OMSEM- Optimum Management System with Environment Monitoring

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Contract JOE3-CT95-0028

PUBLISHABLE FINAL REPORT

March 1996 to February 1999

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

OMSEM:

Optimum Management System with Environment Monitoring

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Objectives:

The aim of OMSEM project is oriented towards the;

- *Cost reduction in Industrial cogeneration plants through an automatic procedure for optimum load allocation during plant operations.*
- *Reduction of plant pollutant emissions through the optimisation of operational environmental costs and constraints.*

With reference to an industrial cogeneration plant two main systems have been taken into consideration as shown in Fig. 1:
• the electric grid internal to the factory;
• the thermal cogeneration plant.

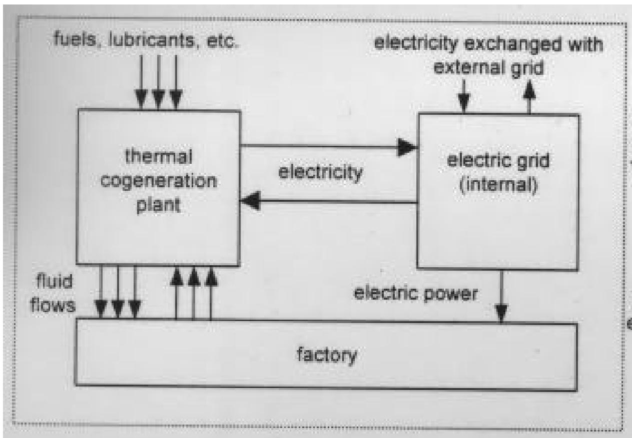


Fig. 1 Industrial Cogeneration System

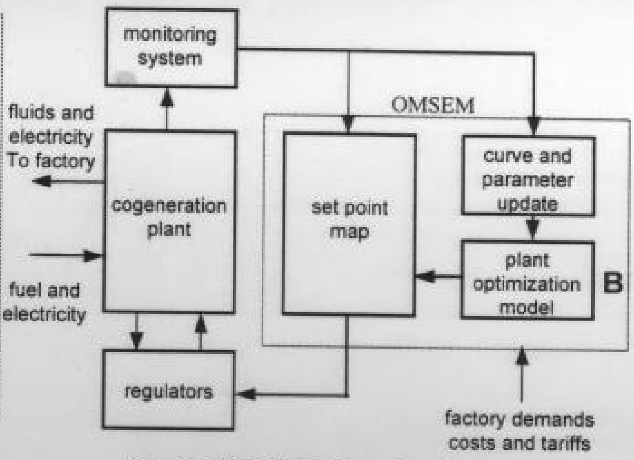


Fig. 2 OMSEM Description

There is a mutual exchange of electric power between the electric grid and the thermal plant. The whole plant supplies electricity and various hot fluids (i.e. steam at different pressure and temperature levels, and hot water) to the factory. To accomplish such a job the plant receives electric power and fuels from outside.

Figure 2 shows OMSEM description: block **A** receives monitoring data as input and establishes state parameters updating characteristics curves of the components; block **B** receives state parameters, factory demands, fuel costs and electricity tariffs as input, gives optimum set points as output. Objective function is the sum of plant unbalance and costs.

To demonstrate OMSEM capabilities two industrial plants have been considered:
1. FIAT-MIRAFIORI shop ENERGY SYSTEM.
2. HELLENIC ASPROPYRGOS REFINERY ENERGY SYSTEM (HAR).

TECHNICAL DESCRIPTION:

Steady state behaviour of a plant is described by an equation set

$$F (u, x, y) = 0 \tag{1}$$

and conditions expressed by a set of inequalities

$$D (u, x, y) > 0 \tag{2}$$

In general equations **F** are highly non-linear and express conservation of mass and energy, Newton's second law of motion, second law of thermodynamics, other phenomena such as heat transfer, pressure loss, etc., as well as fluid properties and auxiliary equations, and machines and equipment's specifications. **D** represents a set of thermodynamic and geometric conditions which determines the domain of existence of the solution of problem (1).
u takes into account the history of the plant evolution (fouling , performance deterioration, etc.). **z** and **y** are the vectors of unknown variables and degree of freedom

Fig. 3 shows the general schematic view of OMSEM modules. To calculate the output quantities any module must activate sections, which treat thermodynamic, mechanical, emission, cost, and control aspects.

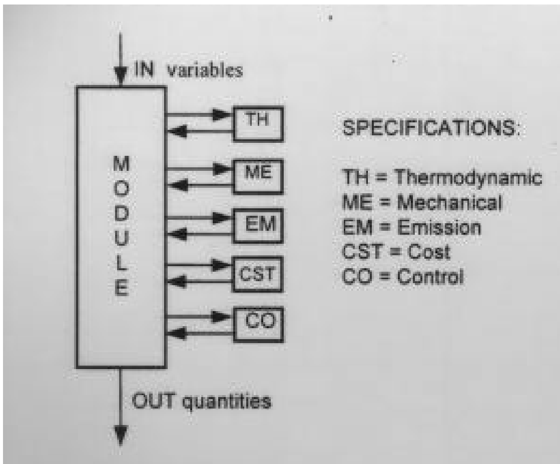


Fig. 3 Module Description

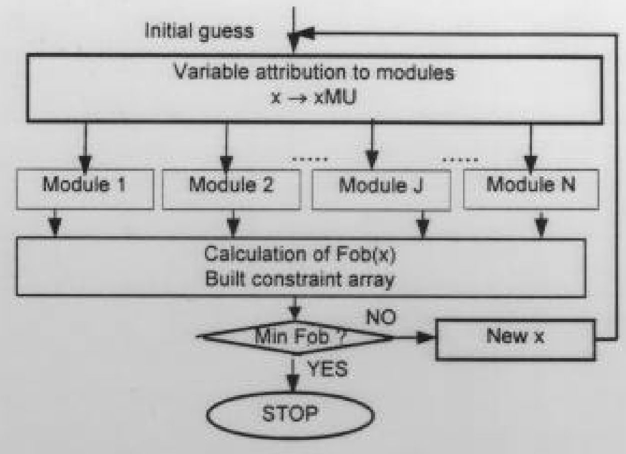


Fig. 4 Modular Structure of Calculation Method

Following algorithms have been investigated to search the minimum of an objective function, which contains both economic and environmental aspects :

1. Equality Constraint Recursive Programming Algorithm (ECRQP).
2. Genetic Algorithm.
3. Simulated Annealing.
4. Hybrid Algorithm:
    - GeneticAlgorithm → Supervisor
    - ECRQP → Local Solver

Since the component equations are non-linear and quite numerous for complex plants an **E**quality **C**onstraint **R**ecursive **P**rogramming **A**lgorithm (ECRQP) has been adopted in order to speed up the description of the plant components.

The block diagram of such program is shown in Fig. 4. It can be noted that after the input procedure the program is executed by a section, which distributes variables to the various modules. Then module calculations are performed, they may be split among parallel processors. In another section outputs are collected together to build the objective function (F ob) and the constraint structure of the optimisation problem.

OMSEM Organisation

The OMSEM system is organised:

1. To establish the plant component state parameters (or functions) which needs the plant history, inverse calculations are required. Inputs are the monitoring data.
2. To achieve the best economic objective, the calculation of the optimum set point map to allocate loads on the various plant components requires the solution of a non-linear economic-functional model.

> Plant component specifications, geometric data and alternative global parameters are needed. These specifications may be obtained from the manufacturer data if available, otherwise these data are obtained solving sizing problem using CGSPO code (Combined Gas Steam Plant Optimisation) which has already been built by URM3 in the framework of JOULEII.

Plant component costs have been expressed by means of the contributions related to:
- plant operative depreciation and deterioration as function of component loading;
- the consumption of working fluids, and energy carriers (fuel and electricity from the outer grid);
- The environmental aspects (i.e. costs related to internal and external environmental).

The Optimum Management System with Environmental Monitoring (OMSEM) System Prototype is a computer program which seeks to optimise the performance of combined heat and power plant. This optimisation program has been based on two combined heat and power plants.

The OMSEM program used to run the models for these two combined heat and power plants is situated at Università degli Studi di Roma Tre (URM3). Simulation of the two plants has been made available to the project partners through an internet connection at the following address **http://jou3.dimi.uniroma3.it** . A user accessing this site is able to run simulations of each of the FIAT and HAR plants but requires a suitable user name and password. The OMSEM system prototype consists of four subsystems:

(i) COMD (Component Mechanical Design). The Università degli Studi di Roma Tre (URM3) and Fachhochschule Schmalkalden/Thur (FHS) are the responsible for COMD subsystem. This subsystem carries out the thermodynamic and mechanical modelling of the two plants. It achieves optimum plant operation through the optimisation of a suitable objective function by taking into account component availability, costs of operation, environmental costs and constraints .

(ii) COEM (Component Environmental Modeling). The National Technical University of Athens (NTUA) is responsible for the COEM subsystem. The COEM subsystem provides:
(a) An estimation of the quantity of each pollutant emitted by the plants.

(b) The costs associated with the pollutants. These costs are then included in the objective function used to optimise the plant.

(iii) TSAC (Total Systems analysis and Costing Subsystem). The University of Ulster (UU) is responsible for this subsystem. The function of TSAC is to provide costs for the operation of the plant components. The costs provided by TSAC include: costs for fuel, labour, depreciation, amortisation and supplies. These costs are then included in the objective function used to optimise the plant.

(iv) DBMS (Data Base Management System). Cap Gemini Italia SpA is responsible for this subsystem. The DBMS facilates the interactions between the user and the three subsystems COMD, COEM and TSAC. In addition Cap Gemini has provided the partners with an Internet connection enabling them to run the OMSEM simulation.

The System has been validate by ENEA during the Validation task.

Component Mechanical Design (COMD)

COMD task is the design and development of thermodynamical, fluidynamical and mechanical models for plant components. Moreover the implementation of the mathematical formulation of the above models in order to establish the optimum plant load allocation.

To achieve the optimum plant operations by means of optimised load allocation procedures a simultaneous solution method based on a modular approach has been used. Simultaneous means that all the unknown variables are foreseen (thus each of them assume a value) at any step (iteration). Since all the unknown quantities are assumed in the iteration the contributions of any component to the objective function (components unbalance, costs, etc.) and to the constraint structure as well may be calculated. Therefore the plant performance (when it is in an unbalanced condition), costs, emissions of pollutants and the objective function are evaluated.

Components are de scribed by algebraic relationship s and by differential equations, which are reduced to algebraic ones by adopting a finite difference procedure.

Performance of a plant component is related to its load level. This relationship is influenced by its history (ageing. deterioration, fouling, maintenance and so on).

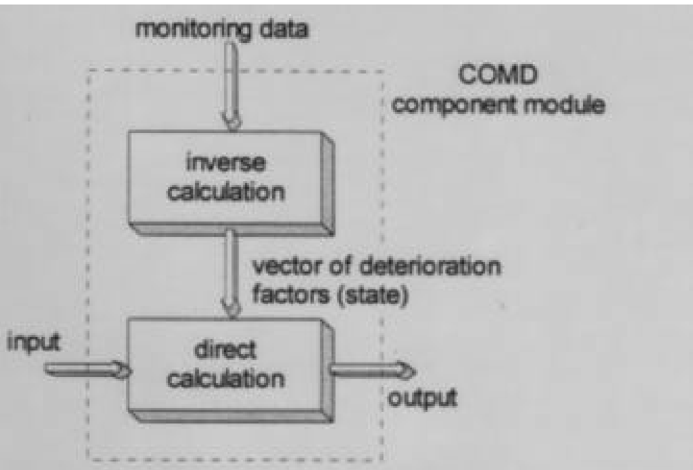


Fig. 5 Component State Evaluation

COMD approach to calculate component module output may be represented as shown in Fig. 5. Monitoring data at the actual plant operating conditions are given as input to COMD software. It performs an inverse calculation to obtain the deterioration factors, which are stored in a file (database) and are used for direct calculation in the appropriate section. Input quantities to COMD models for the direct calculation are:

- factory needs (i.e. electric power and thermal power demands);
- component design data and all related parameters (e.g. number of compressor stages, areas of heat transfer surfaces and so on);
- site ambient conditions;
- Deterioration factors previously obtained by inverse calculations.

The COMD output quantities are input to the other sections (TSAC and COEM) which contribute to the module objective function and constraint structure.

The state recognition has been implemented based on the definition of deterioration factors, which take into account globally the change of components performance in respect to the new condition. An adaptive technique for the actual curve design description has been adopted. The deterioration factors are evaluated from the monitoring data, which refers to the measured points.

Overview and classification of the components to be modelled

The various components of a power plant or of a cogeneration plant may be considered mostly open systems of different complexity. In some components, e.g. in a GAS EXPANDER with BLADE COOLING, both heat and work are transferred to or extracted from the fluid(s) under consideration, whilst the composition of the fluids remains unchanged or is changed but to mixing processes. COMPRESSORS (fixed & variable geometry), CONTROL STAGES (in a steam turbine), PUMPS, and STEAM TURBINES may often be considered adiabatic, i.e. only work is transferred to or extracted from the respective fluid with the heat transferred being negligible. Another group of components is characterized by no work being done but heat being released due to chemical reactions and transferred: COMBUSTION CHAMBER in a boiler (with radiative heat transfer), GAS TURBINE COMBUSTION CHAMBER, DUCTBURNER. Numerous components can be identified transferring heat from one fluid to another: AIR PREHEATER, CONDENSATE PREHEATER, CONDENSER, COOLER, COOLING TOWER, DEAERATOR, DESSICATION DEVICE, ECONOMISER, EVAPORATOR, FEED WATER PREHEATER, FEEDWATER VESSEL, HEAT EXCHANGER, SUPERHEATER. The AIR INTAKE FILTER, CONTROL VALVES, FLOW METERS, FLOW DIVIDERS, FLOW JUNCTIONS, PIPES, THREE-WAY VALVES, THROTTLING DEVICES: VALVES, BUTTERFLY VALVES, PERFORATED PLATES, FLASH, INJECTION, SATURATING UNITS, STEAM DRUMS are all characterized by no work being done and by these components being considered more or less perfectly isolated (adiabatic). Other components, e.g. ELECTRIC MOTORS or GENERATORS, just convert two types of work. More specifically, electrical work is converted to mechanical or vice versa. Due to the inevitable dissipative effects, part of the work input is `lostA and will be extracted from this type of systems via an appropriate cooler. A pump or a blower may be required to provide circulation for the cooling sub-system.

Several components of power plants or of cogeneration plants can be considered composed of the aforementioned components, e.g. *GAS TURBINES* (consisting of one or more *COMPRESSORS* plus *GAS TURBINE COMBUSTION CHAMBER* plus *GAS EXPANDER with BLADE COOLING);* or *STEAM GENERATORS.*

General Models and Governing Equations

The components operations simulated in the computer models are generic in nature and apply to any manufacturers components. So both empirical and physical modelling have been adopted for the present modules. The component models have been described:

1. by the governing conservation equations at the steady state steady conditions:
    - mass
    - energy
    - momentum
2. by second law of thermodynamic;
3. by constitutive equations describing phenomena on physical or empirical basis;
4. by auxiliary equations.

The analysis of thermal systems requires appropriate methods to calculate both the thermal (p, v, T) and the caloric properties ((u), h, s) of the various pure and/or mixed fluids entering and/or exiting from the respective sub-systems. In addition, the transport properties, i.e. viscosity and thermal conductivity must be calculated.

Ideal Gases

Fortunately enough, both air and the gases resulting from the combustion processes can be considered ideal gases with the thermal properties related by the respective very simple equation of state, and the caloric properties to be calculated with the specific heat capacities depending but on the temperature.

Within OMSEM, the chemical reactions have been modelled in separate routines. For the calculation of both the enthalpies and entropies of ideal gases and their mixtures, FHS used the method presented by Harmens, 1978.

The essential advantages of the method are

- the physical background instead of the frequently used curve fitting,
- the associated validity over a practically unlimited range of temperatures, and the
- numerical reliability as a result of the transformation mentioned.

The method has as well as to the aforementioned gases successfully been applied to mixtures of hydrocarbon gases down to very low temperatures. Very recently, some new results have got to the knowledge of FHS about temperature depending specific heat capacities of air and combustion gases indicating very accurate results up to temperatures of about 1000 °C, but some accuracy limitations for higher temperatures.

Water and steam

In September 1997, the Industrial Standard IAPWS-IF 97 for the thermodynamic properties and supplementary equations for other properties of water and steam has been released by the International Association for the Properties of Water and Steam (IAPWS): Wagner. Kruse (1998). It should generally be used for industrial applications from 99-01-01. The respective

FORTRAN codes and a DLL are available from Prof. Wagner at Ruhr University Bochum. Compared to the previously used IFC-67 formulation, first experience indicates a pronounced decrease of CPU-time. Even more, a number of property evaluations can now be done in a straightforward manner rather than by iterative methods.

Non-ideal behaviour of flue gas due to sulphur being present in the fuel

Environmental protection legislation requires either (I) Flue Gas Desulphurisation or (2) limits the sulphur content of fuels allowed for utilisation.

If, however, even minor portions of Sulphuric Oxides are present in the flue gas, the dew temperature will be elevated compared to the mere water vapour dewpoint. This has a minor effect on the energy balance of a Heat Recovery Steam Generator, which in most practical applications is negligible. The elevated dew temperature and the associated precipitation of a very acid condensate will contribute to fouling and deterioration of the heat exchanger surfaces.

The acid dewpoint may be calculated using a correlation set up by Haase and Borgmann as early as 1962. A more sophisticated approach has been published by Halstead and Talbot in 1980. The latter has been programmed and used to calculate both the acid dewpoint and the influence of the condensation of sulphuric acid on the amount of heat to be extracted from a flue gas when cooled down to ambiguity temperature, e. g. 25 °C . Due to the portion of sulphur oxides normally being really small, the influence on the heat to be extracted is found negligible. Some very small amount of condensate is formed at temperatures well above the water dew point. This condensate has a high level of acidity.

Methodology of heat exchanger design and operational behaviour calculations:

Effectiveness-NTU -Method

A generally accepted method to characterise the operation of a heat exchanger both under design and off-design conditions is the effectiveness-NTU-method (Kays and London, 1964). The effectiveness g of a heat exchanger is closely related to the amount of entropy produced due to the transfer of heat being necessarily associated with a temperature difference. Hence, in addition to its internal advantages, the effectiveness-NTU-method can be considered favourable in connection with thermodynamic analyses. For a number of other flow arrangements, explicit formulations are e.g. compiled in (Kakac et al., 1983). Others can be found in the VDI Heat Atlas (1993).

(Minimum) Temperature Difference Method

Both the design and the operational behaviour of heat exchangers can also be described using a representative temperature difference, to be properly defined and agreed upon. The following definitions are, e.g., used in a VGB guideline (VGB Richtlinie R 110 L). The specific temperature differences given in this guideline have been used to establish default values within the respective program modules.

Non-dimensional characteristics of heat transfer equipment

Two separate streams of fluid are involved in the operation of heat exchanging equipment. Therefore, two non-dimensional characteristics are required to correlate the flow rates of the two fluid streams and the respective pressure drop. Because heat exchangers are normally handled as adiabatic systems, i.e. the external losses of heat are considered negligible compared to the amount of heat exchanged, the heat extracted from the hot stream equals that added to the cold stream. The coupled energy conversion then can be described by a third non-dimensional characteristic.

METHODOLOGY OF TURBOMACHINERY DESIGN AND OFF DESIGN CALCULATIONS:

Principles of the description of polytropic compression and expansion processes

The procedure adopted and described in more detail in the technical report can be applied to either expansion or compression processes. All types of fluids can be handled, if an appropriate equation of state is at hand. It is valid even in case of phase transitions (condensation, evaporation) occurring during the process as long as the process can be considered quasi-static.

Transformation of characteristics provided by the manufacturer into a set of non-dimensional characteristics

A set of routines has been developed for the transformation to non-dimensional characteristics. In addition to the manufacturer provided characteristics, these routines require information about the outer diameter of the impeller and about the size of the cross sections of the compressor inlet plane, of the compressor exhaust, and of both the entrance and the exit plane of the bladed parts of the machine. Once established, the non-dimensional characteristics can be used by other sets of routines available for any steady-state calculations under variable load conditions. A third set of routines is at hand to re-transform the nondimensional characteristics into the dimensional forms typically used, but with e.g. the operating range of Reynolds-numbers changed or with the compressor used for other fluids than originally designed for.

The method profits from the advantages of the concept of similitude. It is especially useful for process design studies, including the prediction of steady-state partial load operation.

An essential disadvantage of the method is associated with the manufacturer provided characteristics being required, even though this information will normally be available and may even be based on results of test runs done with the particular machine considered.

Modelling based on fluid-flow calculations

Fluid-flow calculations give a deeper insight into the mechanisms relevant for the energy conversion inside the machine. As given in more detail in the appendix of the technical report, a rigorous one-dimensional steady-state flow calculation method for compressible fluid flow has been developed which is done along subsequent sections.

The Air Intake Filter as an example of a component with adiabatic flow and no work being done:

Flow characteristics of the air intake filter

The AIR INTAKE FILTER is considered a section of ductwork with the resistance to flow being essentially proportional to the square of the volume flow rate, and one or more imbedded barrier filtration units with the resistance to flow being essentially a linear function of the volume flow rate. Depending on the environmental conditions found at the particular site, and on the type of filtration equipment used, the air intake filter is preceeded or followed by an anti-icing device.

Based on previous experience with the operation of a barrier type hot gas filtration unit and on modelling work for the IEA hot gas test filtration unit, the overall flow characteristics is expressed as an Euler-Reynolds-polynomial.

The overall filtration area is an appropriate choice as the reference cross section area, its size will be some m2 and depend on the unit size of the installation. The reference length, however, is associated with the structure of the filter material used. For a fibre filter, typical values will be found in the range of 10 to 20 mm, the mean diameter of the fibres. Similar reference lengths have to be considered in case of porous ceramic structures.

The fibre filters essentially operate according to the deep-bed filter concept. The separation of particles is due to mere obstruction at very low filter face velocities while inertial effects dominate at higher filter face velocities. The normal operating filter face velocity for these filters is in the transition regime, aiming at a relative optimum with respect to pressure drop, separation efficiency and size of the equipment.

In barrier type filtration equipment, in contrast, the operation essentially aims at the separation taking place on the surface of the filter rather than in the depth of the filter structure. Under these conditions, a dust cake builds up on the upstream surface of the filter element(s); only a minor portion of the particles should normally penetrate into the filter structure. Due to continuous growth of the cake thickness the resistance to flow is increasing with time. In order to limit the resistance to flow the cake is removed from time to time, e.g. by injecting compressed air into a number of filter elements in reverse flow direction, without interrupting the normal flow. This "pulse cleaning" is initiated either by a time clock or by a differential pressure switch or - in special applications - by other, more sophisticated criteria.

Barrier type filters with the separation taking place on the upstream surface are less permeable in general and operated at lower filter face velocities, i.e. Re-numbers. For the sections containing an active filtration area, the modelling had to make up for the additional pressure drop associated with the filter cake being built up as a function of time. This was done utilising an increment ? $[Re(Eu)^{05}](t)$ which is zero in the case the filtration area considered exhibits its baseline pressure drop.

Filter cake considerations

The filter cake is a porous structure with the porosity depending on the type of particles gathered. No simple methods exist neither to calculate the representative cross section area for a porous structure, e.g. from data related to the size of the dust separated, nor to determine the thickness of the cake.

Data from an inverse calculation, however, giving the pressure drop across the air intake filter unit in the virgin state and the pressure drops both for the start and the stop of the pulse cleaning process could, however, be transformed into non-dimensional characteristic curves. The result is then used to predict the operational behaviour of the filter as a cyclic process.

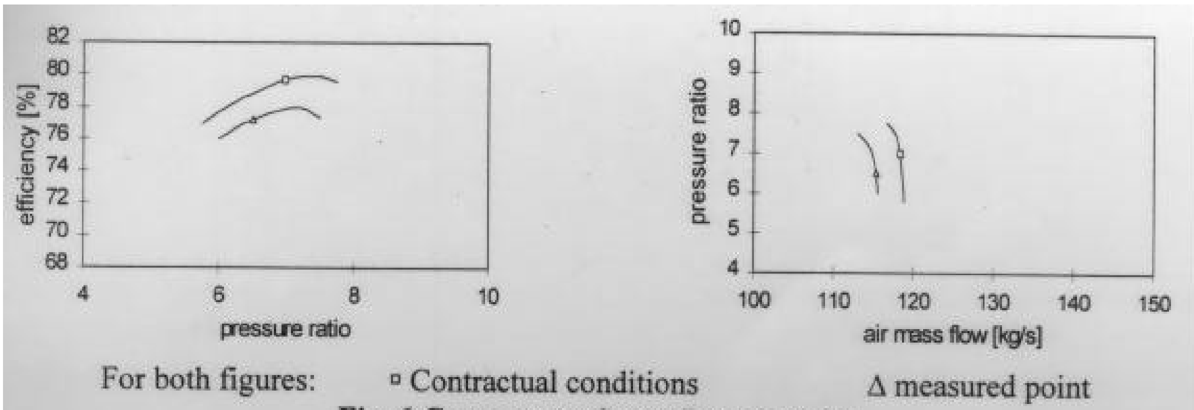
The modules developed both for FIAT MIRAFIORI and HAR plants are:

Components compressor, combustion chamber, gas expander cooled and uncooled, economiser, evaporator, superheater, steam turbine, attemperator, drum, deareator, fixed and variable speed pumps, valve and de-superheating, splitter, junction, valve and orifice, tank, mixer, electric generator, electric grid, manifolds, and so on.

Macro modules gas turbine, waste heat recovery boiler, steam generator.

Model Calibration

In accordance with the OMSEM activities, six prototypes have been designed and produced with reference to the various sections of the two case study plants. To validate the capability of the section prototypes and to check the results obtained (using modules developed) with that of one given by the manufacturer different tests have been carried out. Some examples are reported as follows: Fig. ó (a) and (b) reports compressor characteristic curves related to new and actual state (obtained by inverse calculation). The monitoring data being as input.



For both figures: ▫ Contractual conditions Δ measured point

Fig. 6 Compressor State: Deteriorated

Each component model has been calibrated using plant available data. For example Fig. 7 shows the gas turbine exhaust gas temperature versus gas turbine power output. It may be observed that there is a good agreement between the manufacturer curve (full curve), plant measured points (represented by empty circles) and results obtained by the present models (represented by empty triangles).

A map of a turbogas section is shown in Fig. 8. This figure represents the behaviour with the exhaust gas bypass completely closed and with the condition that the hot water temperature at the exit of heater is fixed at 140°C. Thus the water mass flow and steam water mass flow varies. Fig. 8 shows the variation of gas turbine exhaust temperature, steam temperature, hot water and steam mass flows, and fuel mass flow versus the produced electric power. Calculated fuel mass flow is compared with the measured one. The agreement is quite good.

Results and calculations

To verify the capability of plant prototypes a set of optimum load allocation has been carried out. The boundary conditions and tariffs considered as a reference data have been obtained from FIAT and HAR.

As an example it is reported a set of calculation which has been performed based on the reference data and compared with that of FIAT operating conditions. It is observed that there are differences in fuel consumption and steam production. It can be concluded that the Turbogas section is fouled. Accordingly inverse calculation have been performed to establish the deteriorated parameters. Table l shows actual state parameters obtained for the compressors, gas expanders, waste heat recovery boilers, and water heaters by inverse calculation using OMSEM codes.

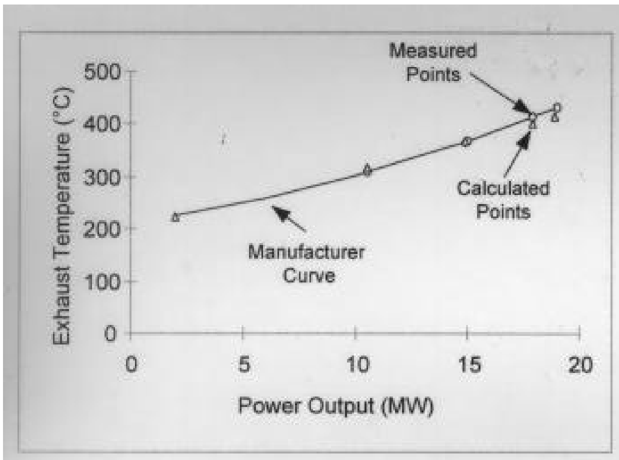
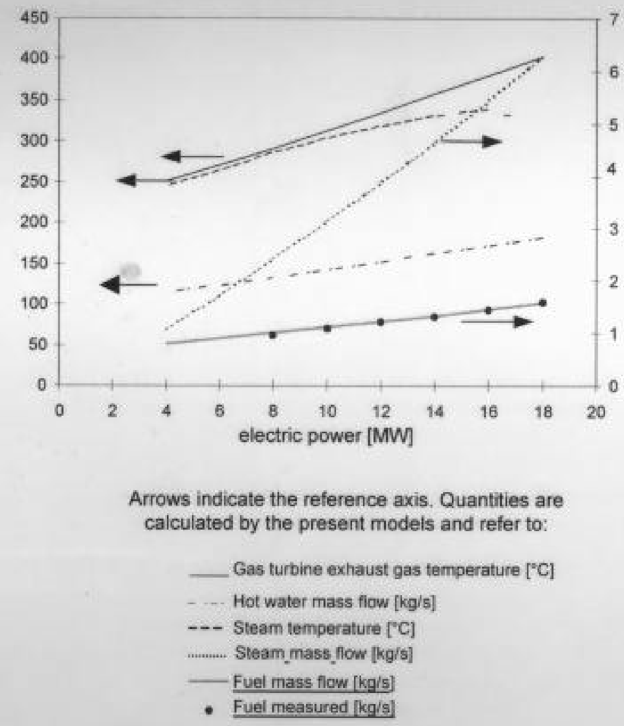


Fig. 7 Gas Turbine Power Output vs. Gas Expander Exit Temperature



Arrows indicate the reference axis. Quantities are calculated by the present models and refer to:

Fig. 8 Waste Heat Recovery and Water Heater Section

Table l Actual State Parameters

State parameters	fb	fd	ff
Compressors	**0.990**	**0.990**	**0.932**
Gas expanders	**1.000**	**0.960**	**0.955**

fb = affecting the effective flow areas

fd = affecting the flow deflection through the deviation angle

ff = affecting the loss mechanism in the blade rows

state parameters	$\mathbf{f}_{HT}$
Waste Heat Boiler	**0.97**
Water Heater	**0.75**

$\mathbf{f}_{HT}$ = surface fouling factor affecting the heat transfer rate

Table 2 reports the global costs obtained by OMSEM software for the simulation and optimum load allocation related to the new and actual component statuses. Case #1 refers to the simulation results obtained by OMSEM code with actual component statuses. Case #2 shows the load allocation with actual component statuses, as it is observed FIAT total cost is improved by 2.4%, and further increased to 4.4% (case #3) with maintained (new) component statuses.

Table 2 FIAT Simulation and optimum load allocation global results (Obtained by URM3 code)

Case #	TOTAL COSTS [%]
1	**100.0**
2	**97.6**
3	**95.6**

Case #1 - FIAT simulation results.
Case #2 - Optimum load allocation with **Actual** plant statuses.
Case #3 - Optimum load allocation with not **fouled** components.

Component Environmental Modeling (COEM)

Environmental Considerations in the Techno-economic Optimization of Energy Systems

Three main actions have to be completed in order to perform optimization of an energy system with environmental considerations:

(i) Quantitative estimation of the various emissions of each system: *component environmental modelling.*
(ii) Proper monetization of the damage caused by each pollutant on the environment and introduction of these costs into the objective function: *internalization of the environmental costs.*
(iii) Development of software for component environmental modeling and the internalization of the environmental costs.
A brief description of the work performed for each action is given in the following.

Component Environmental Modeling

The two energy systems, which serve as application examples in this work, have two types of units emitting pollutants: gas turbines and steam boilers. Exhaust gases of any of these units can be considered as consisting of

- major constituents, e.g., CO_2, H_20, O_2, N_2, etc., and
- minor constituents, e.g., CO, SO_2, NO_x, etc.

The quantities of major constituents are estimated by the chemical reactions equations related to the combustion. The numerical values of the parameters involved are estimated by use of experimental data such as O_2 or CO_2 content in the exhaust gases.

Minor constituents can be estimated by at least two methods:

a. Use of basic principles (combustion theory, thermodynamics, chemical kinetics, etc. and detailed design and operation characteristics of equipment.
b. Parametric Environmental Modeling (PEM), which is a semi-analytic approach: the quantity of each pollutant is estimated by an analytic equation as a function of operation parameters of the system. The form of the function is determined rather empirically and the numerical values of the parameters involved are determined by use of the experimental data collected for various operating conditions.

Given the available information and resources, approach (b) has been the only possible choice in this work. Experimental data provided by the two plants have been used to develop the models.

Internalization of the environmental costs.
Costs of industrial activity included in the price paid by the consumer are said to be "internalized". Some are related to environmental protection, i.e., they are "internal environmental costs". Other environmental costs related to the activity are born by society in general rather than paid for, e.g. in electricity bills. The unpaid costs are called "external environmental costs". Some of the people who bear these costs may not benefit from the particular industrial activity, e.g. in transboundary pollution. From the point of view of society as a whole, if the cost of energy supply excluding environmental protection or safety measures is called "internal general cost", then:

Total Cost = Internal General Cost
+ Internal Environmental Cost
+ External Environmentl Cost

Methods for estimation of external environmental costs.
Three approaches have been identified in the literature for estimation of the external (environmental and social) cost of energy production:

(i) Indirect methods: They aim at measuring the value of goods not traded in formal markets, such as life, scenic, and recreational goods.
(ii) Direct methods (Damage cost): They are used to measure goods for which economic costs can be readily assessed, such as the value of lost agricultural products, or the cost of repairing damaged goods.
(iii) Proxy methods (Avoidance cost): They are used to measure the costs of avoiding the initiating insult rather than the cost of the damage created by the insult.

Values given in the literature in the form of charge (or cost) per unit of each emission have been used in the present work. Of course, different values (coming from different methods) will produce different optimum results. An analysis can be performed in order to reveal the sensitivity of the optimal solution to the values of these cost parameters.

Approaches for internalizing environmental externalities.
External environmental costs are internalized by market-based approaches. The Organization for Economic Cooperation and Development (OECD) identifies four classes of economic approaches for environmental protection: (i) charges, (ii) market-creation, (iii) subsidies and (iv) deposit-refund systems.

The deposit-refund approach is not particularly relevant to the systems examined in this study. On the other hand, the application of the market-creation approach is very difficult at the moment for several reasons but primarily because an appropriate legal framework has not been created yet in European countries. The remaining two approaches (charges and subsidies) can both be used in this work

lntroduction of environmental cost into the objective function.

It is assumed here that for each pollutant emitted or a hazard caused by the plant to the environment it is possible to evaluate the cost of the damage caused to the environment by a function of the form

$$G_{ei} = C_{ei}\, f_{pi}\, P_i \qquad (3)$$

Where

P_i measure of the ith pollutant or hazard (e.g., quantity of a pollutant),

C_{ei} unit environmental cost due to the ith pollutant or hazard.

f_{pi} environmental penalty factor related to the ith pollutant or hazard: it accounts for the sensitivity and self purification rate of a particular environment .

The functions G_{ei} are additive terms in the objective function.

Several studies conducted in Europe and the U.S.A. attempt to determine values of C_{ei} for various pollutants . They are not complete, the results may differ from one to the other and they may have a high degree of uncertainty. However, it seems that there is a consensus: it is better to use these results and internalize the environmental costs than not to apply it at all.

COEM Software.

Software has been developed to calculate the quantity of each pollutant by each component of the two plants and to calculate the environmental cost terms of the objective function. Values for unit environmental cost of each pollutant in the form which is appropriate in this project (e.g., ECU per kg of emitted pollutant) have been found in the literature and have been incorporated in the software as default values. The user may change the unit costs at will.

A fair treatment of the industrial cogeneration systems from the point of view of environmental externalities requires that any quantity of electricity purchased from the network is charged according to the emissions of the central power plants. Default values of emissions are given in the software, but the user may give any other set of values.

Total subsystem Analysis and Costing (TSAC)

Overview of TSAC Design

The total cost of operating the plant costs consists of three parts:

i) The sum of the costs calculated by the TSAC subroutines for each plant component.
ii) Electricity cost based on net plant production, factory demand and electricity tariff.
iii) Environmental cost associated with component emissions.

The electricity and environmental costs are calculated separately by COMD and COEM and are not calculated by TSAC. TS AC consists of eleven costing subroutines written in C++ compiled into the main OMSEM program. Each subroutine provides costs for a particular component type, these component types are listed below:

Component type considered by TSAC		
steam boiler	pump	compressor
generator	steam turbine	cooling tower
heat-exchanger	burner	gas turbine
motor	tank	

When requested by OMSEM, TSAC provides a component cost. These subroutines provide the hourly costs for fuel, labour, depreciation, amortisation, maintenance and supplies. The costs calculated by each of the subroutines are very similar. A general description of the cost calculations is described below.

Fuel Costs
Fuel costs are calculated using the fuel tariff and the fuels used by the component.

Cost of Supplies
Depending on the type of component, supplies are categorised as either chemicals for feed water treatment or cooling water or is set to zero.

Labour Cost
Labour costs are calculated for all component types. The total labour cost for each component is calculated using a labour tariff and the number of operators required at each grade.

Depreciation Cost
Depreciation costs for all components are calculated using one of three methods:

[i] Depreciation at constant rate over the service life of the component.
[ii] Depreciation as a fixed percentage of the current value of the component.
[iii] Depreciation proportional to component load.

Amortisation Cost
The amortisation cost of a fixed asset shows any changes from the expected depreciation as a result of operating a component outside its design conditions.

Component Maintenance Costs
The component maintenance cost is the sum of three components, planned maintenance routine maintenance and extraordinary maintenance. Both the routine and planned maintenance costs are supplied by the user. The extra ordinary maintenance cost is calculated by TSAC and shows any changes from the expected maintenance costs as a result of operating a component outside its design conditions.

The cost factors and indices for the cost subroutines can be modified by the user and are contained in the OMSEM data base. Values for these factors and indices can be entered bv the user through the DBMS and SCHEDULER. Costs for individual plant components are calculated using this user-definable data together with the loading and fuel used by the plant components. The loading and fuels used by the components are calculated by COMD.

Validation of TSAC

When the TSAC subroutines were integrated into the main OMSEM program it was necessary check that the costs calculated by the TSAC subroutines were consistent with expected values. In order to ensure that this was so default values required for the costing subroutines were forwarded to Cap Gemini and the costs calculated by the integrated subroutines were compared with those calculated at the UU.

When a full simulation of the FIAT plant became available on the OMSEM web site costs were calculated using the TSAC routines for 53 components. Further validation was carried out on the FIAT and HAR plants by ENEA.

In cooperation with the partners the overall design of OMSEM was established and the role of TSAC within OMSEM was clearly defined.

The TSAC subsystem was developed on the basis of generic chemical and mechanical engineering principles.

The TSAC calculation routines employ user definable factors and indices which enable the TSAC routines to be customised to a particular application.

The TSAC subsystem was used to calculate costs for both the FIAT and HAR plants. The results calculated by the subsystem were validated against expected values.

DBMS Subsystems

DBMS design

The Database contains the data related to the past and present working mode of the plants described by OMSEM. The other subsystems which compose the OMSEM system can access and retrieve data stored into the database.

The design of the Database has been based on the conceptual data model. The schema in figure 9 shows the conceptual data modeling for OMSEM.

The OMSEM Software prototype is based on a Client/Software architecture. The user inserts and sends data from a Client to the Server station using an Internet connection. In the Server, a CGI routine gets the data and it starts the simulation. The simulation provides the optimum set point, which are written in several output files. The following figure shows the operating mode schema and the block diagram of OMSEM Prototype.

How OMSEM System works

The OMSEM Software Prototype runs on an IBM RISC 6000 located at URM 3 premises. An Apache server has been installed on this computer and it is running.

Two pages compose the OMSEM site. The first page is public. Since, the second page could show confidential data, the access to this page is restricted and a login and a password is required. OMSEM partners know login and password. In the reserved page there are the main function of the OMSEM software prototype: the button, which starts the execution of the plant optimization.

In order to start the OMSEM executable, the user should insert the data required, which are sends to the server using the POST method. In the server side, the data are written in more input files, depending on data typology and the simulation starts. The executable reads both the user data and plant data from the database. When all data are been read, the executable search the.better solution in order to provide the optimum set point. This operation can spend more time, depending by the speed of the computer. The search of the solution proceeds by step. User sets the number of step. If the execution reaches the last step, the solution achieved can not be the optimum solution. If the solution is reached before the last step, the executable ends his search and it writes the output files. If the executable cannot find the solution, it ends his search before the last step. The results are written in a file and shown to the user. The graphical interface is made in the HTML language and it uses the Internet capabilities. Each table of the database has a mask, which enables the user to read or write data in the table.

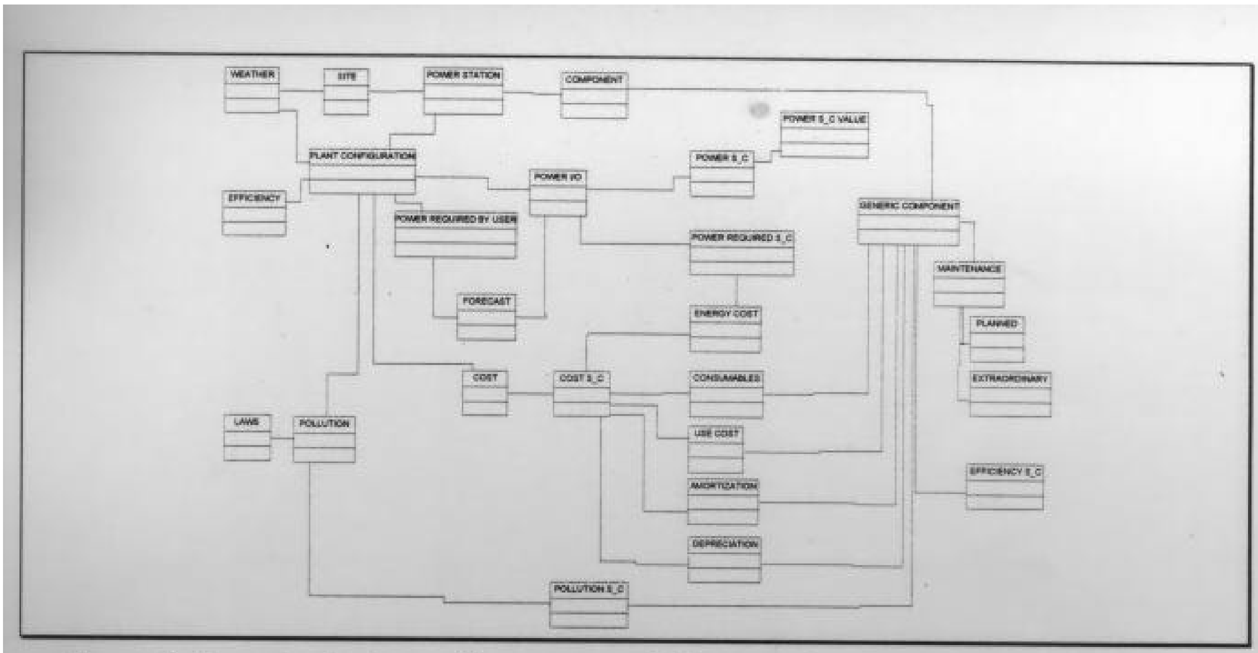


Figure 9. Conceptual schema. The acronyms S_C means that the table stores data referred to single component and not for the whole plant.

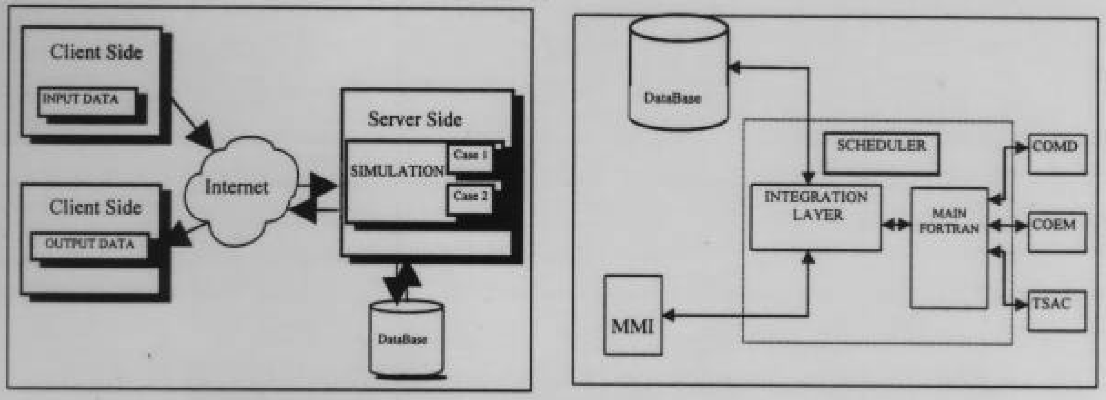


Fig. 10: OMSEM Software operating mode schema and block diagram.

For communication between HTML masks and database the standard Common Gateway Interface, or CGI, has been used. The CGI scripts have been written in C or PERL languages.
The following figures show the public (Fig. 11a) and the reserved page (Fig. 11b) of the OMSEM site.

http://jou3.dimi.uniroma3.it/

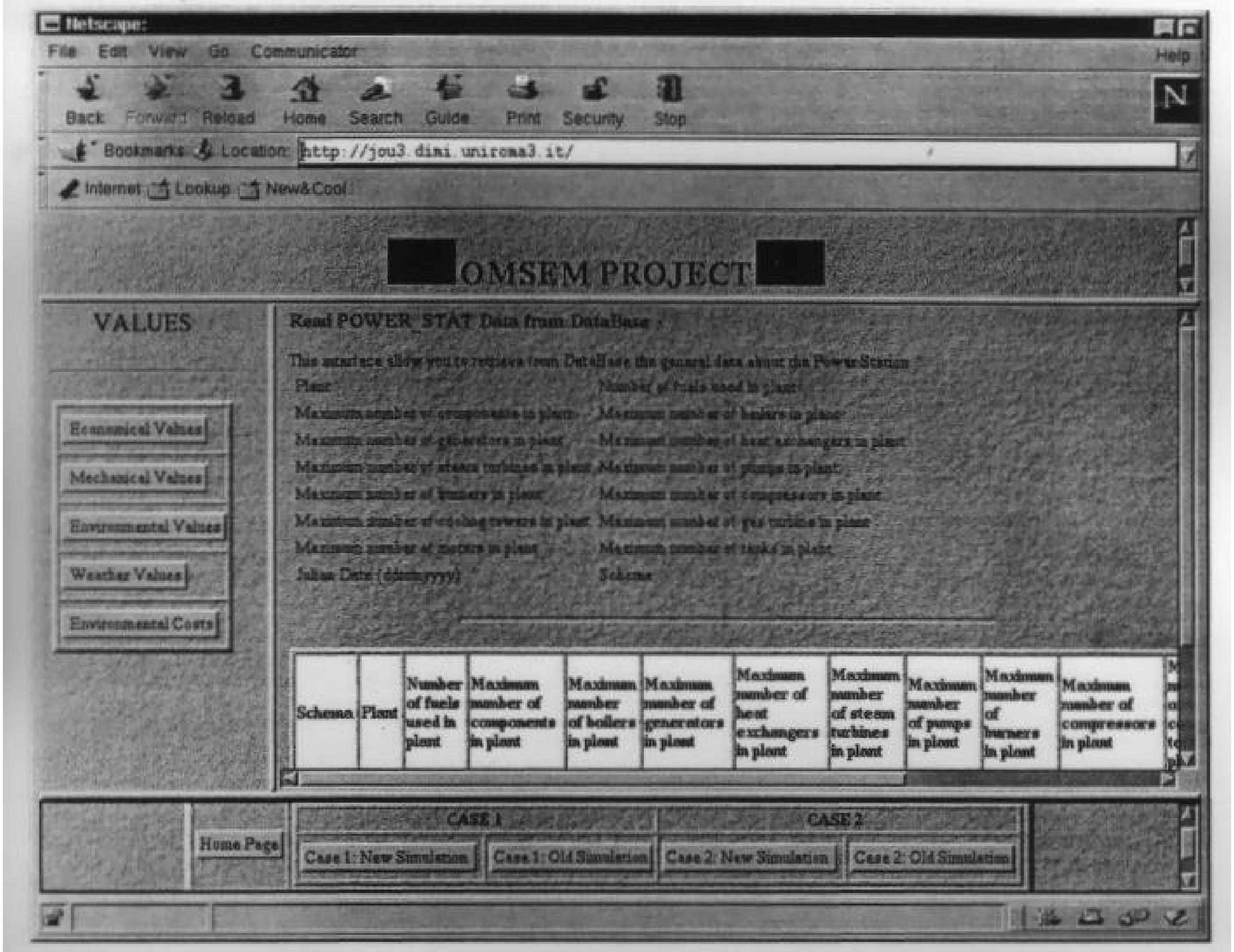
OMSEM
System Requirements Document

Document No: [illegible]
Issue No.: 1.2
Date: 30 July 1996

Distribution:

- Cap Gemini S.p.A.
- Università di Roma 3
- ENEA

Fig.11a: Public page of the OMSEM SITE.



Read POWER_STAT Data from DataBase :

This interface allow you to retrieve from DataBase the general data about the Power Station

Plant
Number of fuels used in plant
Maximum number of components in plant
Maximum number of boilers in plant
Maximum number of generators in plant
Maximum number of heat exchangers in plant
Maximum number of steam turbines in plant
Maximum number of pumps in plant
Maximum number of burners in plant
Maximum number of compressors in plant
Maximum number of cooling towers in plant
Maximum number of gas turbine in plant
Maximum number of motors in plant
Maximum number of tanks in plant
Julian Date (ddmmyyyy)
Schema

Schema	Plant	Number of fuels used in plant	Maximum number of components in plant	Maximum number of boilers in plant	Maximum number of generators in plant	Maximum number of heat exchangers in plant	Maximum number of steam turbines in plant	Maximum number of pumps in plant	Maximum number of burners in plant	Maximum number of compressors in plant

Fig.11b: Reserved page of the OMSEM SITE.

Test activity – Overview
The OMSEM System Software has been tested, before of the start of the Validation Activity. Software modules and procedures are verified through unit tests: they are performed to verify the internal working mode (white box testing), and the correctness of their external interfaces (black box testing). Subsystems are been verified through integration tests. The approach to integration test has been bottom-up: specific tests have been designed to check the integration of modules before testing the function as a whole. Black box tests have been run.

OMSEM Validation

Validation activity is to demonstrate that OMSEM system is really capable to allocate in proper manner the loads on different plant units, simulate the real plant behavior, and finding the configuration giving the economic optimum, and highlighting consequences on energy and environment.

These concepts generated three different activity types: verification, validation, evaluation. The verification is the activity aimed at checking that the program is actually able to run and change in a correct way the allocation of loads to the different plant units (gas-turbine, steam generators, steam turbines, combined groups) when affecting conditions change, either strongly or smoothly. Verification tests are prepared and executed, on the basis of a number of applicable laboratory cases to verify OMSEM behaviour under changing conditions.

The validation is the activity aimed at checking that the program is able to simulate the plant behaviour, by comparing simulation results with real operating data.

The evaluation is the activity to assess whether or not OMSEM actually allows to get the expected benefits in minimising costs, saving primary energy, and reducing pollution, when compared with traditional plant management.

A methodology, for the evaluation of the cogeneration plant EEE (Energetic, Environmental, Economic) performances has been set up, based on indicators.

A computer program tool, called ESAM (EEE Saving Assessment Model), implementing the methodology, has been developed.

Target plants have been studied. A summary of 1997 exercise data has been provided to support the historical analysis of 1997 target plant EEE performances.

Evaluation activity has been undertaken by comparing OMSEM optimisation results with sample points. Results are elaborated by using economic, environmental and energy indicators. Results have been compared to historical data.

Summary of verification activity

Appropriate test cases, forcing the external conditions affecting the cogeneration system to change sharply, have been set up in order to verify the optimisation system for what concerns the load allocation to the several units and components of the plants. Particularly, the factory energy demand and the selling and purchasing energy prices have been changed drastically to check the response of the optimisation system.

The assessment of the optimisation system , in relation with its capability of load al location to the several groups and components of the plants requires the definition of cases in which the main characteristics of the plant change sharply and strongly. An operating condition is taken as starting point, using the data collected directly from the plant. The data are related to an "instant" operating point, therefore hourly values are used.

Two different series of test cases have been carried out, concerning the two implemented models. The input variables are changed, one at a time, (with respect to the reference case), with strong increase and decrease of the variable, even doubled or halved values. In one case, the changes are applied to two variables, simultaneously, in order to assess compensation or degeneration effects of the system.

The test cases types are listed below:

1. Change of the electric demand of the factory (with respect the reference case)
2. Change of the thermal power demand;
3. Change of the natural gas price;
4. Change of the price for the electric energy sold
5. Change of the price for the electric energy purchased
6. Deterioration of 1 group;
7. Increase of the electric energy demand, decrease of the price of the electric energy purchased.

Using data consistent with the real plant, a typical operating condition has been assumed as starting case (Case # 0).

The load allocation to the several units and the percentage load variations, with respect the nominal values, are calculated. The cases analysed were sufficient to check the response characteristics of the optimisation system to input changes.

The test cases referring to the first series are summarised in the following.

- Series 1 model verification Case #0 refers to model I plant operating point. Such operating conditions have been assumed as reference for the optimized load allocation calculations. The cost associated with the reference operating point has been calculated also, according to the model developed in 8770 Euro/h.

The results in all series 1 cases, show the tendency of the optimisation system to produce electricity as much as possible of and sell it to the utility, by using the most efficient equipment as the combined cycle electric energy generators, and at same time keeping a thermal energy output reserve, which is a system constraint.

Even when the purchase price is advantageous and the electricity demand is high, the system tends to buy electric energy as few as possible from grid, and satisfy the factory demand with own-produced electricity which decreases the total production cost.

- Series 2 model verification.
  Case #0 refers to the plant operating point assumed as reference for the optimised load allocation calculations.
  Case #1 refers to case # 0 and is the optimised allocation resulting from the code application. With respect the reference case the total cost is 1.3% lower.

Summary of validation activity

The ultimate objective of the validation is the comparison between the non-optimised calculation (simulation) results and the operating data of the plant.

Cogeneration target plant winter typical load allocations has been provided for validating OMSEM system models, organised by factory energy demands, fuel and electricity prices, ambient conditions, and the corresponding load allocation of the several units.

Results have shown data so achieved are very similar to the real plant. In general, the same order of magnitude for costs (around 9000 Euro/h) is detected.

Electric power, thermal power, flow consumption, emissions are practically the same.

A little difference in costs is due to the labour, which is calculated on annual basis, while OMSEM considers a labour cost depending on the operational load. Similar matches of real and calculated data have been obtained for the other target plant case, too.

Summary of evaluation activity

In plant 1 case, concerning the absolute production costs, a substantial total cost saving comes out from the comparison (4.121%), as result of the optimisation process applied to the specific situation. Going to non optimised to optimised, total cost value is reduced form 9147 to 8770 Euro/h. Fuel gas flow and related emissions have significantly increased, while the other cost items have not changed.

The reason of the economic saving stems from the increased sale of electricity to the grid, paid with a decreased fuel specific consumption. This is obtained by optimum allocation on full loading of combined cycles, the equipment with highest efficiency and reduction of steam pressure through depressurisation valves.

Concerning emissions, the remain on the same values, even with major emphasis on environment cost weight, due to the fact that fuel specific consumption is decreased by optimisation but the absolute energy production is increased.

In plant 2 case, a production cost earning equal to 1.31% has been found out.
A higher rank comparison has been performed using the ESAM tool, which allows the assessment of the actual performances of the optimiser, from a point of view of energy, environment and economy.

Those indexes have been applied to the data of 1997 annual thermal-electric production and consumption with the aim of determining the performance indexes of the plant, in traditional operating conditions.

This allowed to carried out a historical analysis over one year, and indicator values obtained day by day. Minimum, average values for each index have been calculated then calculated which are a reference for comparing OMSEM optimised plant performance to historical ones. Optimised and non optimised calculations have been carried out and the global results in terms of electric, thermal and fuel power, along with prices and other constants, gathered which constitute the input for ESAM tool. The corresponding set of values is calculated by ESAM, The corresponding set of values is calculated by ESAM, through the indicators reported in Annex 1.

Cost indexes focus on the operating (variable) costs, and in particular on fuel costs, electricity exchange costs and pollution costs, with this latter calculated for CO2 only, on the basis of 0.015 Euros/KgCO2.

These costs are all referred to produced powers, electric and thermal, differently weighted in the light of II Principle of Thermodynamics, using conventional efficiencies (0.384 for electric plants, and 0.85 for thermal plants).

The Ceq (Fuel cost of weighted energy unit), the Cae (Fuel cost of pure produced electric energy unit), the Ceq,tot (Energy and emission cost of weighted produced energy unit), and finally the

Cae,tot (Energy cost of electric energy unit) show for plant 1 a decrease of specific production costs, ranging from 1.7 to 8.5 percent.

Concerning the energy indexes, the specific consumption (Sp.Cons.) decreases, and the conventional electric efficiency (El.eff.), and since conventional thermal efficiency (Th.eff.) slightly decreases, the total fuel utilisation factor (FUC) increases, demonstrating a little advantage for plant 1, due to the elimination of steam pressure reductions through depressurisation valves, and the use of most efficient equipment such as combined cycles. REP (Primary energy saving quantity, compared with separated electric and thermal production) and Ir (Primary energy saving percentage gain with cogeneration compared with separated generation) are negative, according to the historical values, but decreasing as absolute values, which means an improvement of saving with optimisation.

Req (weighted utilisation factor), Rae (net electric efficiency) and Ien (Italian energetic index) also increase with optimisation.

Finally, FUS (Fuel Utility Saving), calculated as the exchanged electricity divided by the electric efficiency of a national grid power station, shows the fuel amounts avoided to the national system, by the sale of the self-produced electricity to the external grid.

All index values are significantly aligned with the historical average values.

Concerning the C02 emission indexes, FEG (C02 emission divided by the sum of electric and thermal production) shows that the specific emissions decrease according to fuel saving. The same trend is given by Ico2 ,eq. and Ico2,ae, which give respectively the ratio between the C02 generated and the total weighted power, and the ratio between the C02 generated just for electrical production and the electrical production itself.

Finally, CO2US (CO2 Utility Saving), calculated as the exchanged electricity divided by the CO2 yield of a national grid power station, shows CO2 amounts avoided to the national system, by the sale of the self-produced electricity to the external grid.

Indexes	Units	PLANT 1				
		Historic(av)	Hist. max	Non Optim	Optimum	Var. (%)
Sp.Cons.	-	3.990		5.450	5.205	4.51
El. Eff.	-	0.251	0.467	0.183	0.192	4.72
Th. Eff.	-	0.112	0.314	0.327	0.320	-2.03
FUC	-	0.363	0.552	0.511	0.513	0.39
Ir	-	-0.209	0.258	-0.142	-0.123	13.80
REP	tep/h	-8.688		-10.340	-9.199	11.04
Req	-	0.291	0.497	0.327	0.333	1.75
Rae	-	0.290	0.522	0.298	0.308	3.40
Len	-	0.130	0.600	0.723	0.733	1.33
FEG	kgCO$_2$/kW h	0.492	0.708	0.422	0.420	0.39
ICO$_2$,eq	kgCO$_2$/kW h	0.621	0.927	0.658	0.647	1.72
ICO$_2$,ae	-	0.172	0.500	0.189	0.183	3.09
RCO$_2$	kgCO2/s	-5.030		-2.283	-1.330	41.72
Ceq	E/kWh	0.043	0.044	0.041	0.040	1.72
Cae	E/kW h	0.050	0.058	0.045	0.044	3.29

Ceq,tot	E/kW h	0.033	0.038	0.039	0.037	5.32
Cae,tot	E/kW h	0.051	0.060	0.051	0.046	8.58
FUS	MW	227.402	312.500	219.251	248.663	13.41
CO2US	kg/s	13.610	18.706	13.124	14.885	13.41

Fig. 12. Index values for historical, non optimised and optimised calculations, percent variation. The meaning of indexes is explained within the text.

Conclusion

OMSEM project has proved its capability to develop a method and computation models with the purpose of improving the management of industrial thermal and electric power plants. This is achieved through the simultaneous minimisation of an objective function, which takes into account of economic, environment, energy factors, plant equipment statuses and availability costs, and the optimum allocation of electric and thermal loads to the available units is found.

Further, the implemented models have been proven to respond to external demands in a way which is congruent with the real plant costs, consumption and emissions, when the optimisation is constrained.

OMSEM system effectiveness, as limited to the experimental points on disposal, has found out in reducing costs, which is the main purpose of this research, and also in saving energy and emissions, either augmenting in general the plant total efficiency or reducing exergy losses.

Looking at the whole data, we can say that OMSEM system reduces the cost of produced energy. The few percentage points of economic saving mean an earning from thousands to millions Euro per year.

OMSEM results are affected by cost weight factors, which can be set as a function of plant management strategies. A different result should be found by giving a major weight to the energy and environment factors in the objective function.

However improvements are expected. In particular, the following directions are possible:

a) Capability to create a generic co-generation plant model, tailored on user necessity, by a suitable interactive and graphical interface. In this way, whatever plant could be generated, starting from a basic library of components.
b) Modelling could include a user-defined price for environmental cost functions, in form of taxes (i.e. carbon tax), subsidies, penalties according to local Law regulations, as well as technological abatement intervention of pollution. Further, equipment and labour unit cost should be verified and however easily set by the user.
c) Optimisation of mathematical parameters could address the program search of optimum condition. This should speed up the calculation time and precision, above all for complex system with thousand variables. An additional interface is suggested to provide the user with a list of plant management options (such as management strategies to sell, to buy, to use a particular unit, etc.), translating these choices into a set of user tailored mathematical parameters.

A different point of view is the possibility of application of OMSEM to industrial realities. In this direction, the following paths are suggested:

- Implementation of plant optimised operational maps for different management scenarios. The optimisation code should not make use of a plant "simulator", but it should work by interpolating algorithms on maps. This could notably shorten the calculation time for reaching the optimum point.
- Development of models aimed at studying the plant dynamics.
- Optimisation expert system learning by OMSEM.

As usual in these cases, the optimisation model has been developed off-line first, to prove the advantages of the application; then the product is commercialised with the ultimate objective of supporting the operator or implementation within supervising and control systems.

However, the transition from the scientific application to the market product needs further efforts, for example to reduce the computation time, which require consciousness-raising from the companies of the sector about the intrinsic potential of these tools.

It is intended that goods supplied within this project do not include any Year 2000 impact analysis. Actually, delivered OMSEM software is time-independent or, better, the OMSEM time dependence is not critical as far as the date change (from 1999 to 2000). However, the problem has been avoided using the julian date instead the "normal" date.

Exploitation plans and anticipated benefits

During the OMSEM project development, some papers have already been presented. Moreover there is the intention to write other papers for conferences and journals.

ENEA has become promoter of meeting with some municipal authorities in Italy. In fact, technical meeting have been carried out with the municipal authority of Turin and with

Energy and Environment Local Authority of Rome, in the first months of this year, with the purpose of create possible co-operations and the exploitation of the single modules developed in this project.

A seminar aimed to introduce this product to the major energy utilities is planned in the mid 1999. Also, technical reports on this subject will be made available at the ENEA Consulting Centres, located on the national territory, and to the major enterprises of the sector.

Moreover, ENEA will promote dissemination of information in the frame of the annual meeting of the Italian Energy Managers. Contacts are in progress with several European Companies with the purpose of checking the further developments of this product, getting involved not only the plant managers but even the designers of co-generation and combined cycle plants.

The possibility of presenting further development of this project, oriented to a market product, in the frame of the V European Framework Program, is under evaluation.
Some demonstrations have been done and some are in progress by ENEA and Cap Gemini.

The OMSEM System Prototypes is running at Università di Roma Tre premises. The WEB address is http:\\jou3.dimi.uniroma3.it

ESAM software package. The code is available for using, running under MS-Windows 95 at ENEA Casaccia premises.

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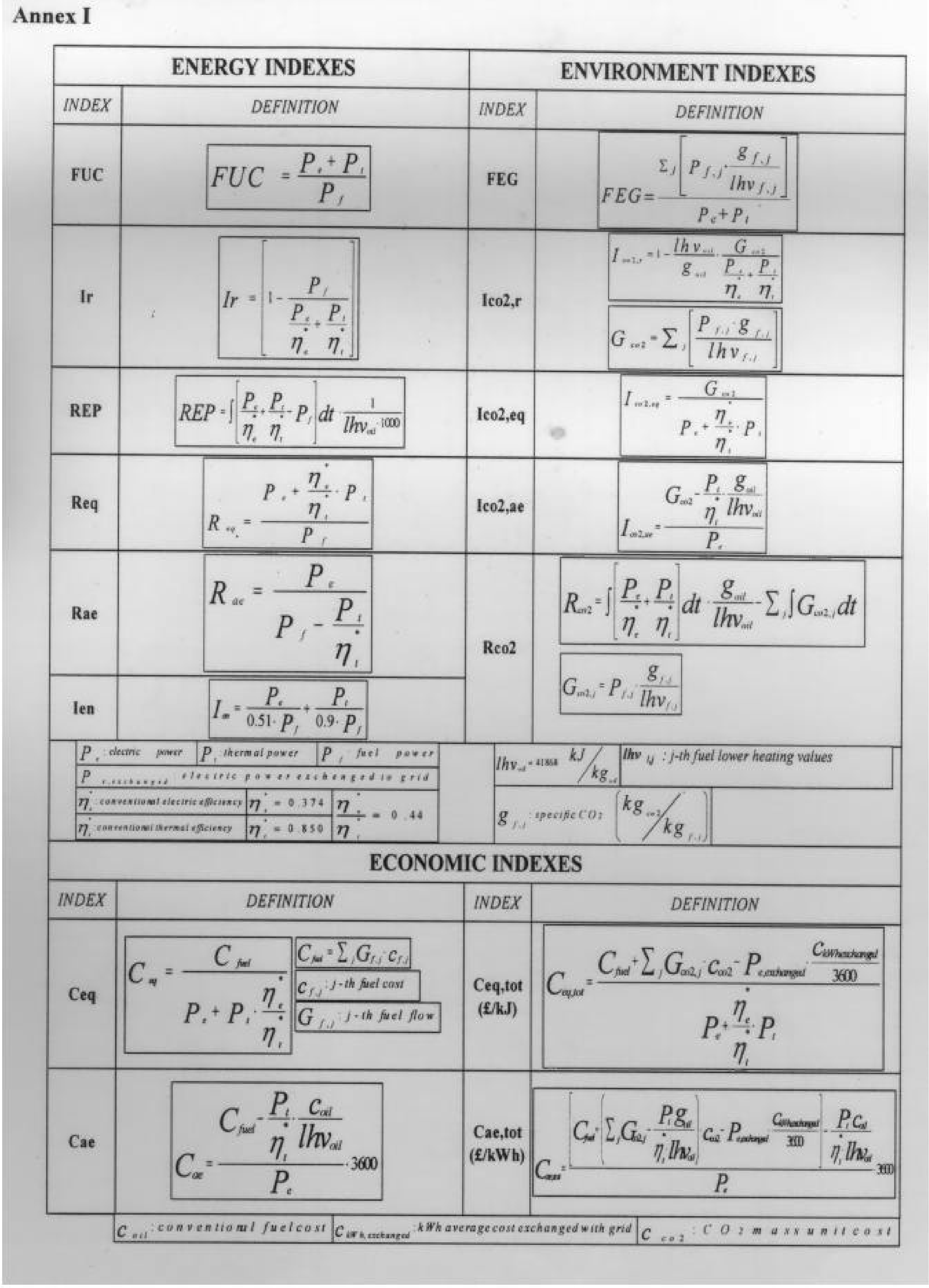

Annex I

ENERGY INDEXES		ENVIRONMENT INDEXES	
INDEX	*DEFINITION*	*INDEX*	*DEFINITION*
FUC	$FUC = \frac{P_e + P_t}{P_f}$	**FEG**	$FEG = \frac{\Sigma_j \left[P_{f,j} \cdot \frac{g_{f,j}}{lhv_{f,j}} \right]}{P_e + P_t}$
Ir	$Ir = \left[1 - \frac{P_f}{\frac{P_e}{\dot{\eta}_e} + \frac{P_t}{\dot{\eta}_t}} \right]$	**Ico2,r**	$I_{co2,r} = 1 - \frac{lhv_{oil}}{g_{oil}} \cdot \frac{G_{co2}}{\frac{P_e}{\dot{\eta}_e} + \frac{P_t}{\dot{\eta}_t}}$ $G_{co2} = \sum_j \left[\frac{P_{f,j} \cdot g_{f,j}}{lhv_{f,j}} \right]$
REP	$REP = \int \left[\frac{P_e}{\dot{\eta}_e} + \frac{P_t}{\dot{\eta}_t} - P_f \right] dt \cdot \frac{1}{lhv_{oil} \cdot 1000}$	**Ico2,eq**	$I_{co2,eq} = \frac{G_{co2}}{P_e + \frac{\dot{\eta}_e}{\dot{\eta}_t} \cdot P_t}$
Req	$R_{eq} = \frac{P_e + \frac{\dot{\eta}_e}{\dot{\eta}_t} \cdot P_t}{P_f}$	**Ico2,ae**	$I_{co2,ae} = \frac{G_{co2} - \frac{P_t}{\dot{\eta}_t} \cdot \frac{g_{oil}}{lhv_{oil}}}{P_e}$
Rae	$R_{ae} = \frac{P_e}{P_f - \frac{P_t}{\dot{\eta}_t}}$	**Rco2**	$R_{co2} = \int \left[\frac{P_e}{\dot{\eta}_e} + \frac{P_t}{\dot{\eta}_t} \right] dt \cdot \frac{g_{oil}}{lhv_{oil}} - \sum_j \int G_{co2,j} \, dt$ $G_{co2,j} = P_{f,j} \cdot \frac{g_{f,j}}{lhv_{f,j}}$
Ien	$I_{en} = \frac{P_e}{0.51 \cdot P_f} + \frac{P_t}{0.9 \cdot P_f}$		

P_e: electric power

P_t: thermal power

P_f: fuel power

$P_{e,exchanged}$: electric power exchanged in grid

$\dot{\eta}_e$: conventional electric efficiency

$\dot{\eta}_t$: conventional thermal efficiency

$\dot{\eta}_e = 0.374$

$\dot{\eta}_t = 0.850$

$\frac{\dot{\eta}_e}{\dot{\eta}_t} = 0.44$

$lhv_{oil} = 41868 \; kJ/kg_{oil}$

$lhv_{f,j}$: j-th fuel lower heating values

$g_{f,j}$: specific CO2 $\left(kg_{co2}/kg_{f,j} \right)$

ECONOMIC INDEXES			
INDEX	*DEFINITION*	*INDEX*	*DEFINITION*
Ceq	$C_{eq} = \frac{C_{fuel}}{P_e + P_t \cdot \frac{\dot{\eta}_e}{\dot{\eta}_t}}$ $C_{fuel} = \sum_j G_{f,j} \cdot c_{f,j}$ $c_{f,j}$: j-th fuel cost $G_{f,j}$: j-th fuel flow	**Ceq,tot (£/kJ)**	$C_{eq,tot} = \frac{C_{fuel} + \sum_j G_{co2,j} \cdot c_{co2} - P_{e,exchanged} \cdot \frac{C_{kWh,exchanged}}{3600}}{P_e + \frac{\dot{\eta}_e}{\dot{\eta}_t} \cdot P_t}$
Cae	$C_{ae} = \frac{C_{fuel} - \frac{P_t}{\dot{\eta}_t} \cdot \frac{c_{oil}}{lhv_{oil}}}{P_e} \cdot 3600$	**Cae,tot (£/kWh)**	$C_{ae,tot} = \frac{\left[C_{fuel} + \left(\sum_j G_{co2,j} - \frac{P_t g_{oil}}{\dot{\eta}_t lhv_{oil}} \right) c_{co2} - P_{exchanged} \cdot \frac{C_{kWh,exchanged}}{3600} - \frac{P_t c_{oil}}{\dot{\eta}_t lhv_{oil}} \right]}{P_e} \cdot 3600$

C_{oil}: conventional fuel cost

$C_{kWh,exchanged}$: kWh average cost exchanged with grid

C_{co2}: CO2 mass unit cost