Multiobjective Design of Interplant Trigeneration Systems

Brígido Jesús Hipólito-Valencia, Luis Fernando Lira-Barragán, José María Ponce-Ortega, and Medardo Serna-González
Chemical Engineering Dept., Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060 México

Mahmoud M. El-Halwagi
Chemical Engineering Dept., Texas A&M University, College Station, TX 77843

Chemical and Materials Engineering Dept., Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

DOI 10.1002/aic.14292
Published online November 27, 2013 in Wiley Online Library (wileyonlinelibrary.com)

A systematic approach for heat integration into an eco-industrial park through an integrated trigeneration system is presented. The approach is based on a new superstructure formulated as a multiobjective mixed-integer nonlinear programming model, where intraplant and interplant heat exchange for the process streams is allowed, in addition to the energy integration into the utility system that is constituted by a steam Rankine cycle (to produce electric power and hot utility), an organic Rankine cycle (to recover waste heat and produce electric power), and an absorption refrigeration cycle (to recover waste heat and provide refrigeration). To run the utility system, several external heat sources (solar, fossil fuels, and biofuels) are considered, which impact the economic, environmental, and social objectives considered in the model. A systematic approach to tradeoff the objectives considered is presented. Two examples are presented, where the advantages of the integrated eco-industrial park are shown. © 2013 American Institute of Chemical Engineers *AIChE J*, 60: 213–236, 2014

Keywords: energy integration, waste heat recovery, interplant integration, eco-industrial park, power plant, absorption refrigeration, trigeneration

Introduction

Currently, the enormous energy demand in the process industries has promoted the development of integrated utility systems. The chemical and process industries consume huge amounts of hot utilities (as medium/low pressure steam), cooling water, and refrigeration (absorption refrigeration for moderate temperature and mechanical refrigeration for low temperature). In this context, the integrated trigeneration system has emerged as a suited solution to integrate the process streams to the utility system (see Figure 1a); where electric power, steam, and refrigeration is produced simultaneously.

For a given process industry, there are several potential solutions to integrate the utility system; in this regard, recently several approaches for the optimal design of utility systems integrated to process streams have been proposed. Particularly, several approaches have been reported for the optimal integration of process streams to cooling water systems (e.g., Mixed Integer Non Linear Programming (MINLP) synthesis of cooling networks,[1] detailed design of cooling networks,[2] optimization models for recirculating cooling water systems,[3] effluent cooling systems,[4] involving multiple cooling towers,[5,6] subambient conditions,[7] for retrofitting,[8] involving pressure drops considerations,[9] and for targetting[10]). Furthermore, some approaches for the optimal integration of process streams to refrigeration systems through absorption refrigeration cycles[11] (ARCs) have been recently reported (integrating solar energy[12] or renewable energy[13] and involving economic and environmental objectives[14]). Additionally, several approaches for the optimal integration of process streams with a steam Rankine cycle (SRC) have been reported (identifying optimal pressure levels,[15] generating sustainable electric energy,[16] involving multiobjective optimization,[17] for targeting,[18] and considering the environmental impact[19]); this integration usually involves the electric power production and the energy recovery from the condenser of the SRC to heat cold process streams (cogeneration). Moreover, several approaches to integrate industries with a central SRC that involve solar energy,[20] the utility system,[21] H_2 production,[22] reductions of fuel, power, and CO_2,[23] targeting for cogeneration potential,[24,25] planning utility systems,[26] total site utility system,[27] exergy for targeting refrigeration,[28] fired heaters,[29] specific minimum temperature difference,[30] and the industrial implementation[31] have been proposed, which has been called total site integration.[32] In addition, Bagajewicz and Rodera[33–35] and Rodera and Bagajewicz[36,37] presented mathematical programming approaches for energy integration across plants, and Stijepovic et al.[38] proposed a targeting approach for waste heat recovery across plants in industrial zones. Perry et al.[39]

Correspondence concerning this article should be addressed to J. M. Ponce-Ortega at jmponce@umich.mx.

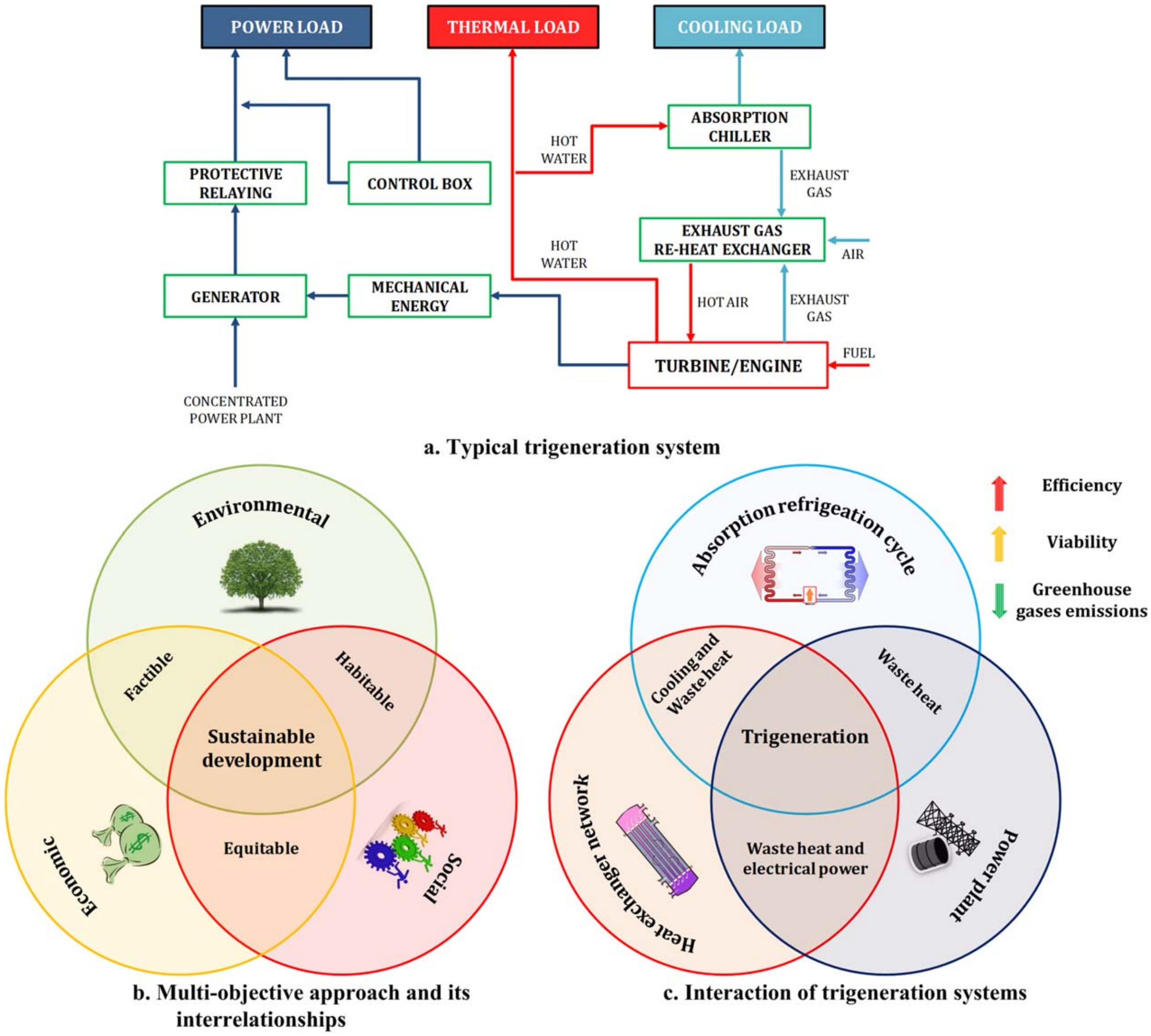

Figure 1. Interaction of trigeneration systems.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

incorporated industrial and residential users in the total site energy integration. Klemes et al.[40] presented new developments for heat integration in total sites, Hackl and Havey[41] proposed a methodology for energy integration inside an industrial cluster, and Zhang et al.[42] integrated the hot discharges/feeds between plants. Recently, the organic Rankine cycle (ORC) has been proposed to recover waste heat (considering the effect of working fluids,[43] analyzing the energetic effects,[44] involving a parametric optimization,[45] an experimental investigation,[46] and an assessment with cogeneration[47]); the ORC is similar to the SRC but using an organic fluid with a lower boiling point. In this sense, recently some approaches have been proposed for the optimal integration of the process streams to an ORC to recover waste heat (using sequential[48] and simultaneous[49] approaches). Conversely, Al-Sulaiman et al.[50] presented a comparison of three trigeneration systems using an ORC, which is driven by solar energy, biomass, and solid oxide fuel cell. Additionally, several approaches have used renewable energy sources (solar energy and biomass) to run trigeneration systems to improve the thermo-economic performance (involving new formulations,[51] applications,[52] energy and exergy analyses,[53] hybrid systems,[54] and biomass[55]). Tora and El-Halwagi[56] proposed a heuristic approach for combining a SRC and an ARC, where the system was operated by solar energy, heat from process streams, and fossil fuels. Kong et al.[57] used a trigeneration system driven by a stirling engine, and Varbanov and Klemes[58] incorporated fuel, power, and CO_2 reductions in the total site energy integration.

However, none of the previously reported methodologies have considered the integration of a community of industries into an eco-industrial park involving a shared utility system where is included a SRC, an ORC, and an ARC (an eco-industrial park integrated to a trigeneration system). The implementation of the trigeneration system within an eco-industrial park increases the sustainability through the reduction of greenhouse gas emissions (GHGE) and the associated environmental foorprints[59]; and simultaneously enhances the performance and increases the economic effectiveness (with a gas–diesel engine,[60] in competitive markets,[61] and with reciprocating engines[62]; see Figures 1b, c). Nevertheless,

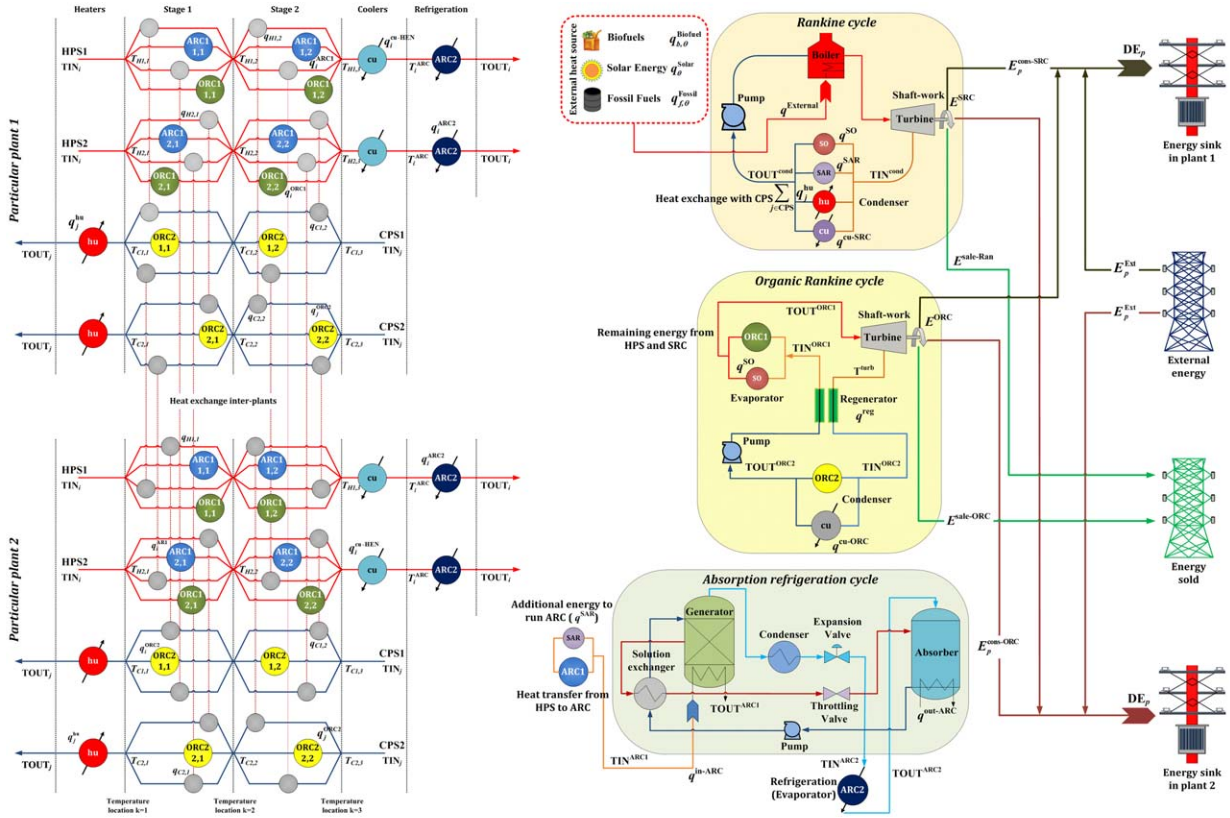

Figure 2. Proposed superstructure for energy integration in eco-industrial parks.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

there are a lot of potential options to synthesis an eco-industrial park energetically integrated; and therefore, there is required a systematic procedure for the optimal integration. Furthermore, usually the energy source used to operate the SRC is prespecified, which impacts drastically on the economic, environmental, and social dimensions because these are intrinsically related (see Figure 1b). In this regard, government incentives can be used to promote the use of cleaner forms of energy to reduce the GHGE and/or generate jobs.[63]

Therefore, in this article is proposed a systematic approach for the optimal design of eco-industrial parks energetically integrated (see Figure 2), where the process streams from several participating industries can exchange heat intra and inter the participating plants; also a shared and integrated central utility system is considered where there is a SRC, an ORC, and an ARC. The proposed model determines the optimal configuration and operating conditions for the integrated eco-industrial park. Furthermore, the proposed approach considers the optimal integration of solar energy, fossil fuels, and biofuels to run the SRC. To solve the proposed approach, a superstructure to integrate the proposed scheme is presented, and a mathematical programming model is formulated to simultaneously minimize the total annual cost (TAC) and the environmental impact for the GHGE as well as to maximize the generated jobs.

Problem Statement

The problem addressed in this article can be described as follows: Given a set of process industries located in the same place that can be converted into an eco-industrial park, where there are process streams that require heating, cooling, and/or refrigeration. The process streams have fixed inlet and target temperatures and heat capacity flow rates. For cooling, there is available cooling water; whereas for heating there is available medium/low pressure steam from the condenser of a shared steam power plant, where electric power is produced and distributed, and this power plant uses different energy sources (solar, biofuels, and fossil fuels) to operate. There are specific demands for electric power in each plant that must be satisfied. To recover the heat excess of the hot process streams, it is possible to install an ORC, and an ARC to satisfy the refrigeration requirements. The electric power produced by the SRC can be used either to satisfy partially the energy demands of different plants or for sale. The remaining heat exiting the ORC is removed using cooling utilities; whereas, the remaining heat exiting the SRC can be used to heat the cold process streams, to operate the ARC and to run the ORC. Also, the cold process streams can obtain heat at low temperature from the condenser of the ORC.

To synthesize an eco-industrial park that is energetically integrated, the superstructure shown in Figure 2 is proposed in this article; this superstructure is a schematic representation for two industrial plants, each one with two hot and two cold process streams and considering two stages for heat transfer between process streams in the same plant and inter-plant (the number of inner stages in the superstructure is stated as the maximum of hot and cold process streams from all participating plants). Heat exchange can occur between any pair of hot and cold process streams of any plant in any stage of the superstructure (allowing this way series, parallel, and series-parallel arrangements) as well as between the shared utility system (SRC, ORC, and ARC) and the process streams. A solar collector, fossil fuels, and biofuels can be used as heat sources in the SRC. The temperatures for the stages of the superstructure are optimization variables. Also the existences of the considered units are optimization variables. The overall greenhouse gas emissions (NGHGE) for fossil fuels and biofuels are computed using the life cycle analysis methodology to account for the overall emissions (the GREET or BESS software can be used in this task).

The problem consists in determining the optimal configuration and operating conditions for the integrated eco-industrial park that minimizes the TAC and the NGHGE accounting for the generated jobs. The TAC includes the capital costs for the heat transfer units in the heat exchanger network (HEN), SRC, ORC, ARC, and solar collector, as well as the operating costs for fossil fuels, biofuels, cooling water, pumping, and external electricity, minus the sales obtained for the power produced in the power plants and tax credits.

It should be noted that this superstructure shown in Figure 2 is general and can be extended to any number of process streams and plants.

Model Formulation

The following subscripts are used in the model formulation; i denotes any hot process stream, j any cold process stream, k any stage in the superstructure, and p represents the plants that conform the eco-industrial park. The sets used to denote the fossil fuels, biofuels, and the time periods (months for this case) are F, B, and Θ, with their corresponding indexes f, b, and θ. The superscript ORC1 is used to represent the heat exchangers that transfer waste heat from the HEN to run the ORC; ORC2 for the exchangers that match the condenser of the ORC to the cold process streams. The superscripts cu-ORC, reg-ORC, and turb-ORC represent cooling water, regenerator, and turbine, all these within of the ORC. The superscripts SO and SAR denote the exchangers that match low pressure stream obtained from the condenser of the steam power plant with the ORC and ARC; cu-SRC denotes cooling water, turb-SRC turbine, and hu heating utility proceeding from the condenser of the SRC. The superscript ARC1 denotes the exchangers that transfer heat from the hot process streams to the generator of the ARC, and ARC2 denotes the exchangers for the hot process streams that require refrigeration; gen, abs, and exch represent the generator, absorber, and solution exchanger of the ARC. HPS is a set of hot process streams, CPS is a set for cold process streams, and ST is the set for the number of stages of the superstructure, and finally, P is a set used to indicate the participating plants.

The proposed optimization formulation is based on the superstructure presented in Figure 2; this model includes the following relationships: total heat transfer balance for each stream, energy balance for each stage of the superstructure, energy balances for the heating and cooling utilities, temperature feasibility constraints, upper bound constraints, and constraints for the temperature differences in the heat transfer units, overall energy balance for the SRC, overall energy balance for the ORC, overall energy balance for the absorption refrigeration system, optimal size for the solar collector, and maximum availability for the fuels, electric energy balance, economic objective function, environmental objective function, and social objective function.

Total heat balance for each process stream

The total energy balance for any hot process stream i is described as the sum of the energy exchanged in any stage of the superstructure with any cold process stream j of any plant ($q_{i,j,k}^{\mathrm{HEN}}$), the energy transferred to the ARC ($q_{i,k}^{\mathrm{ARC1}}$), and the ORC ($q_{i,k}^{\mathrm{ORC1}}$) plus the energy removed with cooling water ($q_i^{\mathrm{cu\text{-}HEN}}$) and refrigeration ($q_i^{\mathrm{ARC2}}$)

$$(\mathrm{TIN}_i-\mathrm{TOUT}_i)\mathrm{FCp}_i=\sum_{k\in \mathrm{ST}}\sum_{j\in \mathrm{CPS}} q_{i,j,k}^{\mathrm{HEN}}+\sum_{k\in \mathrm{ST}} q_{i,k}^{\mathrm{ARC1}} +\sum_{k\in \mathrm{ST}} q_{i,k}^{\mathrm{ORC1}}+q_i^{\mathrm{cu\text{-}HEN}}+q_i^{\mathrm{ARC2}},\ i\in \mathrm{HPS} \tag{1}$$

Similarly, for any cold process stream j, the total heat obtained is from the hot process streams through the superstructure ($q_{i,j,k}^{\mathrm{HEN}}$) plus the energy obtained from the condenser of the ORC ($q_{j,k}^{\mathrm{ORC2}}$) and the medium/low pressure steam from the condenser of SRC ($q_j^{\mathrm{hu\text{-}HEN}}$)

$$\left(\mathrm{TOUT}_j-\mathrm{TIN}_j\right)\mathrm{FCp}_j=\sum_{k\in \mathrm{ST}}\sum_{i\in \mathrm{HPS}} q_{i,j,k}^{\mathrm{HEN}} +\sum_{k\in \mathrm{ST}} q_{j,k}^{\mathrm{ORC2}}+q_j^{\mathrm{hu\text{-}HEN}},\ j\in \mathrm{CPS} \tag{2}$$

where, TIN is the inlet temperature, TOUT is the target temperature, and FCp is the heat capacity flow rate for the process streams.

Energy balance for each stage of the superstructure

The next relationships are required to determine the internal temperatures of the proposed superstructure ($T_{i,k}$, $T_{j,k}$). Then, for each hot process stream i, the heat exchanged in any stage k of the superstructure $\left(\left(T_{i,k}-T_{i,k+1}\right)\mathrm{FCp}\right)$ is equal to the sum of the heat transferred to any cold process stream ($q_{i,j,k}^{\mathrm{HEN}}$), the ARC ($q_{i,k}^{\mathrm{ARC1}}$), and to the ORC ($q_{i,k}^{\mathrm{ORC1}}$); this balance is stated as follows

$$\left(T_{i,k}-T_{i,k+1}\right)\mathrm{FCp}_i=\sum_{j\in \mathrm{CPS}} q_{i,j,k}^{\mathrm{HEN}}+q_{i,k}^{\mathrm{ARC1}}+q_{i,k}^{\mathrm{ORC1}},\ k\in \mathrm{ST},\ i\in \mathrm{HPS} \tag{3}$$

For the cold process streams, the energy obtained in each stage of the superstructure comes from the hot process streams ($q_{i,j,k}^{\mathrm{HEN}}$) and the ORC ($q_{j,k}^{\mathrm{ORC2}}$)

$$\left(T_{j,k}-T_{j,k+1}\right)\mathrm{FCp}_j=\sum_{i\in \mathrm{HPS}} q_{i,j,k}^{\mathrm{HEN}}+q_{j,k}^{\mathrm{ORC2}},\ k\in \mathrm{ST},\ j\in \mathrm{CPS} \tag{4}$$

Heating and cooling utilities

Once the cold process streams have exchanged heat in the inner stages of the superstructure, the target temperatures can be achieved gaining energy from low pressure steam from the SRC, which is used as hot utility

$$\left(\mathrm{TOUT}_j-T_{j,1}\right)\mathrm{FCp}_j=q_j^{\mathrm{hu\text{-}HEN}},\ j\in \mathrm{CPS} \tag{5}$$

The hot process streams can transfer energy with cooling water at the exit of the internal stages of the superstructure

$$\left(T_{i,\mathrm{NOK}+1}-T_i^{\mathrm{ARC}}\right)\mathrm{FCp}_i=q_i^{\mathrm{cu\text{-}HEN}},\ i\in \mathrm{HPS} \tag{6}$$

Likewise, the hot process streams that require refrigeration can be refrigerated through the ARC

$$\left(T_i^{\text{ARC}} - \text{TOUT}_i\right)\text{FCp}_i = q_i^{\text{ARC2}}, i \in \text{HPS} \quad (7)$$

where, $T_{j,1}$ is the temperature of the cold process stream j at the stage 1 and T_i^{ARC} is the inlet temperature of the hot process stream i to the exchanger of the ARC. It should be noted that T_i^{ARC} is lower or equal than the temperature of the hot process stream i in the last stage of the superstructure ($T_{i,\text{NOK}+1}$).

Temperature feasibility constraints

To ensure a proper temperature decrement from the left-hand side (hottest) to the right-hand side (coldest) through the superstructure, the following constraints must be included

$$T_{i,k} \geq T_{i,k+1}, k \in \text{ST}, \; i \in \text{HPS} \quad (8)$$

$$T_{j,k} \geq T_{j,k+1}, k \in \text{ST}, \; j \in \text{CPS} \quad (9)$$

$$T_i^{\text{ARC}} \geq \text{TOUT}_i, \; i \in \text{HPS} \quad (10)$$

$$\text{TOUT}_j \geq T_{j,1}, \; j \in \text{CPS} \quad (11)$$

$$T_{i,\text{NOK}+1} \geq T_i^{\text{ARC}}, \; i \in \text{HPS} \quad (12)$$

It is important to note that the inlet temperature for any hot process stream i is equal to the temperature of the first frontier of the superstructure

$$T_{i,1} = \text{TIN}_i, i \in \text{HPS} \quad (13)$$

Similarly, the inlet temperature for any cold process stream j is equal to the temperature of the last border of the superstructure

$$T_{j,\text{NOK}+1} = \text{TIN}_j, j \in \text{CPS} \quad (14)$$

Upper bound constraints

Upper and lower bound constraints are used to determine the existence of the considered units, which occurs only if the corresponding load is greater than zero (and the corresponding binary variable z is 1); otherwise, the unit does not exist (and the corresponding binary variable z is zero). These logical relationships are expressed as follows.

For the heat exchanger units between process streams through the superstructure

$$\delta z_{i,j,k}^{\text{HEN}} \leq q_{i,j,k}^{\text{HEN}} \leq z_{i,j,k}^{\text{HEN}} Q_{i,j}^{\text{HEN-max}}, i \in \text{HPS}, j \in \text{CPS}, k \in \text{ST} \quad (15)$$

For the heat transfer units of the match of the hot process stream i to the ORC

$$\delta z_{i,k}^{\text{ORC1}} \leq q_{i,k}^{\text{ORC1}} \leq Q_{i,k}^{\text{HEN-max}} z_{i,k}^{\text{ORC1}}, i \in \text{HPS}, k \in \text{ST} \quad (16)$$

For the units that are used to transfer heat from the cold process streams j to the ORC

$$\delta z_{j,k}^{\text{ORC2}} \leq q_{j,k}^{\text{ORC2}} \leq Q_{j,k}^{\text{HEN-max}} z_{j,k}^{\text{ORC2}}, j \in \text{CPS}, \; k \in \text{ST} \quad (17)$$

For the heat transfer units between the hot process streams i and the ARC

$$\delta z_{i,k}^{\text{ARC1}} \leq q_{i,k}^{\text{ARC1}} \leq Q_{i,k}^{\text{HEN-max}} z_{i,k}^{\text{ARC1}}, i \in \text{HPS}, k \in \text{ST} \quad (18)$$

For the coolers refrigerating the hot process streams i

$$\delta z_i^{\text{ARC2}} \leq q_i^{\text{ARC2}} \leq Q_i^{\text{HEN-max}} z_i^{\text{ARC2}}, i \in \text{HPS} \quad (19)$$

For the match between cold process streams j and the hot utility

$$\delta z_j^{\text{hu-HEN}} \leq q_j^{\text{hu-HEN}} \leq Q_j^{\text{HEN-max}} z_j^{\text{hu-HEN}}, j \in \text{CPS} \quad (20)$$

For the heat exchangers between the SRC and the ARC (q^{SAR}) and the ORC (q^{SO})

$$\delta z^{\text{SAR}} \leq q^{\text{SAR}} \leq Q^{\text{SRC-max}} z^{\text{SAR}} \quad (21)$$

$$\delta z^{\text{SO}} \leq q^{\text{SO}} \leq Q^{\text{SRC-max}} z^{\text{SO}} \quad (22)$$

For the coolers of the hot process streams i, ORC ($q^{\text{cu-ORC}}$) and SRC ($q^{\text{cu-SRC}}$) using cooling water, the following relationships apply

$$\delta z_i^{\text{cu-HEN}} \leq q_i^{\text{cu-HEN}} \leq Q_i^{\max} z_i^{\text{cu-HEN}}, i \in \text{HPS} \quad (23)$$

$$\delta z^{\text{ORC}} \leq q^{\text{cu-ORC}} \leq Q^{\text{ORC-max}} z^{\text{ORC}} \quad (24)$$

$$\delta z^{\text{cu-SRC}} \leq q^{\text{cu-SRC}} \leq Q^{\text{SRC-max}} z^{\text{cu-SRC}} \quad (25)$$

For the regenerator of the ORC

$$\delta z^{\text{ORC}} \leq q^{\text{reg-ORC}} \leq Q^{\text{ORC-max}} z^{\text{ORC}} \quad (26)$$

For the solar collector that can be used to heat the SRC

$$\delta z^{\text{Solar}} \leq q_\theta^{\text{Solar}} \leq Q^{\text{SRC-max}} z^{\text{Solar}}, \theta \in \Theta \quad (27)$$

For the pump ($E^{\text{pump-ORC}}$) and the turbine (E^{ORC}) of the ORC

$$\delta z^{\text{ORC}} \leq E^{\text{pump-ORC}} \leq Q^{\text{ORC-max}} z^{\text{ORC}} \quad (28)$$

$$\delta z^{\text{ORC}} \leq E^{\text{ORC}} \leq Q^{\text{ORC-max}} z^{\text{ORC}} \quad (29)$$

where, the parameters $Q^{\text{HEN-max}}$, $Q^{\text{SRC-max}}$, and $Q^{\text{ORC-max}}$ are upper limits for the load of the corresponding units, δ is a small parameter, and z is a binary variable used to select the unit (a value of 1 indicates that the unit exists and a value of zero indicates that the unit does not exist).

It should be noted that the components of the ORC use the same binary variable because the ORC is treated as optimization variable, and these components exist when the ORC is selected to appear in the optimal solution.

Constraints for the temperature differences in the heat transfer units

Positive temperature differences are required to calculate the heat transfer area for each heat exchanger in the network. These temperature differences are activated only when the units exist (z equals 1) and must be greater than the minimum temperature difference allowed. For each heat transfer unit, there are required two constraints, one for the hot side and other for the cold side. These constraints are stated as follow.

a. In the HEN

For heat exchange units between process streams

$$dT_{i,j,k}^{\text{HEN-hot}} \leq T_{i,k} - T_{j,k} + \Delta T_{i,j}^{\text{HEN-max}}\left(1 - z_{i,j,k}^{\text{HEN}}\right), \quad i \in \text{HPS}, j \in \text{CPS}, k \in \text{ST} \quad (30)$$

$$dT_{i,j,k+1}^{\text{HEN-cold}} \leq T_{i,k+1} - T_{j,k+1} + \Delta T_{i,j}^{\text{HEN-max}}\left(1 - z_{i,j,k}^{\text{HEN}}\right), \quad i \in \text{HPS}, j \in \text{CPS}, k \in \text{ST} \quad (31)$$

For the coolers that use cooling water

$$dT_i^{\text{cu-HEN-hot}} \leq T_{i,\text{NOK}+1} - \text{TOUT}_i^{\text{cu-HEN}} + \Delta T_i^{\text{cu-HEN-max}}\left(1 - z_i^{\text{cu-HEN}}\right), i \in \text{HPS} \quad (32)$$

$$dT_i^{\text{cu-HEN-cold}} \leq T_i^{\text{ARC}} - \text{TIN}_i^{\text{cu-HEN}} + \Delta T_i^{\text{cu-HEN-max}}\left(1 - z_i^{\text{cu-HEN}}\right), i \in \text{HPS} \quad (33)$$

For hot utility

$$dT_j^{\text{hu-HEN-hot}} = \text{TIN}^{\text{hu-HEN}} - \text{TOUT}_j, j \in \text{CPS} \quad (34)$$

$$dT_j^{\text{hu-HEN-cold}} \leq \text{TOUT}^{\text{hu-HEN}} - T_{j,1} + \Delta T_j^{\text{hu-HEN-max}}\left(1 - z_j^{\text{hu-HEN}}\right), j \in \text{CPS} \quad (35)$$

b. In the SRC
For heat exchange between the SRC with the ORC

$$dT^{\text{SO-hot}} = \text{TIN}^{\text{cond-SRC}} - \text{TOUT}^{\text{ORC1}} \quad (36)$$

$$dT^{\text{SO-cold}} = \text{TOUT}^{\text{cond-SRC}} - \text{TIN}^{\text{ORC1}} \quad (37)$$

Similarly, for the heat exchange between the SRC with the ARC

$$dT^{\text{SAR-hot}} = \text{TIN}^{\text{cond-SRC}} - \text{TOUT}^{\text{ARC1}} \quad (38)$$

$$dT^{\text{SAR-cold}} = \text{TOUT}^{\text{cond-SRC}} - \text{TIN}^{\text{ARC1}} \quad (39)$$

For the cooler of the SRC using cooling water

$$dT^{\text{cu-SRC-hot}} = \text{TIN}^{\text{cond-SRC}} - \text{TOUT}^{\text{cu-SRC}} \quad (40)$$

$$dT^{\text{cu-SRC-cold}} = \text{TOUT}^{\text{cond-SRC}} - \text{TIN}^{\text{cu-SRC}} \quad (41)$$

where, the inlet and outlet temperatures for the condenser of the SRC are equal to inlet and outlet temperatures of the hot utility used to heat the cold process streams, respectively.

$$\text{TIN}^{\text{cond-SRC}} = \text{TIN}^{\text{hu-HEN}} \quad (42)$$

$$\text{TOUT}^{\text{cond-SRC}} = \text{TOUT}^{\text{hu-HEN}} \quad (43)$$

c. ORC
The following relationships are required for the heat exchangers between hot process streams i and the ORC

$$dT_{i,k}^{\text{ORC1-hot}} \leq T_{i,k} - \text{TOUT}^{\text{ORC1}} + \Delta T_i^{\text{ORC1-max}}\left(1 - z_{i,k}^{\text{ORC1}}\right), i \in \text{HPS},\ k \in \text{ST} \quad (44)$$

$$dT_{i,k+1}^{\text{ORC1-cold}} \leq T_{i,k+1} - \text{TIN}^{\text{ORC1}} + \Delta T_i^{\text{ORC1-max}}\left(1 - z_{i,k}^{\text{ORC1}}\right), i \in \text{HPS},\ k \in \text{ST} \quad (45)$$

For the heat exchangers between cold process streams j and the ORC

$$dT_{j,k}^{\text{ORC2-hot}} \leq \text{TIN}^{\text{ORC2}} - T_{j,k} + \Delta T_j^{\text{ORC2-max}}\left(1 - z_{j,k}^{\text{ORC2}}\right), j \in \text{CPS},\ k \in \text{ST} \quad (46)$$

$$dT_{j,k+1}^{\text{ORC2-cold}} \leq \text{TOUT}^{\text{ORC2}} - T_{j,k+1} + \Delta T_j^{\text{ORC2-max}}\left(1 - z_{j,k}^{\text{ORC2}}\right), j \in \text{CPS},\ k \in \text{ST} \quad (47)$$

For the coolers using cooling water in the condenser of the ORC

$$dT^{\text{cu-ORC-hot}} = \text{TIN}^{\text{ORC2}} - \text{TOUT}^{\text{cu-ORC}} \quad (48)$$

$$dT^{\text{cu-ORC-cold}} = \text{TOUT}^{\text{ORC2}} - \text{TIN}^{\text{cu-ORC}} \quad (49)$$

For the regenerator in the ORC

$$dT^{\text{reg-ORC-hot}} = T^{\text{turb-ORC}} - \text{TIN}^{\text{ORC1}} \quad (50)$$

$$dT^{\text{reg-ORC-cold}} = \text{TIN}^{\text{ORC2}} - \text{TOUT}^{\text{ORC2}} \quad (51)$$

d. In the ARC
For the heat exchange from hot process streams i to the ARC in each stage of the superstructure, the following relationships are used

$$dT_{i,k}^{\text{ARC1-hot}} \leq T_{i,k} - \text{TOUT}^{\text{ARC1}} + \Delta T_i^{\text{ARC1-max}}\left(1 - z_{i,k}^{\text{ARC1}}\right), i \in \text{HPS},\ k \in \text{ST} \quad (52)$$

$$dT_{i,k+1}^{\text{ARC1-cold}} \leq T_{i,k+1} - \text{TIN}^{\text{ARC1}} + \Delta T_i^{\text{ARC1-max}}\left(1 - z_{i,k}^{\text{ARC1}}\right), i \in \text{HPS},\ k \in \text{ST} \quad (53)$$

Similarly, for the units used to refrigerate the hot process streams

$$dT_i^{\text{ARC2-hot}} \leq T_i^{\text{ARC}} - \text{TOUT}^{\text{ARC2}} + \Delta T_i^{\text{ARC2-max}}\left(1 - z_i^{\text{ARC2}}\right), i \in \text{HPS} \quad (54)$$

$$dT_i^{\text{ARC2-cold}} = \text{TOUT}_i - \text{TIN}^{\text{ARC2}}, i \in \text{HPS} \quad (55)$$

It should be noted that the inlet and outlet temperatures from the participating systems are known parameters.

Temperature feasibility constraints

Finally, all the temperature differences for the heat exchangers required must be greater than the minimum temperature difference

$$\Delta T^{\min} \leq dT_{i,j,k}^{\text{HEN-hot}}, i \in \text{HPS}, j \in \text{CPS}, k \in \text{ST} \quad (56)$$

$$\Delta T^{\min} \leq dT_{i,j,k+1}^{\text{HEN-cold}}, i \in \text{HPS}, j \in \text{CPS}, k \in \text{ST} \quad (57)$$

$$\Delta T^{\min} \leq dT_i^{\text{cu-HEN-hot}}, i \in \text{HPS} \quad (58)$$

$$\Delta T^{\min} \leq dT_i^{\text{cu-HEN-cold}}, i \in \text{HPS} \quad (59)$$

$$\Delta T^{\min} \leq dT_j^{\text{hu-HEN-cold}}, j \in \text{CPS} \quad (60)$$

$$\Delta T^{\min} \leq dT_{i,k}^{\text{ORC1-hot}}, i \in \text{HPS},\ k \in \text{ST} \quad (61)$$

$$\Delta T^{\min} \leq dT_{i,k+1}^{\text{ORC1-cold}}, i \in \text{HPS},\ k \in \text{ST} \quad (62)$$

$$\Delta T^{\min} \leq dT_{j,k}^{\text{ORC2-hot}}, j \in \text{CPS},\ k \in \text{ST} \quad (63)$$

$$\Delta T^{\min} \leq dT_{j,k+1}^{\text{ORC2-cold}}, j \in \text{CPS},\ k \in \text{ST} \quad (64)$$

$$\Delta T^{\min} \leq dT_{i,k}^{\text{ARC1-hot}}, i \in \text{HPS}, k \in \text{ST} \quad (65)$$

$$\Delta T^{\min} \leq dT_{i,k+1}^{\text{ARC1-cold}}, i \in \text{HPS}, k \in \text{ST} \quad (66)$$

$$\Delta T^{\min} \leq dT_i^{\text{ARC2-hot}}, i \in \text{HPS} \quad (67)$$

where, $\Delta T^{\max}$ and $\Delta T^{\min}$ are upper and lower bounds for the temperature differences of the heat exchanger units.

Overall energy balance for the SRC

For modeling purposes, this article considers a coefficient of performance (COP) for the ARC (COP^{ARC}) and efficiency factors for the SRC (η^{SRC}) and the ORC (η^{ORC}). Additionally, the optimal size for the solar collector is determined considering simultaneously the monthly solar radiation available on the selected site and the maximum availabilities to satisfy the energy requirements of the systems.

The external energy sources are only supplied to the SRC; in this context, q^{External} represents the total energy provided by the solar collector ($q_{\theta}^{\text{Solar}}$), biofuels ($q_{b,\theta}^{\text{Biofuel}}$), and fossil fuels ($q_{f,\theta}^{\text{Fossil}}$)

$$q^{\text{External}} = q_{\theta}^{\text{Solar}} + \sum_{b \in B} q_{b,\theta}^{\text{Biofuel}} + \sum_{f \in F} q_{f,\theta}^{\text{Fossil}}, \theta \in \Theta \quad (68)$$

Then, the power produced by the SRC is given by the following relationship

$$E^{\text{SRC}} = q^{\text{External}} \eta^{\text{SRC}} \quad (69)$$

The electric energy required for pumping the working fluid in the SRC is obtained as follows

$$E^{\text{pump-SRC}} = E^{\text{SRC}} \eta^{\text{pump-SRC}} \quad (70)$$

The total heat load transferred in the condenser ($q^{\text{cond-SRC}}$) is obtained by the sum of the total energy provided to the boiler of the SRC (q^{External}), the power required by the pump ($E^{\text{pump-SRC}}$), minus the generated electric power by the system (E^{SRC}), which is stated as follows

$$q^{\text{cond-SRC}} = q^{\text{External}} + E^{\text{pump-SRC}} - E^{\text{SRC}} \quad (71a)$$

In addition, the total heat load required in the condenser ($q^{\text{cond-SRC}}$) is the sum of the heat exchanged with the ARC (q^{SAR}), the ORC (q^{SO}), the hot process streams i from any plant ($q_j^{\text{hu-HEN}}$), and cooling water ($q^{\text{cu-SRC}}$)

$$q^{\text{cond-SRC}} = q^{\text{SAR}} + q^{\text{SO}} + \sum_{j \in CPS} q_j^{\text{hu-HEN}} + q^{\text{cu-SRC}} \quad (71b)$$

Overall energy balance for the ORC

The electric power generated in the ORC (E^{ORC}) is determined considering the sum of the energy provided to the cycle ($\sum_{i \in HPS} \sum_{k \in ST} q_{i,k}^{\text{ORC1}} + q^{\text{SO}}$) and multiplied by an efficiency factor (η^{ORC}) that depends on the selected organic fluid and the operating conditions that are optimized before the integration process

$$E^{\text{ORC}} = \left(\sum_{i \in HPS} \sum_{k \in ST} q_{i,k}^{\text{ORC1}} + q^{\text{SO}} \right) \eta^{\text{ORC}} \quad (72)$$

The demanded pumping power in the ORC is calculated considering the energy produced and the efficiency factor for the pump ($\eta^{\text{pump-ORC}}$)

$$E^{\text{pump-ORC}} = E^{\text{ORC}} \eta^{\text{pump-ORC}} \quad (73)$$

where $\eta^{\text{pump-ORC}}$ depends on the energy produced by the ORC and it usually takes values lower than 0.06.

The total heat load for the condenser of the ORC ($q^{\text{cond-ORC}}$) is equal to the sum of the heat sent from the hot process streams to the ORC ($q_{i,k}^{\text{ORC1}}$), plus the heat obtained from the SRC (q^{SO}), the power consumed by the pump ($E^{\text{pump-ORC}}$), minus the power produced by the power plant (E^{ORC})

$$q^{\text{cond-ORC}} = \sum_{i \in HPS} \sum_{k \in ST} q_{i,k}^{\text{ORC1}} + q^{\text{SO}} + E^{\text{pump-ORC}} - E^{\text{ORC}} \quad (74a)$$

The energy rejected by the condenser of the ORC ($q^{\text{cond-ORC}}$) can be sent to the cold process streams ($q_{j,k}^{\text{ORC2}}$) and to cooling water of the ORC ($q^{\text{cu-ORC}}$)

$$q^{\text{cond-ORC}} = \sum_{j \in CPS} \sum_{k \in ST} q_{j,k}^{\text{ORC2}} + q^{\text{cu-ORC}} \quad (74b)$$

The heat load required in the regenerator ($q^{\text{reg-ORC}}$) depends on the generated electricity in the ORC and this can be calculated through the following expression

$$q^{\text{reg-ORC}} = E^{\text{ORC}} \eta^{\text{reg-ORC}} \quad (75)$$

where $\eta^{\text{reg-ORC}}$ is the efficiency for the regenerator in the ORC and it usually takes values lower than 0.045. The efficiencies are obtained from previously reported values found in the literature.[35]

Notice that the condensers used by the power cycles remove the heat that cannot be integrated with other units.

Overall energy balance for the ARC

The refrigeration required for the hot process streams (q_i^{ARC2}) must be equal to the energy rejected to the condenser of the ARC ($q^{\text{cond-ARC}}$) plus the energy sent to the absorbent of the ARC ($q^{\text{abs-ARC}}$), minus the energy supplied to the generator ($q^{\text{gen-ARC}}$) and the energy supplied to the pump of the ARC ($E^{\text{pump-ARC}}$)

$$\sum_{i \in HPS} q_i^{\text{ARC2}} = q^{\text{cond-ARC}} + q^{\text{abs-ARC}} - q^{\text{gen-ARC}} - E^{\text{pump-ARC}} \quad (76)$$

The COP is the ratio of the waste heat supplied to the evaporator (q_i^{ARC2}) and generator ($q^{\text{gen-ARC}}$). The pumping energy is neglected compared to the heat duties of the ARC and is not considered in the calculation of the COP. This is stated as follows

$$\text{COP}^{\text{ARC}} = \frac{\sum_{i \in HPS} q_i^{\text{ARC2}}}{q^{\text{gen-ARC}}} \quad (77)$$

The heat load required in the generator is equal to the sum of the energy of the hot process streams in the stages of the superstructure ($q_{i,k}^{\text{ARC1}}$) and the waste heat from the condenser of the SRC (q^{SAR})

$$q^{\text{gen-ARC}} = \sum_{i \in HPS} \sum_{k \in ST} q_{i,k}^{\text{ARC1}} + q^{\text{SAR}} \quad (78)$$

The next equations are required to determine the heat load of the components of the ARC, where η is the efficiency for each component with respect to energy supplied to the cycle.

For the absorber

$$q^{\text{abs-ARC}} = \eta^{\text{abs-ARC}} \left(\sum_{i \in HPS} q_i^{\text{ARC2}} + q^{\text{gen-ARC}} \right) \quad (79)$$

For the energy consumed by the pump

$$E^{\text{pump-ARC}} = \eta^{\text{pump-ARC}} \left(\sum_{i \in \text{HPS}} q_i^{\text{ARC2}} + q^{\text{gen-ARC}} \right) \quad (80)$$

And finally, for the exchanger of the ARC

$$q^{\text{exch-ARC}} = \eta^{\text{exch-ARC}} \left(\sum_{i \in \text{HPS}} q_i^{\text{ARC2}} + q^{\text{gen-ARC}} \right) \quad (81)$$

Optimal size for the solar collector and maximum availability for the fuels

The proposed model considers that a solar collector can provide energy to the SRC; in this case, the useful solar energy ($Q_\theta^{\text{Use-Solar}}$) is obtained accounting for the available solar radiation in the specific location where the solar collector is installed as well as the efficiency of the equipment. Then, the following relationships model the performance of the solar collector and determine its size. In addition, if the solar collector is not required, then the solar energy supplied to the system is zero ($q_\theta^{\text{Solar}} = 0, \forall \theta \in \Theta$)

$$q_\theta^{\text{Solar}} \leq Q_\theta^{\text{Use-Solar}} A^{\text{Solar}} \frac{1}{D_\theta}, \forall \theta \in \Theta \quad (82)$$

where A^{Solar} represents the optimal area of the solar collector and D_θ is a conversion factor for the units of time.

Usually the availability of the biofuels fluctuates during the year; therefore, the next relationship models this variation

$$q_{b,\theta}^{\text{Biofuel}} \leq \frac{\text{Heating}_b^{\text{Power}} \text{Avail}_{b,\theta}^{\max}}{D_\theta}, b \in B, \theta \in \Theta \quad (83)$$

where $\text{Heating}_b^{\text{Power}}$ is the heating power for the biofuel b and $\text{Avail}_{b,\theta}^{\max}$ represents the maximum amount of the biofuel b available over the time period θ.

Similarly, if the availability of fossil fuels also presents a seasonal restriction, it is considered as follows

$$q_{f,\theta}^{\text{Fossil}} \leq \frac{\text{Heating}_f^{\text{Power}} \text{Avail}_{f,\theta}^{\max}}{D_\theta}, f \in F, \theta \in \Theta \quad (84)$$

Electric energy balance

The power produced by the ORC (E^{ORC}) is equal to the sum of the energy consumed by the plants ($E_p^{\text{cons-ORC}}$), plus the energy sold ($E^{\text{sale-ORC}}$) by the ORC

$$E^{\text{ORC}} = \sum_{p \in \text{P}} E_p^{\text{cons-ORC}} + E^{\text{sale-ORC}} \quad (85)$$

Similarly, the energy produced in the SRC (E^{SRC}) is equal to the energy consumed by the plants ($E_p^{\text{cons-SRC}}$) plus the energy sold ($E^{\text{sale-SRC}}$)

$$E^{\text{SRC}} = \sum_{p \in \text{P}} E_p^{\text{cons-SRC}} + E^{\text{sale-SRC}} \quad (86)$$

The power demanded for each plant (DE_p) is equal to the sum of the consumed power in each plant from the SRC ($E_p^{\text{cons-SRC}}$) and the ORC ($E_p^{\text{cons-ORC}}$), plus the external power needed (E_p^{Ext}) so that the process is carried out in the plants

$$\text{DE}_p = E_p^{\text{cons-SRC}} + E_p^{\text{cons-ORC}} + E_p^{\text{Ext}}, p \in \text{P} \quad (87)$$

where p is an index used to indicate the plants; whereas P is the set for all p.

Economic objective function

The economic objective function consists in minimizing the TAC, which is the sum of the costs generated by the project (operating costs, *Opec* and capital costs *Capc*) minus the incomes (from the energy produced in the SRC and ORC, *Sprc* and the tax credits for the reduction of GHGE, *Tcr*)

$$\min \ \text{TAC} = Opec + Capc - Sprc - Tcr \quad (88)$$

The operating cost includes the associated costs for the cooling required in the HEN, SRC, ORC, and ARC, plus the pumping power demanded in the previous systems, plus the external energy required for the SRC (which can be obtained from the solar collector, fossil fuels, and biofuels) as well as for the plants

$$Opec = H_Y \left(\begin{array}{l} C_i^{\text{cu}} \sum_{i \in \text{HPS}} q_i^{\text{cu-HEN}} + C^{\text{cu}} q^{\text{cu-SRC}} + C^{\text{cu}} q^{\text{cu-ORC}} + C^{\text{cu}} q^{\text{cond-ARC}} + C^{\text{elect-b}} E^{\text{pump-ORC}} \\ \qquad + C^{\text{elect-b}} E^{\text{pump-SRC}} + C^{\text{elect-b}} E^{\text{pump-ARC}} + C^{\text{elect-b}} \sum_{p \in \text{P}} E_p^{\text{Ext}} \end{array} \right)$$
$$+ C^{\text{Solar}} \sum_{\theta \in \Theta} \left(q_\theta^{\text{Solar}} D_\theta \right) + \sum_{f \in F} \sum_{\theta \in \Theta} \left(C_f^{\text{Fossil}} q_{f,\theta}^{\text{Fossil}} D_\theta \right) + \sum_{b \in B} \sum_{\theta \in \Theta} \left(C_b^{\text{Biofuel}} q_{b,\theta}^{\text{Biofuel}} D_\theta \right) \quad (89)$$

where H_Y is the annual operating time, C^{cu} is the unitary cost for the cooling utility required for the system. $C^{\text{elect-b}}$ is the unitary sale price for the electric power. C^{Solar}, C^{Fossil}, and C^{Biofuel} are the unitary costs for energy sources consumed in the SRC. E^{pump} is the demanded power in the pump and E_p^{Ext} is the external energy required in the plant p.

The annualized capital cost includes the fixed (*Fixcap*) and variable (*Varcap*) capital costs of the heat exchange units (including the heat exchangers between process streams and incorporated units, coolers, and heaters) as well as for the pumps, turbines installed in the SRC and ORC, and the components that constitute the ARC

$$Capc = Fixcap + Varcap \quad (90)$$

The fixed cost is independent of the size of the units and this is calculated accounting for each component of the system as follows

$$
Fixcap = k_F \left(\begin{array}{l}
\sum_{i\in HPS}\sum_{j\in CPS}\sum_{k\in ST} CF_{i,j}^{HEN} z_{i,j,k}^{HEN} + \sum_{i\in HPS} CF_i^{cu\text{-}HEN} z_i^{cu\text{-}HEN} + \sum_{j\in CPS} CF_j^{hu\text{-}HEN} z_j^{hu\text{-}HEN} \\
+ \sum_{i\in HPS}\sum_{k\in ST} CF_i^{ORC1} z_{i,k}^{ORC1} + \sum_{j\in CPS}\sum_{k\in ST} CF_j^{ORC2} z_{j,k}^{ORC2} \\
+ \sum_{i\in HPS}\sum_{k\in ST} CF_i^{ARC1} z_{i,k}^{ARC1} + \sum_{i\in HPS} CF_i^{ARC2} z_i^{ARC2} \\
+ CF^{cu\text{-}ORC} z^{ORC} + CF^{turb\text{-}ORC} z^{ORC} + CF^{pump\text{-}ORC} z^{ORC} + CF^{reg\text{-}ORC} z^{ORC} \\
+ CF^{boiler} + CF^{cu\text{-}SRC} + CF^{turb\text{-}SRC} + CF^{pump\text{-}SRC} \\
+ CF^{cond\text{-}ARC} + CF^{pump\text{-}ARC} + CF^{gen\text{-}ARC} + CF^{abs\text{-}ARC} + CF^{exch\text{-}ARC} \\
+ CF^{SO} z^{SO} + CF^{SAR} z^{SAR} + CF^{Solar} z^{Solar}
\end{array} \right) \quad (91)
$$

where CF represents the fixed costs for exchangers and complementary units, whereas z is the binary variable to consider the existence of the heat exchanger unit. It should be noted that the fixed costs for the units of the SRC and the ARC are not multiplied by a binary variable because these cycles always exist due to the energy requirements. Although for the variable part of the cost, which depends on the size of the units, it is expressed as follows

$$
Varcap = k_F \left(\begin{array}{l}
\sum_{i\in HPS}\sum_{j\in CPS}\sum_{k\in ST} CV_{i,j}^{HEN} \left\{ \frac{q_{i,j,k}^{HEN}\left(1/h_{i,k}+1/h_{j,k}\right)}{\left[\left(dT_{i,j,k}^{HEN\text{-}hot}\right)\left(dT_{i,j,k+1}^{HEN\text{-}cold}\right)\left(dT_{i,j,k}^{HEN\text{-}hot}+dT_{i,j,k+1}^{HEN\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{HEN}} \\
+ \sum_{i\in HPS} CV_i^{cu\text{-}HEN} \left\{ \frac{q_i^{cu\text{-}HEN}\left(1/h_i+1/h^{cu\text{-}HEN}\right)}{\left[\left(dT_i^{cu\text{-}HEN\text{-}hot}\right)\left(dT_i^{cu\text{-}HEN\text{-}cold}\right)\left(dT_i^{cu\text{-}HEN\text{-}hot}+dT_i^{cu\text{-}HEN\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{cu\text{-}HEN}} \\
+ \sum_{j\in CPS} CV_j^{hu\text{-}HEN} \left\{ \frac{q_j^{hu\text{-}HEN}\left(1/h^{hu\text{-}HEN}+1/h_j\right)}{\left[\left(dT_j^{hu\text{-}HEN\text{-}hot}\right)\left(dT_j^{hu\text{-}HEN\text{-}cold}\right)\left(dT_j^{hu\text{-}HEN\text{-}hot}+dT_j^{hu\text{-}HEN\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{hu\text{-}HEN}} \\
+ \sum_{i\in HPS}\sum_{k\in ST} CV_i^{ORC1} \left\{ \frac{q_{i,k}^{ORC1}\left(1/h_i+1/h^{ORC1}\right)}{\left[\left(dT_{i,k}^{ORC1\text{-}hot}\right)\left(dT_{i,k}^{ORC1\text{-}cold}\right)\left(dT_{i,k}^{ORC1\text{-}hot}+dT_{i,k}^{ORC1\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{ORC1}} \\
+ \sum_{j\in CPS}\sum_{k\in ST} CV_j^{ORC2} \left\{ \frac{q_{j,k}^{ORC2}\left(1/h^{ORC2}+1/h_j\right)}{\left[\left(dT_{j,k}^{ORC2\text{-}hot}\right)\left(dT_{j,k}^{ORC2\text{-}cold}\right)\left(dT_{j,k}^{ORC2\text{-}hot}+dT_{j,k}^{ORC2\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{ORC2}} \\
+ \sum_{i\in HPS}\sum_{k\in ST} CV_i^{ARC1} \left\{ \frac{q_{j,k}^{ARC1}\left(1/h_i+1/h^{ARC1}\right)}{\left[\left(dT_{i,k}^{ARC1\text{-}hot}\right)\left(dT_{i,k}^{ARC1\text{-}cold}\right)\left(dT_{i,k}^{ARC1\text{-}hot}+dT_{i,k}^{ARC1\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{ARC1}} \\
+ \sum_{i\in HPS} CV_i^{ARC2} \left\{ \frac{q_j^{ARC2}\left(1/h^{ARC2}+1/h_i\right)}{\left[\left(dT_i^{ARC2\text{-}hot}\right)\left(dT_i^{ARC2\text{-}cold}\right)\left(dT_i^{ARC2\text{-}hot}+dT_i^{ARC2\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{ARC2}} \\
+ CV^{cu\text{-}ORC} \left\{ \frac{q^{cu\text{-}ORC}\left(1/h^{ORC2}+1/h^{cu\text{-}ORC}\right)}{\left[\left(dT^{cu\text{-}ORC\text{-}hot}\right)\left(dT^{cu\text{-}ORC\text{-}cold}\right)\left(dT^{cu\text{-}ORC\text{-}hot}+dT^{cu\text{-}ORC\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{cu\text{-}ORC}} \\
+ CV^{cu\text{-}SRC} \left\{ \frac{q^{cu\text{-}SRC}\left(1/h^{cond\text{-}SRC}+1/h^{cu\text{-}SRC}\right)}{\left[\left(dT^{cu\text{-}SRC\text{-}hot}\right)\left(dT^{cu\text{-}SRC\text{-}cold}\right)\left(dT^{cu\text{-}SRC\text{-}hot}+dT^{cu\text{-}SRC\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{cu\text{-}SRC}} \\
+ CV^{SO} \left\{ \frac{q^{SO}\left(1/h^{SO}+1/h^{cond\text{-}SRC}\right)}{\left[\left(dT^{SO\text{-}hot}\right)\left(dT^{SO\text{-}cold}\right)\left(dT^{SO\text{-}hot}+dT^{SO\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{SO}} \\
+ CV^{SAR} \left\{ \frac{q^{SAR}\left(1/h^{SAR}+1/h^{cond\text{-}SRC}\right)}{\left[\left(dT^{SAR\text{-}hot}\right)\left(dT^{SAR\text{-}cold}\right)\left(dT^{SAR\text{-}hot}+dT^{SAR\text{-}cold}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{SAR}}
\end{array} \right)
$$

$$\left(\begin{array}{l} +\mathrm{CV}^{\text{reg-ORC}} \left\{ \dfrac{q^{\text{reg-ORC}}\left(1/h^{\text{reg-hot}}+1/h^{\text{reg-cold}}\right)}{\left[\left(dT^{\text{reg-ORC-hot}}\right)\left(dT^{\text{reg-ORC-cold}}\right)\left(dT^{\text{reg-ORC-hot}}+dT^{\text{reg-ORC-cold}}\right)/2+\delta\right]^{1/3}} \right\}^{\beta^{\text{reg-ORC}}} \\ +\mathrm{CV}^{\text{turb-ORC}}\left(E^{\text{ORC}}\right)^{\beta^{\text{turb-ORC}}}+\mathrm{CV}^{\text{pump-ORC}}\left(E^{\text{pump-ORC}}\right)^{\beta^{\text{pump-ORC}}} \\ +\mathrm{CV}^{\text{boiler}}\left(q^{\text{External}}\right)^{\beta^{\text{boiler}}}+\mathrm{CV}^{\text{turb-SRC}}\left(E^{\text{SRC}}\right)^{\beta^{\text{turb-SRC}}}+\mathrm{CV}^{\text{pump-SRC}}\left(E^{\text{pump-SRC}}\right)^{\beta^{\text{pump-SRC}}} \\ +\mathrm{CV}^{\text{cond-ARC}}\left(q^{\text{cond-ARC}}\right)^{\beta^{\text{cond-ARC}}}+\mathrm{CV}^{\text{exch-ARC}}\left(q^{\text{exch-ARC}}\right)^{\beta^{\text{exch-ARC}}}+\mathrm{CV}^{\text{gen-ARC}}\left(q^{\text{gen-ARC}}\right)^{\beta^{\text{gen-ARC}}} \\ +\mathrm{CV}^{\text{abs-ARC}}\left(q^{\text{abs-ARC}}\right)^{\beta^{\text{abs-ARC}}}+\mathrm{CV}^{\text{pump-ARC}}\left(E^{\text{pump-ARC}}\right)^{\beta^{\text{pump-ARC}}}+\mathrm{CV}^{\text{Solar}}\left(A^{\text{Solar}}\right)^{\beta^{\text{Solar}}} \end{array} \right) \quad (92)$$

where k_F is the factor used to annualize the inversion, δ is a small value used to avoid infeasibilities in the optimization process, whereas CV is the area cost coefficients for exchangers between process streams and incorporated units; β is a parameter used to consider the economies of scale (it usually takes a value between 0.6 and 0.9) and finally, h represents the film heat transfer coefficients. To calculate the Log Mean Temperature Difference (LMTD) for the heat exchanger units, this work uses the Chen's approximation[64] to avoid logarithmic terms in the optimization model.

The most important income is the selling of power, which is generated by the SRC and the ORC. This is calculated as follows

$$Sprc=H_Y\left(C^{\text{elect-s}}E^{\text{sale-SRC}}+C^{\text{elect-s}}E^{\text{sale-ORC}}\right) \quad (93)$$

where $C^{\text{elect-s}}$ is the unitary selling price for the electricity, $E^{\text{sale-SRC}}$ and $E^{\text{sale-ORC}}$ are the generated powers in the SRC and ORC, respectively.

Tax credit reduction (Tcr) includes the revenues obtained by the tax credits for the reduction in the GHGE and these are calculated taking into account the reduction of GHGE compared to a fossil fuel of reference (coal)

$$Tcr=R^{\text{Solar}}\sum_{\theta\in\Theta}\left(q_\theta^{\text{Solar}}D_\theta\right)+\sum_{\theta\in\Theta}\sum_{b\in B}\left(R_b^{\text{Biofuel}}q_{b,\theta}^{\text{Biofuel}}D_\theta\right) +\sum_{\theta\in\Theta}\sum_{f\in F}\left(R_f^{\text{Fossil}}q_{f,\theta}^{\text{Fossil}}D_\theta\right) \quad (94)$$

where R^{Solar}, R_b^{Biofuel}, and R_f^{Fossil} are the unitary tax credits for solar energy, biofuels, and fossil fuels, respectively.

Environmental objective function

The environmental objective function is an indirect environmental impact assessment through the overall quantification of the GHGE. The GHGE for solar collectors are assumed to be zero; however, when the fossil fuels and biofuels are burned, these release GHGE that represent an adverse effect on the environment. Therefore, the environmental objective function is stated as follows

$$\min \mathrm{NGHGE}^{\text{Overall}}=\sum_{\theta\in\Theta}\sum_{f\in B}\left(\mathrm{GHGE}_f^{\text{Fossil}}q_{f,\theta}^{\text{Fossil}}D_\theta\right) +\sum_{\theta\in\Theta}\sum_{b\in B}\left(\mathrm{GHGE}_b^{\text{Biofuel}}q_{b,\theta}^{\text{Biofuel}}D_\theta\right) \quad (95)$$

where $\mathrm{NGHGE}^{\text{overall}}$ (ton of CO_{2eq} per year) represents the overall GHGE discharged to the environment by the fossil fuels and biofuels to satisfy the energy requirements, whereas $\mathrm{GHGE}_b^{\text{Biofuel}}$ and $\mathrm{GHGE}_f^{\text{Fossil}}$ are the individual GHGE for the fossil fuel f and biofuel b. It is important to mention that the individual GHGE are determined through the life cycle analysis (the GREET software can be used for this purpose)[65] given in units of ton of CO_{2eq} reduction per kJ provided.

Social objective function

There are several aspects that can be evaluated within the social scope in the proposed project; however, a relevant point of view is the creation of jobs owing to this factor can improve the economic conditions of the local region and surroundings.[14] In this regard, this work considers the social impact associated to the generation of jobs for the production of the biofuels and fossil fuels as well as for the operation of the solar collector to satisfy the energy requirements in the system. The generated jobs are determined indirectly for the production of the biofuels and fossil fuels as well as for the operation of the solar collector to satisfy the energy requirements in the system. To carry out this task, the jobs and economic development impact (JEDI) model is useful to quantify the number of jobs that can be generated per unit of energy produced by each energy source (solar collectors, fossil fuels, and biofuels). Miller and Blair[66] have used the JEDI model for economic and social sciences, which is based on an input–output analysis. The input–output analysis is based on the use of multipliers, where a multiplier is a simple ratio of a total systemic change over the initial conditions resulting from a given economic activity. This provides estimates of the total impact resulting from an initial change on economic output (employment) through the implementation or termination of a project. The size of a multiplier depends on several economic factors, such as the level of local spending for a given industry, degree of sales outside the local region, industry type, and other regional considerations. Self-sufficient areas in which businesses purchase more local inputs and export greater amounts have higher multipliers. Additionally, some industries might be much more dependent than others on the local area for materials and labor. The multipliers are estimated through economic input–output models. Input–output models, which were originally developed to trace supply linkages in the economy, quantify the effects of change of expenditure within a regional economy on multiple industrial sectors. As the construction and operational phases of a project involve the input of materials, work force labor, and goods and services from a number of sectors, the accrued jobs that are ultimately generated by expenditures of energy sources supply chains depend on the extent to which those expenditures are spent locally and on the structure of the local economy.

Table 1. Economic Data for the Considered Examples

Example	1	2
Working fluid in the ORC	R245fa	*n*-Hexane
Working fluid in the ARC	Lithium bromide–water	Lithium bromide–water
k_F (y^{-1})	0.23	0.23
H_Y (h/y)	8000	8000
ΔT^{min} (°C)	10	10
β^{exch} (dimensionless)	0.65	0.65
$\beta^{turb\text{-}SRC}$ (dimensionless)	0.41	0.41
C^{cu} (US$/kWh)	1.2744E-3	1.2744E-3
$C^{elect\text{-}b}$ (US$/kWh)	0.08	0.08
$C^{elect\text{-}s}$ (US$/kWh)	0.06	0.06
C^{Solar} (US$/kWh)	0.012	0.012
η^{Ran}	0.4	0.37
$\eta^{pump\text{-}SRC}$	0.05	0.05
η^{ORC}	0.1497	0.138
$\eta^{pump\text{-}ORC}$	0.05	0.05
$\eta^{reg\text{-}ORC}$	0.041	0.041
COP^{ARC}	0.7	0.7
$\eta^{abs\text{-}ARC}$	0.5372	0.5372
$\eta^{pump\text{-}ARC}$	0.00005	0.00005
$\eta^{exch\text{-}ARC}$	0.0535	0.0535
CF (US$)	0	0
CV (US$/$m^2$)	1650	1650
Tax credits (US$/t CO_2 eq)	5	5

According to the spending pattern and the specific state economic structure, different expenditures support different levels of employment, income, and output. Input–output analysis can be considered as a method for evaluating and summing the impacts of a series of effects generated by an input expenditure. To determine the total effect for yielding biofuels, fossil fuels, and solar collectors, three separate impacts are examined: direct, indirect, and induced.

a. Direct effect: the immediate (or on-site) effect created by an expenditure. For example, in constructing a plant, direct effects include the on-site contractors and crews hired to construct the plant. Direct effects also include the jobs at the plant that build the process equipment.
b. Indirect effect: the increase in economic activity that occurs when contractors, vendors, or manufacturers receive payment for goods or services and in turn are able to pay others who support their business. For instance, indirect effects include the banker who finances the contractor, the accountant who keeps the contractor's books, the steel mills and electrical manufacturers, and other suppliers that provide the required materials.
c. Induced effect: the change in wealth that occurs or is induced by the spending of those persons directly and indirectly used by the project.

The total effect from a single expenditure can be calculated by summing all three effects, using regional-specific multipliers and personal expenditure patterns.[67,68]

Finally, the social function consists is maximizing the number of jobs created by the project

$$\max NJOBS^{Overall} = \sum_{\theta\in\Theta}\sum_{f\in B}\left(NJOB_f^{Fossil} q_{f,\theta}^{Fossil} D_\theta\right) + \sum_{\theta\in\Theta}\sum_{b\in B}\left(NJOB_b^{Biofuel} q_{b,\theta}^{Biofuel} D_\theta\right) + \sum_{\theta\in\Theta}\left(NJOB^{Solar} q_\theta^{Solar} D_\theta\right) \quad (96)$$

where $NJOB_f^{Fossil}$, $NJOB_b^{Biofuel}$, and $NJOB^{Solar}$ represent the unitary number of jobs generated per kJ provided by fossil fuels, biofuels, and solar collector. Therefore, $NJOBS^{Overall}$ is equal to jobs per year.

Solution strategy

The proposed model is a multiobjective mixed-integer nonlinear programming model, and to solve this model, the following solution strategy was implemented to consider the tradeoffs among the economic, environmental, and social objectives involved. First the program was coded in the General Algebraic Modeling System[69]; to solve the associated problem, the solvers DICOPT, CONOPT, and CPLEX are used to solve the associated mixed-integer nonlinear programming, nonlinear programming, and linear programming problems, respectively. The problem is solved for minimizing to total net cost to determine the best economic solution (which corresponds to the maximum GHGE); then the program is solved for minimizing the GHGE (which corresponds to the maximum cost); and then the problem for minimizing the net TAC with upper constraints for the GHGE (between the limits determined previously) is solved. In each solution are quantified the generated jobs. These solutions are plotted into a two-dimension graph (net TAC vs. GHGE) indicating the generated jobs to identify the best solutions that satisfy the specific requirements given by the designer.

Results

Two examples are solved applying the proposed mathematical formulation to show the main advantages of the proposed methodology. The value for the parameters k_F, H_Y, ΔT^{min}, β, C, η, CF, and CV are presented in Table 1. The location considered for the installation of the project is Morelia, Mexico, which has the coordinates N 19°42′08″ and W 101°11′08″ and a parabolic trough solar collector is used for the examples. Table 2 shows the useful energy that can be collected per month by the solar collector.

The results are shown in Pareto curves to identify the tradeoffs between the different objectives considered. Moreover, different solutions are selected from the Pareto curves to explore in detail these solutions. Thus, the decision makers can select the operation point taking into account the three relevant aspects (economic, social, and environmental).

Table 3 shows the fossil fuels and biofuels considered by the two examples, as well as their heating power, the GHGE, the unit cost, and the unit number of jobs created by each fuel.

Table 2. Useful Collected Energy Per Month for the Solar Collector for the Considered Examples

Month/Type of Solar Collector	PTSC [kJ/(m^2 month)]
January	409,293
February	443,016
March	577,530
April	571,860
May	555,768
June	454,410
July	443,610
August	439,425
September	394,470
October	410,967
November	407,430
December	522,288

Table 3. Data for the Fossil and Biofuels Considered in the Examples Presented

#	Fuel	Heating power (kJ/kg)	GHGE (t CO_2 eq/kJ)	Cost ($/kJ)	Generation of Jobs (Jobs/kJ)
Fossil Fuels					
1	Coal	35,000	2.21357×10^{-7}	1.5559×10^{-6}	1.06281×10^{-11}
2	Oil	45,200	8.05408×10^{-8}	18.2447×10^{-6}	1.81677×10^{-11}
3	Natural gas	54,000	7.90892×10^{-8}	5.8349×10^{-6}	5.25431×10^{-11}
Biofuels					
1	Biomass	17,200	2.44307×10^{-8}	2.0303×10^{-6}	6.6964×10^{-8}
2	Biogas	52,000	2.68216×10^{-8}	8.5388×10^{-6}	5.25431×10^{-7}
3	Softwood	20,400	3.3482×10^{-8}	2.5332×10^{-6}	1.46691×10^{-8}
4	Hardwood	18,400	3.3482×10^{-8}	2.8975×10^{-6}	5.43641×10^{-8}
5	Biodiesel	40,200	5.13283×10^{-8}	31.3092×10^{-6}	2.46582×10^{-6}
6	Bioethanol	29,600	5.8436×10^{-8}	14.4212×10^{-6}	2.87453×10^{-6}

EXAMPLE 1. *This example considers two plants, where only the first one requires refrigeration. Each plant has two hot process streams and two cold process streams. The stream data and performance for the ORC, ARC,* **and** *SRC for this example are given in Table 4; whereas Table* 5 *contains the maximum amount monthly available for the biofuels and fossil fuels considered in this example*.

Figure 3 shows the Pareto curve obtained considering a tax credit of US$5/t CO_{2eq}. In this figure, the Pareto curve shows the tradeoffs between the NGHGE with respect to the TAC. The continuous line (for NGHGE values 0–134,460t CO_{2eq}/y) represents the optimal solutions, where the right end is the best economic solution, the worst environmental solution, and the corresponding number of generated jobs is relatively low. The left end represents the configuration for the lowest NGHGE and the maximum TAC obtained; an important aspect to note is the tendency of the line, for lower NGHGE, the TAC is higher, whereas the number of jobs (NJOBS) fluctuates between 800 and 1000 with exception of both extreme solutions. For discussion of the results obtained, two intermediate solutions are identified in the Pareto curve.

Table 4. Data for Example 1

Stream	TIN (°C)	TOUT (°C)	FCp (kW/°C)	*h* (kW/m^2°C)	kW
Plant one					
HPS1	125	30	38.75	1	3,681.25
HPS2	85	25	18.75	1	1125
cu	32	45		1	
CPS1	35	140	20	1	2100
CPS2	25	95	36.25	1	2537.5
Plant two					
HPS1	187	60	30	1	3810
HPS2	127	50	50	1	3850
cu	32	45		1	
CPS1	87	155	60	1	4080
CPS2	47	127	20	1	1600
SRC					
Condenser	165	154		1	
cu-SRC	30	40		1	
ORC					
Evaporator	48	116		1	
Turbine		63			
Regenerator				1	
Condenser	41	30		1	
cu-ORC	18	28		1	
ARC					
Generator	130	105		1	
Evaporator	14	45		1	
Energy demanded					
Plant one					1550
Plant two					2000

Scenario A

Figure 4 shows the optimal configuration for the solution A, in this representation there are three heat exchangers between interplant matches, from the hot process streams of the Plant one to the cold process streams of the Plant two, they sum 4637.5 kW; a cooler for HPS2 of the Plant two with 1312.5 kW; two heaters, one for CPS1 and other for CPS2, with 4080 and 1600 kW, respectively. Also, there are two process streams in the Plant one that require refrigeration and transfer 4806.25 kW to the ARC. There is an ORC1 heat transfer unit that sends 1710 kW to run the ORC.

For Scenario A, the ARC has an absorber with 6270.371 kW, a condenser with a heat load of 5402.534 kW, the power consumed by the pump is 0.584 kW, an exchanger of 624.469 kW, and the generator contains a heat load of 6866.071 kW that are transferred by the SRC. The ORC produces 255.987 kW of electrical power, the heat load for the regenerator and pump are 10.495 and 12.799 kW, respectively; here is required cooling water with a heat load of 1466.812 kW. The SRC produces 8094.24 kW of electric power generated by 20,235.99 kW of heat load that is sent to the boiler; the pumping power required is 404.712 kW and the total heat load in the condenser is 12,546.071 kW, for this Scenario A (economic optimal solution) is not required for the solar collector. Figure 6 shows that coal is the main fuel used and for the months of January and July, there is required about 33% of natural gas of the total heat load; the energy source generates 134,460 t CO_{2eq}/y yielding US$33,987.70/y of tax credits.

The power plants generate 8350.227 kW, which is enough to provide the energy demanded of both plants (3550 kW) and sell 4800.227 kW producing US$2,304,108.78/y of profit. Table 6 summarizes the costs associated to the solution of Scenario A.

Scenario B

Figure 5 presents the optimal design for Scenario B, which uses a combination of fossil fuels, biofuels, and the solar collector (see Figure 6 to identify the external energy used in each month) to supply the required energy to the SRC and to produce 6394.24 kW of electric power. The area of the required solar collector is 23,166.718 m^2 and the energy supplied to the boiler is 15,985.599 kW. The waste energy available in the condenser is taken to heat the cold process streams of the particular Plant two (2995 and 1600 kW of heating) and to run the ARC (5316.071 kW). It is important to note that the energy available in the condenser for Scenario B is greater than the energy available in the

Table 5. Monthly Amount Available for the Biofuels and Fossil Fuels for Example 1 (t/month)

	Biofuels				Fossil fuels		
	Biomass	Biogas	Softwood	Hardwood	Coal	Oil	Natural Gas
January	10	45	30	30	1000	1000	8000
February	10	15	30	30	1500	7000	3000
March	40	60	25	25	4000	6000	2500
April	50	65	25	25	5000	6500	3500
May	70	65	23	23	7000	6500	2300
June	15	10	23	23	1500	1000	2300
July	10	10	15	15	1000	1000	1500
August	50	10	15	15	5000	1000	1500
September	40	80	20	20	4000	1000	2000
October	40	70	25	25	4000	7000	2500
November	30	60	25	25	3000	6500	2500
December	20	50	30	30	2000	9000	3000

condenser for Scenario C. Also, there is needed a pumping power of 319.712 kW.

In the HEN, there are two heaters for the particular Plant two, one for CPS1 (2995 kW) and one for CPS2 (1600 kW), there are four interplant heat exchanger units (a total heat load of 5722.5 kW), one cooler (1312.5 kW) for HPS2, an ORC1 heat transfer unit (1710 kW), and two ARC2 heat exchangers for HPS1 and HPS2 with 2596.25 and 1125 kW, respectively.

The ORC produces 255.987 kW of electric energy; the regenerator has a heat load of 10.495 kW, the pump consumes 12.799 kW, the cooling utility has 1466.812 kW which are provided by the ORC1 heat exchanger with 1710 kW from the HPS1 of the Plant two. The generator of the ARC is supplied by a SAR heat exchanger (5316.071 kW); the condenser sends out 4182.924 kW and the absorber 4854.849 kW; the pumping power is 0.452 kW, the solution exchanger consumes 483.497 kW, while the evaporators receive 3721.25 kW provided by the ARC2 heat exchangers from the HPS of Plant one.

The energy produced by the SRC is 6650.227 kW, selling 3100.227 kW and producing US$1,488,108.78 of profit, notice that this is 35% lower than Scenario A and 65% greater than Scenario C. Figure 6 shows that the main external energy sources for the solution of Scenario B are coal and solar, 63 and 21% of the heat load supplied to the SRC, respectively; besides, this external energy source yields US$157,954.49/y of tax credits and, therefore, a net TAC of US$1,447,901.09/y.

Scenario C

For Scenario C (Figure 7), there are five heat transfer units, two in series for HPS1 of the Plant one with 1085 and 1627.5 kW, in the Plant two there are three heat exchangers, two for HPS1 that sum 2100 kW and one for HPS2 with 910 kW of heat load. Moreover, there are two coolers, one for HPS2 of the Plant one with 562.5 kW and other for HPS2 of the Plant two that contains 2940 kW. Also, there are two heaters for CPS1 and CPS2 of the particular Plant two, with 2995 and 1600 kW, respectively. Furthermore, there are two ARC2 heat exchangers in the particular plant 1 of 968.75 and 562.5 kW and an ORC1 heat exchanger for HPS1 of 1710 kW.

In this representation of Figure 7, the SRC produces 4375.806 kW of electricity, which is fed by a solar collector of 3266.747 m^2 in addition to fossil fuels and biofuels. Figure 6 shows that coal remains as the main fuel (about 90% of total external energy source). The pumping power is 208.79 kW, also for condensers, there are required three heat exchangers to transfer 6782.5 kW, where 4595 kW correspond to the heaters of the cold process streams and 2187.5 kW are sent to the ARC. In this regard, the generator consumes 2187.5 kW, the condenser 1721.223 kW, the absorber 1997.713 kW, an exchanger with 198.953 kW, a pump that consumes 0.186 kW, and finally, for the evaporators there are required two heat exchangers that receive 1531.25 kW obtained from the hot process streams from the Plant one. Conversely, the ORC produces 255.987 kW of electrical power and has a regenerator of 10.495 kW, the pumping power is 12.799 kW, and cooling utility is 1466.812 kW.

The power plants produce 4631.793 kW, which is enough to supply the energy needed in the eco-industrial park and for sale (1081.793 kW) obtaining US$519,260.85/y of profit; however, this configuration produces less electric energy than the configuration of Scenario A. In addition to the electrical energy produced in the SRC (generated by solar collector, fuels, and biofuels) generates US$36,828.18 of tax credits. Moreover, Scenario C yields a net TAC of US$1,480,025.46/y, which is 49% greater than Scenario A. Table 6 describes all the costs for the Scenario C.

Scenario D

Figure 8 shows the configuration for the Scenario D, where the SRC produces 3550 kW of power using a solar

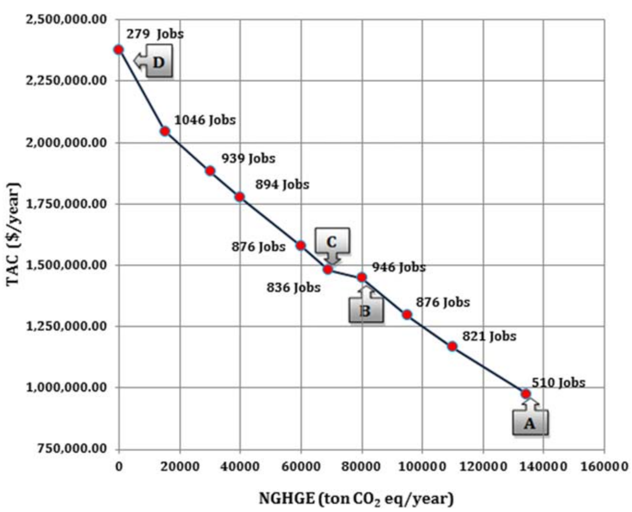

Figure 3. Pareto curve for Example 1.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

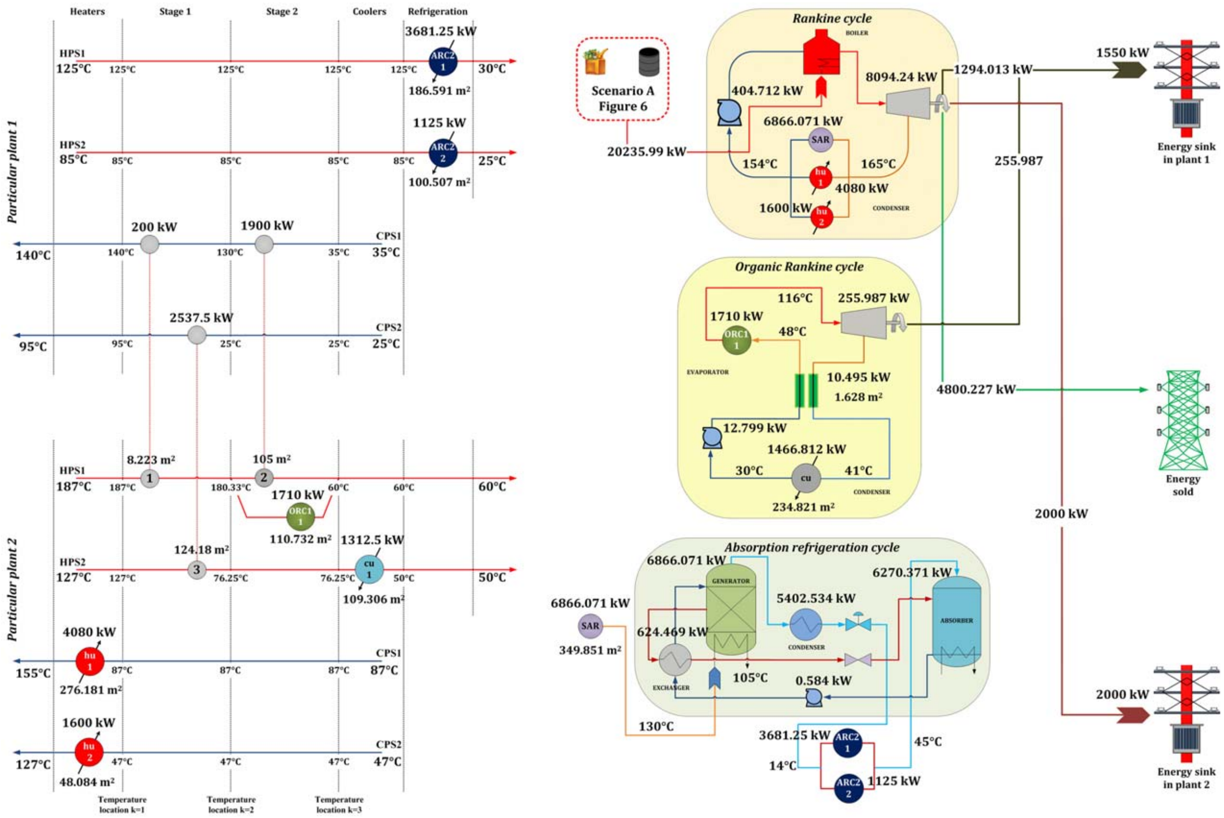

Figure 4. Optimal configuration for minimum TAC, solution for Scenario A of Example 1.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

collector of 60,683.76 m^2 and the remaining energy from the power cycle is used as heating utility, moreover, there is a SAR heat exchanger to transfer 993.137 kW to the ARC; the pumping energy is 177.5 kW.

In the ARC, there is a heat transfer unit (1194.36 kW) for HPS1 of the Plant two and the generator [this heat load is not enough to run totally the ARC and to satisfy the cooling requirements; therefore, the generator is also fed by a SAR exchanger (993.137 kW)]. In addition, the condenser has a heat load of 1721.223 kW, the absorber of 1997.712 kW, the solution exchanger of 198.953 kW, and the energy consumption of the pump is 0.186 kW. Moreover, there are two ARC2 heat exchangers, one for HPS1 with 968.75 kW and other with 562.5 kW for HPS2, both of the Plant one.

The HEN contains seven heat transfer units; where the units 1, 2, and 7 exchange heat within the same plant (2021.86 kW, Plant one; 480 kW, Plant two), and the heat exchangers 3, 4, 5, and 6 are interplant units (they sum 3306.26 kW of total heat load). Two coolers are required in the configuration, one for HPS2 of the Plant one (562.5 kW) and one for HPS2 of the Plant two (3370 kW), also two heaters for CPS of the Plant two (3389.36 kW, CPS1 and 1120 kW, CPS2) and two ARC2 exchangers for HPS of the Plant one (968.75 kW, HPS1 and 562.5 kW, HPS2), and an ARC1 exchanger with 1194.36 kW.

For this solution, there is not required the ORC. Only is required a solar collector and it provides the total energy needed in the system. This scenario produces 279 jobs and zero GHGE (minimum NGHGE), US$309,769.19 of tax credits, which is the biggest respect to Scenarios A, B, and C; and the TAC of US$2,378,333.80/y is higher than previous scenarios. Table 6 shows the costs for Scenarios A, B, C, and D.

Comparison for the different scenarios of Example 1

To show the advantages of the proposed methodology, the following analysis is presented. Table 6 provides the operating and capital costs of the different configurations, notice that the ORC has the same values for the Scenarios A, C, and B. The sold energy comes from the SRC and the major tax credits are from the use of the solar collectors. Moreover, for Scenario C, the solar collector requires an area of 3266.747 m^2 and for solution B has an area of 23,166.718 m^2 (see Figures 5 and 7). Also, the use of low pressure steam from the condenser of the SRC greatly reduces the TAC.

The Scenario A has operating and capital costs of US$3,330,791.33/y, where 45% represents the operating cost and 55% the capital cost; however, the profit obtained by the sale of the generated energy by the power plants is US$2,304,108.78/y, generating a net TAC of $US992,694.84/y. This scenario corresponds to the minimum TAC obtained; nevertheless, the number of jobs is relatively small and the amount of NGHGE is the highest.

Scenario D represents the minimum NGHGE generated; this has a total cost of US$2,688,103/y, and provides US$309,769.19/y of tax credits but there is not profit; therefore, the net TAC is 2,378,333.80/y. This configuration represents the lowest number of generated jobs (231 jobs less than Scenario A). Although it gives the minimum for the GHGE, the net TAC is greater than the one of Scenario A.

Table 6. Costs for the Different Scenarios of Example 1

Concept	Scenario A	Scenario B	Scenario C	Scenario D
Operating costs (US$/y)				
Cooling for HEN	13,381.20	13,381.20	35,708.68	40,092.62
Cooling for ORC	14,954.44	14,954.44	14,954.44	–
Cooling for SRC	–	–	–	–
Cooling for ARC condenser	55,079.91	42,645.74	17,548.21	17,548.21
Pumping for SRC	259,015.66	204,615.66	140,025.80	113,600.00
Pumping for ORC	8,191.58	8,191.58	8,191.58	–
Pumping for ARC	373.51	289.19	119.00	119.00
Solar collector	–	424,684.16	59,884.86	932,940.00
Biofuels	18,169.25	43,472.15	43,472.15	–
Fossil fuels	1,135,239.76	558,564.68	481,246.59	–
External electricity	–	–	–	–
Capital costs (US$/y)				
Exchangers for HEN	18,068.22	27,975.21	32,436.30	41,346.16
Coolers	8,022.87	8,022.87	14,343.05	14,763.96
Solar collector	–	217,289.91	30,640.12	569,117.26
SRC				
Boiler	717,262.27	566,618.61	387,757.34	314,579.40
Turbine	736,495.34	668,638.33	572,336.76	525,304.89
Exchanger for SRC-ORC	–	–	–	–
Exchanger for SRC-ARC	17,089.76	14,471.37	8,125.34	4,863.30
Exchanger for SRC-HEN (hu)	19,359.52	18,303.39	18,303.39	18,115.16
Cooling utility	–	–	–	–
Pump	32,579.31	25,736.81	17,612.62	14,288.75
ORC				
Exchanger for HEN-ORC	8,090.76	8,090.76	8,090.76	–
Turbine	52,731.42	52,731.42	52,731.42	–
Regenerator	520.87	520.87	520.87	–
Exchanger for ORC-HEN	–	–	–	–
Coolers	13,188.36	13,188.36	13,188.36	–
Pump	3512.19	3512.19	3512.19	–
Absorption Refrigeration System				
Exchanger for HEN-ARC (Feed)	–	–	–	5999.66
Generator	5452.09	4221.29	1737.01	1737.01
Condenser	22,993.93	17,803.10	7325.76	7325.76
Absorber	150,488.90	116,516.37	47,945.10	47,945.10
Exchanger HEN-ARC (Refrigeration)	18,954.68	18,304.82	17,854.78	17,854.78
Pump	46.98	36.37	14.96	14.96
Solution exchanger	1528.43	1183.39	486.95	486.95
Energy sold (US$/y)				
SRC	2,304,108.78	1,488,108.78	519,260.85	–
ORC	–	–	–	–
Tax credits (US$/y)				
Solar collector	–	141,010.21	19,883.90	309,769.19
Biofuels	8160.37	16,944.28	16,944.28	–
Fossil fuels	25,827.33	–	–	–
NJOBS (Jobs/y)	510	946	836	279
NGHGE (t CO_2eq/y)	134,460	80,000	69,000	0
Total operating cost (US$/y)	1,504,405.34	1,310,798.83	801,151.35	1,104,299.84
Total capital cost (US$/y)	1,826,385.99	1,783,165.54	1,234,963.16	1,583,803.16
Sold total energy cost (US$/y)	2,304,108.78	1,488,108.78	519,260.85	–
Total tax credits (US$/y)	33,987.71	157,954.50	36,828.18	309,769.19
TAC (US$/y)	992,694.84	1,447,901.09	1,480,025.46	2,378,333.80

The Scenario C offers a major diversity in the use of external energy sources and, therefore, a greater number of generated jobs (836 jobs), the amount of GHGE (69,000 t CO_{2eq}/y) is lower than the one of Scenario A (134,460 t CO_2eq/y). The TAC is US$2,036,114.51, where 39% corresponds to the operating cost. The saving obtained is US$519,260.85/y and the tax credits are US$36,828.18/y; this way, Scenario C yields a net TAC of US$1,480,025.46/y, which is lower than the one of Scenario D and greater than the one of Scenario A. Conversely, Scenario B yields a greater number of generated jobs (110 jobs more than the ones of Scenario C), but 11,000 t CO_{2eq}/y of GHGE more than the solution of Scenario C. However, the net TAC obtained (US$1,447,901.09/y) is 2% lower than the solution of Scenario C, which represents US$1,480,025.46/y. In this regard, both solutions for Scenarios C and B provide a considerable TAC (65% greater than Scenario A and 60% lower than Scenario D).

Moreover, the traditional solution for energy integration in single plants, without interplant integration and without considering the central SRC, ORC, and ARC was implemented. This solution represents a total heating cost of US$ 583,971.84/y, the total cooling water cost is US$ 29,769.98/y, the refrigeration cost is $ 280,962.00/y, the total capital cost is US$ 91,899.80/year, and the external electric power required represents US$ 2,272,000/y. This way, the TAC for this traditional single-plant energy integration is US$ 3,272,000/y; it should be noticed that this total costs is 228,

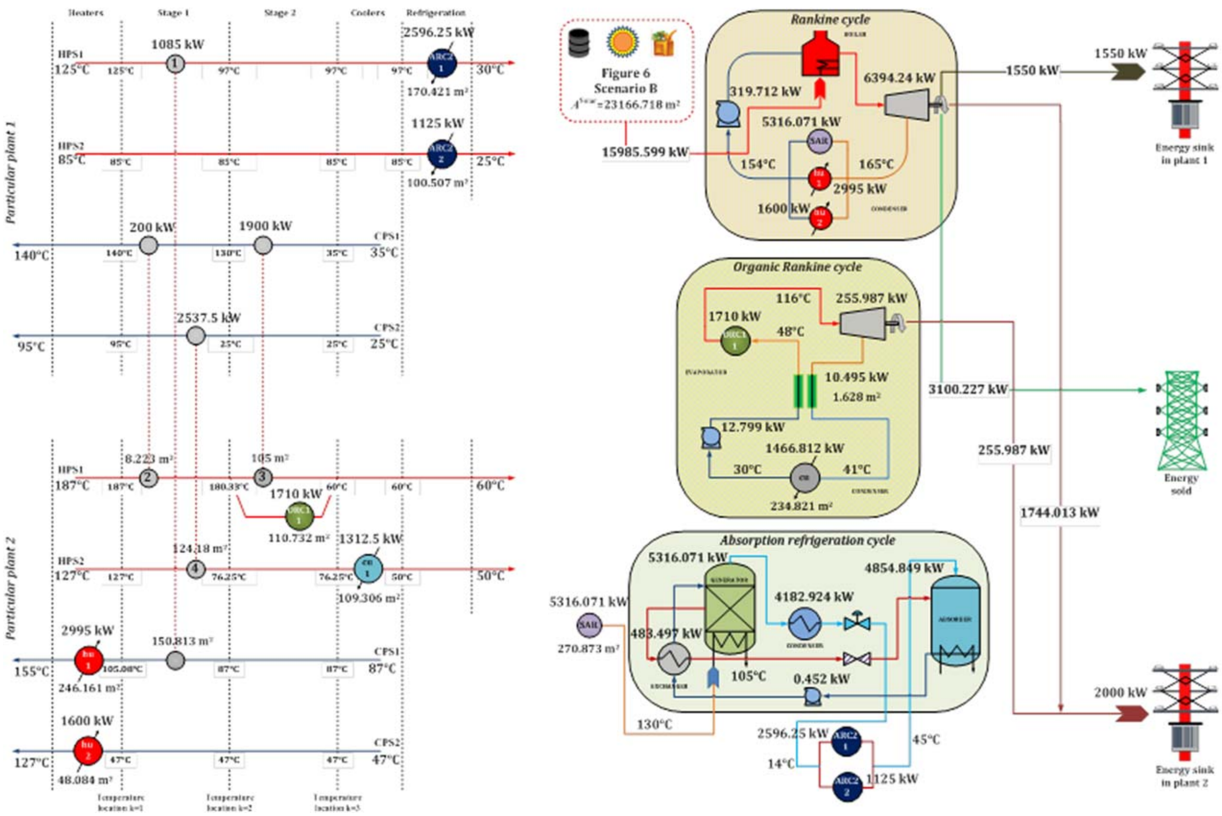

Figure 5. Optimal configuration for Scenario B of Example 1.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

125, 120, and 37% greater than the solutions for Scenarios A, B, C, and D identified from the Pareto curve obtained with the proposed methodology.

EXAMPLE 2. *This example considers one particular plant with three hot process streams and three cold process streams, and other plant with three hot process streams and two cold process streams. The stream data and performance for the SRC, ORC, and ARC for this example are given in Table* 7, *whereas Table* 8 *shows the maximum amount monthly available for the biofuels and fossil fuels considered in this example.*

Figure 9 shows the Pareto curve obtained considering a tax credit of US\$5/t CO_{2eq}. The continuous line (for NGHGE values 0–88,554.143) represents the optimal solutions, where the right end is the best economic solution and the left point represents the configuration for the minimum

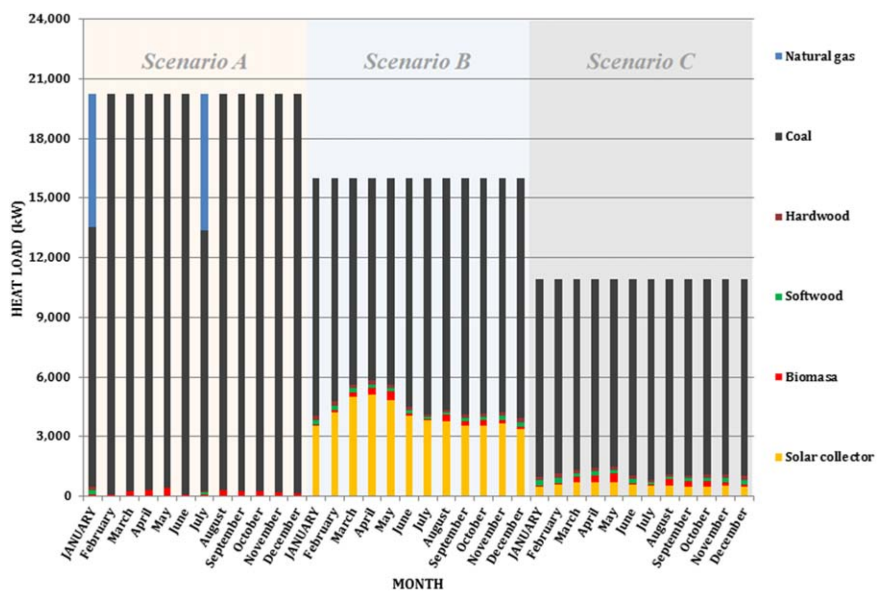

Figure 6. Energy sources required for each month of the different scenarios for the Example 1.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

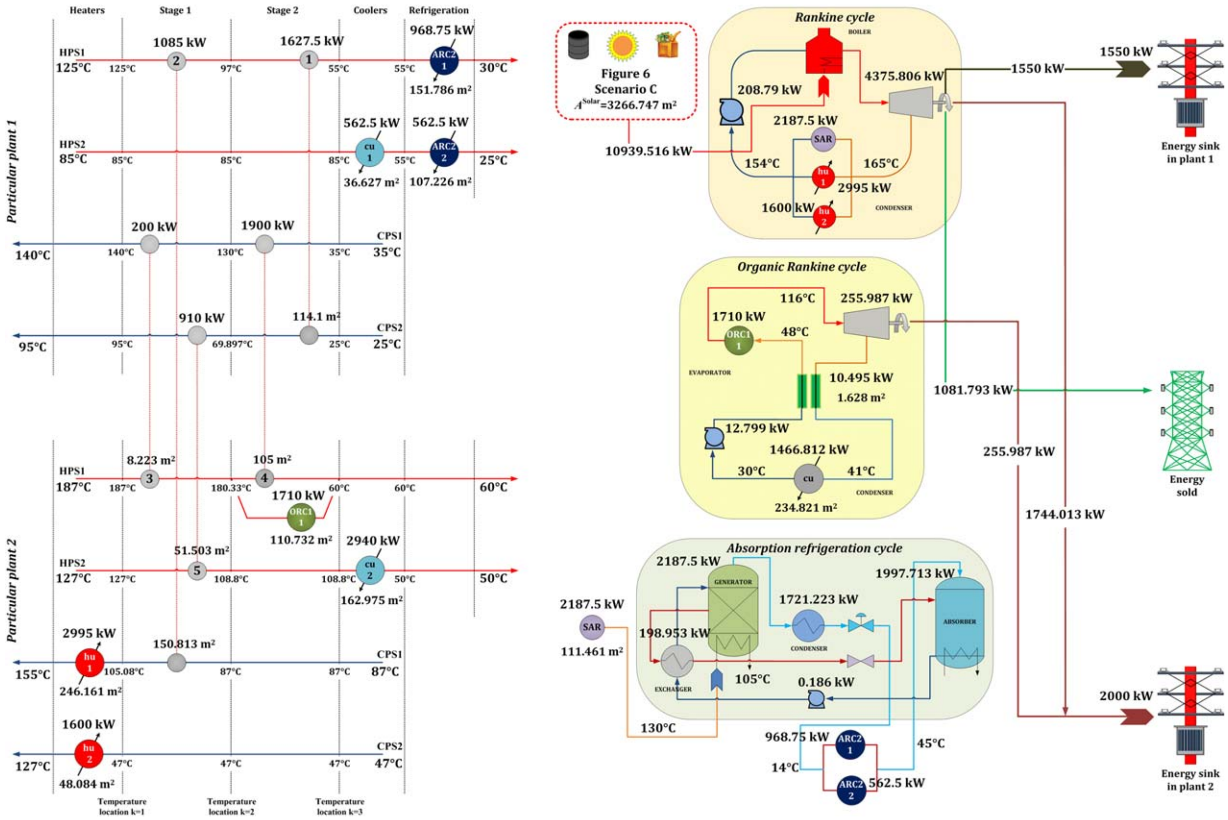

Figure 7. Optimal configuration for the Scenario C of Example 1.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

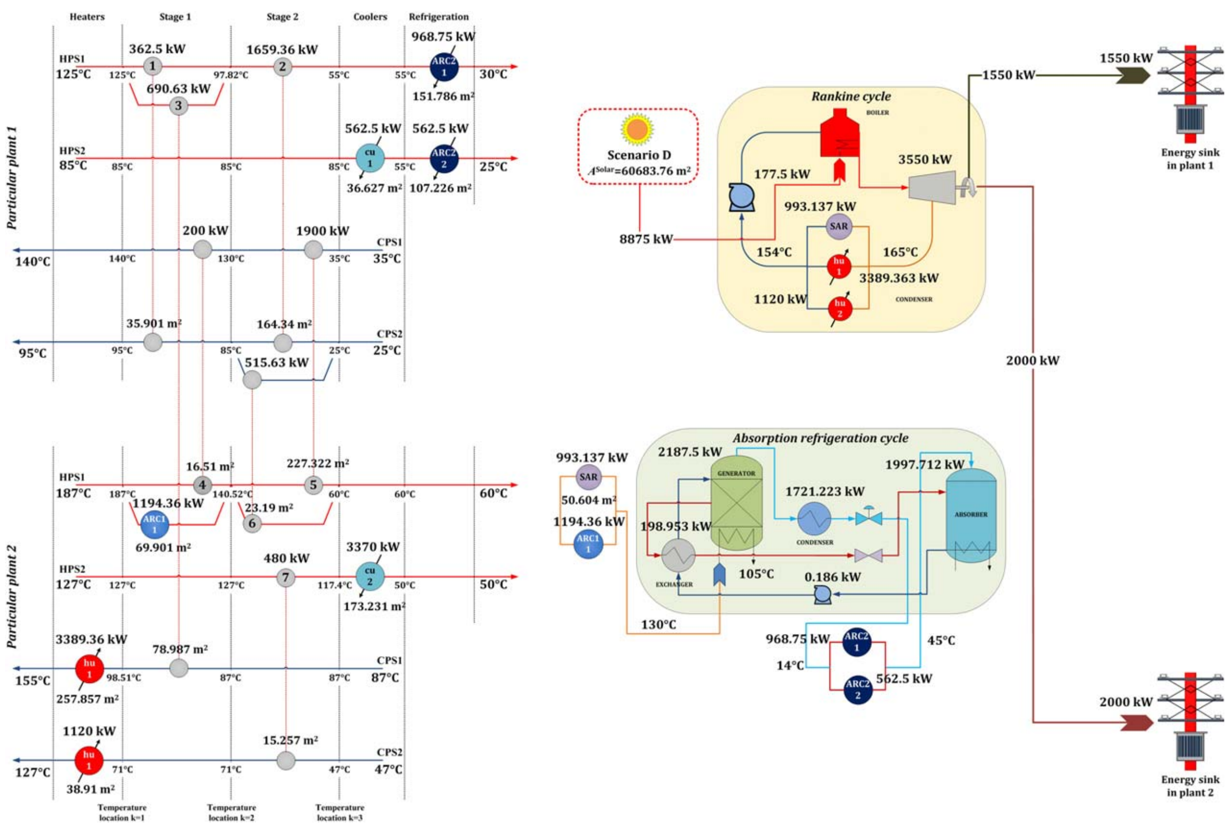

Figure 8. Configuration for Scenario D of Example 1 (minimum NGHGE).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 7. Data for Example 2

Stream	TIN (°C)	TOUT (°C)	FCp (kW/°C)	h (kW/m^2°C)	kW
Particular plant one					
HPS1	60	45	11.06	1	165.9
HPS2	57	18	16.67	1	650.13
HPS3	42	15	22.9	1	618.3
cu	25	35		1	
CPS1	60	130	43.8	1	3066
CPS2	25	55	32	1	960
CPS3	46	111	65	1	4225
Particular plant two					
HPS1	253	123	11.8	1	1534
HPS2	190	30	7.8	1	1248
HPS3	210	150	31.16	1	1869.6
cu	32	45		1	
CPS1	116	141	39.14	1	978.5
CPS2	61	97	51.99	1	1871.64
SRC					
Condenser	157	146		1	
cu-SRC	30	40		1	
ORC					
Evaporator	71	148.5		1	
Turbine		129			
Regenerator				1	
Condenser	115.9	70		1	
cu-ORC	32	45		1	
ARC					
Generator	117	86.7		1	
Evaporator	5	15		1	
Energy demanded					
Plant one					4250
Plant two					1830

NGHGE and the maximum TAC obtained; it should be noted that the tendency shows that for lower GHGE, there are higher TACs. The number of generated jobs is between 500 and 800, except for the extreme solutions, where these are 245 and 461 jobs, respectively. From this Pareto curve, three scenarios are selected for further description of the Pareto curve.

Scenario A

Figure 10 presents the solution for Scenario A, which is the best economic solution; there are four heat exchangers between the process streams (with a total heat transferred of 2741.709 kW); also, there are required four heaters, three in the Plant one (2510.5 kW, CPS1; 757.101 kW, CPS2, and 3220.189 kW, CPS3) and one for CPS2 (1871.64 kW) of the Plant two; a cooler for HPS1 (165.9 kW) in the Plant one; three ARC2 exchangers, two in Plant one (for HPS2 of 447.231 kW and for HPS3 of 618.3 kW) and one more for HPS2 (243.189 kW) of Plant two; and besides an ARC1 exchanger with a heat load of 1869.6 kW. The boiler of the SRC receives 12,890.409 kW from biofuels and fossil fuels as external energy source (see Figure 12) and the generator of the SRC produces 4769.451 kW of electric power. The pumping power required is 238.473 kW. It should be noted that all the low pressure steam (8359.43 kW) of the condenser is sent to the HEN as heating utility.

The ARC is run by the ARC1 exchanger that uses heat from HPS3 of the Plant two; which transfers 1869.6 kW. The heat load in the condenser is 1471.085 kW, in the absorber is 1707.394 kW, and in the exchanger is 170.04 kW, whereas the consumed energy by the pump is 0.159 kW. Also, there are three heat transfer units (ARC2) for the hot process streams that transfer heat to the evaporators (a heat load of 1308.72 kW). In this configuration, there is no need of the ORC, therefore, part of the energy produced in the SRC (2939.451 kW) is sent to the Plant one, where besides there is required external energy (1310.549 kW) to supply the demanded energy; and 1830 kW are sent to the Plant two to provide the demanded energy in this plant. Figure 12 shows the amount of biofuels and fossil fuels needed to feed the SRC, coal is the main fuel and only during the month of April natural gas supplies 14% of the required heat load. Table 9 shows that the capital and operating costs for this scenario are US$1,172,643.45/y and US$1,663,393.80/y, respectively; besides, 245 generated jobs, 88,554.143 t CO_{2eq}/y of GHGE, US$7,150.58/y by tax credits, to yield a net TAC of US$2,828,886.66/y.

Scenario B

The solution of Scenario B (see Figure 11) has four heat exchangers between process streams (with 2741.71 kW of total heat transferred), where three are interplant exchangers. Furthermore, there are required two heat exchangers for plant one (2510.5 kW for CPS1 and 3977.29 kW for CPS3) and an exchanger for CPS2 (1871.64 kW) of the Plant two (one less than the solution of Scenario A). Also, there is required a cooler for HPS1 (165.9 kW) of Plant one. In Plant one also, there are required two ARC2 exchangers, one for HPS2 (650.13 kW) and the other for HPS3 (618.3 kW), and one more for HPS2 (40.29 kW) of Plant two. There is also required an ARC1 exchanger with a heat load of 1869.6 kW for HPS3 of Plant two.

The generator of the ARC is fed by the ARC1 exchanger (1869.6 kW). It should be noted that the heat load for the heat exchanger of the ARC of Scenario B is the same that of the one of Scenario A. The heat load in the condenser is

Table 8. Available Monthly Amount for Biofuels and Fossil Fuels for Example 2 [t/month]

	Biofuels				Fossil fuels		
Month	Biomass	Biogas	Softwood	Hardwood	Coal	Oil	Natural Gas
January	10	10	20	30	1000	1000	1200
February	9.0	8.0	15	20	1500	700	1300
March	10	8.0	15	20	1000	600	950
April	7.0	6.5	10	15	800	650	1000
May	7.0	6.5	13	10	7000	850	1900
June	5.5	7.0	10	13	1500	1000	2300
July	10	10	15	15	1000	1000	1500
August	20	10	15	15	2000	1000	1500
September	35	8.0	10	10	3000	1000	1000
October	30	7.0	25	25	3000	1200	1500
November	30	15	25	25	1800	1500	2500
December	20	15	30	30	2000	900	3000

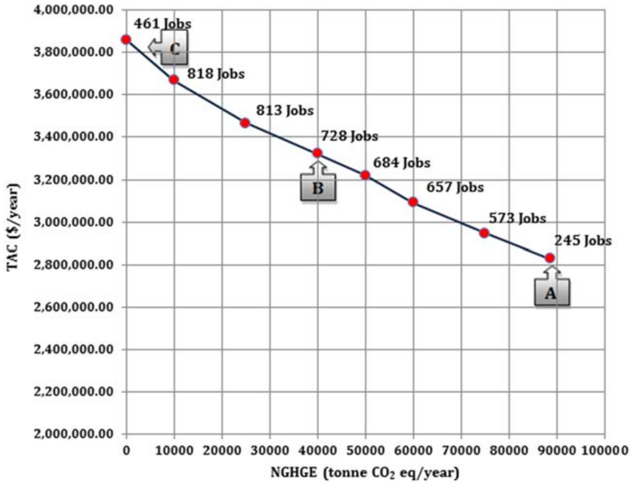

Figure 9. Pareto curve for Example 2.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

1471.085 kW, the absorber has 1707.394 kW of heat load, the heat load in the solution exchanger is 170.04 kW, and 0.159 kW of energy are required by the pump. Also, there are three heat exchangers in the HEN that transfer heat to the evaporators to yield a total load of 1308.72 kW. The SRC is fed by a solar collector of 39,234.881 m^2, also, there is a contribution by biofuels and fossil fuels to generate 12,890.409 kW and producing 4769.451 kW of electric power. The pumping power required is 238.473 kW. It should be noted that the heat load in the condenser (8359.43 kW) is the same as Scenario A; however, this is distributed in three heating utilities.

There is not required the ORC for Scenario B, and the energy produced by the SRC, 2939.451 kW are sent to Plant one, where besides is required external energy (1310.549 kW) to supply the demanded energy; and 1830 kW are transferred to Plant two. Figure 12 shows the main external energy sources for the solution of Scenario B; where 53% is supplied by the solar collector and 44% from coal. The production of the energy supplied to the SRC yields 728 jobs (66% higher than Scenario A) and US$249,921.30/y of tax credits (97% greater than Scenario A); moreover, the associated costs are US$3,573,120.77/y to yield a net TAC of US$3,323,199.47/y. Table 9 shows a detailed description of the costs for Scenarios A and B.

Scenario C

Figure 13 shows the solution for Scenario C; this solution presents a HEN with one interplant heat exchanger (555.5 kW) and a heat exchanger for the HPS2 of Plant one with 53.31 kW and another one for HPS1 of Plant two with 978.5 kW. Also, there are two coolers, one for HPS1 of 165.9 kW and other one for HPS2 (1154.4 kW) of the Plant two. There are four heaters, with heat loads of 2510.5 kW for CPS1, 906.69 kW for CPS2, and 4225 kW for CPS3, these in Plant one and one for CPS2 (1871.64 kW) of Plant two. Besides, in the Plant one, there are required two ARC2 exchangers, one for HPS2 (596.82 kW), one for the HPS3 (618.3 kW), and other one for HPS2 (93.6 kW) of Plant two. There is also required an ARC1 exchanger with a heat load of 1869.6 kW for HPS3 of Plant two. Therefore, the heat load for the components of the ARC is the same than the solutions of

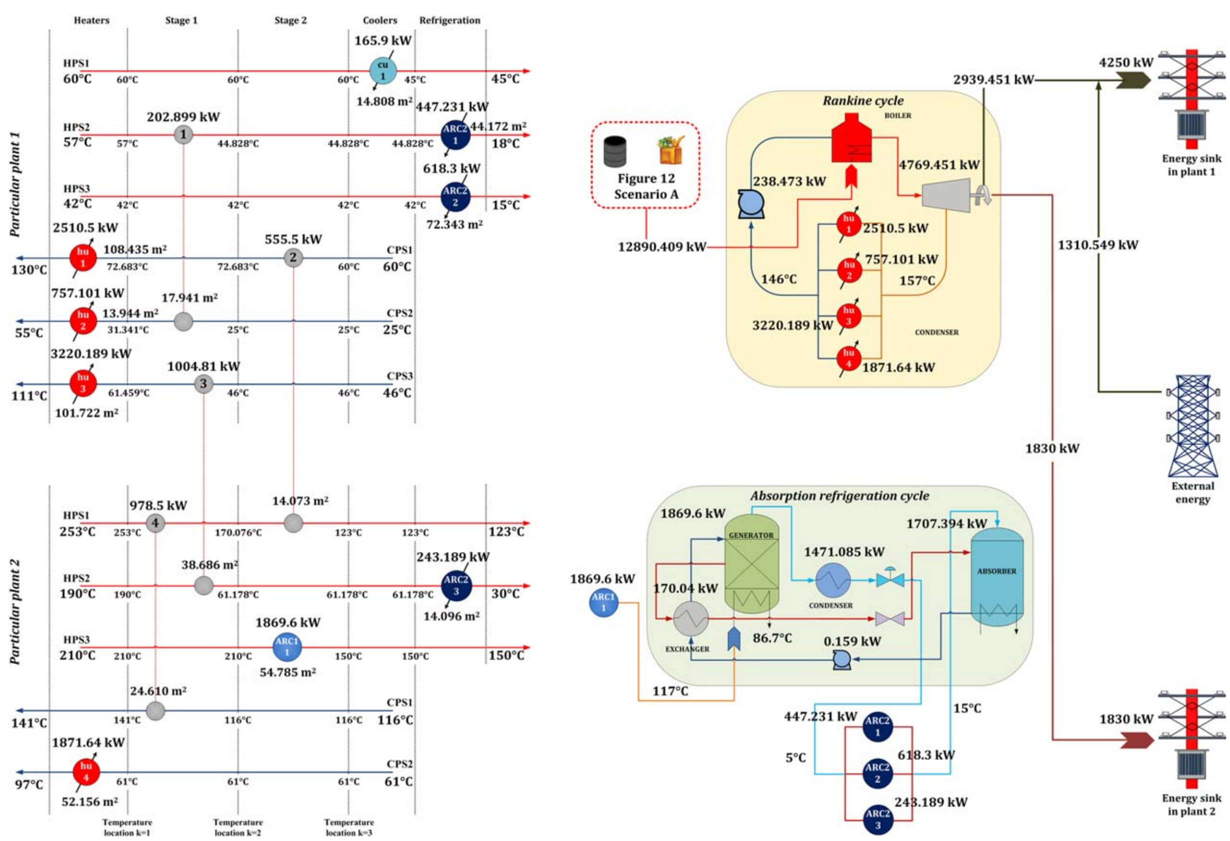

Figure 10. Configuration for Scenario A of Example 2 (minimum TAC).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 9. Results Comparison for Example 2

Concept	Scenario A	Scenario B	Scenario C
Operating costs (US$/y)			
Cooling for HEN	1691.38	1691.38	13,460.72
Cooling for ORC	–	–	–
Cooling for SRC	–	–	–
Cooling for ARC condenser	14,998.01	14,998.01	14,998.01
Pumping for SRC	152,622.43	152,622.43	173,698.91
Pumping for ORC	–	–	–
Pumping for ARC	101.70	101.70	101.70
Solar collector	–	719,240.10	1,542,164.70
Biofuels	8073.72	29,403.32	–
Fossil fuels	647,155.30	278,623.25	–
External electricity	838,751.23	838,751.23	417,221.67
Capital costs (US$/y)			
Exchanger for HEN	11,753.54	10,888.77	6050.76
Heating utility	–	–	–
Cooling utility	2,187.96	2,187.96	6877.30
Solar collector	–	367,999.64	940,859.09
SRC			
Boiler	456,907.83	456,907.83	520,004.77
Turbine	592,911.49	592,911.49	625,206.01
Exchanger for SRC-ORC	–	–	–
Exchanger for SRC-ARC	–	–	–
Exchanger for SRC-HEN (hu)	22,706.51	21,324.99	23,878.26
Cooling utility	–	–	–
Pump	19,197.04	19,197.04	21,848.06
Absorption refrigeration system			
Exchanger for HEN-ARC (Feed)	5120.84	5120.84	5120.84
Generator	1484.58	1484.58	1484.58
Condenser	6261.14	6261.14	6261.14
Absorber	40,977.44	40,977.44	40,977.44
Exchanger HEN-ARC (Refrigeration)	12,706.05	11,998.57	12,706.05
Pump	12.79	12.79	12.79
Solution exchanger	416.18	416.18	416.18
Energy sold (US$/y)			
SRC	–	–	–
ORC	–	–	–
Tax credits (US$/y)			
Solar collector	–	238,813.24	512,053.42
Biofuels	3727.95	11,108.05	–
Fossil fuels	3422.63	–	–
NJOBS (Jobs/y)	245	728	461
NGHGE (t CO_{2eq}/y)	88,554.143	40,000	0
Total operating cost (US$/y)	1,663,393.80	2,035,431.45	2,161,645.73
Total capital cost (US$/y)	1,172,643.45	1,537,689.32	2,211,370.19
Total energy sold (US$/y)	–	–	–
Total tax credits (US$/y)	7150.58	249,921.30	512,053.42
TAC (US$/y)	2,828,886.66	3,323,199.47	3,860,962.50

Scenarios A and B. The SRC is fed by a solar collector of 100,310 m^2 that generates 14,670.517 kW of heat transferred to the boiler to produce 5428.091 kW of electric power, where 3598.091 kW are sent to Plant one and 1830 kW are transferred to Plant two, as this is not enough to satisfy the demanded energy, there is required external energy (651.909 kW), which is lower than the one required for the solutions of Scenarios A and B. The pumping power is 271.405 kW. The heat load in the condenser is 9513.83 kW.

The associated costs for this Scenario C are US$2,161,645.73/y and US$2,211,370.19/y for operating and capital costs, respectively; and this presents a Tcr by US$512,053.42/y. Notice that previous costs are higher than the ones of Scenarios A and B; besides this Scenario C generates 461 jobs and zero GHGE (minimum NGHGE), yielding a net TAC of US$3,860,962.50/y.

Comparison for the different scenarios of Example 2

Table 9 shows the costs for the different scenarios of Example 2. It should be noted that the solution of Scenario A represents the minimum net TAC, constituted by a TAC of US$2,836,037.25/y (58% of operating cost) and tax credits of US$7,150.58/y. This scenario has 483 and 216 number of jobs lower than Scenarios B and C, respectively; and this Scenario A has the greatest amount of NGHGE (88,554.143 t CO_2eq/y).

The solution of Scenario C represents the minimum NGHGE (zero); however, this presents a net TAC of US$3,860,962.50/y, which is 27 and 14% higher than solutions of Scenarios A and B, respectively. Notice that there is a solar collector of 100,310 m^2 and this yields US$512,053.42/y of tax credits, and 53% more jobs than the solution of Scenario A.

The solution of Scenario B is considered the best configuration for this example, this has a net TAC of US$3,323,199.47/y, which is 15% higher than solution of Scenario A and 14% lower than solution of Scenario C, besides this produces 728 jobs, which is 66 and 37% greater than solutions of Scenarios A and C, respectively. The amount of generated GHGE is 55% lower than the solution of Scenario A.

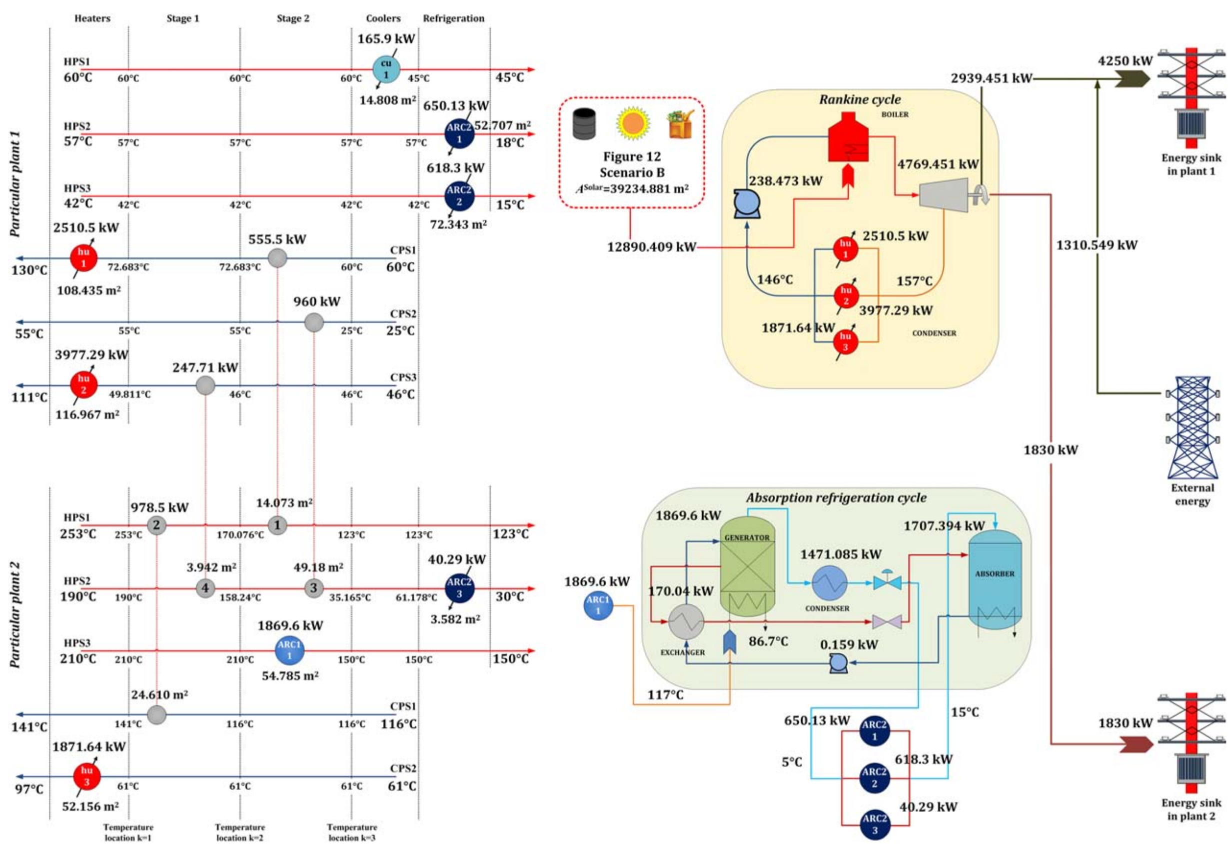

Figure 11. Optimal configuration of the solution of Scenario B of Example 2.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Furthermore, the traditional solution for single-plant energy integration without considering the central SRC, ORC, and ARC yields a total heating cost of US$ 1,482,666.08/y, a total cooling water cost of US$ 17,411.97/y, a total refrigeration cost of $ 123,256.71/y, a total capital cost of US$ 52,435.75/y, and the external electric power required represents U$ 3,891,200.00/y. Therefore, the TAC for this traditional single-plant energy integration is US 5,566,970.53/y, which is 96, 67 and 44% greater than the solutions for Scenarios A, B, and C obtained with the proposed methodology.

Table 10 shows the size for each problem addressed in this article as well as the average of the Central Processing Unit (CPU) time consumed for the solution of each point of the Pareto curve in a computer with an i5–2430M processor at 2.4 GHz and 4 GB of RAM.

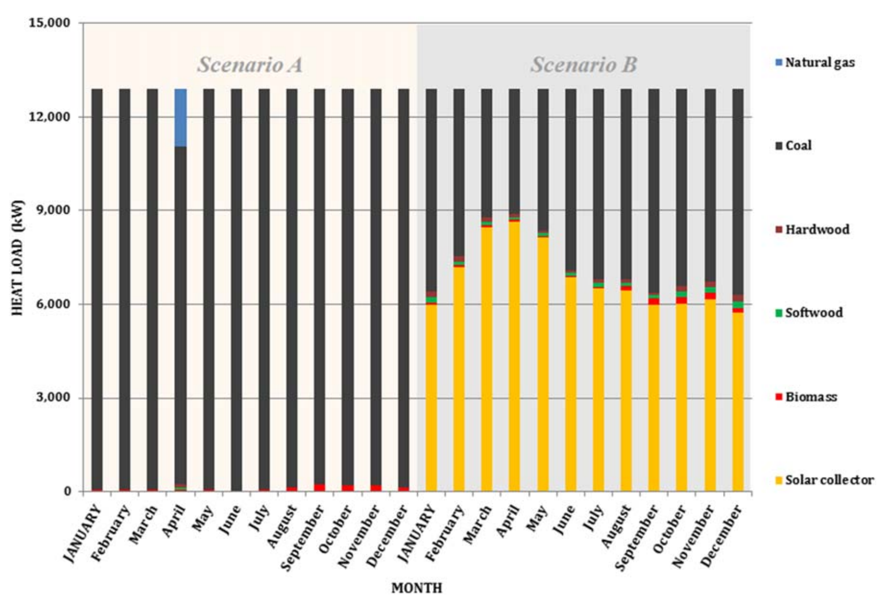

Figure 12. External energy sources applied over each month for the different analyzed scenarios for the Example 2.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

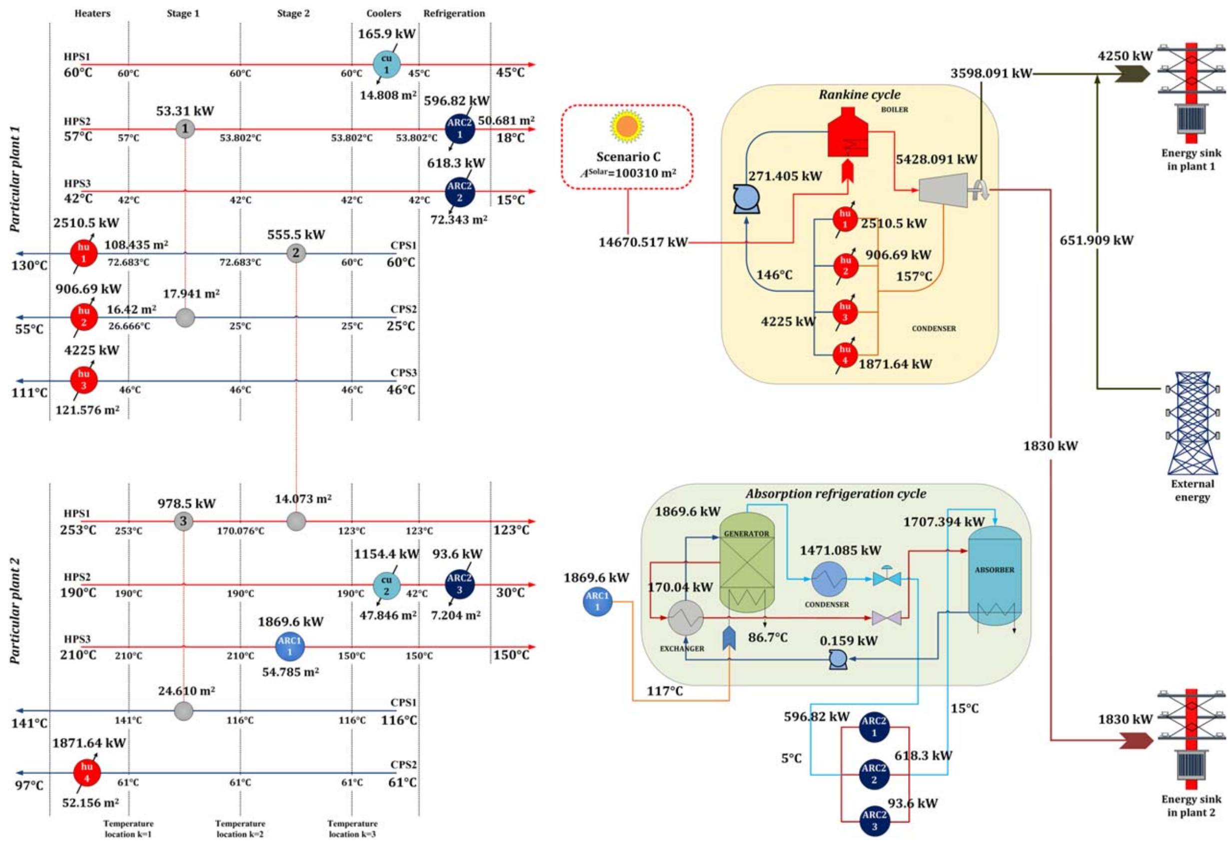

Figure 13. Configuration for Scenario C of Example 2 (minimum NGHGE).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Conclusions

This article has proposed a mathematical programming model for the optimal heat integration into an eco-industrial park through a trigeneration system; the proposed model has considered possible intraplant and interplant heat integration. Moreover, this model considers simultaneously the minimization of the TAC, the minimization of the overall GHGE, and the maximization of the number of jobs that can be created by the use of different types of primary energy sources. Two example problems have shown that the use of this approach for designing energy integrated eco-industrial parks allows reducing significantly the associated costs. This way, the proposed approach allows reducing the use of external cooling and heating utilities, pumping and at the same time the possible production of electric power through the power plants to satisfy the electricity demanded in the participating plants and the possibility to sell the excess of electricity. In addition, in the presented examples is shown that the use of renewable energy, significantly reduces the GHGE promoting the sustainability of the project.

The proposed model is based on a new superstructure that allows the simultaneous consideration of the capital and operational costs for the system, as well as the sale of the excess of electricity produced in the power plants. Finally, the proposed superstructure was formulated as a mathematical programming model that was solved without numerical complications.

Table 10. Problem Size and CPU Time for Each Example Presented

Concept/Example	Example 1	Example 2
Constraints	424	578
Continuous variables	429	609
Binary variables	73	116
CPU time (s)	95	131

Acknowledgment

The authors acknowledge the financial support from the Mexican Council of Science and Technology (CONACyT) and the Scientific Research Council of the Universidad Michoacana de San Nicolás de Hidalgo.

Notation

Greek letters

β = exponent for area of the heat transfer units
δ = small number
η = efficiency
θ = time period

Parameters

Avail = maximum availability
C = unit operational cost
$C_b^{Biofuel}$ = unit operational cost for biofuel b
$C^{elect-s}$ = unit sale power price
$C^{elect-b}$ = unit buy power price
C_f^{Fossil} = unit operational cost for fossil fuel f
C^{Solar} = unitary operational cost for solar energy
CF = fixed cost for the heat transfer units and device of ORC, AR, solar collector, and SRC
COP = coefficient of performance
CV = variable cost for the heat transfer units and device of ORC, AR, solar collector, and SRC

dT^{hot} = temperature difference for the hot side
dT^{cold} = temperature difference for the cold side
D_0 = conversion factor, day–month
DE_p = power demand in the plant p
FCp_i = heat capacity flow rate for hot process stream i
FCp_j = heat capacity flow rate for cold process stream j
h = film heat transfer coefficient
$Heating^{Power}$ = heating power
H_Y = annual operating time
k_F = factor used to annualize the capital costs
$Q^{HEN\text{-}max}$ = upper bound for heat load of the process streams
$Q^{SRC\text{-}max}$ = upper bound for heat load of the steam Rankine cycle
$Q^{ORC\text{-}max}$ = upper bound for heat load of the organic Rankine cycle
$Q^{Use\text{-}Solar}$ = useful solar radiation in the specific location
R = tax credit for the reduction of GHGE
T^{turb} = outlet temperature for the organic working fluid in the turbine of the ORC
TIN = inlet temperature
TOUT = outlet temperature
ΔT^{max} = upper bound for temperature difference
ΔT^{min} = minimum approach temperature difference

Superscripts

abs = absorber
ARC = absorption refrigeration cycle
ARC1 = heat exchanger unit where the heat excess from hot process streams is removed
ARC2 = hear exchanger where the hot process streams are cooled
cu = cooling water
cond = condenser
exch = exchanger
gen = generator
GHGE = greenhouse gases emissions
hu = heating utility
ORC = organic Rankine cycle
ORC1 = heat exchanger where hot process streams transfer energy to the organic Rankine cycle
ORC2 = heat exchanger where the organic Rankine cycle transfers energy to cold process streams
SRC = steam Rankine cycle
reg = regenerator
turb = turbine

Subscripts

b = biofuel
f = fossil fuel
i = hot process stream
j = cold process stream
k = index for stage (1,. . ., NOK) and the temperature location (1,. . ., NOK +1)
NOK = total number of stages

Sets

CPS = $\{j/\ j$ is a cold process stream$\}$
HPS = $\{i/\ i$ is a hot process stream$\}$
P = $\{p/\ p$ is a particular plant$\}$
ST = $\{k/\ k$ is a stage in the superstructure, $k = 1, \ldots,$NOK $\}$
F = $\{f/\ f$ is a fossil fuel$\}$
B = $\{b|\ b$ is a biofuel$\}$

Variables

A^{Solar} = solar collector area
$Capc$ = capital cost
dT^{hot} = temperature difference for the hot side
dT^{cold} = temperature difference for the cold side
$Fixcap$ = fixed capital cost
E^{cons} = energy consumed in the plant
E^{sale} = energy sold from power plants
E_p^{Ext} = external power needed in the plant p
E^{pump} = power consumed for the pump
E^{ORC} = power generated in the ORC
E^{SRC} = power generated in the SRC
NGHGE = overall greenhouse gases emissions
NJOBS = number of generated jobs
$Opec$ = operating cost
q = heat load of heat exchanger units from the HEN, ARC, ORC and SRC
q_θ^{Solar} = heat load of the solar collector in period θ
$Sprc$ = savings owing to the sale of the electricity that is generated in the power plants
TAC = total annual cost
Tcr = tax credits reduction
T_i^{ARC} = outlet temperature for the hot process stream i from the exchanger of the AR
$T_{i,k}$ = temperature of hot process stream i at the hot side of stage k
$T_{j,k}$ = temperature of cold process stream j at the hot side of stage k
$Varcap$ = variable capital cost
z = binary variable

Literature Cited

1. Ponce-Ortega JM, Serna-González M, Jiménez-Gutiérrez A. MINLP synthesis of optimal cooling networks. *Chem Eng Sci*. 2007;62(21): 5728–5735.
2. Ponce-Ortega JM, Serna-González M, Jiménez-Gutiérrez A. A disjunctive programming model for simultaneous synthesis and detailed design of cooling networks. *Ind Eng Chem Res*. 2009;48(6):2991–3003.
3. Ponce-Ortega JM, Serna-González M, Jiménez-Gutiérrez A. Optimization model for re-circulating cooling water systems. *Comput Chem Eng*. 2010;34(2):177–195.
4. Rubio-Castro E, Serna-González M, Ponce-Ortega JM. Optimal design of effluent-cooling systems using a mathematical programming model. *Appl Therm Eng*. 2010;30(14–15):2116–2126.
5. Rubio-Castro E, Serna-González M, Ponce-Ortega JM, El-Halwagi MM. Synthesis of cooling water systems with multiple cooling towers. *Appl Therm Eng*. 2013;50(1):957–974.
6. Gololo KV, Majozi T. On synthesis and optimization of cooling water systems with multiple cooling towers. *Ind Eng Chem Res*. 2011;50(7):3775–3787.
7. Wechsung A, Aspelund A, Gundersen T, Barton PI. Synthesis of heat exchanger networks at subambient conditions with compression and expansion of process streams. *AIChE J*. 2011;57(8):2090–2108.
8. Reddy CCS, Rangaiah GP, Wei LL, Naidu SV. Holistic approach for retrofit design of cooling water networks. *Ind Eng Chem Res*. 2013;52(36):13059–13078.
9. Gololo KV, Majozi T. Complex cooling water systems optimization with pressure drop consideration. *Ind Eng Chem Res*. 2013;52(22): 7056–7065.
10. Shenoy AU, Shenoy UV. Targeting and design of CWNs (cooling water networks). *Energy*. 2013;55:1033–1043.
11. Srikhirin P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. *Renew Sustain Energy Rev*. 2001;5(4):343–372.
12. Tora EA, El-Halwagi MM. Integration of solar energy into absorption refrigerators and industrial processes. *Chem Eng Technol*. 2010; 33(9):1495–1505.
13. Ponce-Ortega JM, Tora EA, González-Campos JB, El-Halwagi MM. Integration of renewable energy with industrial absorption refrigeration systems: systematic design and operation with technical, economic, and environmental objectives. *Ind Eng Chem Res*. 2011; 50(16):9667–9684.
14. Lira-Barragán LF, Ponce-Ortega JM, Serna-González M, El-Halwagi MM. Synthesis of integrated absorption refrigeration systems involving economic and environmental objectives and quantifying social benefits. *Appl Therm Eng*. 2013;52(2):402–419.
15. Maréchal F, Kalitventzeff B. Identification of the optimal pressure levels in steam networks using integrated combined heat and power method. *Chem Eng Sci*. 1997;52(17):2977–2989.
16. Gutiérrez-Arriaga CG, Serna-González M, Ponce-Ortega JM, El-Halwagi MM. Multi-objective optimization of steam power plants for sustainable generation of electricity. *Clean Technol Environ Policy*. 2012;15(4):551–566.
17. Bamufleh HS, Ponce-Ortega JM, El-Halwagi MM. Multi-objective optimization of process cogeneration systems with economic, environmental, and social tradeoffs. *Clean Technol Environ Policy*. 2013;15(1):185–197.
18. Manesh KMH, Abadi SK, Amidpour M, Hamedi MH. A new targeting method for estimation of cogeneration potential and total annualized cost in process industries. *Chem Eng Res Des*. 2013;91(6):1039–1049.
19. Manesh KMH, Navid P, Amidpour M, Hamedi MH. New procedure for optimal design of cogeneration system with considering

environmental impacts and total cost. *Clean Technol Environ Policy*. In press. DOI:10.1007/s10098-012-0576-0.
20. Zoschak RJ, Wu SF. Studies of the direct input of solar energy to a fossil-fueled central station steam power plant. *Solar Energy*. 1975; 17(5):297–305.
21. Hu CW, Ahmad S. Total site heat integration using the utility system. *Comput Chem Eng*. 1994;18(8):729–742.
22. Li M, Rao AD, Samuelsen GS. Performance and costs of advanced sustainable central power plants with CCS and H2 co-production. *Appl Energy*. 2012;91(1):43–50.
23. Klemes J, Dhole VR, Raissi K, Perry SJ, Puigjaner L. Targeting and design methodology for reduction of fuel, power and CO2 on total sites. *Appl Therm Eng*. 1997;17(8–10):993–1003.
24. Bandyopadhyay S, Varghese J, Bansal V. Targeting for cogeneration potential through total site integration. *Appl Therm Eng*. 2010;30(1):6–14.
25. Ghannadzadeh A, Perry S, Smith R. Cogeneration targeting for site utility systems. *Appl Therm Eng*. 2012;43:60–66.
26. Liew PY, Alwi SRW, Varbanov PS, Manan ZA, Klemes JJ. Centralised utility system planning for a total site heat integration network. *Comput Chem Eng*. 2013;57:104–111.
27. Manesh KMH, Amidpour M. Abadi KS, Hamedi MH. A new cogeneration targeting procedure for total site utility system. *Appl Therm Eng*. 2013;54(1):272–280.
28. Hackl R, Harvey S. Applying exergy and total site analysis for targeting refrigeration shaft power in industrial clusters. *Energy*. 2013;55:5–14.
29. Varghese J, Bandyopadhyay S. Fired heater integration into total site and multiple fired heater targeting. *Appl Therm Eng*. 2012;42;111–118.
30. Varbanov PS, Fodor Z, Klemes JJ. Total site targeting with process specific minimum temperature difference (ΔTmin). *Energy*. 2012; 44(1):20–28.
31. Chew KH, Klemes JJ, Alwi WRS, Manan AZ. Industrial implementation issues of total site heat integration. *Appl Therm Eng*. 2013; 61(1):17–25.
32. Dhole VR, Linnhoff B. Total site targets for fuel co-generation, emissions, and cooling. *Comput Chem Eng*. 1993;17(1):S101–S109.
33. Bagajewicz M, Rodera H. Energy savings in the total site heat integration across many plants. *Comput Chem Eng*. 2000;24(2–7):1237–1242.
34. Bagajewicz M, Rodera H. On the use of heat belts for energy integration across many plants in the total site. *Can J Chem Eng*. 2001; 79(4):633–642.
35. Bagajewicz M, Rodera H. Multiple plant heat integration in a total site. *AIChE J*. 2002;48(10):2255–2270.
36. Rodera H, Bagajewicz MJ. Targeting procedures for energy savings by heat integration across plants. *AIChE J*. 1999;45(8):1721–1742.
37. Rodera H, Bagajewicz MJ. Multipurpose heat-exchanger networks for heat integration across plants. *Ind Eng Chem Res*. 2001;40(23): 5585–5603.
38. Stijepovic VZ, Linke P, Stijepovic MZ, Kijevcanin ML, Serbanovic S. Targeting and design of industrial zone waste heat reuse for combined heat and power generation. *Energy*. 2012;47(1):302–313.
39. Perry S, Klemes J, Bulatov I. Integration waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. *Energy*. 2008;33(10):1489–1497.
40. Klemes JJ, Varbanov PS, Kapustenko P. New developments in heat integration and intensification, including total site, waste-to energy, supply chains and fundamentals concepts. *Appl Therm Eng*. 2013; 61(1):1–6.
41. Hackl R, Havey S. Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters. *Appl Energy*. 2013;112:1500–1509.
42. Zhang BJ, Luo XL, Chen QL. Hot discharges/feeds between plants to combine utility streams for heat integration. *Ind Eng Chem Res*. 2012;51(44):14461–14472.
43. Liu BT, Chien KH, Wang CC. Effect of working fluids on organic Rankine cycle for waste heat recovery. *Energy*. 2004;29(8):1207–1217.
44. Mago PJ, Luck R. Energetic and exergetic analysis of waste heat recovery from a microturbine using organic Rankine cycles. *Int J Energy Res*. 2013;37(8):888–898.
45. Dai YP, Wang JF, Gao L. Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. *Energy Convers Manag*. 2009;50(3):576–582.
46. Gu W, Wang WY, Zheng B. Theoretical and experimental investigation of an organic Rankine cycle for a waste heat recovery system. *J Power Energy*. 2009;223(5):523–533.
47. Hogerwaard J, Dincer I, Zamfirescu C. Analysis and assessment of a new organic Rankine based heat engine system with/without cogeneration. *Energy*. 2013;62:300–310.
48. Desai NB, Bandyopadhyay S. Process integration of organic Rankine cycle. *Energy*. 2009;34(10):1674–1686.
49. Hipólito-Valencia BJ, Rubio-Castro E, Ponce-Ortega JM, Serna-González M, Nápoles-Rivera F, El-Halwagi MM. Optimal integration of organic Rankine cycle with industrial processes. *Energy Convers Manag*. 2013;73:285–302.
50. Al-Sulaiman FA, Hamdullahpur F, Dincer I. Performance comparison of three trigeneration systems using organic Rankine cycles. *Energy*. 2011;36(9):5741–5754.
51. Al-Sulaiman FA, Dincer I, Hamdullahpur F. Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: part I-formulations. *Energy Convers Manag*. 2013;69:199–208.
52. Al-Sulaiman FA, Dincer I, Hamdullahpur F. Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: part II-applications. *Energy Convers Manag*. 2013;69:209–216.
53. Zhai H, Dai YJ, Wu JY, Wang RZ. Energy and exergy analyses on a novel hybrid solar heating, cooling and power generation system for remote areas. *Appl Energy*. 2009;86(9):1395–1404.
54. Wang J, Dai Y, Gao L, Ma S. A new combined cooling, heating and power system driven by solar energy. *Renew Energy*. 2009;34(12): 2780–2788.
55. Maraver D, Sin A, Royo J, Sebastian F. Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. *Appl Energy*. 2013;102:1303–1313.
56. Tora EA, El-Halwagi MM. Integral conceptual design of solar-assisted trigeneration systems. *Comput Chem Eng*. 2011;35:1807–1814.
57. Kong XQ, Wang RZ, Huang XH. Energy efficiency and economic feasibility of CCHP driven by stirling engine. *Energy Convers Manage*. 2004;45(9–10):1433–1442.
58. Varbanov PS, Klemes JJ. Integration and management in renewables into total sites with variable supply and demand. *Comput Chem Eng*. 2011;35(9):1815–1826.
59. Hossain KA, Khan F, Hawboldt K. SusDesign-an approach for a sustainable process system design and its application to a thermal power plant. *Appl Therm Eng*. 2010;30(14–15):1896–1913.
60. Balli O, Aras H, Hepbasli A. Thermodynamic and thermo-economic analyses of a trigeneration (TRIGEN) system with a gas-diesel engine: part I-methodology. *Energy Convers Manag*. 2010;51(11): 2252–2259.
61. Chicco G, Mancarella P. From cogeneration to trigeneration: profitable alternatives in a competitive market. *IEEE Trans Energy Convers*. 2006;21(1):265–272.
62. Stojiljkovic MM, Stojiljkovic MM, Blagojevic BD. Mathematical modeling and optimization of trigeneration systems with reciprocating engines. *Therm Sci*. 2010;14(2):541–553.
63. Chouinard-Dussault P, Bradt L, Ponce-Ortega JM, El-Halwagi MM. Incorporation of process integration into life cycle analysis for the production of biofuels. *Clean Technol Environ Policy*. 2011;13(5): 673–685.
64. Chen JJJ. Letter to the editor: comments on improvement on a replacement for the logarithmic mean. *Chem Eng Sci*. 1987;42(10): 2488–2489.
65. GREET Version 2.7, Copyright 2007 UChicago Argonne, LLC, 2007.
66. Miller RE, Blair PD. Input-Output Analysis: Foundations and Extensions. Cambridge, UK: Cambridge University Press, 2009.
67. You F, Tao L, Graziano DJ, Snyder SW. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input-output analysis. *AIChE J*. 2012;58(4):1157–1180.
68. Goldberg M, Sinclair K, Milligan M. Job and economic development impact (JEDI) model: a user-friendly tool to calculate economic impacts from wind projects. Golden, CO. NREL. 2004.
69. Brooke A, Kendrick D, Meeruas A, Raman R. *GAMS-Language Guide*. Washington, DC: GAMS Development Corporation, 2013.

Manuscript received Aug. 2, 2013, and revision received Oct. 23, 2013.