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A Reconciliation Method Based on a Module Simulator
An Approach to the Diagnosis of Energy System Malfunctions

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Abstract

The decay of existing power plants is caused primarily by mechanical factors, human errors, environmental effects, control deviations, and defects in materials. These causes are reflected in performance malfunctions of the processes. In a highly integrated and complex energy system, it is difficult to detect and evaluate the origin of a malfunction. A diagnosis methodology for power generation systems which addresses this is presented here and illustrated by its application to the TADEUS problem (Valero et al., 2004, 2002a). The proposed methodology is based on a comparison between two operating conditions, namely, the test operating conditions (TOP), which reflect actual operating conditions, and the reference operating conditions (ROP), which can be based on simulated thermal balances or an acceptance test. Energy and exergy balances as well as analytical models are used to simulate plant performance at either TOP or ROP and these, along with data collection from the plant, characterize a complete database for the plant. Such a database includes variables which can be classified as either free (variations in their values are the cause of malfunctions) or dependent. A reconciliation-simulation algorithm corrects the values of the free variables for a given *heat rate* and *total power* to pre-malfunction values. In order to demonstrate the reliability of the approach, it is applied to the combined cycle power plant outlined in the TADEUS problem. It is shown that the results generated by this methodology provide relevant information of the present condition of the plant.

Keywords: Diagnosis, malfunctions, heat rate, reference and test state.

1. Introduction

In defining the term diagnosis, a very useful definition is the one quoted in the TADEUS paper (Valero et al., 2002a,b) which states, ”*Diagnosis is the art of discovering anomalies in the operati[ng] conditions of energy systems*”. In order to deal with the problem of diagnosis, a thermoeconomic diagnosis methodology which localizes anomalies and quantifies their impacts on existing power plants is presented here. The problem proposed in TADEUS (Valero et al., 2004, 2002a) is used as the bench-test so as to prove the applicability of this methodology. In contrast to other methodologies developed thus far for the diagnosis of power plants and based on the fuel-impact concept (Valero, Torres, and Lozano, 1990; Zaleta-Aguilar, Royo, and Valero, 1997,), on Lagrangian techniques (Reini, 1994; Lozano et al., 1994), on non-Lagrangian approaches (Reini, Lazzaretto, and Macor, 1995), or on the structural theory concept (Valero, Serra, and Lozano, 1993), the methodology presented in this paper is based on energy and exergy analyses using the well-known thermodynamic index, the *heat rate (HR, inverse of the efficiency),* and the total *power generated.* This methodology, called the *Reconciliation in Heat Rate and Power* methodology, applies primarily to existing power plants where different malfunctions and external variations during operation are common, and knowledge and thermoeconomic appraisal of the impact on the plant due to malfunctions is required. The methodology itself is comprised of four stages:

I. Classification of the information from the plant at the test state.

II. Classification of the information from the plant at the reference state.

III. Re-assignation of variables (free variables) as likely causes of malfunctions.

IV. Development of the reconciliation-by-causes module.

An explanation of each one of these stages is presented below.

As to the plant in the TADEUS problem, it is comprised of two gas turbines GT-A and GT-B (125 MW each), two HRSGs (A and B), and a steam turbine (about 100 MW) as shown in *Figure 1.* The problem consists in diagnosing the deviation occurring at operating conditions (Valero et al., 2003) when three anomalies, two in the first gas turbine and one in the first HRSG, arise, namely,

1) filter fouling,
2) erosion of the gas turbine, and
3) high pressure super-heater fouling.

These anomalies are simulated by means of i) increasing the design pressure drop (+25%); ii) modifying the design values of the flow coefficient (+2,5%) and polytropic efficiency (−1%); and iii) increasing the design approach point temperature (+10%). For further details, please see Valero et al. (2003).

Finally, comments about the reliability and feasibility of the methodology are given below consistent with the results generated from its application to the TADEUS problem.

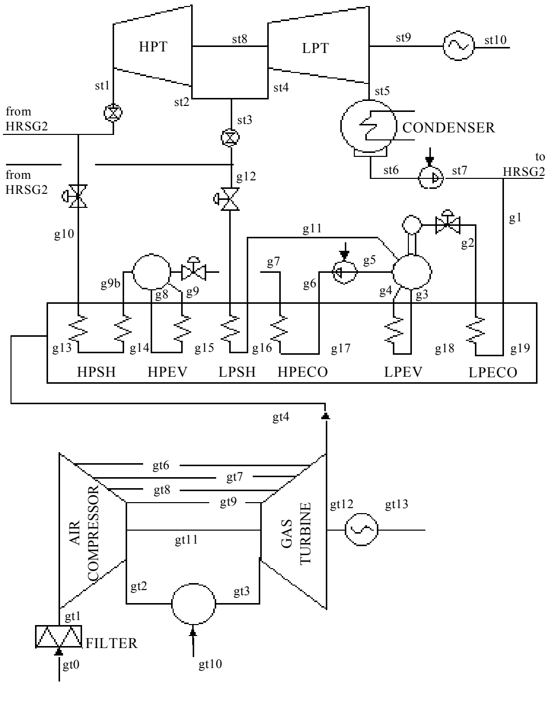

Figure 1. Schematic of the combined cycle power plant proposed for the TADEUS problem (Valero et al., 2004, 2002a,b).

2. Test Operating Conditions (TOP)

One of the most important steps in setting up a precise diagnosis involves information extracted from the power plant in operation during a performance test as well as the analytical and numerical models available for characterizing plant behaviour. In fact, there are two general groups of information for the applying the methodology, namely,

a) data measured in the plant,
b) data yielded from an analytical/ numerical model.

Finally, comments about the reliability and feasibility of the methodology are given below consistent with the results generated from its application to the TADEUS problem.

2.1 Data measured in the plant

Data measured in the plant refers to information gleamed from measurement instruments located at strategic points within the plant. With respect to the TADEUS problem, variables appearing in TABLE I are measured during a performance test.

2.2 Data yielded from an analytical/numerical model during a performance test.

In addition to measured data, analytical/ numerical models which characterize and simulate the power plant can be used to determine additional data. A significant number of the analytical/numerical models for each section of the plant are found in Valero et al. (2002a,b). TABLE II shows a brief description of the required models for the energy components as well as the information generated by the models.

In summary, the number of variables/data collected for a test state, n_{top}, is defined as

$$n_{top} = \begin{cases} \text{variables/data from measurements} \\ + \\ \text{variables/data from models} \end{cases} \quad (1)$$

TABLE I. VARIABLES TO BE MEASURED (DIRECTLY OR INDIRECTLY) IN THE PLANT THE TADEUS PROBLEM.

Measurement Point		**Data**
Ambient	gt0	P, T, T_w
IGV	gt1	$\%\alpha$
Compressor inlet	gt1	P, T, T_w
Compressor discharge	gt2	P, T
Compressor air-extractions for GT cool down	gt5,6,7,8	P, T, $\dot{m}$
Combustion chamber fuel inlet	gt10	P, T, HHV, LHV, ρ $\dot{m}$
Combustion chamber gases outlet (GT inlet)	gt3	P
GT gases outlet	gt4	P, T
Generated power in the GT and ST	gt13, st10	$\dot{W}_{gen}$
Power consumed by ancillaries in the HRSG and ST (feedwater pumps, etc.)	Only power entering the cycle	$\dot{W}_{aux}$
HRSG stack gases	g20	P, T, x_i
Steam generated in the HRSG (HP-SH, LP-SH)	g10, g12	P, T, $\dot{m}$
HP_ST and LP-ST steam-inlet	st1, st3	P, T
HP-ST steam outlet and LP-ST steam inlet	ST2, st4	P, T
ST exhausted steam	st5	P
Condenser outlet conditions	st6	P, T, $\dot{m}$
Feedwater	g5	P, T, $\dot{m}$
Discharge and suction of the condenser and feed pumps	g6, st7, g1	P, T

3. Reference Operating Conditions (ROP)

As defined earlier, the reference operating condition (ROP) in a combined cycle power plant should contain information about the plant without anomalies. Actually, the ROP is not normalized and can be referred to conditions from a

a) Thermal balance (at the ISO or site condition),

b) Acceptance test (at start-up, after an overhaul, or as defined by an owner),

c) Simulator (at design or off design).

Whatever the case, it is necessary to complete the collection of data by using the models described in TABLE II. It is also possible to develop an ROP data collection as shown in TABLE III.

TABLE II. ANALYTICAL/NUMERICAL MODELS REQUIRED FOR THE ADDITIONAL VARIABLES THE TADEUS PROBLEM.

Section	**Required Analytical/Numerical Models**	**Data Generated**
Air	Relative humidity properties, model h, s, v	h, s ,%R
Steam	Properties h, s, y, v	h, s, v
Filters	Pressure drop in filters. Temperature difference (in case coolers are present)	$\Delta P_{filters}$ ΔT_{air}
Compressor	Isentropic efficiency. Admission area coefficient	η_{iso} ϕ_A
Combustion chamber	Both energy and mass balances applied to the combustion chamber	Air flow, T_{gasses} (combustion chamber outlet)
GT as a system	Both energy and mass balances	
GT nozzles	Isentropic efficiency Admission area coefficient	η_{iso} ϕ_A
HRSG	Thermal efficiency or delta temp. approach and pinch	η or ΔT´s
Generators	Mechanical and electrical losses Energy balance	ST -Shaft power
ST as a system		Expansion line end point (ST)
HP-ST	Isentropic efficiency model Admission area coefficient (if a control system does not exist)	η_{iso} ϕ_A
LP-ST	Isentropic efficiency model Coeff. Admission area (If any do not control system exists)	η_{iso} ϕ_A
Condenser	Efficiency and effectiveness	η
Pumps	Efficiency model	η_{iso},
Overall	Heat rate Pressure ratios Mass ratio at joints and junctions	HR R_P R_m

TABLE III. DEFINITION OF THE REFERENCE STATE AND ANALYTICAL MODELS TO DETERMINATE THE DATA COLLECTION.

ROP Definition	Analytical Models	Additional Data (determined)
Data from a a) Thermal balance (ISO or site condition) or b) Acceptance test (after an overhaul, or as defined by an owner)	Efficiency maps, admission coefficients, mass and energy balances in components, mass and pressure ratios in extractions, performance maps from manufacturers	P, T, $\dot{m}$, h, s, η, η_{iso}, ϕ_A, R_p R_m, Δp, ΔT, HR, and $\dot{W}$

In general, the number of variables/data collected for a reference state, n_{rop}, is given by;

$$n_{rop} = \begin{cases} \text{inlet variables/data} \\ + \\ \text{calculated variables/data} \end{cases} \qquad (2)$$

Thus, it must be true that in analytical terms, the number of TOP and ROP variables must be equal, i.e.

$$n_{rop} = n_{top} \qquad (3)$$

4. Re-Assignation of (Free) Variables as Likely Causes of Malfunctions (Anomalies)

As is well known, simulators allow the determination of values for the n variables which characterize the thermodynamic steady state of an energy system. This requires a mathematical model composed of n x n equations and variables. A certain number of these variables may be defined as independent and the rest as dependent. Thus,

$$n = m + o \qquad (4)$$

where *m* is the number of independent variables and *o* the number of dependent variables. In the reconciliation methodology proposed here, use is made of the simulator model previously proposed in TADEUS. From this simulator, a mathematical model for the *heat rate* and *total work* as a function of the independent variables can be obtained, i.e.

$$\begin{aligned} HR &= HR(M_1, M_2, ..., M_m) \\ \dot{W} &= \dot{W}(M_1, M_2, ..., M_m) \end{aligned} \qquad (5)$$

It is important to stress that the heat rate (HR) and the total power generated ($\dot{W}$) vary due to different causes (M), which can be external or internal to the plant. External variations can result from

i) ambient conditions and

ii) fuel quality,

while internal variations can arise due to

i) the presence of anomalies (intrinsic components effect),

ii) the dependence of component behavior on the working condition (induced effects), and

iii) control system intervention.

When several anomalies occur at the same time, the effect and evaluation of a particular cause can become a difficult task.

5. Free Variables ($M_{1...m}$)

Using the definition of the total derivative, from equation (5) it is possible to assume that DHR and $D\dot{W}$ can be expressed as

$$\begin{aligned} DHR &= \frac{\partial HR}{\partial M_1} dM_1 + \frac{\partial HR}{\partial M_1} dM_2 + ... + \frac{\partial HR}{\partial M_m} dM_m \\ D\dot{W} &= \frac{\partial \dot{W}}{\partial M_1} dM_1 + \frac{\partial \dot{W}}{\partial M_1} dM_2 + ... + \frac{\partial \dot{W}}{\partial M_m} dM_m \end{aligned} \qquad (6)$$

Each term in the two equations above correspond to an impact on heat rate and power, respectively, when an anomaly M_i occurs in the model.

For the sake of simplicity, an alphanumeric code for the localization of the (M_i) variables within the plant, which will be used to correct the heat rate and power, is proposed. The first two-letter-term stands for the section of the plant, i.e. GT for the gas turbine section and ST for the steam turbine section. For example, the two-numerical term which appears in *Figure 2* corresponds to the number of gas (or steam) turbines in operation and the correction number. For a better understanding of the alphanumeric code an example is given next.

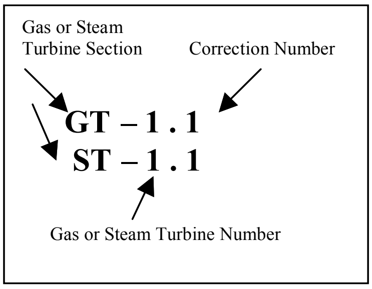

Figure 2. Schematic of the correction code for variable localization.

TABLE IV in the Appendix outlines the correction parameters for the gas turbine and steam turbine, respectively, operating at opencycle. It is worth highlighting that the corrections follow a particular order:

i) Causes due to ambient factors

ii) Causes due to control systems

iii) Internal causes to the systems or subsystems

Undoubtedly the first causes are unavoidable while the second ones can be avoided at low cost, as they require loop control adjustments only. The third ones are the most costly, as they involve maintenance and replacement of parts. Internal or intrinsic causes appear as a consequence of internal factors to the subsystems, e.g., erosion, deposits, breakages, leakages due to wear out, etc. Reconciliation begins by eliminating the former two causes in order to avoid undesirable effects in the subsystems and then finds the last causes, if present, which are the main reasons for the high costs of a malfunction.

6. Development of the Reconciliation-by-Causes Module

Development of the methodology calls for a thorough completion of the following points:

1) Establishment of an analytical model of the components;
2) Establishment of an operating test condition;
3) Establishment of an operating reference condition;
4) Determination of the free variables (malfunctions); and
5) Development of the Reconciliation-by-Causes Module (test - reference).

The first point is achieved by developing an analytical simulator with the equations provided in the TADEUS problem so that mass and energy balances corresponding to each one of the subsystems are obtained. Additional equations for the determination of the average temperature of the combustion chamber and others parameters are also required. The power plant is simulated using the *Engineering Equation Solver* (EES) software.

As explained above, the source of data for the reference and test operating conditions is a matter of choice. In our case, we have taken up design values for the implementation of the reference condition and off-line data for the test condition. Using an analytical module called the *Reconciliation-by-Causes Module*, both conditions are compared so as to trace the internal or external malfunctions causing the deviations in heat rate and total power. The reconciliation-by-causes module functions by modifying one malfunction variable at a time in order to evaluate heat rate and power values and compare them with those of the reference conditions. This module (see *Figure 3*) allows one to establish the impacts on the heat rate and power generated by the plant and to infer the control, external, or internal variables to the plant, which are the origin of these impacts.

To ascertain the deviations in each one of the variables (M_i) affecting the heat rate and power, the following steps are taken:

1. The first call of the module evaluates $M_{1\ldots m}$ at the TOP condition and the HR and $\dot{W}$ are obtained.

2. The second call of the module replaces only the first M_1 value with the ROP condition, and, thus, obtains a corrected HR and $\dot{W}$.

3. These corrected values are subtracted from those obtained in the 1st step resulting in ΔHR and $\Delta\dot{W}$ (Equations. (7a) and (7b)).

4. This process (steps 1 to 3) are repeated again and again, i.e. singly replacing the $M_{2,3\ldots m}$, while keeping the others constant and in the process obtaining the respective ΔHR and $\Delta\dot{W}$.

Upon completion of the above steps, the TOP HR and $\dot{W}$ are reconciled to those for the ROP conditions.

```
 MODULE  RECON($M_1,M_2,\ldots M_m$:HR,W)
 $HR=HR(M_1,M_2,\ldots M_m)$
 $W=W(M_1,M_2,\ldots M_m)$
 END

CALL  RECON  ($M_{ST1.1,T},M_{ST1.2,T},\ldots M_{GT2.13,T}:HR_T,W_T$)
CALL  RECON  ($M_{ST1.1,R},M_{ST1.2,T},\ldots M_{GT2.13,T}:HR_{ST1.1},W_{ST1.1}$)
 $\Delta HR_{ST1.1}=HR_T-HR_{ST1.1}$
 $\Delta W_{ST1.1}=W_T-W_{ST1.1}$
CALL  RECON  ($M_{ST1.1,R},M_{ST1.2,R},\ldots M_{GT2.13,T}:HR_{ST1.2},W_{ST1.2}$)
 $\Delta HR_{ST1.2}=HR_{ST1.1}-HR_{ST1.2}$
 $\Delta W_{ST1.2}=W_{ST1.1}-W_{ST1.2}$
 •
 •
 •
CALL  RECON  ($M_{ST1.1,R},M_{ST1.2,R},\ldots M_{GT2.13,R}:HR_R,W_R$)
 $\Delta HR_{GT2.13}=HR_{GT2.13}-HR_R$
 $\Delta W_{GT2.13}=W_{GT2.13}-W_R$
```

Figure 3. Schematic of the Reconciliation-by-Causes Module declaration and calls.

$$HR_{TOP}-HR_{ROP}=\left(\frac{\dot{Q}_{TOP}}{\dot{W}_{TOP}}\right)-\left(\frac{\dot{Q}_{ROP}}{\dot{W}_{ROP}}\right) \quad (7a)$$

$$HR_{TOP}-HR_{ROP}=\left(\frac{\dot{Q}_{TOP}}{\dot{W}_{TOP}}-\frac{\dot{Q}_1}{\dot{W}_1}\right)+\left(\frac{\dot{Q}_1}{\dot{W}_1}-\frac{\dot{Q}_2}{\dot{W}_2}\right)\ldots$$
$$+\left(\frac{\dot{Q}_m}{\dot{W}_m}-\frac{\dot{Q}_{ROP}}{\dot{W}_{ROP}}\right) \quad (7b)$$

7. Results

TABLE V in the Appendix shows the results of a run of the reconciliation-by-causes module for deviations (malfunctions) due to causes which affect the HR and $\dot{W}$. Note that the shaded cells, appearing in the ΔHR column, mean that only those variables falling into the criteria of this methodology are regarded as having an impact on the HR. The HR impact values can be obtained by means of the following equation;

$$\Delta\$HR = \Delta HR \cdot F\$ \qquad (8)$$

where for the results presented here, ΔHR is in kJ/kWh and F$ in $/kJ. From equation (8), it is clear that the impact will depend partly on the fuel price at the time of the evaluation. This diagnosis is feasible for being applied to existing power plants through the implementation of real-time systems.

8. Conclusions

This paper has presented a diagnosis methodology for energy systems. It was then applied to the power plant model proposed as part of the TADEUS problem. Results show how the *Reconciliation in Heat Rate and Power Methodology* can be reliably applied to power plants.

In previous works of diagnosis (Valero, Torres, and Lozano, 1990; Reini, 1994; Lozano et al., 1994; Reini, Lazzaretto, and Macor, 1995; Valero, Serra, and Lozano, 1993), there is a clear tendency to develop the diagnosis methods with analytical equations based on linearizations, etc. In contrast, in the present reconciliation methodology, no linearizations, etc. are employed. Instead, a n x n simulation model implemented in a reconciliation-by-causes module allows one to determine the causes of the the impacts on HR and $\dot{W}$ as a function of the m free (independent) variables. In effect, it is as if one were repairing the plant from its TOP conditions to its ROP conditions, anomaly by anomaly, first discarding the environmental effects, then the control effects, and finally the internal causes. Thus, it is possible to determine the impact of malfunctions subsystem by subsystem and aid in the making of maintenance decisions. In this way, it is expected that diagnosis for energy systems (combined cycles, for example) can be implemented in existing power plants in order to assist the operators by providing them with a useful level of information about the present state of the plant with respect to some nominal state. The goal, of course, is to maintain the satisfactory performance of the plant.

At present, this diagnosis methodology has been applied to more than eight combined cycle power plants located in Mexico, which are the property of the Federal Electricity Commission (CFE). From an experimental perspective, we have been testing and implementing manufacturer correction curves and gleaming a number of advantageous results over that of conventional methods.

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Nomenclature

A	effective area
F$	fuel price
GT	gas turbine
HHV	Higher Heating Value
HR	heat rate ($\dot{Q}/\dot{W}$)
h	specific enthalpy
IGV	inlet guide vanes
LHV	Lower Heating Value
$\dot{m}$	mass flow rate
m	number of free variables (anomalies)
n	number of variables in a mathematical model
o	number of dependent variables
p	pressure
$\dot{Q}$	rate of heat transfer
R	humidity
R_p	pressure ratio
R_m	mass flow ratio
ROP	reference operating conditions
s	specific entropy
ST	steam turbine
T	temperature
TOP	test operating conditions
U	overall heat transfer coefficient
v	specific volume
$\dot{W}$	power

Greek

α	IGV angle
β	pressure ratio
ϕ	mass flow coefficient ($(\dot{m}/p)\sqrt{T}/\sqrt{f(R_p)}$)
η	efficiency

Subscripts

aux	auxiliary
gen	generated
HP	high pressure
LP	low pressure
RH	reheat
SH	superheat
w	wet bulb

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Appendix

TABLE IV. CORRECTION PARAMETERS FOR HEAT RATE AND POWER RECONCILIATION DURING COMBINED CYCLE OPERATION

CODE	PARAMETER	DESCRIPTION
GT-1.1	P_0	The ambient pressure, temperature, air cooling system and humidity affects the specify volume of the air and also the admission mass flow of the compressor.
GT-1.2	T_0	
GT-1.3	humidity	
GT-1.4	air cooling	
GT-1.5	the heating value of the fuel	A change in the fuel quality will affect the mass flow of fuel admitted to the combustion chamber.
GT-1.6	the inlet temperature	A change in the turbine inlet temperature may be caused by a change of the control set-point of the combustion chamber.
GT-1.7	filters pressure drop	Fouling in the air-filters directly affects compressor operation and, consequently, the heat rate.
GT-1.8	the GT outlet pressure drop to the HRSG	The change in the turbine outlet pressure is due to blockages or new designs which may appear in the HRSG.
GT-1.9	combustor pressure drop	A pressure drop in the combustor directly impacts GT efficiency and, consequently, the power generated as well as the heat rate.
GT-1.10	compressor efficiency	Once all the variables indirectly affecting the compressor are corrected, it becomes possible to evaluate the impact on the compressor due to an interior malfunction.
GT-1.11	turbine admission area ϕ	This variable represents the attrition of nozzles due to erosion or sediments.
GT-1.12	compressor admission area ϕ	The compressor area, can be modified as well when erosion or sediments appear.
GT-1.13	electrical or mechanical losses	These kind of losses are due to the decay of the generator and an increase in shaft friction.
ST-1.1	main steam temperature or $\Delta T_{approach}$	A change in the main steam temperature is due to a variation in the HRSG. Therefore, it is an indirect cause due to the control system.
ST-1.2	ΔT_{pinch}	A change in the temperature of the evaporators (HP, LP) is due to a variation in the HRSG,. Therefore, it is an indirect cause due to fouling or the control system.
ST-1.3	main steam pressure or admission area ϕ	The cause of change in the main steam pressure will depend on the control mode: fixed or sliding pressure control. For fixed mode, it will be a problem of the control valves; and for sliding mode, it will be due to erosion or sediment in the admission areas detected by the admission coefficient of the turbine (HP, LP).
ST-1.4	pumps efficiencies	A change in this temperature is chiefly due to changes in vacuum pressure or the sub-cooling temperature of the condenser (hot-well). It affects the heat absorbed in the HRSG and, therefore, the heat rate.
ST-1.5	electrical or mechanical losses	These kind of losses are due to decay of the generator and an increase in shaft friction.
ST-1.6	steam turbine efficiency	Steam turbine efficiency represents a degradation affecting its own operation.
ST-1.7	Δp_{loss}	Pressure losses in the HRSG pipes can change due to fouling and internal decay.
ST-1.8	make-up water ratio	The ratio between the main steam and make-up water mass flow defines the likely HRSG leakages. This ratio modifies the heat ratio as well.
ST-1.9	ancillary power ratio	The ratio between the consumed power by ancillary subsystems and the power generated by the steam turbine is a factor which somewhat affects the heat rate.
ST-1.10	vacuum pressure	Vacuum pressure changes are strongly impacted by weather and other subsystems upstream of the exhaust steam. Therefore, it is mostly regarded as an induced impact. The reference value must be corrected to be compared to the test value. Moreover, any other change is probably due to fouling and heat transfer area loss in the condenser.

TABLE V. HEAT RATE AND POWER RECONCILIATION ANALYSIS
BETWEEN A TEST AND A REFERENCE STATE

Variable	Ref. (Valero et al., 2003)	Test (Valero et al., 2003)	Δ	ΔHR [kJ/kWh]	$\Delta\dot{W}$ [kW]	Cost * [$/MWh]
AMBIENT						
P_0 [bar]	0.987	0.987	0	0	0	0
T_0 [ºC]	15	15	0	0	0	0
R [%]	60	60	0	0	0	0
FILTER GT-A						
$\Delta p_{filters}$ [bar]	0.009	0.0119	0.0029			
FILTER GT-B						
$\Delta p_{filters}$ [bar]	0.009	0.009	0	0	0	0
COMPRESSOR GT-A						
η [%]	87.46	87.06	–0.4	11.68	–1067	0.2789
ϕ	7324	7474.15	150.15	1.51	2654	0.0361
COMPRESSOR GT-B						
η [%]	87.46	87.24	–0.22	6.39	–591	0.1526
ϕ	7324	7437.55	113.55	0.79	2037	0.0188
COMBUSTOR GT-A						
LHV [kJ/kg]	45437	45437	0	0	0	0
$T_{admission,GT}$ [ºC]	1152	1145	–7	12.22	–2248	0.2918
Δp_{loss} [%]	1	1	0	0	0	0
η [%]	99.4	99.4	0	0	0	0
COMBUSTOR GT-B						
LHV [kJ/kg]	45437	45437	0	0	0	0
$T_{discharge}$ [ºC]	1152	1151	–1	1.85	–380	0.0442
Δp_{loss} [%]	1	1	0	0	0	0
η [%]	99.4	99.4	0	0	0	0
TURBINE AND GENERATOR GT-A						
ϕ	1112.5	1144.67	32.17	1.1	1146	0.0263
η [%]	88.5	87.61	–0.89	25.96	–1225	0.6199
Electromech. losses [%]	1.79	1.79	0	0	0	0
TURBINE AND GENERATOR GT-B						
ϕ	1112.5	1115.99	3.49	0.15	126	0.0036
η [%]	88.5	88.5	0	0	0	0
Electromech. losses [%]	1.79	1.79	0	0	0	0
HRSG GT-A						
$\Delta p_{loss\text{-}gas}$ [%]	2	2	0	0	0	0
$\Delta p_{loss\text{-}HPSH}$ [bar]	11.17	11.17	0	0	0	0
$\Delta p_{loss\text{-}LPSH}$ [bar]	2.324	2.324	0	0	0	0
$\Delta p_{loss\text{-}eco,eva}$ [bar]	1.244	1.244	0	0	0	0
$\eta_{pump\ HP}$ [%]	87	87	0	0	0	0
$\eta_{pump\ LP}$ [%]	83.42	83.42	0	0	0	0
$\Delta T_{approach,HPSH}$	24.98	27.48	2.5	1.2	–57	0.0286
$\Delta T_{approach,LPSH}$	16	16	0	0	0	0
$\Delta T_{pinch,HPSH}$	8	8	0	0	0	0
$\Delta T_{pinch,HPSH}$	15	15	0	0	0	0

Variable	**Ref. (Valero et al., 2003)**	**Test (Valero et al., 2003)**	**Δ**	**ΔHR [kJ/kWh]**	**$\Delta\dot{W}$ [kW]**	**Cost* [$/MWh]**
HRSG GT-B						
$\Delta p_{loss\text{-}gas}$ [%]	2	2	0	0	0	0
$\Delta p_{loss\text{-}HPSH}$ [bar]	11.17	11.17	0	0	0	0
$\Delta p_{loss\text{-}LPSH}$ [bar]	2.324	2.324	0	0	0	0
$\Delta p_{loss\text{-}eco,eva}$[bar]	1.244	1.244	0	0	0	0
$\eta_{pump\ HP}$ [%]	87	87	0	0	0	0
$\eta_{pump\ LP}$ [%]	83.42	83.42	0	0	0	0
$\Delta T_{approach,HPSH}$	24.98	24.98	0	0	0	0
$\Delta T_{approach,LPSH}$	16	16	0	0	0	0
$\Delta T_{pinch,HPSH}$	8	8	0	0	0	0
$\Delta T_{pinch,HPSH}$	15	15	0	0	0	0
STEAM CYCLE						
ϕ_{HP}	52.569	52.579	0	0	0	0
ϕ_{LP}	402.79	402.75	0	0	0	0
η_{HP} [%]	85.82	85.82	0	0	0	0
η_{LP} [%]	80.13	80.11	0	0	0	0
Electromech. losses [%]	2	2	0	0	0	0
CONDENSER						
Vacuum pressure	0.1448	0.1448*	0	0	0	0
Make-up water [kg/s]	0	0	0	0	0	0
GENERAL SYSTEM DATA						
Combined cycle heat rate [kJ/kWh]	7425.7	7491	65.3	65.3	---	1.5594
Combined cycle power generation [kW]	354000	354186	---	186	186	---