An Off-design Thermoeconomic Input-Output Analysis of a Natural Gas Combined Cycle Power Plant

Sajjad Keshavarzian[a], Francesco Gardumi[b], Matteo Rocco[c], Emanuela Colombo[d]

[a] *Department of Energy, Politecnico di Milano, Milan, Italy, sajjad.keshavarzian@polimi.it*
[b] *Department of Energy, Politecnico di Milano, Milan, Italy, francesco.gardumi@polimi.it*
[c] *Department of Energy, Politecnico di Milano, Milan, Italy, matteovincenzo.rocco@polimi.it*
[d] *Department of Energy, Politecnico di Milano, Milan, Italy, emanuela.colomno@polimi.it*

Abstract:

In the current and forecasted energy scenario, Natural Gas Combined Cycle (NGCC) power plants are requested increasingly flexible operation. The continuous changes in the capacity factor of the power plants and the increasing number and steepness of ramp-ups could largely affect the thermodynamic and economic performance of the plants and undermine their competitiveness.

In order for industrial operators to adopt competitive strategies to increase the flexibility of the power plants, the effect that off-design operation has on the cost structure of plant products needs to be addressed. Thermoeconomics provides tools and models to meet such objective.

The study presents an application of Thermoeconomic Input-Output Analysis (TIOA) to a NGCC power plant subject to flexible operation in Italy. The on- and off-design performance of the plant is assessed, considering two load control mechanisms for off-design operation: Inlet Guide Vanes (IGVs) with constant Turbine Outlet Temperature (TOT) or constant Turbine Inlet Temperature (TIT). The Input-Output model is derived from a detailed off-design Thermodynamic model designed in Thermoflow Thermoflex™, and it is stand-alone: it computes the cost structure of the plant products and the Thermoeconomic performance indicators as continuous functions of the gas turbine load, independently from the Thermodynamic model.

In the first place, the on- and off-design models of the plant are set up. Secondly, the detailed economic cost analysis is performed. Eventually, the stand-alone Input -Output model is derived: the Technical Coefficients and the Input Coefficients are computed from the fuels and products in the Thermodynamic model at different loads; by regression of the obtained values, continuous functions of the load are derived for each coefficient; finally, the stand-alone model is designed, including these functions in the Leontief Inverse matrix.

The results provide an evaluation of the off-design performance of the power plant for the two control strategies, and a tool for the choice of the most efficient one. After specialised analysts set up and run the off-design Thermodynamic model, the power plant operators may perform production scenarios and predictions through the stand-alone Input-Output model independently. This may help abate barriers for industrial practitioners, given by the complexity, computational effort and difficult interpretation of off-design thermodynamic and cost models.

Keywords:

NGCC; Flexibility; Thermoeconomic Input-Output Analysis; Exergoeconomic cost.

1. Introduction

According to the guidelines of EU Energy Roadmap 2050, Natural Gas Combined Cycle (NGCC) power plants may become the main backup technology in the low carbon European electricity system [1]. Following the current trend, the average capacity factor may decrease, the number of ramp-up cycles and their steepness increase, the amplitude of load variations increase. This implies that NGCCs may experience an increase of production costs and decrease of revenues, which undermines their competitiveness and possibly the adequacy of the grid [2,3] . In order to lower the production costs and benefit from price peaks on the markets, operators need to best respond to the request for flexibility. Plant configuration and operation strategies must be accordingly modified [4,5].

In this section, the relevance of Thermoeconomics for off-design performance analysis is highlighted and the objectives of the study are introduced.

1.1. Performance evaluation of NGCC power plants

In order for industrial operators to adopt strategies to best respond to the request for flexibility, tools must be designed to predict the implications of increased operational flexibility over the economic and thermodynamic performance of the power plants.

Several thermodynamic models have been proposed for off-design operation, most of them quasi-stationary: the response time of the Heat Recovery Steam Generator (HRSG) to thermal transients is considerable, but it is not a key variable when performing averaged evaluations over yearly profiles [6-8]. Together with thermodynamic analyses, economic evaluations are of concern under the industrial point of view. Techno-economic analysis provides a picture of the cost of the product and its variation, but it doesn't look into the productive structure of the process, therefore it doesn't pinpoint the causes for cost increases in off-design [9].

Literature suggests Thermoeconomic Analysis (TA) as an appropriate tool to evaluate the cost of energy system products and their structure. TA explodes the productive structure and allows internal evaluations on the response of each component to off-design operation. *Kotas et al.* introduced the concept of structural coefficients to estimate to which extent the variation of the efficiency of a component in a chain influences another component in the chain [10]. This is a key concept in the industrial practice, both for production planning and diagnostic purposes [11,12]. *Valero et al.* provided a synthesis of this concept introducing the Input-Output approach for Thermoeconomic Analysis of generic systems [13,14]. Input-Output is well established in economics to analyse the interaction between economic sectors, producers and consumers [15]. Applied to the performance analysis of power plants, it provides a clear picture of the relationships between resources and products of the various components.

1.2. Objective and structure of the work

Thermoeconomic analysis is usually performed for on-design conditions, neglecting the effects of the off-design operation on the final cost. However, in the described context power plants mostly operate in off-design. Therefore, considering the off-design performance may become fundamental for minimizing the levelised cost. Literature has addressed this need [16-18]. Nonetheless, in some cases the complexity of off-design Thermoeconomic models may make them unfit to be directly employed by industrial practitioners.

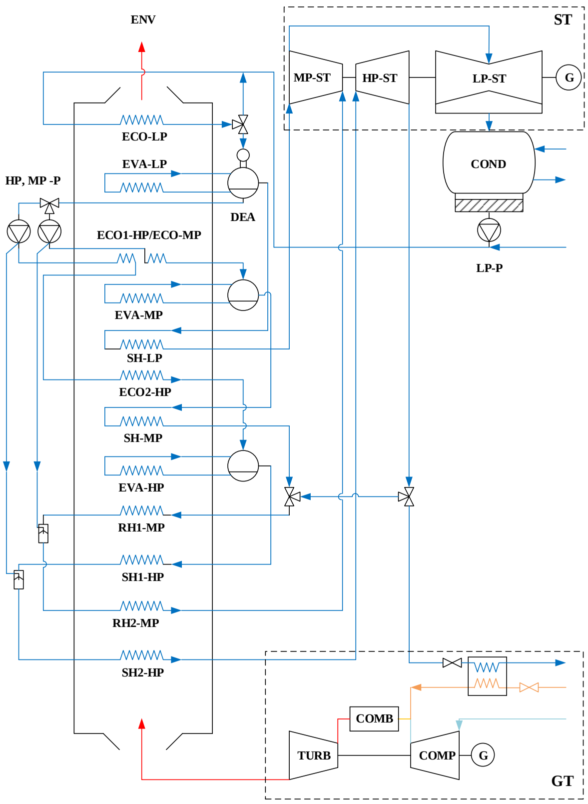
The present work applies Thermoeconomic Input-Output Analysis (TIOA) to a *Natural Gas Combined Cycle* (NGCC) power plant subject to flexible operation in Italy. The on-design and the off-design performance under two alternative load control mechanisms are analysed. The Input-Output model computes the cost structure of the plant products and the related Thermoeconomic performance indicators as continuous functions of the load of the gas turbine, independently from the Thermodynamic model. It is derived from the Thermodynamic model as follows: the Technical Coefficients and the Input Coefficients are computed from the fuels and products in the Thermodynamic model at different loads; by interpolation of the obtained values, continuous functions of the load are derived for each coefficient; finally, the stand-alone Input-Output model is designed, including these functions in the Leontief Inverse matrix. Such approach doesn't introduce any significant methodological advancement. In principle, the same results can be obtained by traditional TA. However, it reduces the complexity of the assessment and proposes a relevant application in the Italian energy system: it may be employed by power plant operators to determine the cost structure of the product, to predict the system performance and to perform diagnosis of the

system under flexible operation without recurring to the detailed Thermodynamic model for each off-design condition.
The study is structured as follows:

1. **Thermodynamic model.** The on- and off-design Thermodynamic model of the power plant is designed, considering two different load control mechanisms for its off-design operation: *Inlet Guide Vanes* (IGVs) with constant *Turbine Outlet Temperature* (TOT) or constant *Turbine Inlet Temperature* (TIT).
2. **Economic cost model.** The economic cost analysis of the plant is performed, evaluating the total fixed and variable costs of the components.
3. **Thermoeconomic Input-Output model.** The Thermoeconomic Input-Output model of the plant is set up, defining the Resource, Product, Loss categories; the Junction Ratios; the waste reallocation matrix. The Technical and Input Coefficients are derived, as continuous functions of the gas turbine load.
4. **Performance evaluation of the plant.** The on- and off-design performance of the plant is assessed and the two load control mechanisms are compared.

2. Thermodynamic on- and off-design model

The Thermodynamic model of the power plant is based on the plant of *La Casella* (PC), operated by Enel S.p.A., in northern Italy. It consists of four groups, each made of one gas turbine and a coupled vertical HRSG. Since the groups are identical, the analysis is performed only on one group. The software *Thermoflow Thermoflex*™ was employed to perform the detailed thermodynamic simulation of the plant in both on- and off-design conditions: it is a zero-dimensional software for power plants modelling, which iteratively solves the mass and energy balances at the nodes of a network of pre-defined or user-defined components. In this section, the plant layout is described, together with the software setup.



Equipments	Symbol
Environment	ENV
Gas turbine	GT
Deareator	DEA
Steam Turbine	ST
Economizer LP	ECO-LP
Evaporator LP	EVA-LP
Superheater LP	SH-LP
Economizer MP,HP1	ECO-MP,HP
Evaporator MP	EVA-LP
Superheater MP	SH-MP
Reheater 1MP	RH1-MP
Reheater 2MP	RH2-MP
Economizer 2HP	ECO2-HP
Evaporator HP	EVA-HP
Superheater 1HP	SH1-HP
Superheater 2HP	SH2-HP
Pump LP	LP-P
Pump MP	MP-P
Pump HP	HP-P
Condensor	COND

Figure 1. Power plant model and legend of the components.

2.1. Plant layout and main assumptions

Common inputs. The analysed group consists of the following main components: gas turbine (GT - *Siemens V94.3a*), which generates a design net electric power of 252.5 MW with a TIT of 1295.6 °C; HRSG with 13 heat exchangers operating on three steam pressure levels; steam turbine (ST) with on-design 131.5 MW electric power generation, and condenser (COND). The configuration of the power plant is shown in Figure 1 and the main software input data are listed in Table 1. Ambient temperature and pressure are also listed in Table 1; the molar air composition refers to *Kotas* [10].

Inputs to the on-design model. In addition to the common inputs, pinch points of evaporators, sub-cooling temperatures of economisers, steam outlet temperatures at superheaters are fixed for each pressure level. Starting from such constraints, the mass and energy balance equations of the system are closed, the remaining properties of all the streams are computed and the geometric features of the components are derived. The on-design model is validated by comparison of the results with the operation data available from the power plant.

Inputs to the off-design model. In the off-design model, the geometric characteristics of the components derived by the previous simulation become an input, together with the gas turbine load and the related off-design control mode. The aim of the off-design model is to compare two load control mechanisms of the power plant, because the operator can choose between them to enhance the performance in flexible operation. Therefore, the non-controllable quantities like the environmental conditions are assumed to be fixed in all the simulations. The properties of all the streams are now dependent variables and they are computed as functions of the load of the gas turbine. This implies that also the mass flow rate, temperature and pressure of the steam in the three pressure levels and the global heat duty become dependent variables. The off-design model is validated through comparison with the on-design model at 100% load of the gas turbine.

The main inputs of the on- and off-design models are listed in Table 1.

Table 1. Inputs for on- and off-design Thermodynamic model.

Parameters	**Values**
Common inputs	
Environment T and P	288.15 K, 1.01325 bar
Condenser pressure	0.0336 bar
Cooling water ΔT	6.5 K
Inputs to on-design model	
Gas Turbine model and design power	Siemens V94.3a, 252 MW
Air and fuel mass flow rate	635.9 kg/s, 14.17 kg/s
HP, MP, LP steam T at turbine inlet	813, 813, 618 K
HP, MP, LP steam P at turbine inlet	88.8, 12.6, 3.3 bar
HP, MP, LP steam turbine nominal efficiency	85, 88, 91 %
Recirculation ratio at ECO-LP	29 %
Desired water/steam temperatures at heat exchangers outlet	According to the STs requirement
Mass flow ratios at branching	According to the design layout
Inputs to off-design model	
Gas turbine load	Decreased from 100% to 50%
Off-design gas turbine control mode	TOT or TIT control
UA [W/K] of heat exchangers in HRSG	Given by the on-design computation

Both the on-design and off-design models compute temperature, pressure and mass flow rates of each stream. From such values, the related exergy rates are derived.

2.2. Off-design control mechanisms

In off-design conditions, the steam turbines of the analysed combined cycle work in sliding pressure. Therefore, the load of the whole power plant is controlled through the gas turbine by closure of the compressor's Inlet Guide Vanes (IGVs). When the valves are completely closed, the load of the gas turbine is reduced to 50% of the nominal load. When the air mass flow rate is reduced, the fuel flow rate is also reduced according to two control mechanisms:

- **Constant Turbine Outlet Temperature (TOT).** This reduces the thermal stresses over the heat exchangers in the bottoming cycle in off-design. The TIT decreases consequently;
- **Constant Turbine Inlet Temperature (TIT).** This is claimed to limit the global reduction of efficiency. The TOT increases, but the parts of the HRSG exposed to the highest temperatures are safe, since they were originally sized for a simple steam cycle, with higher temperatures.

These two control logics represent two limit conditions: the first one guarantees the least thermal stress on the components of the bottoming cycle, the second one may increase the off-design efficiency.

3. Economic cost model

The economic model is based on the *Total Revenue Requirement* (TRR) method, described by *Bejan et al.* in [19]. The Purchased Equipment Costs (PECs) are based on the industrial database of *Thermoflow Thermoflex*™ and they are listed in Table 2. The remaining cost items are computed as a percentage of the total PEC.

Table 2. Purchased Equipment Costs from the industrial database.

Equipment	**Cost [M€]**
Gas turbine	66.025
Steam turbine	32.261
HRSG	25.040
Condenser	2.442
Pumps	0.514
Deareator	0.426
Piping	0.823

In line with *Cafaro et al.*, the aggregated costs of the steam turbine and of the pumps are allocated to the single components proportionally to the mechanical power, respectively delivered and absorbed; similarly, the global cost of the HRSG is allocated on each heat exchanger proportionally to the thermal power transferred [20]. The values of the fixed and variable O&M costs are also available as aggregated for a whole group composed by a gas turbine and an HRSG. Based on industrial literature review [20-24], the yearly fixed O&M costs amount to 15.37 €/kW, while the variable O&M costs amount to 3.27 €/MWh [21]. They are allocated to the components proportionally to their PEC, according to *Bejan et al.* [19]. It is assumed that 2001 is the year of the evaluation: thus, all costs are computed in 2001 €. The actual production schedule of the case study power plant is obtained from the databank of *Gestore dei Mercati Energetici* [25] and it refers to 2006.

A TRR value of 9,474 current M€ is computed, of which 7,268 M€ is the cost for the fuel. The levelised cost is hence computed and it is allocated on each component proportionally to its PEC.

4. Stand-alone Thermoeconomic Input – Output model

In this section, TA is briefly introduced, and its application to the case-study illustrated. Standard TA was originally developed in [13] as a cost allocation technique. Recently, Valero reformulated TA by means of *Input-Output Analysis* (IOA) [26,27], which can be considered the state of the art in economic cost accounting techniques.

4.1. Thermoeconomic Input-Output Analysis: state of the art

Considering one energy system composed of n pieces of equipment, connected to each other and to the environment by flows of exergy, TA can be applied as follows. All the exergy flows are classified according to their "economic" purpose, through the *Resource-Product-Losses* (RPL) criterion [28]. This allows to distinguish among *productive* and *dissipative* components [29]:

- *Productive*: whose main purpose is to generate a useful product;
- *Dissipative*: it does not generate any final product, but it is responsible for disposing of the residues created during production (condensers, filters, SCRs, stacks, etc.).

For each component, the exergy balance and exergy efficiency can be written as (3.1).

$$R_i = P_i + L_i + D_i \qquad \rightarrow \qquad \eta_i = P_i / R_i \tag{3.1}$$

The entire set of n exergy balances can be collected in the typical matrix notation of IOA [14], as shown in Figure 2.

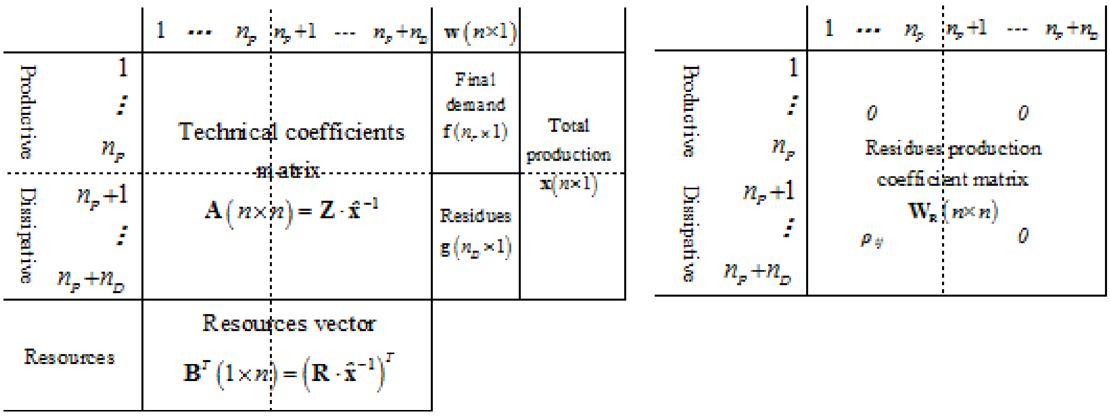


Figure 2. General outline of the Input–Output tables of a physical system.

Details about the RPL classification and the compilation of IO tables can be retrieved in literature [28,30]. Let the generic system be composed of n_P productive components $\mathbb{P} = (1, \ldots, n_P)$ and n_D dissipative components $\mathbb{D} = (n_P + 1, \ldots, n_P + n_D)$, with $n = n_P + n_D$. For this system, the *Transaction matrix* (3.2) is defined, whose elements represent the amount of exergy rate (J/s) produced by ith component and fuelled as a resource to jth component.

$$\mathbf{Z} = \left|\dot{E}_{ij}\right| \qquad i, j \in \mathbb{P} \cup \mathbb{D} \tag{3.2}$$

The definition of *exergy junction ratios* is required to overcome the problem of allocating the product of multiple components as a resource of other components [30,31].

The amount of exergy provided to the environment by productive and dissipative components is respectively collected in the *Final Demand vector* $\mathbf{f}(n_P \times 1)$ and in the *Residue vector* $\mathbf{g}(n_D \times 1)$: these vectors define the *System Output vector* $\mathbf{w}(n \times 1)$ according to (3.3).

$$\mathbf{w} = \begin{vmatrix} \mathbf{f} \\ \mathbf{g} \end{vmatrix} \rightarrow \quad \begin{cases} \mathbf{f} = \left|\dot{E}_{i0}\right| & i \in \mathbb{P} \\ \mathbf{g} = \left|\dot{E}_{i0}\right| & i \in \mathbb{D} \end{cases} \tag{3.3}$$

The *Resource vector* $\mathbf{R}(n \times 1)$ is defined as shown in (3.4) to collect the amount of exogenous resources that directly fuel the system. Therefore, it can be defined in different units, leading to the definition of different costs of the final demand: in standard *Exergy Cost Analysis*, the elements of **R** represent the exergy that feeds each component. Conversely, in *Exergoeconomic Cost Analysis*, such vector is defined by means of monetary values $\dot{Z}_i$. Specifically, the terms $\dot{Z}_i$ represent, in monetary units per unit of time, charges for capital investment and depreciation, as well as operation and maintenance expenses, derived in the previous section.

$$\mathbf{R}: \begin{cases} \mathbf{R}_{ex}\left[\frac{J}{s}\right] = \left|\dot{E}x_i\right| \\ \mathbf{R}_{eco}\left[\frac{€}{s}\right] = \left|\dot{Z}_i\right| \end{cases} \tag{3.4}$$

The *Technical Coefficients matrix* $\mathbf{A}(n \times n)$ and the *Input vector* $\mathbf{B}(n \times 1)$ are defined according to standard IOA, as in (3.5).

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \quad ; \quad \mathbf{B} = \mathbf{R} \cdot \hat{\mathbf{x}}^{-1} \tag{3.5}$$

Thanks to the introduced definitions, it is possible to evaluate the specific and total exergy and economic costs of both system products and residues, according to (3.6), where $\mathbf{c}(n \times 1)$ is the *specific cost vector*, $\mathbf{C}(n \times 1)$ is the *total cost vector*, and $\mathbf{L}(n \times n)$ is the *Leontief Inverse matrix*. In IOA, relation (3.6) is known as the *Leontief Cost Model* (LCM) [15].

$$\mathbf{L} = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \quad \rightarrow \quad \mathbf{c} = \mathbf{L}^{\mathrm{T}} \cdot \mathbf{B} \quad \rightarrow \quad \mathbf{C} = \hat{\mathbf{w}} \cdot \mathbf{c} \tag{3.6}$$

According to the cost accounting practice, the cost of residues should be reallocated to useful products only. This could be done through the proportionality criterion proposed by *Valero* [14]: the cost of residue of the *j*th dissipative component is then allocated to each productive component that feeds it, in proportion to the amount of exergy it delivers to *j*. This is expressed by the *residues cost distribution ratios* ψ_{ji}, defined by (3.7) as the fraction of *j*th resource coming from the *i*th component.

$$\psi_{ji} = \dot{E}_{ij} / \dot{R}_j \quad \rightarrow \quad \sum_{i \in \mathcal{P}} \psi_{ji} = 1 \qquad \forall i \in \mathbb{P}, j \in \mathbb{D} \tag{3.7}$$

A *Residues production coefficients matrix* $\mathbf{W_R}(n \times n)$ can be thus defined to collect the *residues production coefficients* ρ_{ji}, defined in (3.8), in matrix form; this matrix is displayed as Figure 2 (right side).

$$\mathbf{W_R} = \left|\rho_{ji}\right| \quad \rightarrow \quad \rho_{ji} = \begin{cases} 0 & j \in \mathbb{P} \\ \psi_{ji}\left(\dot{P}_j / \dot{P}_i\right) & j \in \mathbb{D} \end{cases} \tag{3.8}$$

Rearranging the cost balances and introducing (3.7) and (3.8), the reallocated specific and total exergy costs of useful products only can be determined as follows:

$$\mathbf{L_R} = \left(\mathbf{I} - \mathbf{A} - \mathbf{W_R}\right)^{-1} \quad \rightarrow \quad \mathbf{c}' = \mathbf{L}_{\mathbf{R}}^{T} \cdot \mathbf{B} \quad \rightarrow \quad \mathbf{C}' = \hat{\mathbf{w}} \cdot \mathbf{c}' \tag{3.9}$$

The standard exergy cost evaluation here formalized leads to the definition of a set of parameters which allow optimization and design evaluation of the system to be performed, as highlighted by [32]:

- *Exergy destruction and losses*, defined by (3.10), reveals the location and the magnitude of the irreversibility within each component.

$$\dot{D}_i + \dot{L}_i = \dot{R}_i - \dot{P}_i \quad \rightarrow \quad \mathbf{D} = \left(1_{1\times n} \cdot \mathbf{Z}\right)^T - \mathbf{Z} \cdot 1_{n\times 1} \tag{3.10}$$

- *Exergy and Monetary costs of exergy destructions*, defined by (3.11), reveals the impact of thermodynamic inefficiencies respectively in terms of exergy and monetary expenses.

$$\mathbf{C}_{\mathbf{ExD}} = \hat{\mathbf{D}} \cdot \mathbf{c} \tag{3.11}$$

Further details can be retrieved in literature [28,33].

4.2. Application of TIOA and derivation of the Technical Coefficients as functions of the plant load

In order to apply TIOA to the considered power plant, the physical structure of the system depicted in Figure 1 is simplified as in Figure 3.

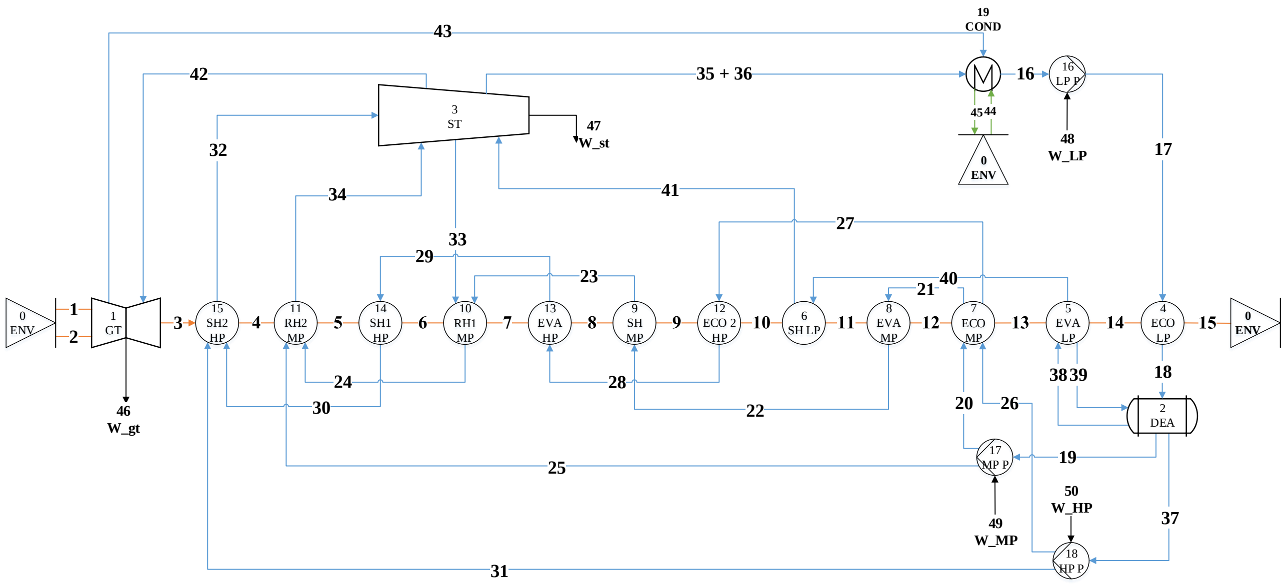


Figure 3. Essential physical structure of the plant.

All the exergy fluxes are grouped according to the RPL criterion introduced in the previous section (Table 3). The Transaction matrix **Z**, System Output vector **w**, Resource vector **R** and Residues production coefficients matrix $\mathbf{W_R}$ can be compiled and the Leontief Cost Model can be applied. The main global results of the TIOA consist in the exergy and exergoeconomic costs of the products and in the related costs of exergy destructions.

TIOA is applied to different off-design conditions: from 100% to 50% of the nominal power of the gas turbine, by steps of 5%, for both TIT and TOT load control mechanisms. For each of these points the Technical Coefficients matrix and the Input Coefficients vector are derived, based on the results of the Thermodynamic off-design model. Afterwards, functions of the gas turbine load are obtained for each of the coefficients through a regression procedure. The linear regression results the most suited (best values of R^2 for all the coefficients). This allows users, such as power plant operators, to analyse the Thermoeconomic off-design performance at any load, independently from the Thermodynamic model. Relying on the off-design Thermodynamic model would have two major drawbacks:

- the computational time is in the order of minutes;
- the model must be run for every specific load for which information is needed.

The inputs of this stand-alone model are the gas turbine load and the load control mechanism (TIT or TOT). The logical flow of the described procedure is shown in Figure 4.

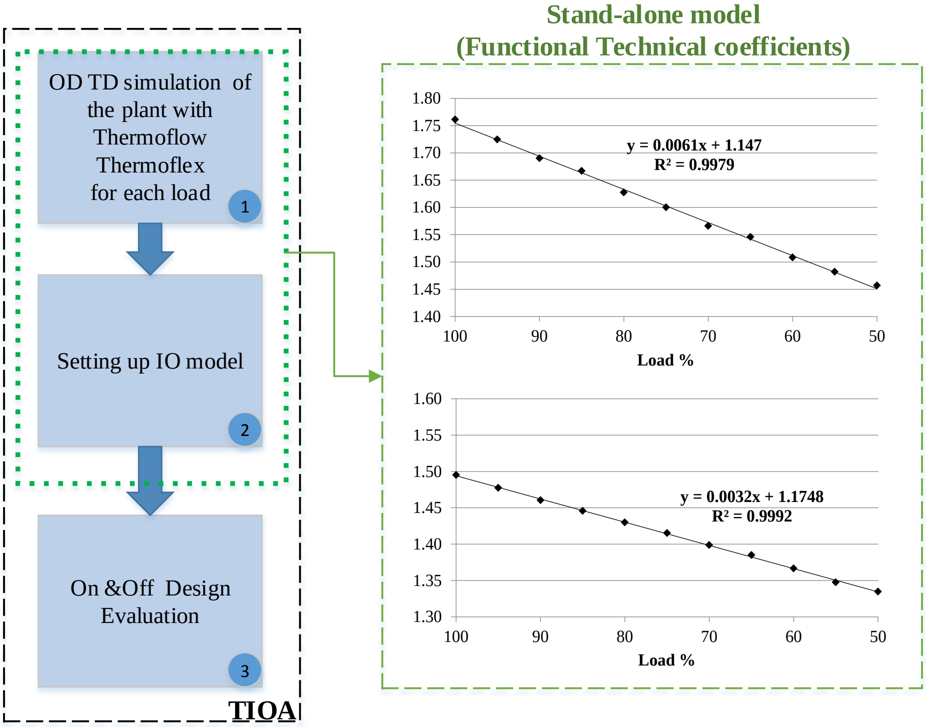


Figure 4. Logical flow diagram of the implementation of the model.

As an outcome of this procedure, eventually all the possible operating conditions of the plant can be represented with one single IO table and the complexity and computational effort of the model are reduced.

Table 3. RPL classification.

Piece of equipment	Fuel (R)	Product (P)	Losses (L)
ENV	-	-	-
GT	2+1+(42-43)	3+46	-
DEA	39	(19-18)+37+38	-
ST	(32+34+41)-(33+35+36+42)	47+48+49+50	-
ECO-LP	14-15	18-17	-
EVA-LP	13-14	39+(40-38)	-
SH-LP	10-11	41-40	-
ECO-MP	12-13	(21-20)+(27-26)	-
EVA-LP	11-12	22-21	-
SH-MP	8-9	23-22	-
RH1-MP	6-7	24-(23+33)	-
RH2-MP	4-5	34-(24+25)	-
ECO2-HP	9-10	28-27	-
EVA-HP	7-8	29-28	-
SH1-HP	5-6	30-29	-
SH2-HP	3-4	32-(30+31)	-
LP-P	48	17-16	-
MP-P	49	20+25-19	-
HP-P	50	26+31-37	-
COND	35+36+43-16	-	45-44

5. On-design evaluation

The relevant results from the on-design model are easily obtained also from traditional TA. The values of exergy destruction, exergy efficiency of components, total exergy and exergoeconomic costs of the products are derived. The costs of exergy destructions may be used to identify the components that, more than others, need to be improved in order to reduce the specific costs of the final products. As can be inferred form Table 4, a reduction of both exergy and economic costs of the products can be pursued mostly through improvement of the performance of GT, ST, EVA-HP and SH1-HP, ordered by importance. Improvements on the gas turbine and the heat exchangers may come from better scheduling of cleaning procedures. It is worth noticing that, except for the GT, the other three components are characterized by high differences between exergy cost of exergy destruction and exergy destruction: this implies that a thermodynamic improvement in these components will positively affect the performances of the others.

Table 4. Results of the TIOA to the on-design case.

N	Comp.	Ex_D	η_{ex}	$c_{ex,P}$	$C_{ex,P}$	$C_{ex,D}$	$c_{eco,P}$	$C_{eco,P}$	Z	$C_{eco,D}$
		kW	-	J/J	kW	kW	€/GJ	€/h	€/h	€/h
1	GT	282,578	0.62	1.6	441673	283,560	22.3	22,053	5,057	14,125
2	DEA	10	0.96	2.5	0	23	74.2	0	33	3
3	ST	14,629	0.90	2.4	305606	32,095	44.0	19,894	2,471	2,080
4	ECO_LP	3,730	0.71	2.5	0	6,510	42.2	0	247	403
5	EVA_LP	1,442	0.83	2.1	0	2,517	34.9	0	114	150
6	SH_LP	688	0.57	3.0	0	1,175	45.7	0	10	64
7	ECO_MP	1,443	0.88	2.0	0	2,569	32.7	0	143	149
8	EVA_MP	2,898	0.82	2.1	0	5,088	34.3	0	181	294
9	SH_MP	844	0.67	2.6	0	1,455	40.6	0	23	82
10	RH1_MP	2,988	0.75	2.3	0	5,242	36.0	0	91	290
11	RH2_MP	3,198	0.82	2.2	0	5,696	33.1	0	133	313
12	ECO2_HP	1,666	0.87	2.0	0	2,973	32.9	0	168	173
13	EVA_HP	9,997	0.83	2.1	0	17,822	33.2	0	517	992
14	SH1_HP	5,752	0.81	2.2	0	10,255	33.5	0	250	565
15	SH2_HP	972	0.82	2.1	0	1,711	32.9	0	40	95
16	LP P	418	0.15	16.8	0	1,023	333.1	0	7	73
17	MP P	14	0.67	3.8	0	36	83.5	0	2	3
18	HP P	420	0.70	3.7	0	1,076	75.0	0	30	79
19	COND	11,348	0.18	12.2	-	-	213.7	-	0	-

6. Off-design evaluation

The output of the LCM is used to compare the two load control mechanisms. As shown in the previous sections, the model can be interrogated providing the load (continuous variable, from 100% to 50%) and the load control mechanism. No additional information is drawn with respect to the TIOA proposed in [13,14], but the approach here employed allows the model to be more easily interrogated by non-analysts. Some key quantities to monitor the global performance may be the exergy and exergoeconomic specific costs of the main productive components. Figure 5 shows the values of the exergy and exergoeconomic costs of the GT and ST products, from 100% to 50% of the load. The trend of the unit exergy cost of the products is different in the two load control strategies: with TOT control, it increases for both GT and ST, which means that the efficiency of both the topping and bottoming cycle decreases. On the contrary, with TIT control, it slightly decreases for the steam turbine, resulting in an increase of efficiency for the bottoming cycle. The specific exergoeconomic cost of GT and ST products always increases as the load decreases, but it increases more with TOT control. In general, the TOT control mechanism results in a greater increase of the costs for both the GT and the ST with respect to the TIT mechanism.

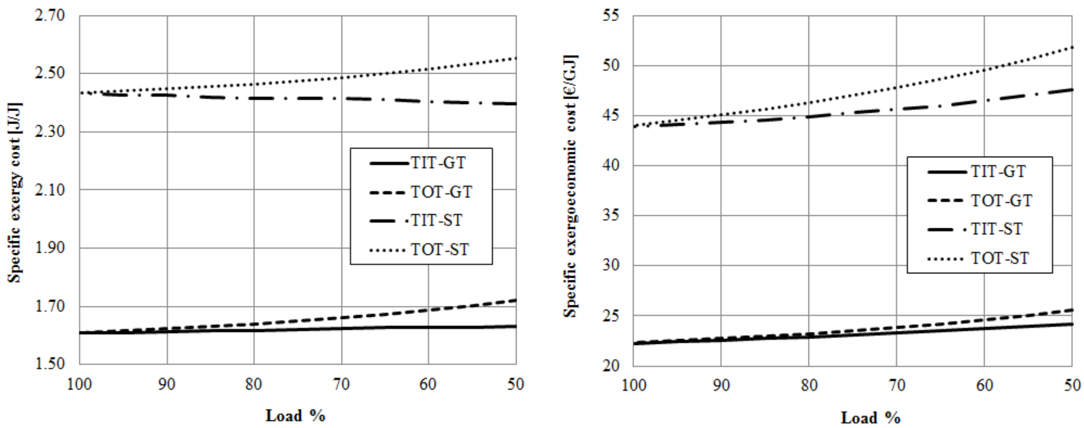


Figure 5. Specific exergy and exergoeconomic costs of GT and ST products.

7. Conclusions

In this paper, TIOA was applied to a NGCC power plant subject to flexible operation in Italy. A Thermoeconomic Input-Output model was designed, starting from an off-design Thermodynamic model and an Economic model. The Leontief Coefficients are obtained from the off-design Thermodynamic model for a number of conditions from 100% to 50% of the load; afterwards, through linear regression, continuous functions of the load are obtained for each of them, and they are included in the Leontief Inverse matrix. The Input-Output model thence becomes stand-alone, in the sense that performance predictions for every load can be performed without making further use of the Thermodynamic model. Therefore, they can be carried out also by users not expert in detailed Thermodynamic modelling with reduced computational effort. The results of the on-design TIOA are discussed with focus on the exergy cost of exergy destruction and exergy destruction of the components, in order to identify the priority of components to be thermodynamically improved. In the second place, the off-design TIOA analyses the performance of the plant with TOT and TIT load control mechanisms in terms of exergy and exergoeconomic specific costs of the main productive components: from here, the TIT load control mechanism results more suitable than the TOT for prolonged off-design operation. The study is not intended to propose any significant methodological advancement in Thermoeconomic Analysis. Nonetheless, it provides a relevant application for the present Italian electricity market context and it proposes a key to help abate barriers for industrial practitioners to employ tools for detailed Thermoeconomic off-design assessments. Only some general exergy figures were presented, in order to show the employed approach and its validity. However, more information on the production structure and the relationships between resources and products of the components can be drawn, by analysis of the Leontief Coefficients. This is a subject of the current research of the authors.

Acknowledgments

The authors would like to thank Enel Produzione, the Director and the staff of La Casella (PC) power plant for their kind collaboration and support to the realization of this study.

Nomenclature

NGCC	Natural Gas Combined Cycle
IGV	Inlet Guide Vanes
TOT	Turbine Outlet Temperature
TIT	Turbine Inlet Temperature
HRSG	Heat Recovery Steam Generator
HP, MP, LP	High, Medium, Low Pressure
PEC	Purchased Equipment Cost
TA	Thermoeconomic Analysis
TIOA	Thermoeconomic Input-Output Analysis
$\dot{\mathrm{R}}, \dot{\mathrm{P}}, \dot{\mathrm{L}}, \dot{\mathrm{D}}$	Exergy flow of Resource, Product, Losses, and Exergy destruction
n_P, n_D	Number of productive/dissipative components in the system
$n = n_P + n_D$	Total pieces of equipment of the system
E	Exergy
Z, A	Transaction matrix/Technical Coefficients matrix
$\mathrm{f}, \mathrm{g}, \mathrm{w}$	Final demand / Residues / System output vectors
R, B	Resource / Input vectors
x	Total production vector
η, k	Efficiency / Unit exergy consumption
κ	Unit exergy consumption between components
c, c	Unit exergy cost, unit exergy cost vector
$C = c \cdot E$, C	Total exergy cost, Total exergy cost vector
L	Leontief Inverse matrix
ψ	Residue cost distribution ratio
ρ, W_R	Residue production coefficient and matrix
$\mathrm{C}_{\mathrm{Ex,D}}$	Exergy destruction and losses vector

References

[1] Holz F, Richter PM, Egging R. The role of natural gas in a low-carbon Europe: Infrastructure and regional supply security in the global gas model. Discussion Papers, DIW Berlin; 2013.

[2] Morales A. U.K. Risks Blackouts Without Incentives for Natural Gas. Bloomberg; 2013.

[3] Duarte E, Sills B. Spain Said to Consider Increasing Aid for Gas-Fired Power Plants. Bloomberg; 2014.

[4] Kumar N, Besuner P, Lefton S, Agan D, Hilleman D. Power plant cycling costs. Contract. 2012;303:275-3000.

[5] Armanasco F, Marzoli M. Valutazione di strategie di esercizio flessibile per cicli combinati CESI Recerca; 2008.

[6] Nord LO, Anantharaman R, Bolland O. Design and off-design analyses of a pre-combustion CO2 capture process in a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. 2009;3:385-92.

[7] Möller BF, Genrup M, Assadi M. On the off-design of a natural gas-fired combined cycle with CO2 capture. Energy. 2007;32:353-9.

[8] Rovira A, Sánchez C, Muñoz M, Valdés M, Durán M. Thermoeconomic optimisation of heat recovery steam generators of combined cycle gas turbine power plants considering off-design operation. Energy Conversion and Management. 2011;52:1840-9.

[9] Peeters A, Faaij A, Turkenburg W. Techno-economic analysis of natural gas combined cycles with post-combustion CO2 absorption, including a detailed evaluation of the development potential. International Journal of Greenhouse gas control. 2007;1:396-417.

[10] Kotas T. The exergy method of thermal power analysis. Butterworth; 1985.

[11] Verda V, Serra L, Valero A. Thermoeconomic Diagnosis: Zooming Strategy Applied to Highly Complex Energy Systems. Part 1: Detection and Localization of Anomalies*. Journal of energy resources technology. 2005;127:42-9.

[12] Verda V. Prediction of the fuel impact associated with performance degradation in power plants. Energy. 2008;33:213-23.

[13] Erlach B, Serra L, Valero A. Structural theory as standard for thermoeconomics. Energy Conversion and Management. 1999;40:1627-49.

[14] Torres C, Valero A, Rangel V, Zaleta A. On the cost formation process of the residues. Energy. 2008;33:144-52.

[15] Leontief W. Input-output analysis. The new palgrave A dictionary of economics. 1987;2:860-64.

[16] Campos-Celador Á, Pérez-Iribarren E, Sala JM, del Portillo-Valdés LA. Thermoeconomic analysis of a micro-CHP installation in a tertiary sector building through dynamic simulation. Energy. 2012;45:228-36.

[17] Arce DFR. A decomposition strategy based on thermoeconomic isolation applied to the optimal synthesis/design and operation of an advanced fighter aircraft system: Virginia Polytechnic Institute and State University; 2003.

[18] Verda V, Borchiellini R. Exergy method for the diagnosis of energy systems using measured data. Energy. 2007;32:490-8.

[19] Bejan A, Moran MJ. Thermal design and optimization: John Wiley & Sons; 1996.

[20] Cafaro S, Napoli L, Traverso A, Massardo A. Monitoring of the thermoeconomic performance in an actual combined cycle power plant bottoming cycle. Energy. 2010;35:902-10.

[21] Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants. U.S. Department of Energy; 2013.

[22] Cost and Performance Review of Generation Technologies, Recommendations for WECC 10- and 20-Year Study Process. Western Electric Coordinating Council; 2012.

[23] Black V. Cost and Performance Data for Power Generation Technologies. Accessed on May. 2012;14:2013.

[24] Simmons S, Charles G. Natural Gas Combined Cycle Combustion Turbines. Northwest Power and Conservation Council; 2013.

[25] Gestore Mercati Energetici, Statistics and Monitoring, accessed on 2/01/2015; 2015.

[26] Valero A, Serra L, Uche J. Fundamentals of exergy cost accounting and thermoeconomics. Part I: Theory. Journal of Energy Resources Technology. 2006;128:1-8.

[27] Valero A, Serra L, Uche J. Fundamentals of Exergy Cost Accounting and Thermoeconomics Part II: Applications. Journal of Energy Resources Technology. 2006;128:9-15.

[28] Querol E, Gonzalez-Regueral B, Perez-Benedito JL. Practical approach to exergy and thermoeconomic analyses of industrial processes: Springer Science & Business Media; 2012.

[29] Lazzaretto A, Tsatsaronis G. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy. 2006;31:1257-89.

[30] Usón S, Kostowski WJ, Kalina J. Thermoeconomic Evaluation of Biomass Conversion Systems. Alternative Energies: Springer; 2013. p. 69-91.

[31] Valero A, Torres C. Thermoeconomic analysis. Exergy, energy system analysis and optimization, Encyclopedia of life support systems (EOLSS), EOLSS Publishers, Oxford. 2006.

[32] Tsatsaronis G, Morosuk T. A general exergy-based method for combining a cost analysis with an environmental impact analysis: Part I—Theoretical Development. ASME 2008 International Mechanical Engineering Congress and Exposition: American Society of Mechanical Engineers; 2008. p. 453-62.

[33] Tsatsaronis G. Thermoeconomic analysis and optimization of energy systems. Progress in energy and combustion science. 1993;19:227-57.