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Optimal Management of Power Systems

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1. Introduction

The increasing energy demand along with the growing concern for environmental issues make energy saving one of the main tasks of present times and it is likely to become even more important in the next decades, as the economic growth is being pursued in developing countries, as China, India and Brazil.

As a consequence, researchers, industries and politicians are required to make significant efforts in this field. More and more stringent regulations on pollution and CO_2 emissions have been issued, which means limiting energy consumption. However, even if policy is an important tool, it cannot be the only one and it is necessary to spread the knowledge on energy systems, energy saving options and energy use rationalisation (Lopes et al., 2005). This is a prerequisite to make right choices for a more efficient use of energy, even if these choices are not mandatory from a “legal” point of view.

Being obvious that this knowledge should be transferred to all the population layers, it is important that the main energy users, as industry, realize that energy is not merely an overhead, as part of business maintenance, but actually a raw material resource required to run the business. Energy management programs should, therefore, become an integral part of the corporate strategy, to increase the business’ profitability and competitiveness. Moreover, knocking down energy costs most of the times means reducing demand on the world’s finite energy sources, cutting pollution and creating a healthier working environment.

The main example in this context is Japan, as the Japanese economy is the most energy efficient in the industrialized world and their improvements in energy efficiency enabled the Japanese industry to increase its output of 40% by spending the same energy in 2001 as in 1973 (Van Schijndel., 2002; Kamal, 1997). In general, the application of good energy management practices and energy-efficient equipment allow a readily achievable, cost-effective, 20% reduction in industrial consumption (Smith et al., 2007)

Energy saving can be realised through different actions on both the utilisation and the production sides (Agency for Natural Resources and Energy, 2004; Meier, 1997). However, it is really a complex task, as many factors influence energy usage, conversion and consumption and these factors are strictly connected to each other. For example, when evaluating an action on energy consumption/conversion, one should take care of the interactions, as one measure influences the saving effect of the other measures. Accordingly that the single contributions to energy saving cannot be simply summed up because of overlapping effects. On the other hand, the combined effect can be higher than the sum of the separate effects as well. Furthermore, it is worth of noting that energy saving represents energy that is not used and, therefore, it cannot be directly measured (except in some cases as, for example, straightforward energy conversion processes).

Therefore, it is necessary to develop and apply new methodologies for total energy management in buildings and industrial plants (Cesarotti et al., 2007, Andreassi et al., 2009).

In this scenario, the installation of energy systems (characterized by multiple energy supplies and energy conversion equipments to meet energy demands) in industrial plants has become increasingly popular in recent years (i.e. combined heat and power – CHP, renewable energy systems) and their proper management becomes crucial to reduce energy costs and environmental impact.

Usually, in fact, the small power plants dedicated to buildings or power plants (nominal power ranging from some hundreds of kWs to 10 MW) are operated simply switching on and off the machines for long time intervals (i.e. night and day, winter and summer). However, the machines typically used in these systems have small thermal inertia, thus allowing quick load variation, and may be operated under partial load.

In most cases operating decisions are made by a control room dispatcher on the basis of empirical data, machine efficiency calculations and/or trial errors. Obviously, this approach cannot keep into proper account all the huge number of variables (and their interaction) affecting the energetic and economic results that may be achieved. In fact, these combined cooling, heating and power systems meet the electricity demand by running the generators and by purchasing electricity from an outside electric power company. The exhaust heat recovered from the thermal engines is reused to handle the heating load which is supplemented by boilers. Analogously, cooling load could be met by recovering heat to power absorption chiller system so providing all or a portion of the cooling load. Any other request of cooling load can be satisfied with an electric power compressor driven air conditioning system. Of course, the main objective is to achieve for each hour the most profitable operation strategy, maximizing the profitability, covering the energy demand and obtaining savings in terms of primary energy and emissions. It becomes obvious that in order to realize the greatest cost savings a proper optimization has to be performed.

In scientific literature, several criteria for the optimization of combined cooling, heating and power systems in industrial plants are available based on different management hypotheses and objective functions. The goal of the models is to optimize the operation of the energy system to maximize the return on invested capital. Many of these models do account for load operations but use simple linear relationships to describe thermodynamic and heat transfer process that can be inherently non-linear. (Arivalgan et al., 2000) presented a mixed-integer linear programming model to optimize the operation of a paper mill. It was demonstrated that the model provides the methods for determining the optimal strategy that minimizes the overall cost of energy for the process industry. (Von Spakovsky et al.,1995) used a mixed integer linear programming approach which balances the competing costs of operation and minimizes these costs subject to the operational constraints placed on the system. Main issue of the presented model is that it is useful to predict the best operating strategy for any given day. Nevertheless, the model validity was strictly dependent on the linear behavior of the plant components. (Frangopoulos et al., 1996) employed linear programming techniques to develop an optimization procedure of a power plant supported by a thermo-economic analysis of the system. (Puttgen & MacGregor, 1996) and (Valero & Lozano, 1993), illustrate a total revenue maximization performed through linear programming subject to constraints due to conservation of mass, thermal storage restrictions and shiftable loads requirement. (Moslchi et al., 1991) divided the energy system into an electric subsystem and a steam subsystem: in the first one steam turbines generate the electricity necessary to meet the power demand, while the second one consists of boilers which use fuel and water to produce steam for industrial processes. The two subsystems were solved separately with solutions coordinated to achieve optimality of the combined systems. Finally, thermo-economics offer the most comprehensive theoretical approach to energy systems analysis where costs are concerned. It is based on the assumption that exergy is the only rational basis to assign cost. In other terms, the main issue is that costs occur and are directly related to the irreversibility taking place within each component. Accordingly thermo-economics could represent a reliable approach to power plants operation optimisation involving thermodynamic and economical aspects (Tstsaronis & Winhold,1985; Temir & Bilge, 2004; Tstsaronis & Pisa, 1994).

The purpose of this chapter is to highlight the importance of the optimal management of power plants in terms of environmental impact, fuel consumption and energy costs. This is done by presenting and applying a mathematical model to identify the optimal operating conditions of energy conversion equipments (i.e. boilers, air-conditioning systems and refrigerators, thermal engines) (Cardona & Piacentino, 2007; Doering & Lin, 1979; Kong et al., 2009; Marik et al., 2005; Kong et al., 2005). In practice, substantial energy savings and/or environmental benefits could be obtained without any action on the power plant components.

2. Main philosophy

The power plant serving an industrial or civil facility is a complex system made up of different components (i.e. primary movers, boilers, refrigerators etc.) that has to satisfy the energy requirements in terms of heat, electricity and cooling. The effectiveness of a power plant is measured through the overall efficiency, which is the ratio between the obtained usable energy (i.e. electrical and thermal energy, cooling energy) and the spent primary energy (i.e. fuel). The difference between spent and useful energy represents waste energy.

The efficiency of a power system is a combination of the components efficiency, defined as the ratio between output and input energy. The maximisation of a power plant efficiency can be, therefore, performed mainly in two ways:

- substituting existing components with higher efficient ones;
- running components as much efficiently as possible.

The first item is related to the existence of different ways to convert primary energy to useful energy and thus different machines and power systems in general, as reciprocating engines, gas turbines, fuel cells and so on up to renewable energy systems which, in principle, convert free available energy to useful one.

The second one is indeed related to the dependence of energy converters efficiency on several parameters, and, therefore, on the instantaneous efficiency of each component of a power plant varies with time. As these efficiency variations may be significant and the energy demand could be satisfied with several power plant operating configurations (i.e. heat from a boiler or a cogenerator), the optimal management of a power plant is as much important as the use of efficient component, with the certain advantage of requiring limited investments.

Next we have to consider that the power produced by the energy system may be not entirely used in the structure that serves, as the electric power may be imported/exported to a utility grid. This means that the electric network acts as an energy storage system that gives and absorbs energy at different costs, defined by the electricity rate. Therefore energetic and economic optimisation do not in general coincide and the concept of power plant optimal management needs to be extended to reducing costs and not (only) primary energy consumption (i.e. maximum efficiency).

This complicates the analysis, as costs are not proportional to the energy content of a certain energy carrier (i.e. methane, gasoline, electricity etc.) and other factors need to be assessed and optimised, as the contract with the electric company. On the other hand, this makes an optimal management strategy much more attractive, as costs can be reduced (or profits can be increased) up to 10% passing from standard to optimal management.

The meaning of optimal management of a power plant is setting the power plant components operating conditions in order to satisfy the energy demand while minimising or maximising a certain objective function (i.e. energy costs/profit, pollutant emissions, fuel consumption, carbon dioxide emissions etc.). This can be done at different detail levels. In the following a simple but sufficiently accurate methodology is proposed.

Before giving the details of the proposed methodology, it is important to highlight that this chapter discusses the opportunities given by running a power system efficiently, but it presupposes that a regular maintenance of the power plant components and the prompt repair of defects are performed. Maintenance is, in fact, one of the most cost-effective methods for avoiding energy waste, as energy losses from poorly maintained or antiquated systems are often considerable. In particular, modern power systems feature sophisticated components that require regular ongoing inspections, measurements and repair for peak operating efficiency.

3. Mathematical model

The system representation can be achieved through a mathematical model which emulates the energy/mass balances existing between the power plant and the served facility. The model allows matching the industrial plant energy demands (electricity, hot water, cold, etc.) through an analysis of the system performance characteristics, taking into account the main subsystems integration issues, their operation requirements and their economic viability.

In this chapter the following equipments are investigated:

- gas engines
- gas steam boilers
- hot water boilers
- mechanical chillers
- absorption chillers

being understood that any other energy converter may be included in the proposed method. In particular, also renewable energy systems may be included in this analysis. In fact, it is true that in the case of wind or solar power generation, the main goal is to produce as much energy from the system as possible to recover the installation cost, but this electrical energy production affects the behavior of the whole energy system. For example, if a wind turbine is producing the electrical power needed by the industrial plant, it may be convenient to reduce the cogenerator load and increase the heat production in the boilers.

As the present approach is devoted to optimal management of the power plant, which is to say those equipment operating conditions (i.e. set-points) that minimize a prescribed cost function, it is not necessary to go into the detail of the equipments behavior. Therefore, all the equipments in the power plant are considered as energy converters, characterized by inputs and outputs and modelled as black-boxes. The outputs depend on the component load or setpoint. It is worth of noting that, although the output could be more than one, as in the case of a gas engine cogenerator (electricity and hot water for example), each equipment is usually defined by only one input (fuel or electric energy).

Conservation equations are considered to solve each subsystem with a quasi-steady approach (i.e. the variables are considered constant between two time steps).

Before starting the description of the numerical model equations, it is essential to introduce the feature of the variables involved in the mathematical representation.

3.1 Input and the output variables

Input variables are subdivided into two main classes, as proposed in (van Schijndel, 2002): controllable and non-controllable variables.

The non-controllable inputs are those related to the energy requirements (i.e. dependent on the industrial plant production plan or the building operation), as, at each time step, the power plant has to supply the “non controllable” energy demand.

The energetic non-controllable inputs are: the cooling demand ($\dot{Q}_{CD}$), the low temperature heat demand ($\dot{Q}_{HwD}$), the high temperature heat demand (steam) ($\dot{Q}_{SD}$) and the electricity demand (P_{ElD}).

The economic non-controllable inputs are the fuel cost (c_f) and the electricity cost. Considering that electricity can be purchased by or sold to the public network, as the power plant electricity output may be higher or lower than the electric demand, the energy costs in sale (s_{El}) and in purchase (c_{El}) are considered. There are two important factors affecting the economic inputs that need to be assessed:

- as different electricity rates are available in the market, and the power plant operation affects the electricity demand from the net, the present methodology may be efficiently combined to a tariff analysis and contract renewal process;
- there may be other terms that affect the energy cost and price due to public incentives, as it happens for renewable energy and high efficiency cogeneration in Europe.

The controllable inputs are the power plant component operating conditions, here uniquely determined by set points varying from 0 (representing switching off) to 1 (representing maximum load).

The total cost (TC), the electricity cost and consumption ($\mathrm{ElC}, \mathrm{P}_{\mathrm{ElBal}}$), the fuel cost and consumption ($\mathrm{FC},\ \dot{\mathrm{m}}_{\mathrm{Tf}}$) are the model outputs. The optimisation procedure is performed on one or a combination of the above outputs.

3.2 The objective function

Simulations are performed pursuing the goal of optimising the equipment operation, in order to satisfy specified criterion. Currently, the following three optimization criteria are the most common:

- minimum cost of operation
- minimum fuel consumption
- minimum pollutant emissions (CO, NO_x,SO_x, Soot, CO_2)

For the last strategy different weights of the different pollutant emissions may be applied. In the present work, we have assumed that they are proportionally weighted with the Italian legislation maximum limits, as reported in section 3.8.

3.3 Modeling the power plant components

The mathematical representation of every subsystem is summarised in Table 1. Each equation is representative of the energy transformations taking place into the correspondent equipment between input and output. Efficiencies forming equations are set point dependent, according to the manufacturer specifications. In fact, the efficiency under nominal operating condition is always available and very often efficiency values at other loads are also known. It is important to keep in mind that efficiency can be limited by mechanical, chemical, or other physical parameters, or by the age and design of equipment. Therefore, deviations from producer efficiency may exist and should be taken into account.
Then, the efficiency (η) of each equipment could be represented by a polynomial function as it follows:

$$\eta = \sum \mathrm{a}_{\mathrm{k}} \mathrm{E}^{\mathrm{k}} \tag{1}$$

where E is the primary input energy and a_k is the polynomial coefficient.
Of course, the more are the known load/efficiency points, the more accurate will be the efficiency profile.
As an example, a cogenerator can be represented as a black-box where fuel is converted, through an efficiency function like (1), in electricity, thermal energy (both low and high temperature) and cooling energy, as shown in Figure 1.
In this scenario, the primary energy power equation for the gas engine is

$$\mathrm{P}_{\mathrm{ge}} = \dot{\mathrm{m}} \cdot \mathrm{H}_{\mathrm{i}} \cdot \mathrm{SP}_{\mathrm{ge}} \tag{2}$$

This chemical power is subdivided in electrical and thermal power on the basis of the machine efficiencies (electric efficiency of the gas engine, thermal efficiency of the gas engine for steam production, thermal efficiency of the gas engine for hot water production, thermal efficiency of the gas engine for cold water production). The values of the presented efficiencies can be directly obtained by the engine manufacturer.

Equipment	Chemical power	Electrical power	Hot water power	Steam power	Cold power
Gas engine	$P_{ge} = \dot{m} \cdot H_i \cdot SP_{ge}$	$P_{elge} = P_{ge} \cdot \eta_{elge}$	$\dot{Q}_{Hwge} = P_{ge} \cdot \eta_{Hwge}$	$\dot{Q}_{Sge} = P_{ge} \cdot \eta_{Sge}$	$\dot{Q}_{Cge} = P_{ge} \cdot \eta_{Cge}$
Mechanical chiller					$\dot{Q}_{Cmc} = P_{Elmc} \cdot \eta_{Elmc}$
Absorption chiller					$\dot{Q}_{Cac} = Q_{Hwgeac} \cdot \eta_{Cac}$
Hot water boiler			$\dot{Q}_{Hwb} = \dot{m}_{fHwb} \cdot H_i \cdot \eta_{Hwb}$		
Steam boiler			$\dot{Q}_{Sb} = \dot{m}_{fSb} \cdot H_i \cdot \eta_{Sb}$		

Table 1. Subsystems mathematical characterization

The numerical results discussed in this chapter have been derived following this approach. Nevertheless, one of the main peculiarities of the presented numerical model is the flexibility. Accordingly, it is possible to easily represent the efficiency on the basis of specific driving parameters as, for example, external temperature, maintenance service level, etc. Following a similar scheme, the boilers heat production as hot water is evaluated as

$$\dot{Q}_{Hwb} = \dot{m}_{fHwb} \cdot H_i \cdot \eta_{Hwb} \tag{3}$$

and, as steam as

$$\dot{Q}_{Sb} = \dot{m}_{fSb} \cdot H_i \cdot \eta_{Sb} \tag{4}$$

Once again the boiler efficiencies can be schematized exclusively on the basis of the manufacturer data or this representation can be improved considering specific drivers. Finally, two chillers have been considered: mechanical and electric chillers. In both cases the chiller cold power production is defined on the basis of a chiller efficiency:

$$\dot{Q}_{Cmc} = P_{Elmc} \cdot \eta_{Elmc} \tag{5}$$

$$\dot{Q}_{Cac} = \dot{Q}_{Hwgeac} \cdot \eta_{Cac} \tag{6}$$

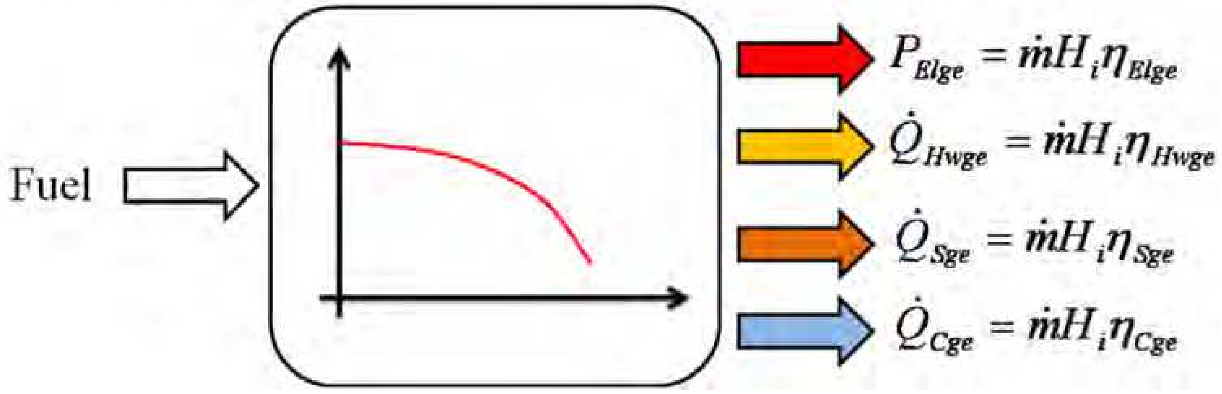

Fig. 1. Representative model of a trigenerator.

3.5 Electricity and thermal balances

The energy model can be divided into two main submodels: the electricity balance and the thermal balance.

Considering the overall power plant and keeping into account the previous sections, the electricity balance can be expressed as follows:

$$P_{ElBal} = P_{Elge} - P_{mc} - P_{ElD} \tag{6}$$

where P_{Elge} is the gas engine electric power output, P_{mc} and P_{ElD} represent the electric power used by the mechanical chiller and the other electric needs of the facility, respectively. Of course, negative values of P_{ElBal} indicate a shortage of electricity.

Once the electricity demand (or the electricity offer to the market) is defined, it is possible to determine the electricity cost, given by:

$$ElC = s_{El} \cdot p\left(P_{ElBal}\right) + c_{El} \cdot n\left(P_{ElBal}\right) \tag{7}$$

where s_{El} and c_{El} represent the cost of electricity in sale and in purchase, respectively, and the function p(x) (n(x)) return the value of the argument x if positive (negative), zero otherwise.

It is worth noting that the electrical efficiencies, which contribute to the definition of the terms in Equation (6), depend on the setpoint according to the manufacture specification. It is therefore clear, and it will be highlighted in the case study section, that a numerical procedure is requested as the main aim of the model is to define the optimal equipments setpoint in order to satisfy a specific request, which depends on the power outputs that, in turn, depend on the setpoint reliant efficiencies.

Electric energy is univocally defined, whereas characterizing thermal energy needs one more specification. Operating temperature must be issued to define the available thermal energy potential. Hence, in principle, infinite thermal balances would be possible.

Three balances have been distinguished in this paper: a hot water balance (T = 80°C), a steam balance (12 bars saturated steam) and a cooling balance (T = -5°C).

To evaluate the supplied fuel to the hot water boiler, a hot water balance can be written as the difference between the cogenerator hot water heat power, $\dot{Q}_{Hwge}$, and the plant hot water power demand, $\dot{Q}_{HwD}$:

$$\dot{Q}_{HwBal} = \dot{Q}_{Hwge} - \dot{Q}_{HwD} \tag{8}$$

A negative value of the balance (i.e. the hot water demand exceeds the cogenerative hot water), implies the hot water boiler usage.

The switching of the absorption chiller depends on the thermal balance (8): if positive it is possible to turn on the absorption chiller, defining the following function:

$$SW_{ac} = p\left(\text{sign}\left(\dot{Q}_{HwBal}\right)\right) \tag{9}$$

The used heat from the CHP systems to the absorption chiller can be calculated as:

$$\dot{Q}_{Hwac} = SW_{ac} \cdot \left(\dot{Q}_{HwBal} - p\left(\dot{Q}_{HwBal} - \dot{Q}_{acmax}\right)\right) \tag{10}$$

where $\dot{Q}_{acmax}$ is the maximum thermal power required by the absorption chiller. The heat demand and the gas supply of hot water boilers are then given by the following equations:

$$\dot{Q}_{Hwb} = -n\left(\dot{Q}_{HwBal}\right) \tag{11}$$

$$\dot{m}_{fHwb} = \frac{\dot{Q}_{Hwb}}{\eta_{Hwb} \times H_i} \tag{12}$$

where ρ and H_i are the density and the lower heating value of the fuel and η_{Hwb} is the hot water boiler efficiency. Analogously, the heat balance, the demand and the gas supply of steam boilers are evaluated as follows:

$$\dot{Q}_{SBal} = \dot{Q}_{Sge} - \dot{Q}_{SD} \tag{13}$$

$$\dot{Q}_{Sb} = -n\left(\dot{Q}_{SBal}\right) \tag{14}$$

$$\dot{m}_{fSb} = \frac{\dot{Q}_{Sb}}{\eta_{Sb} \times H_i} \tag{15}$$

where η_{Sb} is the steam boiler efficiency.

Finally, indicating with cop_{mc}, SP_{mc} and $\dot{Q}_{Cmc}$ the coefficient of performance, the set point and the cold power production of the mechanical chiller respectively, the cold balance and the electricity absorbed by the mechanical chiller are calculated with the following relationships:

$$\dot{Q}_{CBal} = \dot{Q}_{Cmc} + \dot{Q}_{Cac} - \dot{Q}_{CD} \tag{16}$$

$$P_{mc} = \frac{\dot{Q}_{Cmc}}{cop_{mc} \cdot SP_{mc}} \tag{17}$$

3.7 Pollutant emissions

The following pollutant emissions are considered: nitrogen oxides NO_x carbon monoxide CO, sulphur oxides SO_x , carbon dioxide, CO_2 and particulate, Soot.

Being the total mass flow rate used in the power plant given by the sum of the boilers ($\dot{m}_{bf}$) and the gas engine ($\dot{m}_{gef}$) fuel consumption, under the hypothesis that a complete oxidation occurs, the fuel mass balance reads as follows:

$$\dot{m}_{Tf} = \dot{m}_{bf} + \dot{m}_{gef} \tag{18}$$

The SO_x and CO_2 mass flow rates are calculated as a percentage of the mass concentration of carbon, $[C]_m$, and sulphur, $[S]_m$, in the fuel supplied by the energy converters:

$$\dot{m}_{CO_2} = \frac{44}{12} \cdot [C]_m \cdot \dot{m}_{Tf} \tag{19}$$

$$\dot{m}_{SO_x} = \frac{64}{32} \cdot [S]_m \cdot \dot{m}_{Tf} \tag{20}$$

It is worth to note that the result of Equation (15) is only a first tentative value, as the CO_2 mass flow rate will be corrected after having evaluated the CO mass flow rate.

The other pollutant emissions (NO_x and CO) have been calculated on the basis of the equipment experimental emission data, usually given as a function of the load fraction. The pollutant emission mass flow rates for a boiler and gas engine are shown in Figures 2 and 3, respectively.

Accordingly, from a general point of view, CO and NO_x emissions are evaluated as a function of the equipment set point SP:

$$\dot{m}_{CO/NO_x} = f(SP) \tag{21}$$

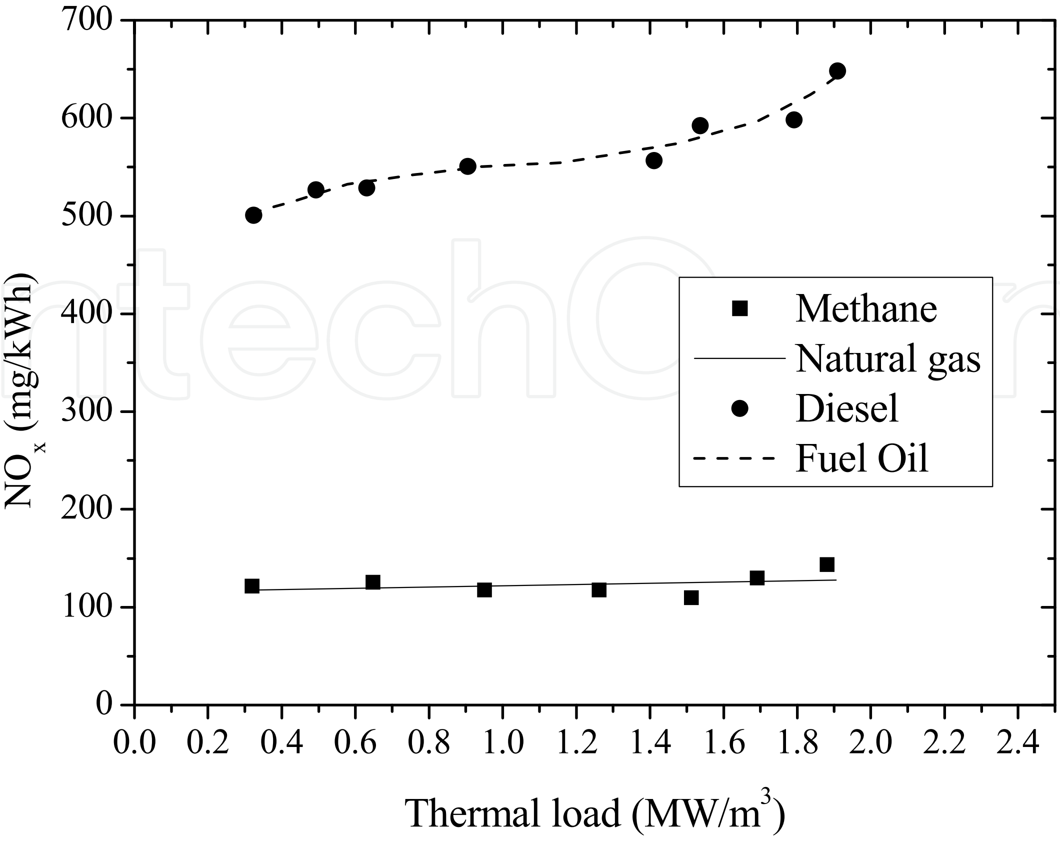

Fig. 2. NOx thermal load influence for the boilers.

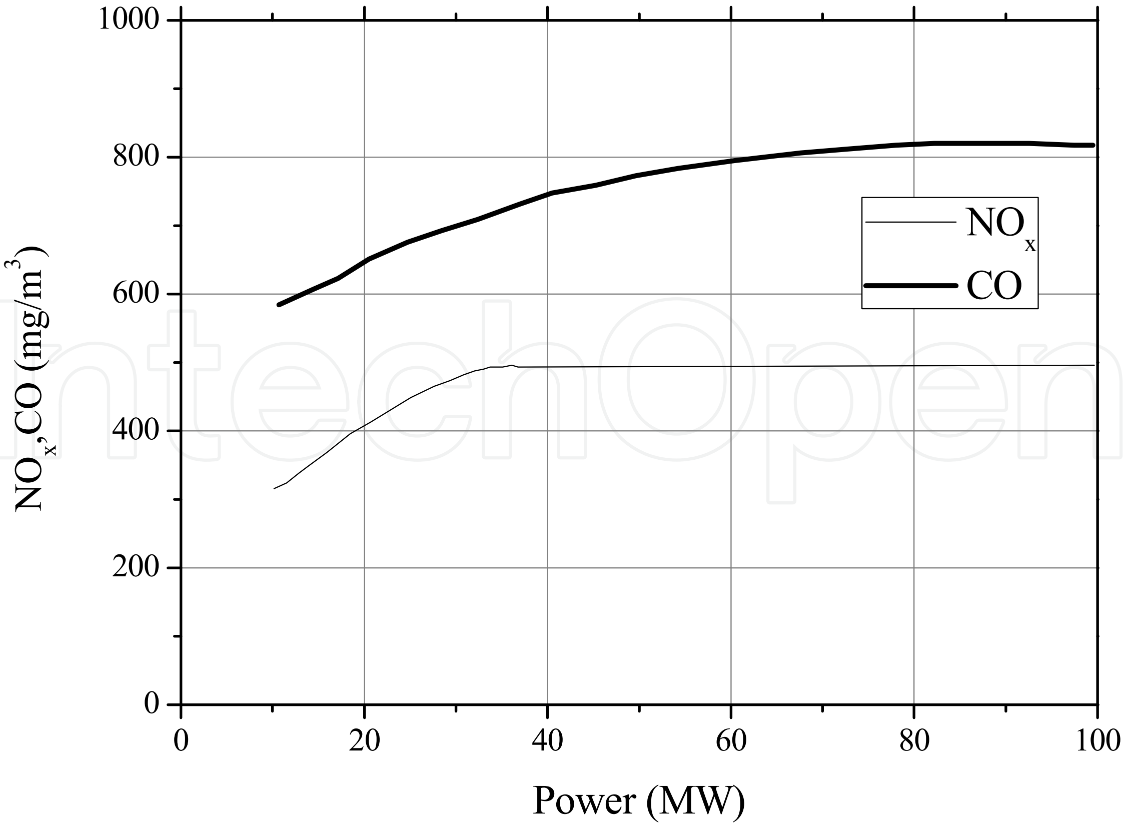

Fig. 3. NOx and CO load influence for the internal combustion engine.

It must be highlighted that part of the consumed electricity could be purchased from the public network. Therefore, to minimise the pollution of the power plant on a fair basis, the emissions deriving from the production of the electric energy drawn from the public network must be estimated and taken into account. For this reason, we have introduced a polluting factor $\mathrm{pf}_{\mathrm{mix}}$ (expressed in kg/kWhe) depending on the mix of the different pollutant emissions (CO, NOx, Soot, SOx) of the national power plants connected to the network:

$$pf_{mix} = kWh_e\left(0.021 \cdot pf_{CO} + 0.418 \cdot pf_{NOx} + 0.296 \cdot pf_{soot} + 0.265 \cdot pf_{SOx}\right) \tag{22}$$

The Italian polluting factors are reported in Table 2 (from ENEL s.p.a.). The coefficients multiplying each pf factor have been chosen on the basis of the current Italian environment limitations (Italian Ministry for the Environment, 2002).

pfCO	pfNOx	pfCO2	pfSOx
0.032	0.6	0.22	0.9

Table 2. 2004 italian pollutant emission factor (kg/kWh)

A similar factor exists also for carbon dioxide (i.e. related to the average electrical efficiency of the national power plants connected to the network):

$$\dot{\mathrm{m}}_{\mathrm{CO}_2} = \mathrm{pf}_{\mathrm{CO}_2} \cdot \mathrm{kWh}_{\mathrm{e}} \tag{23}$$

The carbon dioxide polluting factor, $\mathrm{pf}_{\mathrm{CO}_2}$, has been set to 0.531 $\frac{kg_{CO_2}}{kWh_e}$ according to ENEL s.p.a. data.

3.8 Economic output

The economical optimisation is performed maximising the total cost:

$$\mathrm{TC} = \mathrm{ElC} - \mathrm{FC} \tag{24}$$

where ElC is the electricity cost and FC represents the total fuel cost:

$$\mathrm{FC} = \mathrm{c}_{\mathrm{bf}} \cdot \mathrm{m}_{\mathrm{bf}} + \mathrm{c}_{\mathrm{gef}} \cdot \mathrm{m}_{\mathrm{gef}} \tag{25}$$

where c_{bf} and $\mathrm{c}_{\mathrm{gef}}$ represent the boiler and the engine fuel cost, respectively. It is important to note that, even if the boilers and the internal combustion engines are both fed by natural gas, the values of c_{bf} and $\mathrm{c}_{\mathrm{gef}}$ may be different (i.e. different taxes are applied if the same fuel is used for heat or electricity production). Actually, Current Italian Legislation yields a 0.25 m3/kWh of gas used in CHP defiscalisation (40 %) with respect to standard boilers (this is related to the incentive pay to improve final energy usage).

3.9 Time scale

Even if any time step may be in principle applied to the developed numerical model, the minimum time-step is defined by the time interval between the specific data available by the user on the energy loads.

The energy demand is the time integral calculation of the instantaneous power supplied by the power plant. It can be represented by a continuous function, as shown in Figure 4.

In principle, to represent the energy utilisation curve we should need an infinite number of data. In practice, the available data (i.e. energy consumption and production data) in a plant are far from being instantaneous. Moreover, such a precise data could be even useless due to the method approximations and the related foresight uncertainty.

Performing the optimisation of an energy system management requires a correct time step choice, which must be a right compromise among various effects.

For example, a small time steps guarantee accuracy, but the resulting management criterion may be applicable with difficulty, as the equipment set point adjustment could be inconsistent with the equipment specifications, both in terms of availability of an automated control system or in terms of component thermal inertia (circles in Figure 4). Moreover, the effort required to frequently change the components set point may not be justified by the effective advantage in terms of energy/money saving. It is worth noticing, in fact, that the convenience of turning on or off a thermal machine (i.e. internal combustion engine), depends on the price of electricity, and the time scale of electricity price variation are usually of the order of some hours (i.e. 4, 6, 12 hours). An example of electricity rate is given in the next section.

In this paper, four different time steps have been used, a month, half a day, four hours and one hour in order to highlight the importance of the parameter “time step” in the energy system management.

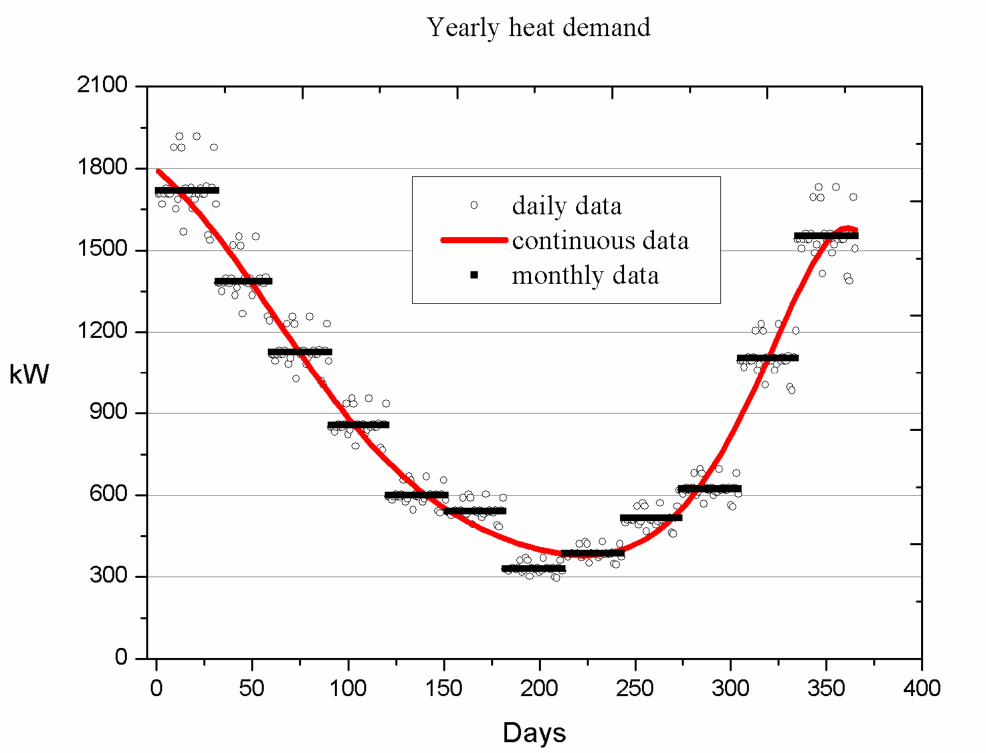

Fig. 4. Yearly thermal demand.

4. Case study

A pharmaceutical industrial plant has been selected as the case study for the present optimization procedure. The power plant consists of:

1 natural gas internal combustion engine
1 steam boiler
1 hot water boiler
1 mechanical chiller
2 absorption chillers

The main characteristics of each component are summarized in Table 3. Energy flows and component interconnections are reported in Figure 5.

EQUIPMENT	Producer	Output	Efficiency
Gas engine	CAT	2000 kWe	0.37
Compression chiller	YORK	4200 kW	3.9
Absorption chillers	YAZAKI	500 kW	0.72
Hot water boiler	RIELLO	2500 kW	0.85
Steam boiler	RIELLO	3200 kW	0.84

Table 3. Equipment specifications

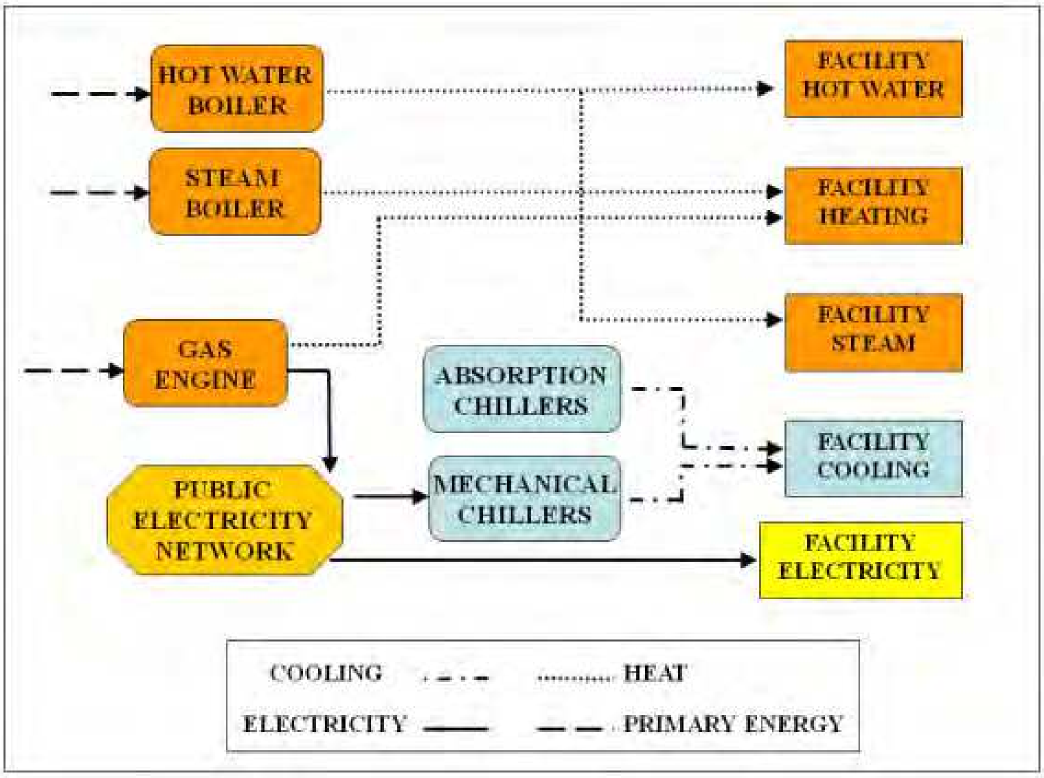

Fig. 5. Power plant energy flows and cooling installation.

The installation is designed for producing domestic hot water and heating (2.5 MW), steam (3.2 MW), cooling (4.3 MW) and electricity (1.2 MW).

The economical results and fuel usage registered in 2005, are used to validate the proposed model. In the standard operation of the power plant, the internal combustion engine is on at full power (set point equal to 1) during the day (7 am – 8 pm) and it is turned-off during the night (8 pm – 7 am). The switching on of the boilers is determined by the heat balance (i.e. heat demand minus the heat eventually available from the thermal engines). The chillers are turned on in function of the cold demand giving higher priority to the absorption chillers if there's heat available from the thermal engines (i.e. summer operation).

The operating range (set point from 0 to 1) of the machines have been discretised through steps of 0.2, being understood that the minimum set point is fixed by the manufacturer or by excessive efficiency degradation (i.e. 40% of full load for the thermal engines).

An important element for the economical optimisation is the electricity rate. In the present case, the electricity rate of the industrial plant is divided into three time bands, as shown in Table 5 (the price includes fixed contributions). Table 4 shows the year cost and consumptions summary, compared with the simulation results. A mean difference of about 2% of reported values is globally appreciable.

Year	2005	simulation	% error
Total cost (k€)	2182	2132	-2.4
Gas usage engine (m3)	1306734	1281906	-1.9
Gas usage boilers (m3)	2334173	2285155	-2.2
Public electricity cost (k€)	984	964	-2.1

Table 4. Energy aspects of the power plant

Time Bands	Price (c€/kWh)
Peak hours	14.59
Full hours	12.98
Empty hours	8.68

Table 5. Electricity rate

5. Results and discussion

The numerical method capabilities have been firstly evaluated performing three different simulations considering the same time scale and different optimisation criteria (minimum cost of operation, minimum consumption of fuel and minimum polluting emissions).

Finally, in order to highlight the numerical results dependence on the available data time scale, four simulations have been performed considering the same optimisation criterion with different time scales.

5.1 Optimisation criterion effect

The following three different optimisation strategies have been considered:

Strategy #1: minimise the total operation cost
Strategy #2: minimise fuel consumption
Strategy #3: minimise polluting emissions

Each simulations has been performed using a time step of 4 hours. Table 6 compares the simulation results for the different optimization criterion.

	Strat. # 1	Strat.# 2	Strat.# 3
Total cost (k€)	1947	2094	2040
Engine fuel consumption (m3)	3405888	3167942	3283027
Boilers fuel consumptions (m3)	291359	375772	324488
Electricity cost (k€)	850	1022	956
CO2 emissions (kg)	14434458	14130819	14299282

Table 6. Four hours time step results

It is immediately detectable that in every simulation, independently from the optimization criterion, the total cost is lower than 2005, thus demonstrating that the previous standard operation was far from being the optimal one, also from an economical point of view. These results also confirm that, often, fuel consumption (i.e. CO_2 emissions) or pollutant emissions reduction, may also yield an economical advantage.

Adopting strategy #1, optimising the total cost, we could save more than the 11% of the original cost. Such an economic saving is obtainable without any installation improving (and then without any additional investment), but only with an optimal management of the power plant components. The operating conditions of the power plant components are reported in Figure 6 and Figure 7. The first graph shows the equipment utilisation factor in function of the set point, thus indicating if the components size have been properly chosen. The second graph, that shows the equipment utilisation yearly distribution, demonstrates if the equipment is characterized by a seasonal behaviour, or if it works almost constantly during the year.

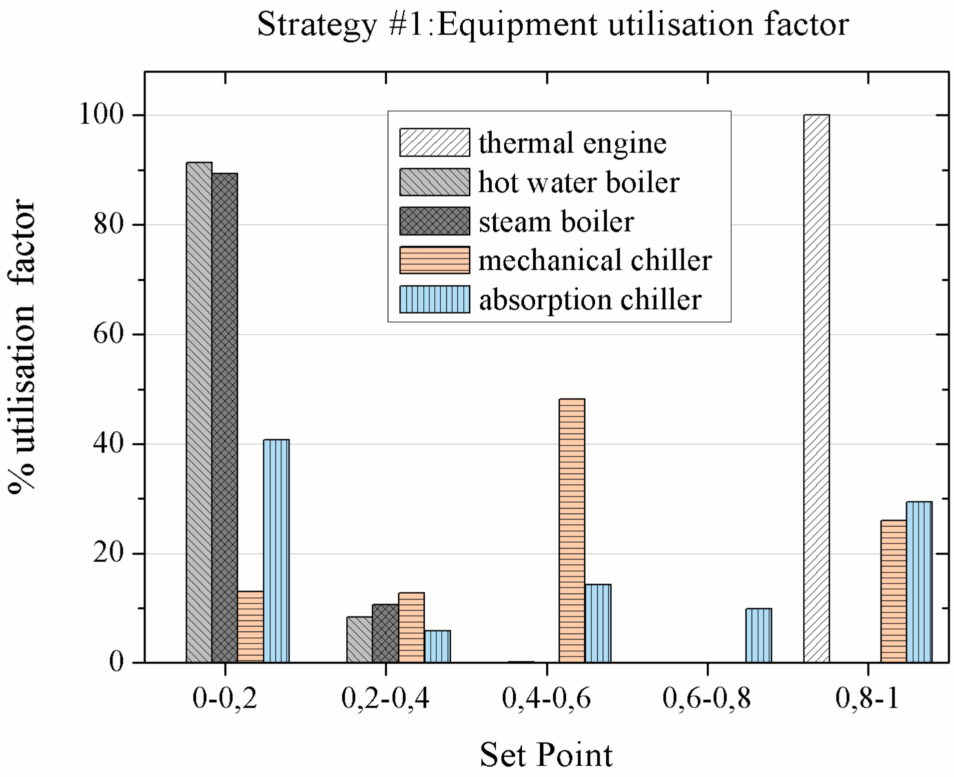

Fig. 6. Strategy #1: equipment utilisation factor.

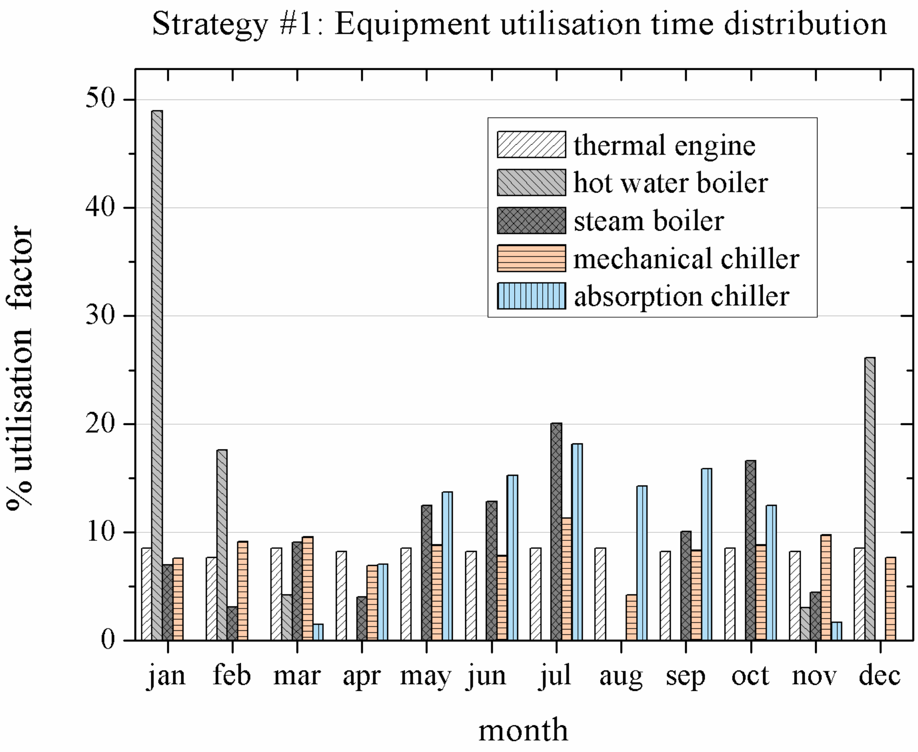

Fig. 7. Strategy #1: equipment utilisation time distribution.

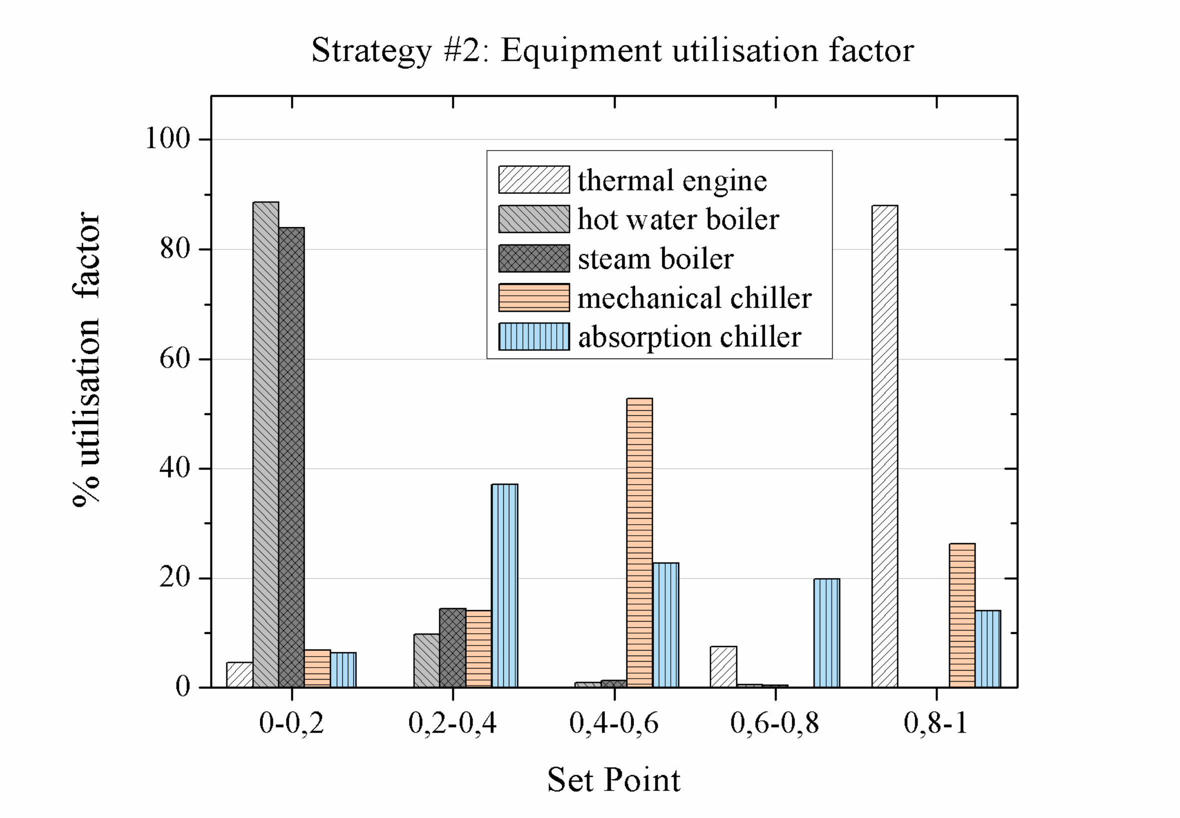

Fig. 8. Strategy #2: equipment utilisation factor.

The cogenerative thermal engine operates always under full load and its use is evenly distributed over the year, underlying a correct design sizing. On the other hand, the boilers are clearly over-sized, as they never work over the 40% of their capabilities. This fact can be explained observing that, originally, the power plant didn't include the cogenerator and the boilers had to satisfy the whole thermal demand. Regarding the cold production, chillers utilisation, both mechanical and absorption, is more regular over the year. Absorption chillers are turned on only during the warm months, when the heat demand is lower than the internal combustion engine heat production.

It may appear singular that minimising the fuel consumption (strategy #2) does not yield the economical optimisation. This is related to the fact that the natural gas cost depends on its usage (see eq. 25), and in particular it is reduced for CHP utilisation. Therefore, it may be economically convenient to consume more gas for CHP operation. On the other hand, when the target is the carbon dioxide emissions minimisation, the high efficiency of the boiler together with a low electricity request may lead to a lower thermal engine utilisation. Comparing Figure 6 and Figure 8, in fact, it is possible to notice that strategy #2 requires a greater use of the boiler with respect to strategy #1. In addition, it can be appreciated a more uniform equipment utilisation over the year. Moreover, the economic optimisation leads a reduction of the thermal engine utilisation as the electricity rate is such that in some periods the electricity purchase from the public network is more convenient than the auto-production. The thermal engine is even turned off in August, during the industrial plant summer closure. These results also highlight the significant effects of the electricity and gas rates on the optimal management of the power plant.(Figure 9)

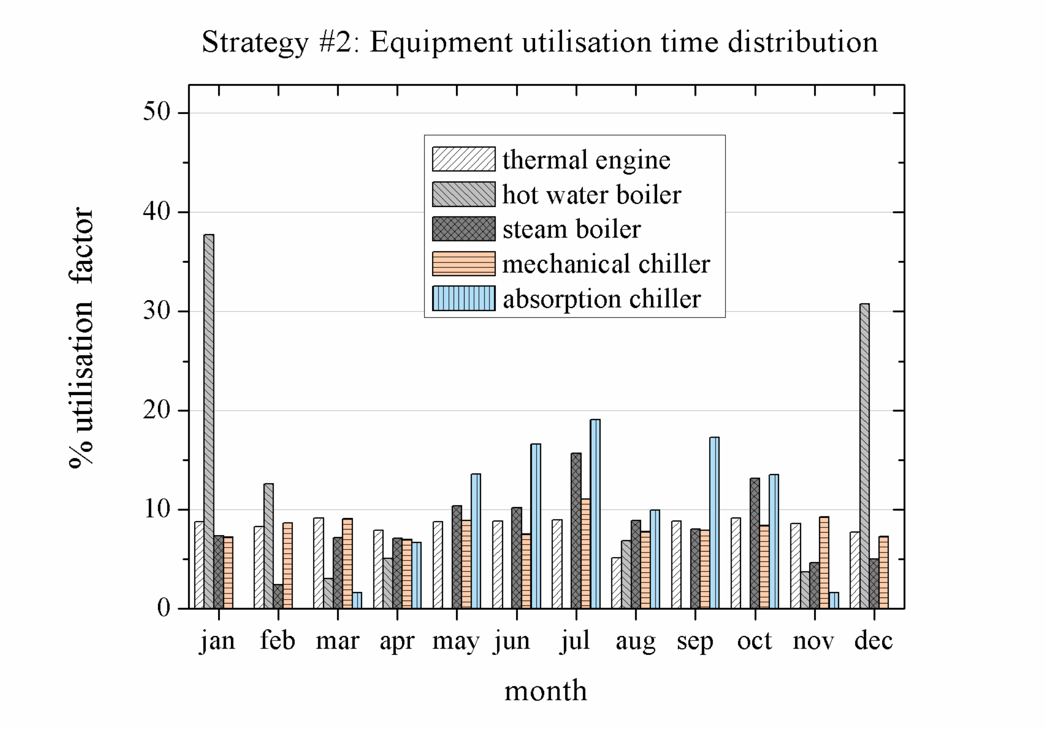

Fig. 9. Strategy #2: equipment utilisation time distribution.

Finally, considering the pollutant emissions as the target function to be minimised, the result is a compromise between the first two strategies, as primarily a function of the environmental impact of the CHP under full load and part load operations. The power plant components operation with strategy #3 is shown in Figure 10 and Figure 11.

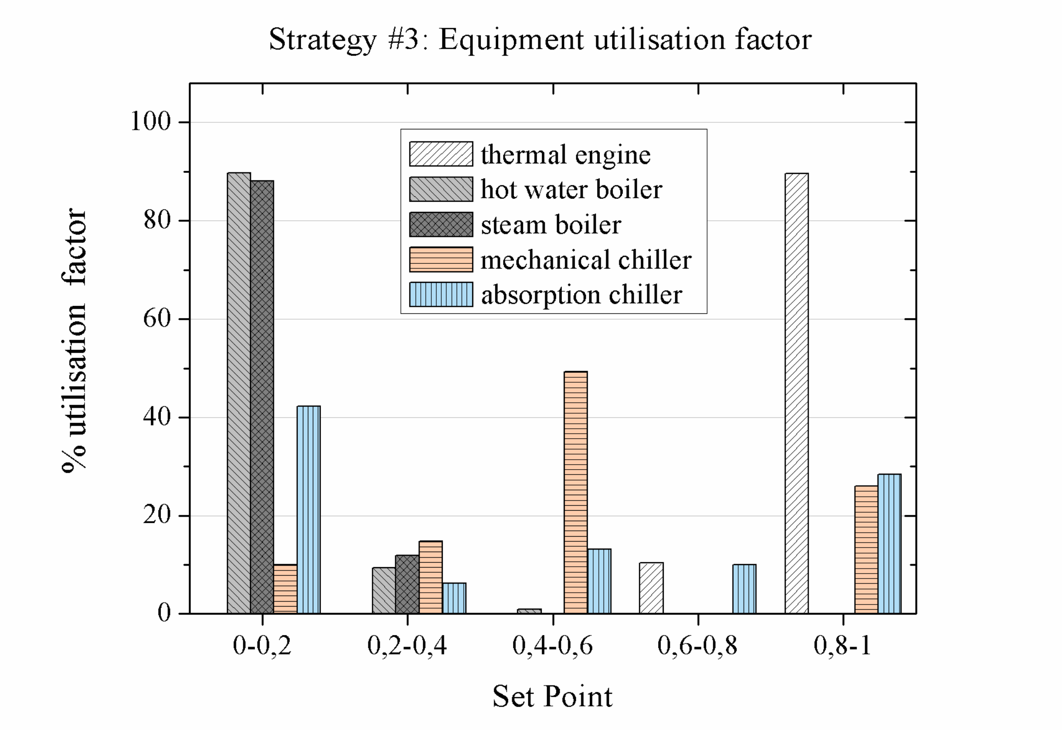

Fig. 10. Strategy #3: equipment utilisation factor.

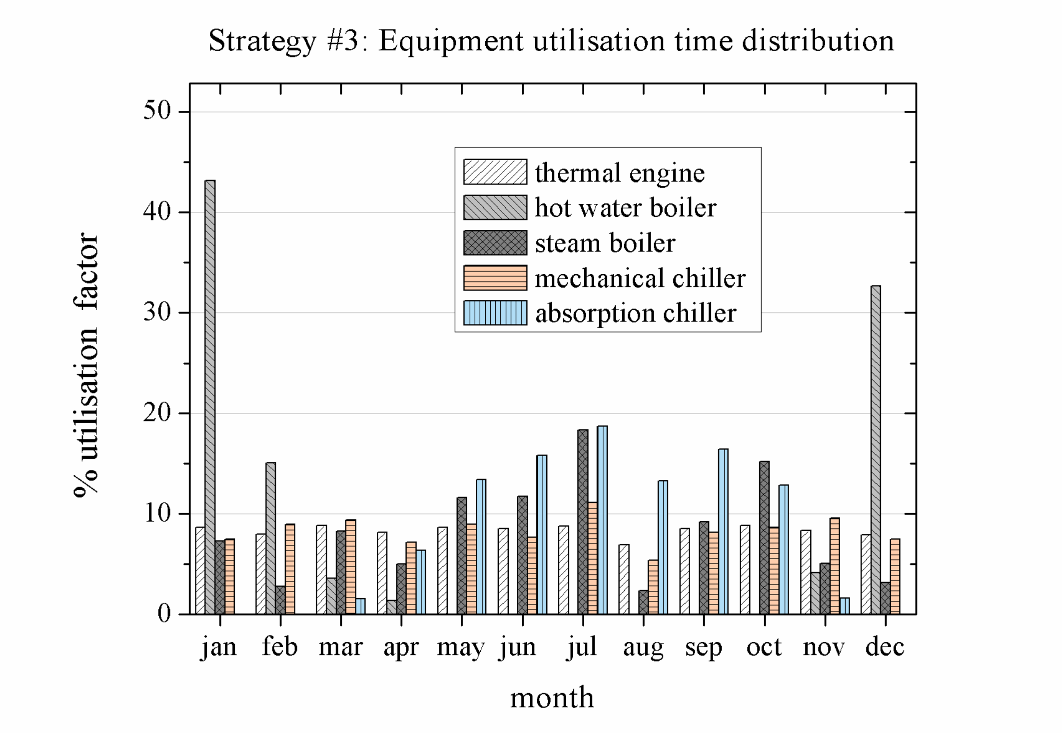

Fig. 11. Strategy #3: equipment utilisation time distribution.

5.1 Time scale effect

In this paragraph, the optimisation strategy #2 results performed on four different time scales are presented. Yearly global results are summarised in Table 7.

	Monthly	12h	4h	1 h
Total cost (k€)	1921	2008	2094	2103
Engine gas usage (m3)	3349123	3195003	3167942	3162428
Boilers gas usage (m3)	274246	352955	375772	390128
Net electricity cost (k€)	844	938	1022	1031
CO2 emissions (kg)	13806563	14086093	14130819	14148523

Table 7. Optimisation results using different time steps

Firstly, as expected, reducing the time-step leads to a fuel consumption reduction, as the optimisation becomes more accurate. Considering that the minimum time-step is determined by the time-scale of energy consumption data, the more frequent is the measurement of fuel and electricity consumption the more accurate is the present methodology.

As the fuel consumption reduces, the total cost rises, such as boilers gas usage, public electricity cost and carbon dioxide emissions. This fact can be easily related to the lower usage of the thermal engine, which means that a greater part of the electric energy demand have to be satisfied by the public network and the boilers have to compensate for the lower heat production by cogeneration. In the matter of CO2, even if boilers efficiencies are higher than the engine one, the emissions are increased because of the fuel mix utilization in public electricity production instead of natural gas only.

As reported in Table 8, mean and variance values of the equipment installation set points decrease as the time step raises, with the exception of the engine mean set point. This is related both to the increased energy demand variation and the higher efficiency of the boilers. Considering the negligible gain (0.003 % as reported in Table 8) observed changing the time step from 4 h to 1h time step and the effort required (both technological and managerial) to make a frequent control of the power plant components, it may be counterproductive to use very small time-steps. It must be also noticed that using a little time step forces a frequent regulation of the equipment set point, thus producing losses that cannot be predicted by the present quasi-steady numerical model. As an example over two weeks, Figure 12 shows how reducing the time step the steam boiler set points vary around its mean value, represented respectively by the bigger time step.

		1 h	4 h	12 h	Month
Thermal engine	mean	0,88	0,93	0,94	0,946
	variance	0,052	0,05	0,04	0,003
Hot water boiler	mean	0,057	0,056	0,053	0,042
	variance	0,016	0,013	0,012	0,006
Steam boiler	mean	0,12	0,12	0,1	0,076
	variance	0,011	0,01	0,009	0,005
Mechanical chiller	mean	0,59	0,57	0,56	0,53
	variance	0,084	0,083	0,081	0,02
Absorption chillers	mean	0,45	0,44	0,41	0,35
	variance	0,155	0,15	0,13	0,09

Table 8. Mean and variance of the equipment installation set points with strategy #2 using different time stepping

Considering the plant regulation point of view, the above results show that with manual power management (which means that the machines are manually regulated and therefore not compatible with small time-steps) it is still possible to achieve impressive results in terms of energy saving. Alternatively, with automatic power management, which theoretically allows a continuous regulation, extra-savings could be obtained.

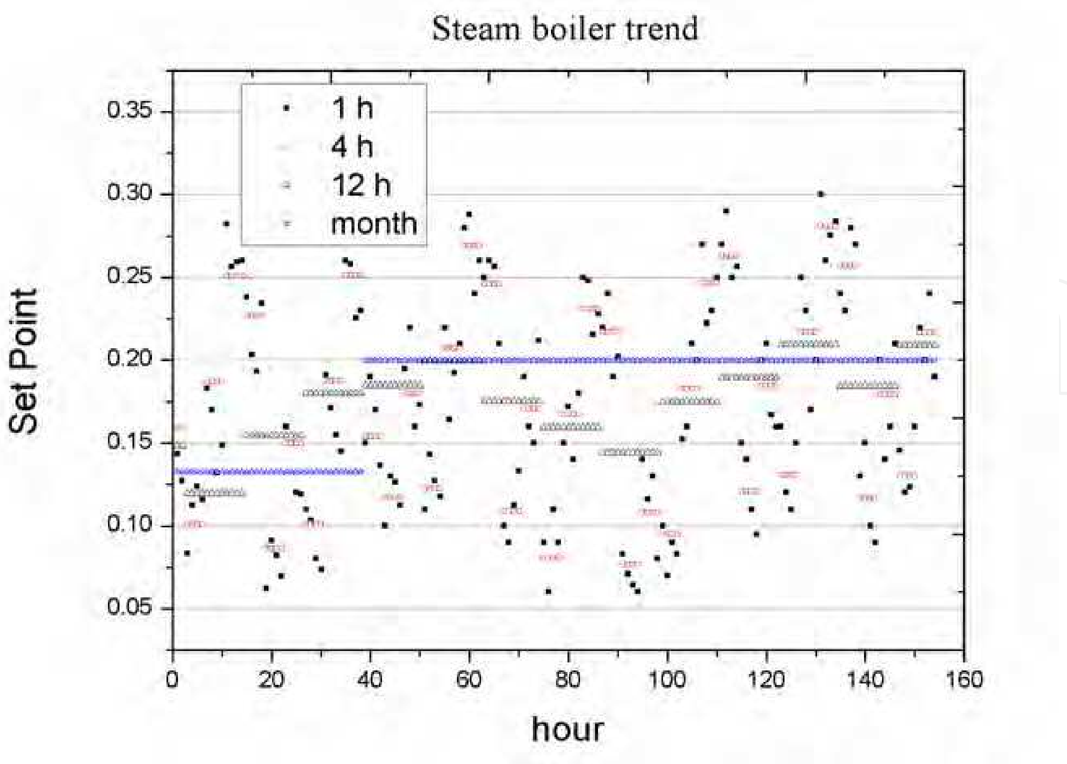

Fig. 12. Two weeks steam boiler set points.

6. Calculating or measuring the energy demand

The facility energy demand, which represent the first of the non-controllable input variables, may be obtained through historical data (i.e. energy bills) or may be directly measured or may result from a combination of the two. The present numerical results clearly highlight that the energy demand data availability is crucial to the success of implementing the proposed methodology, as the time-scale detail on the energy demand data determines the minimum time step between different set points and therefore the effective gain.

It is also important to notice that making the consumption profile on historical data , as done for the present case study, may lead to wrong conclusions and non-economic actions, as energy consumption may significantly vary from year to year, as it is related to several factors as production volume, ambient temperature, daylight length etc.

Therefore, to be effective, the present procedure should be coupled to a real-time energy monitoring system. With modern computers, in fact, the optimisation could be calculated in short times, similar to or smaller than a typical model time-step, thus giving the equipment setpoints “real-time”. Moreover, if the proposed computational procedure is combined to an automatic system to control the equipment set-points, the optimisation could be performed in real-time.

The energy demand from the served facility may be also obtained through another mathematical model, which is in turn built on the basis of historical or measured data. This requires the construction of a consumption model: modeling the industrial plant energy consumption in function of its major affecting factors (i.e. energy drivers), as production volume, temperature, daylight length etc. This model should give the expected consumption in function of time and, again, the time-step should be as small as possible in order to have reliable predictions and to distinguish the plant consumption and the energy drivers variation within the time bands of the energy rate. This could be done by installing a measuring system to record both energy consumption and energy drivers. The meters position within the plant is particularly important in order to correlate the energy consumption to the energy drivers (i.e. different production lines). Therefore, a preliminary analysis based, for example, on the nominal power and the utilization factor of the single machines should be performed in order to build a meters tree.

7. Conclusions

The present chapter discusses the importance of energy systems proper management to reduce energy costs and environmental impact. A numerical model for the optimal management of a power plant in buildings and industrial plants is presented. The model allows evaluating different operating strategies for the power plant components. The different strategies are defined on the basis of a pure economic optimisation (minimisation of total cost) and/or of an energetic optimisation (minimisation of fuel consumption) and/or of an environmental optimisation (minimisation of pollutant emissions). All these strategies have been applied to an energy system serving a pharmaceutical industrial plant demonstrating that, independently from the optimisation criterion, a significant gain can be obtained with respect to the standard operation with every objective function (cost, fuel consumption or pollutant emissions).

Furthermore, given the same optimisation criterion, remarkable differences are observed when varying the time-step, highlighting that the accuracy of the numerical results is strictly dependent on the detail level of the external inputs. In particular, the time-step dependence shows on one hand the importance of continuously monitoring the energy consumption (data available with a high frequency) and on the other hand the uselessness of using very small time scales for the energy system regulation.

The main advantages of the described model are that it is time efficient and its effectiveness is guaranteed whatever is the input data detail. Obviously, the more detailed are the input data, the more accurate are the numerical results. Nevertheless, even using monthly data it has been possible to suggest a cost reducing operating strategy. Moreover, in the presence of an energy consumption monitoring system, the proposed methodology could allow a real-time calculation of the optimal equipment setpoints.

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9. Nomenclature

E	Primary energy	(E)
ElC	Annual electricity cost	(k€)
FC	Annul fuel cost	(k€)
H_i	Lower heating value	(kJ/kg)
P_{ElBal}	Electricity balance	(W)
$P_{E\lg e}$	Gas engine electric power production	(W)
P_{ElD}	Electricity demand	(W)
P_{ge}	Chemical power consumption in the gas engine	(W)
P_{mc}	Mechanical chiller electric power consumption	(W)
$\dot{Q}_{ac\max}$	Absorption chiller (maximum) heat consumption	(W)
$\dot{Q}_{Cac}$	Absorption chiller cold power production	(W)
$\dot{Q}_{CBal}$	Cold balance	(W)
$\dot{Q}_{CD}$	Cold demand	(W)
$\dot{Q}_{Cge}$	Gas engine cold power production	(W)
$\dot{Q}_{Cmc}$	Mechanical chiller cold power production	(W)
$\dot{Q}_{Hwac}$	Heat power from gas engine to absorption chiller	(W)
$\dot{Q}_{HwBal}$	Hot water balance	(W)
$\dot{Q}_{Hwb}$	Boilers heat production as hot water	(W)
$\dot{Q}_{HwD}$	Hot water demand	(W)
$\dot{Q}_{Hwge}$	Gas engine heat production as hot water	(W)
$\dot{Q}_{Sb}$	Boilers heat production as steam	(W)
$\dot{Q}_{SBal}$	Steam balance	(W)
$\dot{Q}_{SD}$	Steam demand	(W)

$\dot{Q}_{Sge}$	Gas engine heat production as steam	(W)
SP_{ge}	Gas engine set point	
SP_{mc}	Mechanical chiller set point	
SW_{ac}	Switch of supply heat of absorption chiller (0 or 1)	
TC	Total annual cost	(k€)
c_{bf}	Boilers fuel cost	(€/kg)
c_{gef}	Gas engine fuel cost	(€/kg)
c_{El}	Cost of electricity	(€/J)
cop_{ac}	Coefficient of performance of the absorption chiller	
cop_{mc}	Coefficient of performance of the mechanical chiller	
m_{bf}	Fuel mass consumption in the boilers	(kg)
m_{gef}	Fuel mass consumption in the gas engine	(kg)
$\dot{m}_{bf}$	Fuel mass flow rate in the boilers	(kg/s)
$\dot{m}_{CO}$	CO mass flow rate	(kg/s)
$\dot{m}_{CO_2}$	CO2 mass flow rate	(kg/s)
$\dot{m}_{fHwb}$	Hot water boiler fuel consumption	(kg/s)
$\dot{m}_{fSb}$	Steam water boiler fuel consumption	(kg/s)
$\dot{m}_{gef}$	Fuel mass flow rate in the gas engine	(kg/s)
$\dot{m}_{NO_x}$	NOx mass flow rate	(kg/s)
$\dot{m}_{SO_x}$	SOx mass flow rate	(kg/s)
$\dot{m}_{Tf}$	Total fuel mass flow rate	(kg/s)
pf_{CO}	CO polluting factor	
pf_{CO_2}	CO2 polluting factor	
pf_{mix}	Global polluting factor	
pf_{NO_x}	NOx polluting factor	
pf_{soot}	Soot polluting factor	
pf_{SO_x}	SOx polluting factor	

Energy Management

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Forecasts point to a huge increase in energy demand over the next 25 years, with a direct and immediate impact on the exhaustion of fossil fuels, the increase in pollution levels and the global warming that will have significant consequences for all sectors of society. Irrespective of the likelihood of these predictions or what researchers in different scientific disciplines may believe or publicly say about how critical the energy situation may be on a world level, it is without doubt one of the great debates that has stirred up public interest in modern times. We should probably already be thinking about the design of a worldwide strategic plan for energy management across the planet. It would include measures to raise awareness, educate the different actors involved, develop policies, provide resources, prioritise actions and establish contingency plans. This process is complex and depends on political, social, economic and technological factors that are hard to take into account simultaneously. Then, before such a plan is formulated, studies such as those described in this book can serve to illustrate what Information and Communication Technologies have to offer in this sphere and, with luck, to create a reference to encourage investigators in the pursuit of new and better solutions.

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