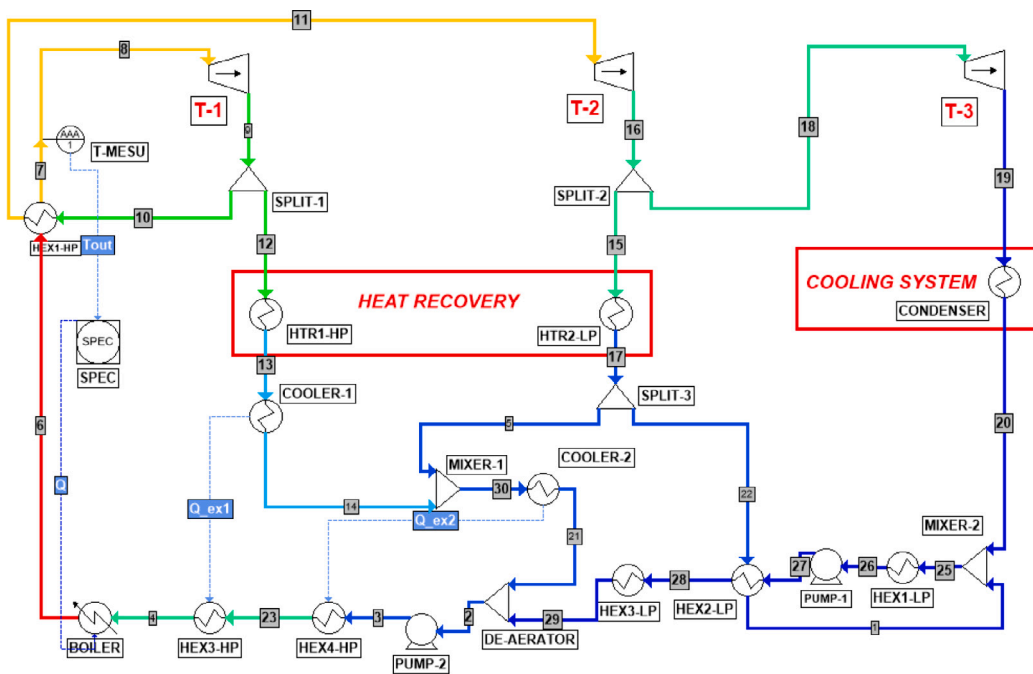


Fig. 3. Process flow diagram of Wonji-Shoa cogeneration facility (Scenario II).

be fed on the process side. As it can be noticed by the connecting information streams and the stream passes on both sides of the exchangers, energy integration is particularly stressed thanks to the fact that there are no stream losses. As a further consequence of the conservation of the water flowrate, the make-up water valve can be closed as well.

2.2.2. Scenario III - GRID: OFF & FACTORY: ON

Finally, the cogeneration system layout for process feeding only is shown in Fig. 4. This scenario stresses the situation when the plant is

running but the grid is down for extraordinary reasons, such as grid electrical energy receiver failure, and there is little pressure on the grid operation center. In this mode, the turbo-alternator could operate for around 89.8 h per year while using a decreased load.

In this scenario, only the sugar plant is the primary energy receiver from the installed cogeneration plant and the boiler produces 59 ton/h of steam at the same operational pressure and temperature. A further difference with respect to the previous scenarios is the absence of the high-pressure extraction stream.

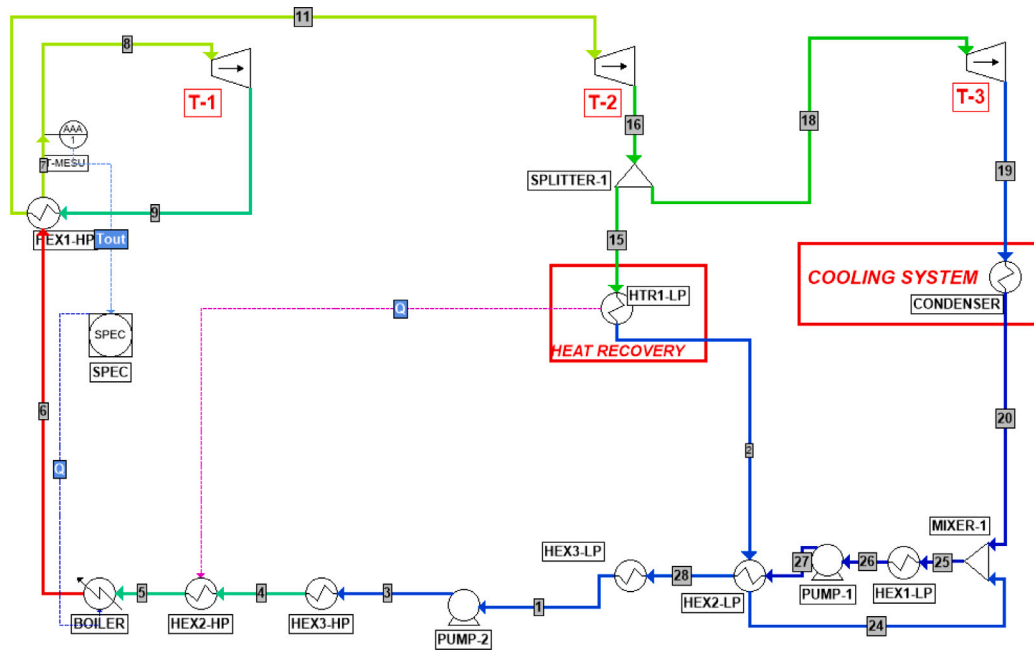


Fig. 4. Process flow diagram of Wonji-Shoa cogeneration facility (Scenario III).

Table 2

Technical data of Wonji-Shoa turbo-alternator power plant — variable according with the operating mode (Wonji-Shoa factory, 2013).

Parameter	Scenario I	Scenario II	Scenario III
Steam flowrate	165 ton/h	130 ton/h	59 ton/h
HP extraction flowrate	20 ton/h	14 ton/h	0 ton/h
LP extraction flowrate	115 ton/h	72 ton/h	43 ton/h
Total power available	31 MW	27 MW	10.4 MW

In order to have a clear overview of the three different scenarios, the main parameters that vary according to the specific plant operating mode are summarized in Table 2.

3. Methodology

In order to effectively carry out the proposed analysis concerning the sugar factory cogeneration section operating modes, multiple methodological tools were exploited. In this section they are distinguished in three main categories, namely the process simulation, the economic assessment and the exergy analysis related ones. The details for each of them are provided in the corresponding subsection.

3.1. Process simulation

In order to have a reliable reproduction of the cogeneration plant, the first step performed was the process simulation setup. As already introduced, ProSimPlus® steady state process simulator was used; it follows a sequential modular approach to calculate all the process parameters starting from the input data and unit specifications. In this description we will still refer to Fig. 2 to point out some features of the Wonji-Shoa cogeneration section digital twin.

First of all, the boiler unit was simulated by means of a duty exchanger module whose related heat, provided by the bagasse combustion, is adjusted to meet the turbine inlet conditions by means of the specification module SPEC. All the heat exchangers of the circuit that can be potentially coupled for heat integration, such as HEX3-HP and COOLER-2, have been simulated by means of double pass conventional heat exchanger modules whose specification is given by the outlet temperature. Moreover, in order to better visualize the temperature

profile of the circuit, streams have been traced according with a color bar ranging from the coldest (blue) to the hottest (red).

Beside the process simulation tools, ProSimPlus® process simulator is provided by a set of additional modules for dedicated analyses that are performed based on the output process parameters. In particular, in this research work the economic evaluation module and the exergy balance were used in order to obtain the results analyzed in Section 4. However, the reliability of the outcome of these modules is based on a proper selection and the implementation of their related parameters and variables according to the real plant operation and the market price. Therefore, in the next sections both the implementation of the exergy analysis and of the exergoeconomic assessment are discussed in detail before showing and analyzing the final outcome.

3.2. Exergy analysis

With regard to the exergy analysis, it has been performed by means of the “Exergy balance” module available in ProSimPlus® process simulator. Since exergy is a thermodynamic function defined with respect to a reference environment, the definition of the latter should be implemented in the calculation module. For this study, standard conditions of 25 °C and 1.01325 bar were selected for temperature and pressure, respectively while the reference chemical composition was assumed to be either gaseous components from the atmosphere, or dissolved species in seawater, or solid compounds present on the earth’s surface.

In addition, since the analysis is carried out within the same software by exploiting results from simulation mass and energy balances, some implicit assumptions in common with the Process simulation environment are followed by the Exergy balance module as well, namely:

- Each process unit is considered at steady state conditions;
- Kinetic and potential energy and exergy variations are negligible;
- The surrounding temperature and pressure are considered constant.

Therefore, the total exergy of the system is calculated as the sum of material, heat and power components. Concerning mass balances, the exergy of a material stream is given in this case by the sum of physical

and chemical exergy. For a process stream with flowrate \dot{m} , the former is given by:

$$B_{ph} = \dot{m} \cdot [(h - h_0) - T_0 \cdot (S - S_0)] \quad (1)$$

where h is the specific enthalpy, S the specific entropy and the subscript 0 refers to the ambient. On the other hand, since the only component of the system under analysis is water, the chemical exergy is simply given by the product between the flowrate and the specific chemical exergy of water.

With regard to physical exergy variations with respect to temperature and pressure, they are calculated according to the equations (Michaelides, 2021):

$$B_T = c_p \cdot \left[(T - T_0) - T_0 \cdot \ln \frac{T}{T_0} \right] \quad (2)$$

$$B_P = \frac{R \cdot T}{M_w} \cdot \ln \frac{P}{P_0} \quad (3)$$

where c_p is the specific heat at constant pressure, R is the gas constant and M_w is the molecular weight.

When dealing with energy balances, heat and power are then the remaining terms to be considered. The exergy flow related to electrical corresponds to its while a coefficient accounting for its temperature difference with respect to the ambient should be applied for heat:

$$B_h = \dot{Q} \cdot \left(1 - \frac{T_0}{T} \right) \quad (4)$$

Moving from balances to the plantwide perspective, the main concept of interest is the exergy efficiency, strictly related to exergy losses and irreversibility, that is defined as:

$$\eta = \frac{B_{out}}{B_{in}} = 1 - \frac{\dot{I}}{B_{in}} \quad (5)$$

where \dot{I} is the irreversibility, or exergy destruction rate, while B_{in} and B_{out} are the inlet and outlet exergy respectively. Given the impossibility of describing in details the thermodynamic model for all the modules present in the simulation, the formulation of exergy efficiency and work are reported here below for the main units only; it is worth remarking that, in case of coupled heat exchangers, the exergy balance calculation is performed only for one of them.

- Turbine

$$\dot{W}_{rev} = B_{in} - B_{out} \quad (6)$$

- Condenser/cooler

$$\eta = \frac{B_{out} - \dot{Q}}{B_{in}} \quad (7)$$

- Boiler/heater

$$\eta = \frac{B_{out}}{B_{in} + \dot{Q}} \quad (8)$$

Since the cogeneration plant experiences heat (i.e. energy and exergy) losses at several stages, more significant indicators from a plantwide point of view can be generated. Based on the exergy measurement and on its destruction rate for each simulated module, three relevant indicators may be graphically represented to provide to the decision maker a clear visualization of the plant exergy consumption. They are namely the intrinsic efficiency (IE), the intrinsic waste (IW) and intrinsic irreversibility (II) that can be reported in the so-called exergetic ternary diagram for each scenario. They are calculated as follows:

$$IE = \frac{\Delta B_{produced}}{\Delta B_{consumed}} \quad (9)$$

$$IW = \frac{\Delta B_{out}^{waste}}{\Delta B_{consumed}} \quad (10)$$

$$II = \frac{\dot{I}}{\Delta B_{consumed}} \quad (11)$$

Furthermore, assuming no external heat loss, the following correlation states true:

$$IE + IW + II = 1 \quad (12)$$

Based on these indicators, one can determine the steam power plant's global and intrinsic efficiencies as well as identify the cause of irreversibility across integrated unit operations. However, the overall efficiency of the cogeneration plant depends on its operating mode according to the provided service:

$$\eta_I = \frac{\dot{W}_{net}}{\dot{Q}_{comb}} \quad (13)$$

$$\eta_{II,III} = 1 - \sum_i \frac{\dot{I}_i}{B_{i,in}} \quad (14)$$

The results of the analysis for the Wonji-Shoa cogeneration plant are thoroughly discussed in the dedicated section and the supplementary exergy related graphics are reported in the appendix sections for the three scenarios.

3.3. Exergoeconomic assessment

Exergy-based cost analysis employs cost partition criteria that are based on the amount of exergy included in each energy flow that occurs throughout the process under study to determine the costs of the products and irreversibilities (destroyed exergy) produced in energy conversion processes (Oyedepo et al., 2015). The second-law costing, thermoeconomics, and exergoeconomics are terms that have arisen to describe techniques for doing exergy-based economic studies. These methods acknowledge the exergy, and not the energy, is the system's valuable commodity, and thus assign costs and/process to exergy-related variables (Rosen and Dincer, 2001). Furthermore, in order to evaluate and optimize an energy system, it is necessary to compare capital-related charges, fuel costs, and operating and maintenance costs using leveled yearly cost since these items could significantly vary during the system's economic lifespan (Ghaebi et al., 2012).

The Wonji-Shoa steam turbine cogeneration facility is here analyzed as a combined heat and power (CHP) utility plant for the production of two different forms of useful energy from a single energy source, i.e. biomass, with an expected power corresponding to 31 MW that is partially used and partially sent to the national grid system. In this research work, its economic analysis was implemented inside the Economic evaluation module of the process simulator on the basis of the plant's capital expenditures (CAPEX), operating expenses (OPEX), working capital, discount rate, yearly income, and profit made during the project's lifetime. For each flow, such as the exergy flow of the material streams, work, or heat entering or exiting the system, a unit exergy cost is also given according to the Lozano and Valero (1993) technique (Lozano and Valero, 1993) for the exergoeconomic assessment. It is worth remarking that, in order to use this technique, the process plant must be divided into subsystems and the process's resources and outputs must be identified and calculated in a controlled volume. The cost related to a material stream will be then given by:

$$C_i^{TOT} = C_i \cdot F_i + C_i^{ex} \cdot B_i \quad (15)$$

where C_i is the non-exergetic specific cost/income related to the stream itself while C_i^{ex} is that related to its exergy.

Although calculations are automatically performed by the software, quantitative insights concerning the different types of costs are provided here below according to the specific cost item for a more clear understanding of the obtained results.

3.3.1. Investment costs

The investment costs are defined as the total upfront investment to be afforded before starting a project. It includes the money for process equipment purchase, building, service facilities and land as well as indirect costs related to engineering, supervision and construction costs. This list of cost items is also known as CAPital EXpenditures (CAPEX). In addition to CAPEX, investment costs also comprises the money set aside as working capital (W_c). Working capital is defined as the capital required to cover the first months of operation during which no income has been obtained yet (Turton et al., 2018). However, this capital does not represent a real expenditure since it can be recovered at the end of the project along with the equipment residual value.

In the simulation module, the pre-estimating technique for modular approach was selected. This methodology allows to calculate the assembled price of a piece of equipment based on the unassembled price and the size factor, automatically retrieved from the simulation results.

When the investment term (time horizon) is attained, the working capital and the economic process's residual value are recovered as if they were a fixed final income. The residual value at the year n of a piece of equipment purchased in year i is determined by:

$$RV_n = I_0^{eq} \cdot \frac{Life_{use} - n}{Life_{use}} \quad (16)$$

where I_0^{eq} is the equipment bare module cost afforded at the year of initial use and $Life_{use}$ is the equipment total useful life. In order to account for the money value over time, a discount rate coefficient is usually applied.

3.3.2. Operating costs

Operating EXpenditures (OPEX) include any expenses incurred in manufacturing operations to maintain the effectiveness of the production process such as the provision of raw materials, the usage of power, utilities, and waste processing.

An additional cost item that should be considered during the operation of the system is maintenance. The cost of maintenance and repairs includes the price of labor, materials and professional supervision, that expenses are difficult to estimate as a specific cost item. For this reason, they are usually accounted for as a percentage of the fixed capital investment on annual basis. In the Economic evaluation module this parameter can be implemented and, for this research work, the selected percentage is equal to 6% for all scenarios.

One last cost item affecting the plant income over its lifetime is the amortization whose value depends on the selected amortization plan. For this study, a straight-line depreciation method was used.

3.3.3. Revenues

The steam turbine cogeneration plant's heat and power output were intended to serve as a hub for the sugar plant's heat and power needs, with an extra electricity being fed to the grid. The operating gains of the system are then represented by equivalent price of electricity and steam provided to sugar factory as well as the surplus electricity sold to the grid.

The net income (NI) of the system for the i th year can be then defined as:

$$NI_i = (In_i^{op} - C_i^{op}) \cdot (1 - \tau) \quad (17)$$

where τ corresponds to the tax rate.

The main difference between investment costs, operating costs and operating gains is that the first ones are paid in "advance", at the beginning of the project, while the latter come in a later moment along the plant operation. For this reason, for OPEX and for the income, the economic assessment should account for the so-called discount rate as discussed in the dedicated section.

Table 3

Technical and economic assessment parameters.

Parameter	Value	Unit
Plant lifetime	25	years
Operating time	10 (Wonji-Shoa factory, 2013)	month/year
Sugar bagasse moisture	49.2 (Sharew et al., 2021)	% kg/kg
Makeup water price	0.2	€/ton
Electricity price	250 (Ethiopian Electric Utility, 2022)	€/MWh
Steam price	25	€/ton
Maintenance cost fraction	6	%
Tax rate	30	%
Discount rate	7	%

Table 4

Combined heat and power electricity production and efficiency.

Parameter	Scenario I	Scenario II	Scenario III
T1 power [MW]	22.54	16.95	6.41
T2 power [MW]	11.98	9.58	3.79
T3 power [MW]	4.83	7.08	2.11
Total power [MW]	39.35	33.61	12.31
Useful power [MW]	146.92	97.5	43.86
Energy yield [%]	26.92	34.47	28.07

3.3.4. Net present value

The yearly cash flow of the cogeneration plant for the i th year is then calculated as the difference between the income, the expenses (i.e. the net income) and eventual additional investments on the same year:

$$CF_i = NI_i - I_i \quad (18)$$

If a discount rate d is introduced to account for the value of money over time, the discounted cash flow up to the i th year can be calculated by introducing the so-called discount factor:

$$DCF_i = \sum_{j=1}^i \frac{CF_j}{(1+d)^j} \quad (19)$$

The net present value of the project at the end of its life can be finally calculated as (Turton et al., 2018):

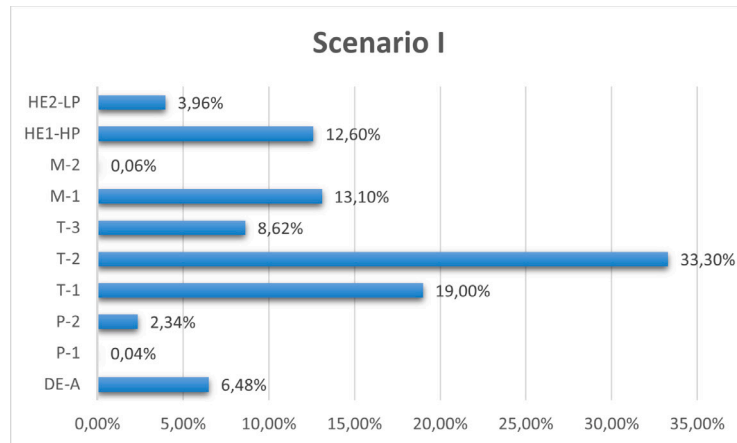
$$NPV_n = DCF_n + RV_n + \frac{W_c}{(1+d)^n} - I_0 \quad (20)$$

where I_0 is the total investment at the beginning of the project. A comprehensive list of the numerical parameters used for the exergoeconomic assessment of the Wonji-Shoa cogeneration plant is provided in Table 3.

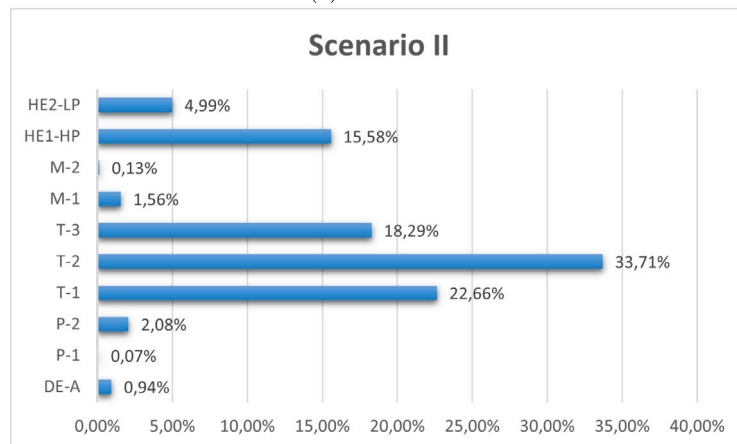
The plant operating period that goes from September to June due to the difficulty of receiving bagasse as fuel on July and August unless the client plant collects the sugarcane in the warehouse, that is not the case for the Wonji-Shoa facility. Startup and shutdown were considered negligible with respect to operating expenditures according to the feedback of the factory head manager. With regard to the price of electricity and steam, their value in euro comes from the conversion between Ethiopia and European countries (i.e. France) by applying the equivalent tax rate. The exergoeconomic analysis results obtained from these parameters are therefore discussed in detail in the following section.

4. Results

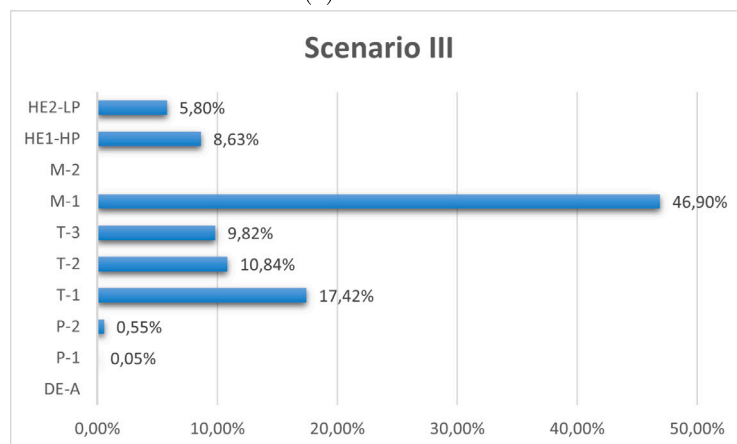
According to the methodologies and the parameters discussed in the previous section, this part of the manuscript presents the obtained results. In particular, the first section addresses the exergy analysis outcome that will provide preliminary results to better understand the final exergoeconomic assessment.



(a) Scenario I



(b) Scenario II



(c) Scenario III

Fig. 5. Unitwise relative irreversibility.

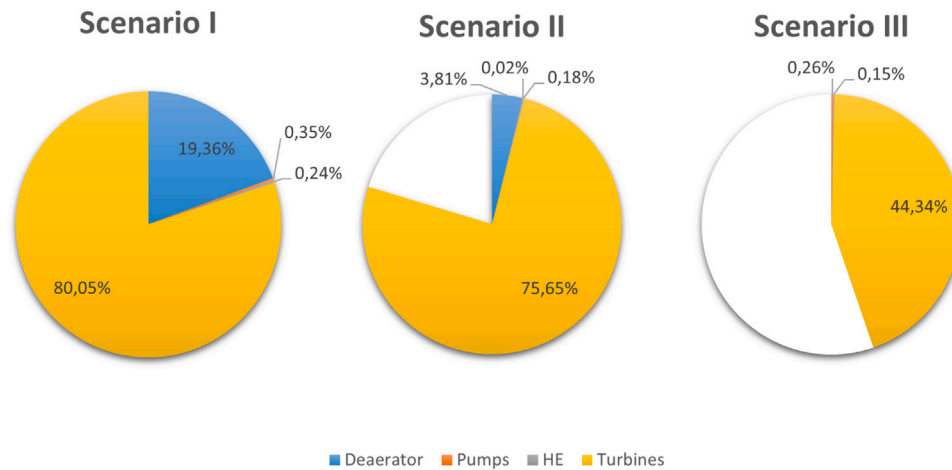


Fig. 6. Assembled equipment price.

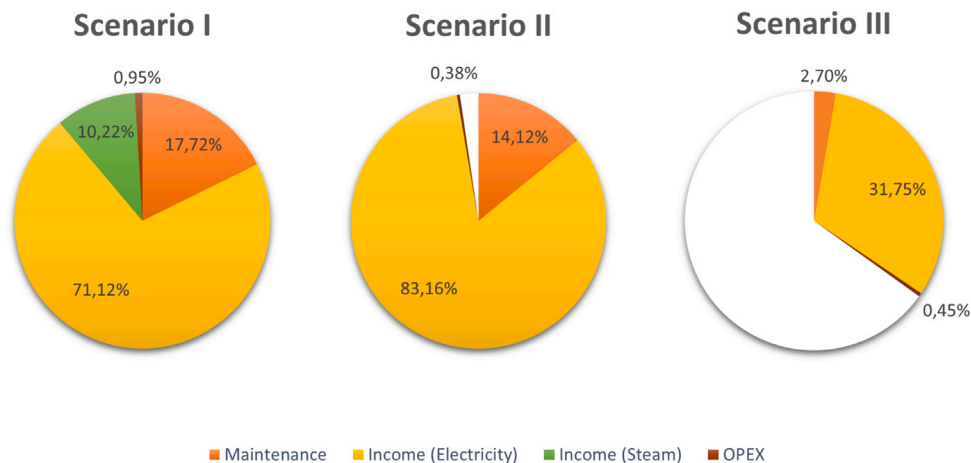


Fig. 7. Operating costs and gains.

4.1. Exergy analysis

The exergy analysis was carried out to assess the rate of irreversibility generated in each subsystem for the three scenarios in order to determine the most critical units that could benefit the most by an efficiency improvement. The performance of the steam turbine power plant was examined with respect to a reference ambient at 298.15 K and 101.3 kPa by means of the dedicated tools already implemented in the ProSimPlus® software.

Starting from plant-wide related results, the global intrinsic efficiency of the cycle considering the steam production with respect to the provided heat duty input is equal to 88.8%, 89.68%, and 64.52% for Scenario I, II and III respectively. In terms of simple efficiency, a higher value equal to 93.14% is observed for the first scenario while the same values are obtained from the global exergy balance on the other two. Finally, the total irreversibility of each scenario is equal to 8.2 MW, 5.86 MW and 9.63 MW. For a better visualization of the

global balances, the corresponding simplified Grassmann diagrams are provided in Appendix A.

With regard to the overall CHP system electrical power production and related efficiencies, they are summarized in Table 4 for the three scenarios. As it can be noticed, although the highest energy amount is produced in Scenario I due to the biggest size of the plant, the highest yield is obtained for Scenario II, i.e. “GRID:ON & FACTORY:OFF”.

However, although global results allow to compare the effectiveness of the different functioning modes, they provide poor insights on the specific unit performance. For this reason, the analysis of each simulated module was broken down into a unit-wise irreversibility assessment and the obtained results have been properly arranged in dedicated charts that are discussed for each operating scenario.

Starting from Scenario I, when the plant is operating both the sugar plant and installed grid system at its full capacity, the plant’s peak simple efficiency of 93.14% and the sum of irreversibility goes to 8.2 MW with some major unit operations that are subject to exergy destruction due to heat energy loss to the surround. The relative irreversibilities

for each unit of the system corresponding to a non-zero value are listed in Fig. 5(a). At first, it can be noticed that the turbine system, in particular T-2, exhibits the highest exergy destruction units at full load operation corresponding to 61% of the total irreversibility (8.62%, 33.3% and 19% for T-1, T-2 and T-3 respectively). This effect can be explained by the considerable pressure drop from 65 bar of the T-1 inlet to 2.6 bar T-2 outlet that causes friction, mixing, heat transfer through a limited temperature differential, uncontrolled expansion and non-quasi-equilibrium compression or expansion. The second subsystem with higher energy losses (i.e. 15.6%) is represented by the feed water heaters that have to increase the temperature of streams coming from different sections of the plant, i.e. vacuum and turbine condensates with make-up water, up to a homogeneous condition. After that, we find mixers, or better Mixer-1. Even in this case, the reason behind this outcome can be related to the mixing of the condensate streams, with highly heterogeneous conditions, coming from the turbine condensates' heat recovery system. In the end, the deaerator unit followed by pumps are the last part of the equipment with a relevant exergy destruction rate that falls nevertheless within the expected range.

The second scenario exhibits a relative irreversibility distribution over the units similar to the first one, as it can be noticed in Fig. 5(b). When the is generating electricity for the grid system only, the global irreversibility falls down to 5.86 MW along with the circulating steam flowrate that goes from 165 to 130 ton/h. Since the CHP system product under this functioning mode is electricity, the three turbines are still the units experiencing the highest irreversibility with an overall relative value raising up to 74.7%. After them, the heater system represents the second subsystem in terms of exergy destruction; its relative irreversibility rate in Scenario II is also higher than Scenario I reaching the 20.57%. Finally, the remaining units follow the same behavior discussed for Scenario I but with a lower relative impact.

As regards the last scenario (cf Fig. 5(c)), when the CHP system it is solely running the sugar processing plant, its global simple efficiency and global intrinsic efficiency are both equal to 64.52%, while the total amount of irreversibility exceeds 9.63 MW. In contrast to the other scenarios, the mixer-1, which collects condensate from the medium and low-pressure heat recovery systems, represents the primary exergy destruction unit with more than 46% relative irreversibility. These losses are the consequence of mainly velocity variation and non-quasi equilibrium compression or expansion. On the other hand, about 38% of the total irreversibility is still due to turbines; their lower impact can be mainly associated with the reduction of the inlet steam flowrate. After turbines, the third subsystem contributing to the plant irreversibility by 14.43% is made of the feed water heaters. These heaters indeed are those who experience the most of the energy transfer with associated losses that play a significant role for the overall plant exergy destruction. A final remark concerns the absence of the deaerator and mixer-2, and the low impact of pumps still due to the low circulating flowrate.

Further details concerning energy losses, destroyed energy and energy efficiency for each unit process can be clearly visualized by means of the so-called ternary diagrams that are, they as well, generated by the process simulation software dedicated module. For the completeness of the analysis they are reported in the dedicated Appendix B for the three operation modes.

Therefore, after completing the exergy analysis, the related outcomes were then coupled with the economic parameters by means of the exergoeconomic assessment whose results are reported in the next section.

4.2. Exergoeconomic assessment

As discussed in the corresponding methodology Section 3.3, the economic assessment was conducted by coupling exergy analysis and engineering economics together in the so-called exergo-economic approach by means of the dedicated tool in ProSimPlus® simulation version 3.6.15.0. The income related to the produced heat and power

was coupled with the total capital and operating expenditures for each configuration corresponding to a specific operating scenario. The fundamental idea behind this analysis is to consider only the equipment required by the specific functioning mode as for a new CHP system to be designed in order to assess the best scenario independently of the existing plant. Component costs are tied to their exergetic efficiency and operational parameters while streams (of material or energy) pricing is based on their individual exergy content rather than their unit mass.

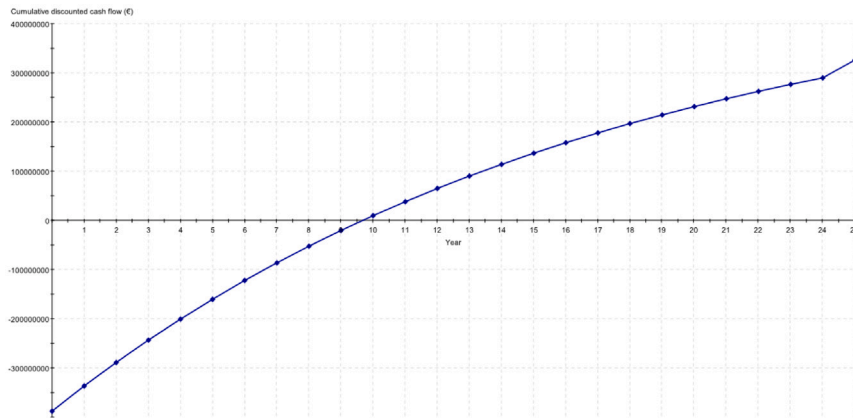
The assembled price for process equipment is reported in Fig. 6, classified according to the specific equipment categories. In particular, in order to compare more easily the required investments for the three different functioning modes, the 100% value of each pie chart corresponds to the total investment costs of Scenario I, i.e. the most expensive. As it can be noticed, the turbines are the most expensive items in all scenarios and, to be precise, their purchase cost decreases along with the operating pressure. The second most expensive unit is the deaerator; this unit is absent in the last configuration since no make-up water is required while in the first case it corresponds to about the 20% of the total purchase cost due to the considerable amount of circulating water and the subsequent bigger size of the unit. As a consequence, the cost of pumps is higher for the first scenario while the cost of heat exchangers is almost stable over the three configurations and of the order of 50000 € per module. In any case, pumps and heat exchangers together represent less than 1% of the total investment.

In any case, in order to assess the net income of the cogeneration system, revenues and operating expenses should be included in the analysis. Following the same approach, the three graphics for operating variables are reported in Fig. 7 for the three scenarios respectively. As it can be noticed, electricity represents the main source of income while operating expenses are a negligible fraction of the operating costs. The latter are mainly related to maintenance in proportion to the equipment costs according to the calculation hypotheses.

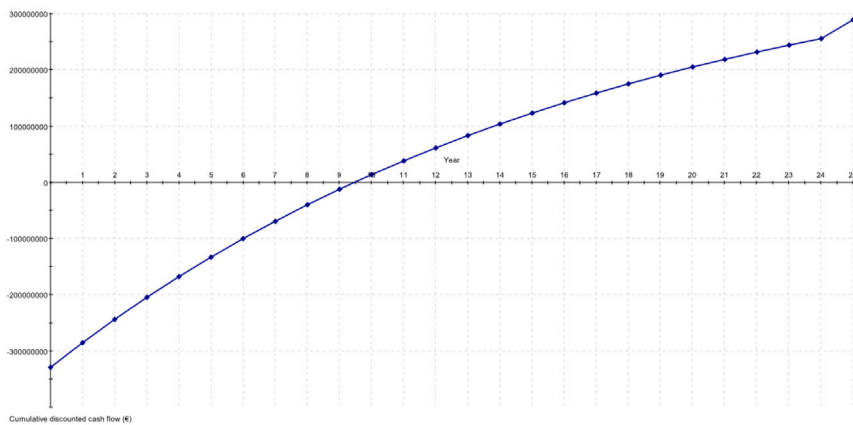
In the first scenario, the produced steam represents nevertheless the 12.5% of the overall gains due to the higher capacity of the system. On the other hand, the produced electricity and steam in Scenario III are equal to the sugar plant demand and therefore their quantity results considerably lower. In terms of net income, calculated as the difference between revenues and costs, the second scenario performs slightly better with a relative percentage equal to 68.6% with respect to the 62.3% of the first one. As concerns the unit-wise economic evaluation, the most expensive units in terms of operation are the boiler and the condenser that account, in every functioning mode, for more than 40% and 15% of the OPEX respectively.

If, on the one hand, the Scenario III can be already identified as the less profitable one, on the other hand, the small differences between the “GRID:ON & FACTORY:ON” and the “GRID:ON & FACTORY:OFF” scenarios requires the detailed yearly cash flow calculation the final outcome to detect best performing functioning mode. Therefore, based on the investment and operating expenses calculated so far, the cogeneration plant discounted cash flow for the three scenarios can be calculated by applying the selected discount rate and including working capital and equipment residual value in the analysis. The cumulative cash flow trends are then reported in Fig. 8 to have a better visualization of their behavior. As it can be noticed soon, despite the lower investment and operating expenses, whether the CHP plant was conceived only to satisfy the sugar process needs, the net present value increases so slowly that its value becomes positive at the very end of the plant lifetime only (cf Fig. 8(c)). The first conclusion that can be drawn from this exergoeconomic analysis is that the plant is not profitable if it is not connected to the energy grid to sell the electricity surplus.

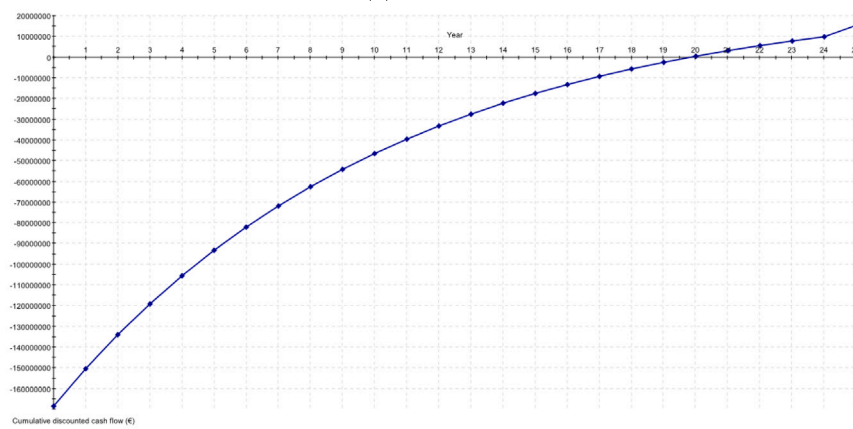
As concerns the two grid-connected scenarios, it can be observed that they have similar trends. However, although the first case requires a higher initial investment, the discount profit increases with a higher slope achieving a final net profit higher than Scenario II. This behavior is due to the higher amortization value of Scenario I. In fact, although the investment costs are lower and the operating gains are slightly



(a) Scenario I



(b) Scenario II



(c) Scenario III

Fig. 8. Cumulative cash flow diagrams.

higher for the CHP plant layout operating only for the grid, the related lower amortization reduces the overall income with respect to the first configuration. From a decision-making perspective, this result makes higher investment solutions, and thus higher plant capacity, a better alternative from an economic point of view. At last, as a further economic indicator, the payout time for each scenario was calculated as well. The obtained values correspond to 84 714, 83 847 and 173 893 h for Scenario I, II and III respectively. In terms of years, according to the selected operating time, they become 9.6, 9.5 and 19.8 years.

In conclusion, based on the exergoeconomic analysis outcome, it is preferable to conduct the CHP plant both to serve the sugar facility and to produce surplus electricity. In case of facility shutdown, the income related to electricity production keeps being significant while, if it is not possible to sell the produced electricity, the profit of the cogeneration plant considerably decreases and it takes about twice the time to pay back the system investment with respect to the other functioning modes.

5. Conclusions

Thanks to the built-in tools of ProSimPlus[®], the exergoeconomic assessment of the Wonji-Shoa sugar factory cogeneration plant was successfully performed and criticalities of the system, along with potential improvements, were accurately identified. Based on the obtained results, some interesting conclusions can therefore be drawn as follows:

- Despite a relatively good efficiency, total exergy losses up to 9.63 MW for the last scenario can be nevertheless assessed for the current layout of the CHP plant;
- Although a major part of the irreversibility is due to the turbine system, in case the exergy analysis were carried out at the early design stage, up to 15% of the exergy losses could have been prevented for all operating modes by means of a more accurate energy integration without needing further investments;
- Concerning the economic aspects, the highest profitability is achieved for the Scenario “GRID: ON” & “FACTORY: ON”, i.e. when the CHP cogeneration system serves both the electricity grid and the sugar factory. On the contrary, a much lower income can be observed when the cogeneration plant provides heat and power to the process only. Thus, in case of non-operational grid connection, it is not worth running the sugar plant production;
- From the methodological point of view, the “Exergy balance” and “Economic evaluation” in-built tools of ProSimPlus[®] simulation software proved to be very helpful. Given the process simulation, they considerably eased the exergy analysis and the cost estimation based on the user input parameters that are easily adjustable according to the study hypotheses.

With regard to possible developments and future applications, the use of the proposed methodology as a decision-making tool could be effectively extended to all those process systems characterized by multiple operating modes for the improvement of the operation management according to specific needs, raw materials and energy sources availability and to deal with market instability. Furthermore, this approach could be coupled with different indicators (e.g. environmental impact, flexibility etc.) for multiobjective process optimization and for combined optimal scheduling of utility and process sections in chemical and energy plants.

Nomenclature

B	Exergy flow	kW
C	Specific material cost	€/kg
CHP	Combined Heat and Power	acronym
c_p	Specific heat capacity	kJ/(kg K)
F	Flowrate	kg/s
h	Specific enthalpy	kJ/kg
I	Investment	€
i	Irreversibility	kW
IE	Intrinsic efficiency	kW/kW
II	Intrinsic irreversibility	kW/kW
In	Income	€/year
IW	Intrinsic waste	kW/kW
$Lif_{e_{use}}$	Useful equipment life	years
\dot{m}	Mass flowrate	kg/s
M_w	Molecular weight	kg/kmol
n	Plant lifetime	years
P	Pressure	bar
\dot{Q}	Heat flow	kW
R	Gas constant	kJ/(kmol K)
RV	Residual value	€
S	Specific entropy	kJ/(kg K)
\dot{W}	Power	kW
W_c	Working capital	€
0	Subscript referring to the ambient	subscript
η	Efficiency	kW/kW
τ	Taxation rate	%

CRedit authorship contribution statement

Shumet Sendek Sharew: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Alessandro Di Pretoro:** Writing – original draft, Methodology, Conceptualization. **Abubeker Yimam:** Validation, Supervision, Data curation. **Stéphane Negny:** Writing – review & editing, Validation, Supervision, Methodology. **Ludovic Montastruc:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Grassmann graphics

This appendix section reports the exergy simplified Grassmann diagrams for each of the three scenarios in Figs. A.9(a)–A.9(c) respectively.

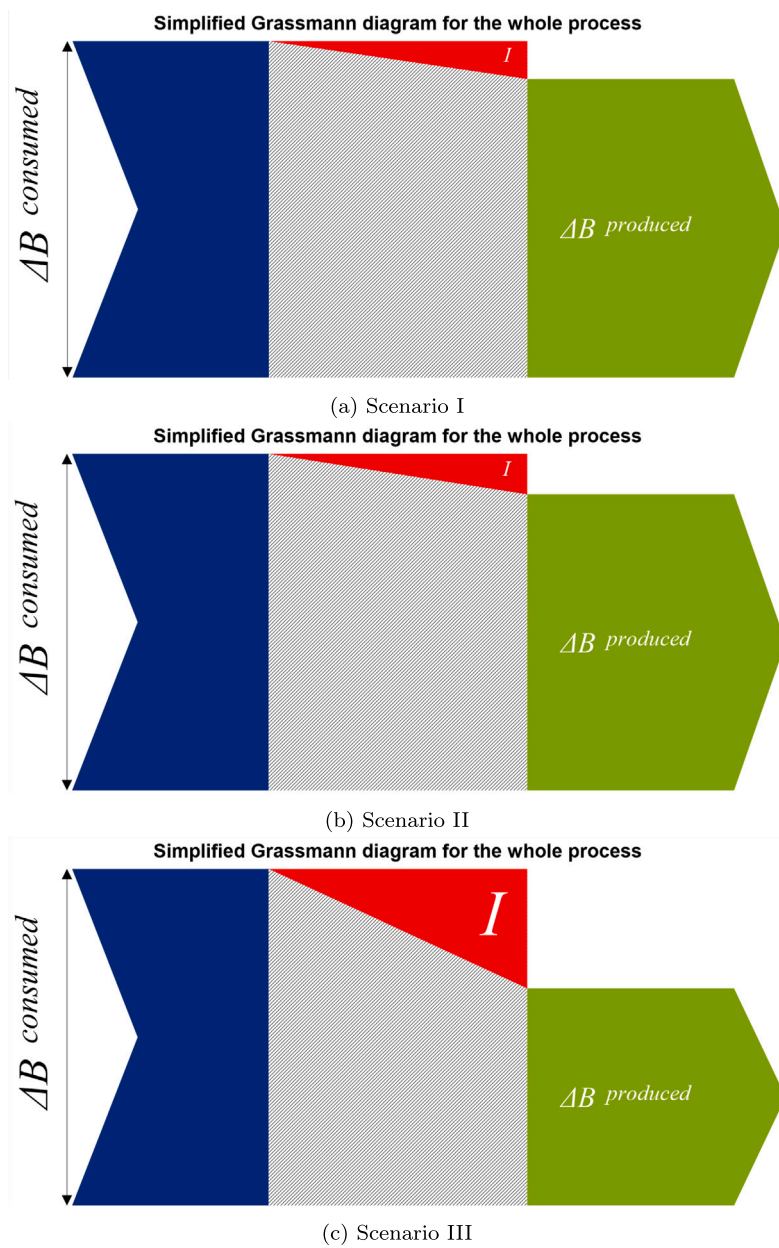


Fig. A.9. Simplified Grassmann diagram.

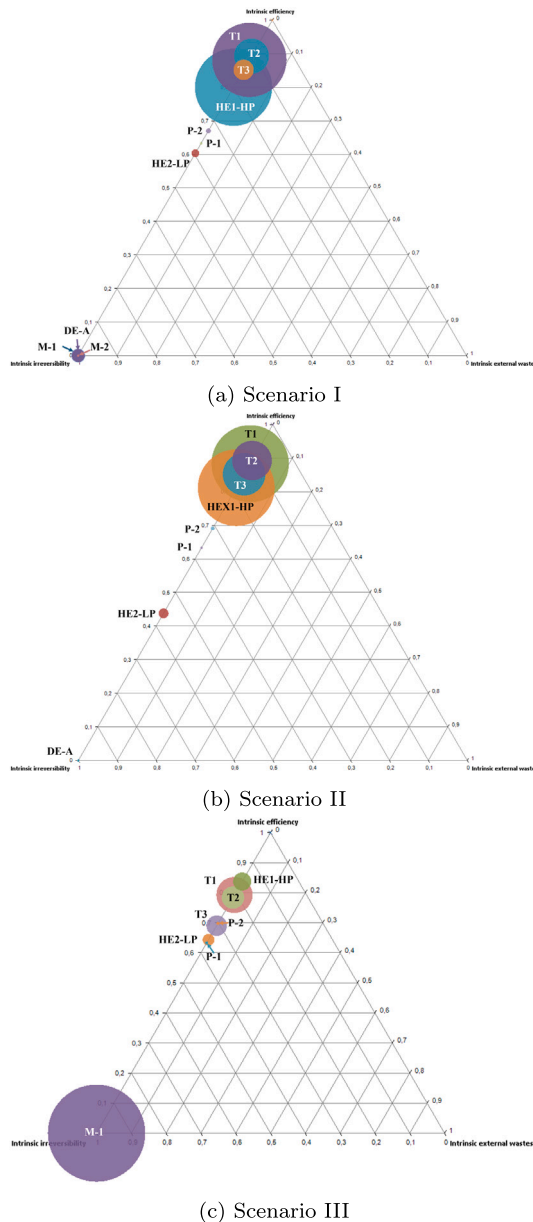


Fig. B.10. Exergetic ternary diagram.

Appendix B. Exergy ternary diagrams

This appendix section reports the exergetic ternary diagrams for each of the three scenarios in Figs. B.10(a)–B.10(c) respectively.

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