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A Viable Approach to the Optimization of Energy Systems

Alberto Mirandola and Anna Stoppato
University of Padova
Department of Mechanical Engineering,
Via Venezia, 1 35131 Padova, Italy
E-mail: <alberto.mirandola, anna stoppato>@unipd.it

Abstract

A progressive step-by-step approach is suggested to optimize energy conversion plants and systems when many conflicting aspects must be considered and a mathematical description of the problem is very hard and/or can only be performed by means of complex and time-consuming calculations. The procedure can easily be adapted to meet different objectives pursued by analysts, designers, operators, and policy makers. Some examples of the application of this approach to different systems, according to different objectives, are presented in this paper.

Key words: Energy systems, optimization, thermoeconomics

1. Introduction

Why is *optimization* important in the scientific and technological environment? The answer to this question seems to be obvious: to optimize means “to do the best” or, more softly, “to do in a satisfactory way”, provided that all aspects and constraints have been taken into account. But, what does optimization mean when:

- many conflicting aspects must be considered so that different objectives can simultaneously be reached?
- some constraints or parameters cannot be expressed in a mathematical way?
- expertise in different disciplines is requested and must be used interactively?
- Now, supposing that optimization is possible, what analysis and assessment method should be used to solve a problem like this?

Our discussion will be focused on the optimization of energy systems (Bejan et al., 1996; Cialani and Giannantoni, 2000; Frangopulos, 1984). There are different levels of energy systems (Figure 1), each one requiring different optimization strategies and methods:

- Energy conversion machines, i.e. devices which transform the energy content of a fluid stream into mechanical work or vice versa; or transform the chemical energy of a fuel into heat; specific sub-levels can concern topics such as combustion, heat transfer, fluid dynamics, etc.;
- Energy conversion plants, generally consisting of several machines and other components assembled in order to produce a process, with the aim of converting the energy of a source into different useful forms of energy;
- Energy systems, consisting of a group or a network of plants which supply suitable forms of energy to systems of users, working within a defined social, economic and environmental context;
- Wider energy systems, whose borders include the ecological environment or the entire biosphere.

Once a particular level has been chosen, the *objective* of the optimization must be defined and a suitable *method* to find the solution must be selected. Both the former (objective) and the latter (method) depend on the chosen level; generally, the more complex the system is, the more difficult it is to define the objective and select the solution method. Dealing with energy systems, the optimization usually involves energetic (minimize fuel consumption), economic (minimize costs or maximize earnings) and environmental (minimize the impact on the environment) aspects (Tsatsaronis, 1998; Valero, 1998, von Spakovsky and Frangopulos, 1993). According to the analyst’s or the user’s viewpoint (politician, plant designer, plant manager, plant owner), each of them can be more important than the others or different concerns can be considered (e.g., social consequences, acoustic or visual impact).

In the authors' opinion, wide and complex energy systems can hardly be optimized according to the classical meaning of this word, i.e. using a mathematical procedure, which takes all the variables and the constraints into account. In this paper, a progressive improvement approach is proposed and discussed. It starts from a possible solution and arrives as "near" as the analyst requires to the best one, passing through a series of feasible solutions.

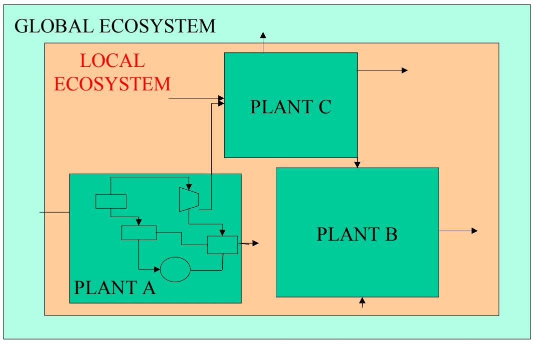

Figure 1. Different levels of energy systems

1.1 First level: optimization of energy conversion machines

The operation of fluid machines and appliances (pumps, turbines, valves, burners, boilers, steam generators, heat exchangers, etc.) can be described by means of the disciplines of fluid dynamics, thermodynamics, combustion, and heat transfer. Their optimization is often performed using efficiency as the objective function and is relatively easy if suitable calculation tools are available. However, *technological constraints* (materials, temperatures, manufacturing processes, etc.) and the *economic parameters* must also be considered, because all of them are crucial to the final decision. The optimization is generally related to the nameplate operation; but, since current operational loads will be variable, knowledge of off-design performance is also required and can be assessed by means of the previous disciplines.

1.2 Second level: optimization of energy conversion plants

Energy conversion plants should supply the requested amount of given forms of energy at the time they are needed by the users. In this case, the search for the "optimum" is more difficult, because different objectives should simultaneously be reached:

- a good overall efficiency is still paramount, of course; but, since efficiency varies versus load, the target is the best average value of efficiency during the plant's lifetime (Lazzaretto et al., 1999); so, an accurate simulation of actual plant operation versus time, taking into account the off-design performance of each device, is needed to choose the most suitable size of the machines and forecast their operational modes; these calculations can be performed by means of effective simulators, where the boundary conditions (environmental parameters, load curves, constraints, etc.) can be introduced; instead of the first-law (energetic) efficiency, the second-law (exergetic) efficiency is more significant in many cases, particularly when different forms of energy have to be cogenerated and/or compared;
- the economic performance of the plant is also an objective; it depends on both the capital cost and the operational cost: the optimum is generally a compromise between these two parameters; it can be calculated, for example, through the Discounted Cash Flow method; but if a more accurate analysis on the cost generation processes is wanted, various thermoeconomic methods can be applied;
- the local environmental performance (impact of the plant on the surrounding area) is another aspect to be considered. In this case the optimal value of the impact would, of course, be zero; but this target means that the plant would not be built. Therefore, acceptable values of emissions must be determined, by cost/benefit analyses or by simply considering that the limits imposed by regulations should not be exceeded. This means that the environmental "optimization" is strictly connected with the economic one within the social-economic context at hand, i.e. within a given kind of society.

1.3 Third level: optimization of energy systems

Energy systems consist of groups or networks of industrial and power plants working within a precise geographical, political, social, and economic context; they interact with all the other systems existing and operating in the same area. So, their problems are similar to the ones described in the preceding section, but the level of complexity is higher: multicriteria analyses must be used to face these problems.

1.4 Fourth level: optimization of wider energy systems, including the biosphere

In this case, the complexity of the analysis is very great. All the previous aspects must be considered, but further analyses are required. For example, referring to the ecological environment (the biosphere), the *global environmental performance* of the system is to be evaluated; according to this viewpoint, the environment is both a *source* (of resources and information) and a *sink*. The results of this analysis can lead to strongly different conclusions with respect to the foregoing approaches.

2. A progressive improvement procedure

Two different ways can be used to optimize plants and systems:

- express all the aspects of the problem in mathematical form and use an optimization tool to get the solution;
- start from a tentative solution and afterwards improve it progressively, by applying the available analysis and assessment methods to their specific fields; in this way the system is "adjusted" and "improved" step by step to get an acceptable final solution which will supply a compromise among different conflicting objectives, according to given priorities. Within each step of the procedure, the basic laws of mechanics, thermodynamics, etc., and proper calculation and simulation tools are employed.

In the authors' opinion, when dealing with complex systems, the former approach is not viable, because too many different parameters and constraints and conflicting targets make the mathematical optimization very difficult or impossible. Moreover, a problem like this does not have "one" solution, but a number of different solutions depending on the stated priorities. So, the most acceptable compromise must be looked for.

As a result of the previous comments, classical "mathematical optimization procedures" are not likely to be applicable to wider energy systems. So, the Energy Research Group[1] at the University of Padova have developed a sequential iterative procedure (Mirandola et al., 2000), whose originality is not the proposal of new methods of analysis but the sequential step-by-step use of different well known theories to improve the quality of an energy system starting from a given initial configuration. So, a progressive improvement is used instead of classical mathematical optimization. Each step of the procedure makes use of some performance indicators by which the assessment of the system according to a certain viewpoint can be obtained. This method, even though it is not able to "optimize" the system according to the classical meaning of this word, can move the analyst towards a particular kind of process as an alternative to another one. In addition, other aspects can eventually be considered: social, political, etc. The decision-maker can also then take these aspects into account; but, of course, they cannot be expressed and manipulated mathematically.

The procedure suggested here is mainly suitable for studying energy conversion plants or systems. A simplified scheme of this procedure is shown in Figure 2a and 2b. In the calculations made, the following methods are used, each one within its specific field of application.

2.1 Energy (First-Law) analysis

After defining a preliminary operational scheme for the process, the principles of mass and energy conservation can be applied to all the streams (of mass and energy), providing a complete picture of all thermodynamic quantities. This "First-Law" analysis is useful as an initial approach to the solution and can enable the designer to obtain a preliminary configuration for the system.

The First Law efficiency η is the most widely used performance indicator and is expressed by

$$\eta = \frac{E_P}{E_F} \tag{1}$$

This efficiency supplies information about the effectiveness of resource exploitation to get the products and can be useful to check the operation of single devices or of the overall plant. However, this parameter is not able to take the "quality" of the energy flows present into account.

2.2 Exergy analysis

Exergy calculations allow different forms of energy to be compared, suggesting that exergy is the "true" thermodynamic value of energy. Improvement in performance can be obtained by reducing the exergy losses, particularly in the subsystems having low exergetic efficiency. Of course, experience is needed to evaluate whether an increase of exergetic efficiency is viable: for example, trying to decrease the exergetic losses of a combustion process is probably useless. The exergy efficiency ηex is used to assess both single devices and plants from an exergetic viewpoint and is expressed by

$$\eta_{ex} = \frac{B_P}{B_F} \tag{2}$$

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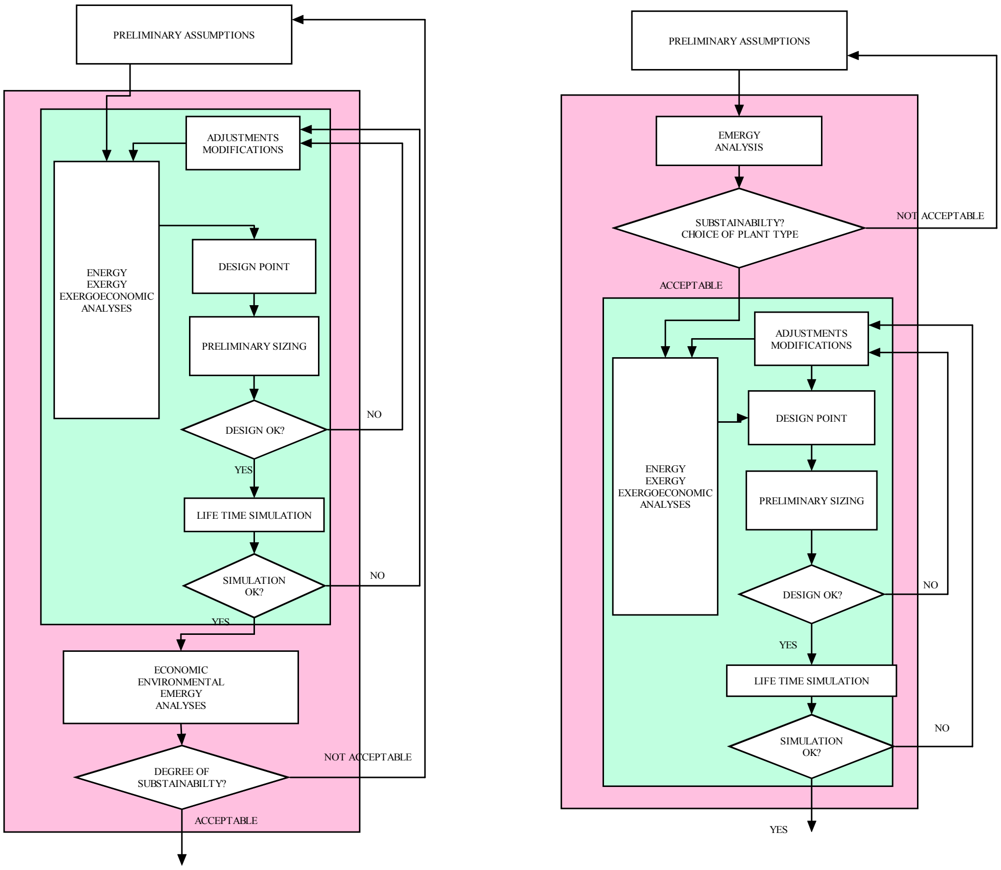
[1] Andrea Lazzaretto, Alarico Macor, Simone Tonon, and the authors of the present paper worked together in suggesting and developing this procedure.



(a) *(b)*

Figure 2. (a) Inside → outside directional procedure, (b) Outside → inside directional procedure

2.3 Thermoeconomic analysis

Thermoeconomic methods (El Sayed and Tribus, 1983; Lozano and Valero, 1993; Tsatsaronis and Winhold, 1985; von Spakovsky and Evans, 1990) are particularly useful to determine the mechanism of exergetic and monetary cost generation in energy conversion processes and give useful information about the most "expensive" plant sub-processes, also suggesting how to improve them.

Two indicators originating from a thermoeconomic analysis are used here. They are useful to compare the behavior of devices of a plant but are not significant in expressing evaluations about plants or wider systems.

The first indicator, D, represents the contribution of each component to the final production cost of the product, i.e.

$$D_i = Z_i + c_{F,i} \cdot I_i \tag{3}$$

where $c_{F,i}$ is the cost of the fuel (input exergy flow) of the i-th component. Note that $\Sigma_i D_i > \Sigma_i Z_i + c_{F,TOT} \cdot \Sigma_i I_i$ because each device is partially responsible for the irreversibilities of all the upstream components, i.e. the amount of irreversibilities (and the related cost) in some component A, can be reduced by improving either the device itself or the downstream devices. For example, if a component B, following A in the flowsheet, is improved, its fuel, supplied by the upstream component A, will decrease, which in turn will lead to a decrease in the irreversibilities in A even though its efficiency has not been improved.

The second indicator is the exergoeconomic factor f (Tsatsaronis and Winhold, 1985), comparing the capital cost of the plant component with that cost associated with the irreversibilities of the process developed by the component itself, i.e.

$$f_i = \frac{Z_i}{Z_i + c_{F,i} \cdot I_i} \tag{4}$$

The range of this indicator is between 0 and 1: If f is close to 0, the cost of irreversibilities is predominant (high value of I, which is the sum of the irreversibilities and the exergy losses related to residue flows); when f is close to 1, the capital cost has greater influence. Generally, in plants running on fossil fuels, a good compro-mise is reached when intermediate values occur.

2.4 Microeconomic evaluations

Economic performance involves many aspects. It indicates how the economic resources required to build and run the plant are exploited by evaluating the profitability of the investment and comparing it with some typical market values of other similar investments.

The production cost of a plant is a simple indicator of the manufacturing efficiency of the process in economic terms. Here, the cost of the product per exergy unit is used for plants and systems and is given by

$$c = \frac{Z + c_F \cdot F}{P} \tag{5}$$

The economic convenience of the plant can be checked by means of two indicators derived from the Discounted Cash Flow method, which usually considers that the construction of a plant requires some time and the associated investment has to be evaluated over the long term. The Internal Rate of Return IRR (equation 6) expresses the value of the discount rate at which the investment involves no economic benefit, while the Profit Index PI (equation 7) links the profit associated with the plant at the end of its economic lifetime (Net Present Worth NPW, i.e. the sum of the discounted cash flows during the economic lifetime of the system) to the investment. Thus,

$$IRR = i : (NPW = 0) \tag{6}$$

$$PI = 1 + \frac{NPW}{Inv} \tag{7}$$

The calculation of PI implies the choice of a proper value for the discount rate i. Conversely, IRR is not influenced by this assumption; and, thus, the sensitivity against market fluctuations is enhanced. Generally, the decision-makers should consider these indicators together, since each one supplies different information.

2.5 Environmental impact assessment (environment as a sink)

Suitable parameters related to the main aspects of pollution in air or water have been assigned, as shown by Equation 8:

$$s_{air},\ s_{water} = \max\left(\frac{S_i}{L_i}\right)$$

$$\left(\begin{array}{l} i = SO_2, NO_x, CO, PM \quad \text{for } s_{air} \\ i = \Delta T, DO, TDS, pH, N, Me \quad \text{for } s_{water} \end{array}\right) \tag{8}$$

The set of polluting substances has been chosen according to the in-force laws and with respect to the peculiarities of energy conversion plants. The value of each emission limit Li has been obtained from the in-force laws as well (EU Council 1988 and 1994, United Nations, 1994). For the air indicator, both the emission levels Si and the emission limits Li have been referred to the exergy of products, taking into account the favorable effect of better energy conversion efficiency. Conversely, water pollution is assessed by considering the level of harmful substances in the water system receiving the discharge flow, since the relation between pollution effects and emission level is very complex.

Anyhow, it should be observed that the influence of each pollutant on the environment is not only related to its own level but also to the interaction among several pollutants, which produces effects that cannot easily be evaluated. That is why the current regulations do not consider these interactions. Other types of environmental impact (ground, biological, health, psychological and sociological) as well as acoustic pollution could be considered in the procedure. At present, they have not been included since they have not been considered as key factors in our case.

2.6 Emergy accounting (environment as a source)

The environmental impact in a more general sense (effect of the emissions on the environment, use of natural resources, etc.) has been qualified by parameters taken from the embodied energy (emergy) analysis. This theory is based on emergy, defined as “the available energy (exergy) of one kind previously required directly or indirectly to make a product or service” (Brown and Ulgiati, 1997; Odum, 1988, 1994 and 1995). The amount of input emergy (expressed as solar emergy) per output energy unit is called transformity (equation 9). The transformity does not account for the nature of the inputs (either renewable or nonrenewable).

An Emergy analysis is helpful in assessing the environmental sustainability of a plant. This is related to both its efficiency in the use of natural resources (renewable and non-renewable) and its level of environmental impact. High sustainability means a capacity for allowing long-term development. In other words, sustainability is a measure of how a system interacts with the environment. The Emergy Sustainability Index ESI is defined by equation (10), where P = product; F = goods, services, etc; R = renewable resources; NR = Non Renewable Resources, i.e.

$$Tr = \frac{Em_{in}}{E} \tag{9}$$

$$\mathrm{ESI} = \frac{\mathrm{P}}{\mathrm{F}} \cdot \frac{\mathrm{R}}{\mathrm{F}+\mathrm{NR}} \qquad (10)$$

3. Development of the procedure

The method, illustrated in Figs. 2a and 2b, proposes a series of "optimization" steps and can be applied following two different directions, called by the Authors the *inside→outside* and *outside→inside* approach, respectively. The former is suitable when a given plant (or system), already existing or planned, must be optimized, the latter when the most convenient kind of plant or set of plants for a given context must be chosen. In the first case, attention is focused on the plant, in the second on the environment (global impact on the biosphere).

Both approaches start from reasonable preliminary assumptions about the configuration and the performance of the system, and, through a series of feasible solutions each one better than the previous one, arrive at a final configuration, which is "as good as the analyst requires". The procedure starts by applying one method of analysis (energetic, economic or environmental) and, when the solution is considered to be acceptable under that viewpoint, shifts to another aspect of the "optimization". In each step of the procedure, the above-defined indicators are calculated and used as guides to improve the current solution or compare different solutions in order to choose the best one. By means of this information, the analyst can change some of the preliminary assumptions and repeat the calculations; and in this way, he/she can assume plant configurations or device performance and characteristics that are judged to be reliable.

Both approaches allow the analyst to stop the procedure after any step if he/she is interested only in evaluating some aspects. At the same time, the flexibility of the method permits the addition of new steps or the use of new indicators, if needed.

3.1 Inside→outside direction

As said before, this approach (Figure 2a) can be used when the performance of an existing plant has to be improved or the design of a planned plant or system "optimized". Starting from a preliminary plant configuration, where given components are connected to each other by mass and energy streams, the values of the main thermodynamic and mechanical quantities are calculated. Afterwards, possible improvements are investigated, involving adjustments of the configuration, re-design of some components, and modifications of thermodynamic quantities and control criteria. At first, by an iterative procedure, the *process* is optimized by means of energetic and exergetic calculations. Then a thermoeconomic analysis supplies further improvement, based on the costs of the exergy flows. Afterwards, the *system* is assessed through evaluations of local environmental impact and economic payback. The last step is performed by e<u>m</u>ergetic evaluations and gives a large-scale assessment of the process, considering the "history" of the resources used by the system from their origin to their final allocation and recycle into the environment. Usually, the e<u>m</u>ergetic calculations cannot suggest further improvement but instead supply general information for evaluating if the plant is acceptable or not from a sustainability point of view.

3.2 Outside→inside direction

When the target of the analysis is to plan a new energy system or to outline the energetic strategy in a given local context, the outside→ inside approach is suitable for determining the most convenient:

- source, e.g., renewable (solar, wind, etc.) resource or fossil fuel (oil, coal, gas, etc.);
- technology, e.g., gas turbine, steam plant, combined plant, traditional boiler, cogeneration system, repowering of existing plants;
- size of the plant or set of different plants.

According to Figure 2b, the first step of the procedure is the emergetic analysis for a first attempt solution or set of solutions, with fixed technology and size, where the most usual values of performance have been assumed, while the detailed configuration is not defined yet. When the most sustainable solution for the present local context has been determined, the next step of the procedure "optimizes" it by means of the energetic, exergetic and thermoeconomic simulation. At last, the economic evaluation and the emissions analysis give the final information needed for the final assessment.

4. Case Studies

To show the potential of this method, two examples will be presented, involving the method's application to the improvement in performance of energy systems having a very different size, level, and set of characteristics:

- improvement of an existing cogeneration power plant by means of the inside→outside approach;
- assessment of the influence of choosing different power plants on the energetic and environmental aspects of a wide regional system (outside→inside approach).

4.1 Cogeneration power plant

The repowering of an existing cogeneration system operating in Northern Italy has been studied (Figure 3). Two different design improvements have been suggested and analyzed by applying the optimization procedure illustrated in the previous sections.

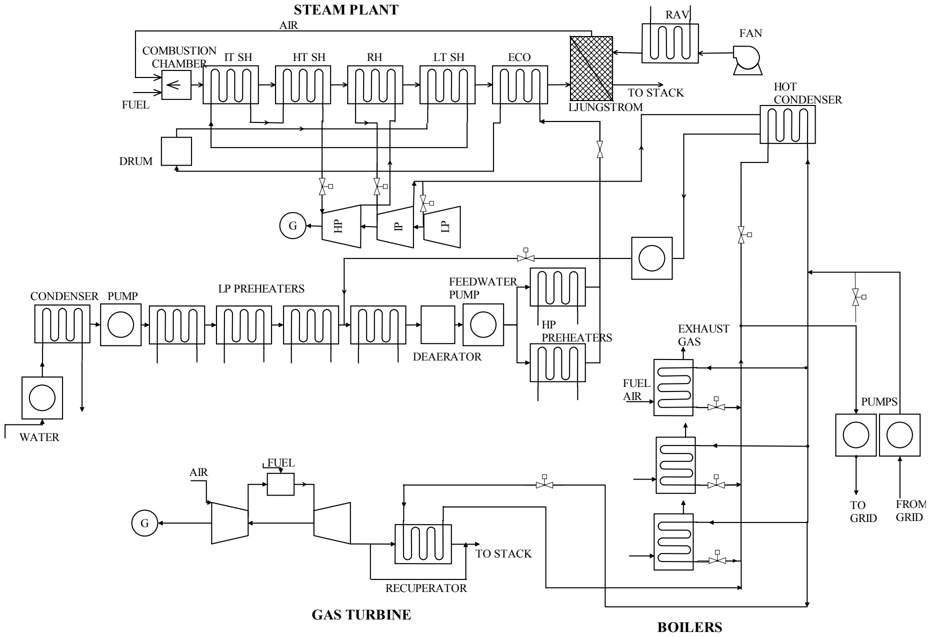


Figure 3. Plant scheme

TABLE I. RATED PARAMETERS OF THE PLANT

Steam plant				**Gas turbine**		
Superheated steam	420 t/h	134 bar	540°C	Air flow rate	176 kg/s	
Reheated steam	370 t/h	30 bar	540°C	Pressure ratio	10	
Steam extraction (max)	250 t/h	3 bar	350°C	Gas turbine exhaust gas	179 kg/s	485 °C
Condensation pressure	0.032 bar			Recuperator exhaust gas	179 kg/s	110 °C
Gross power	136 MW			Gross power	35 MW	

The plant consists of a 136 MWe steam power group, a 35 MWe gas turbine and three integrative boilers supplying 47 MWt each. The present annual electricity generation is about 1000 GWh, heat being supplied as hot water at 120°C/16 bar to a district heating grid. A low pressure extraction from the steam turbine is used in a hot condenser to supply up to 162 MWt, while the exhaust flue gases from the gas turbine feed a recuperator and supply 63 MWt. The electricity can be sold entirely to a local electrical grid, while the plant follows the thermal load by responding to the water flow rate. The main characteristics of the cogeneration units are summarized in TABLE I. Based on the first steps of the inside→outside procedure (see Figure 2a), energetic, exergetic and thermo-economic simulations over one year were carried out on the existing plant, which represents the starting solution to be improved. TABLE II shows that the greatest values of D occur in the evaporator, in the combustion chambers, and in the gas turbine recuperator, which shows the lowest value of f, due to the high temperature difference between hot and cold fluids.

TABLE II. ANNUAL RESULTS OF THE SIMULATION FOR THE EXISTING PLANT

	η	η_{ex}	D	f
	[%]	[%]	[c€/s]	[%]
Evaporator	100	60,38	44.42046	15,81
SP Comb. Chamb.	99,6	75,70	34.12747	5,08
GT Comb. Chamb.	100	65,70	21.14891	11,40
Recuperator	100	37,10	25.10497	5,52
HT SH	100	76,25	3.113202	40,82
SP El. Generator	97,8	98,30	8.010247	64,67
HP1 Turbine	99,0	86,05	7.400827	22,34
Gas Turbine	99,0	93,86	12.3175	42,56
Re-Heater	100	77,81	5.996065	44,09
SH BT	100	82,49	5.510595	52,84
Steam Plant	***52,02***	***38,21***		
Gas Turbine	***80,13***	***37,18***		
Aux Boilers	***93,99***	***17,83***		
TOTAL	**60,37**	**37,25**		

Starting from these results and considering that improving the combustion and evaporation processes is very difficult, two different actions are proposed:

- Set up a heat recovery boiler upstream to the gas turbine recuperator to generate supplementary intermediate pressure steam for the turbine. The thermal power of the recuperator is then reduced to 39 MWt and an increased use of the integrative boilers is needed for peak loads.
- Transform the steam cycle into a combined cycle (CC) by adding a 255.6 MWe gas turbine and replace the boiler by a Heat Recovery Steam Generator. The nameplate electrical output increases up to 332.53 MWe, whereas the thermal power remains unchanged.

Energetic, exergetic and thermoeconomic analyses were carried out on these two proposals. These results allow one to progressively define the size and the required performance of the new devices and choose the most suitable one from Manufacturers' catalogues.

The results of the simulation of annual operation for the main subsystems of the two "optimized" solutions are summarized in TABLE III. An increase of performance is achieved in both solutions. For the latter, the improvement of the exergetic efficiency is quite remarkable.

TABLE III. ANNUAL RESULTS OF THE ANNUAL SIMULATION FOR THE TWO SOLUTIONS

Proposal 1			Proposal 2		
	η	η_{ex}		η	η_{ex}
	[%]	[%]		[%]	[%]
Steam Plant	55.08	39.06	*Cogen. Plant*	59.28	52.23
Gas Turbine	84.84	43.20	*Gas Turbine*	80.13	37.18
Aux Boilers	93.99	17.83	*Aux Boilers*	93.99	17.83
TOTAL	**61.23**	**38.14**	**TOTAL**	**62.88**	**49.43**

The economic and environmental performances of the two plants were evaluated next. The costs of the products and the overall production of electricity and heat (before and after the design modifications) are shown in TABLE IV. In both proposals, the cost of the total output exergy is lower than the present plant's. In addition, considering the increase of the electrical energy generated (23 and 1284 GWh/year, respectively), the annual profit is about 0.9 million Euro for the first one, 23 million Euro for the second. The discount rate is reasonably assumed to be 5%. The two proposals present IP = 1.7 and IRR= 11.4%, and IP = 2 .7 and IRR= 18.2%, respectively. The results are acceptable for proposal 1, while the radically different arrangement for proposal 2 involves a strong improvement of the economic performance.

TABLE IV. COMPARISON BETWEEN EXISTING AND MODIFIED PLANTS

	Cost of products c [€/GJ]	Exergy production [GJ]
Existing plant	15,60	$3{,}49\ 10^6$
Proposal 1	15,28	$3{,}81\ 10^6$
Proposal 2	12,05	$8{,}12\ 10^6$

The local impact on the atmosphere was next evaluated. Due to the aged equipment installed, the pollutant emissions of the actual plant exceed the emission limits set by the European Regulations for plants of new construction, which have been used as the reference (s_{air} = 1.9). Only a minor improvement is obtained with proposal 1 (s_{air} = 1.8), essentially due to a better use of fuel (increase of exergy efficiency), while a significant benefit (s_{air} = 0.5) is achieved with proposal 2, whose new configuration involves reductions in the polluting emissions.

Finally, the global performance of the plant at the larger scale of the biosphere was evaluated by means of an emergy accounting. The main results for the existing plant and the new proposals are summarized in TABLE V.

ESI focuses on the way the process is related to the resources needed to sustain it. For this reason, it does not change significantly when shifting from the original plant to the new solutions, since all of them are based on combustion processes running on fossil fuels. The transformity is slightly lower for proposal 1 and drops for proposal 2. Therefore, resources are converted to the final product with higher efficiency. This is due to the increased efficiency of the conversion step, so that less exergy is lost.

TABLE V. EMERGY INDICATORS

Indicator	Existing plant	Proposal 1	Proposal 2
Tr (seJ/J)	$1.57\ 10^5$	$1.54\ 10^5$	$1.19\ 10^5$
ESI	0.56	0.56	0.58

At the end of the analysis, only the second solution is considered acceptable from the economic and environmental viewpoints.

4.2 Comparison and assessment of different power plants

The output→input procedure was applied to some existing Italian energy conversion plants (see TABLE VI) as a simple example of the capacity of the method to help in a comparison of different technologies to produce electric energy. The results of the analysis are summarized in TABLE VII. Note that they do have validity, i.e. for all the plants of the same class, but only for the specific plants studied.

TABLE VI. ENERGY SYSTEMS EVALUATED

Thermoelectric:660 MW section running on oil, super-critical steam cycle
Cogeneration: 136 MW extraction-condensation steam turbine running on natural gas; 35 MW gas turbine with heat recuperator to power a district heating system
Geo-Thermoelectric: 20 MW standard section based on a geo-thermal system mostly consisting of superheated water.
Gas-Steam Combined: 21 MW gas turbine coupled with a 8.5 MW co-generation steam turbine by means of a recovery boiler.
Hydroelectric: 2×45 MW Pelton turbines on vertical axis. The related water system represents a natural production of 140 GWh on a yearly basis.

The hydroelectric plant shows the best efficiency related to a conversion process where the input and output energy have the same quality in exergy terms and good economic performance. Only the IRR does not present excellent values, because the plant required a very long construction time.

The thermoelectric plant is penalized by the large number of facilities typical of an oil plant, more complex and expensive than in a gas fueled plant.

Considering the emission of pollutants, the hydro plant is the most favorable. Also the geo-thermal one behaves well, but it must be observed that the air quality indicator does not consider some polluting substances peculiar to this class, which should be assessed. Plants running on natural gas have reduced emissions among the combustion plants; but the emergy analysis shows low sustainability (even lower than that of the oil plant), probably because a large amount of non-renewable resources and imported resources are used.

Moreover, the emergy analysis shows that the natural resources involved in the hydro plant are relevant (greater than in the geo-thermal plant).

TABLE VII. RESULTS OF THE ANALYSIS

	Thermoelectric	Cogeneration	Geo-Thermoelectric	Gas-Steam Combined	Hydroelectric
η	0.41	0.79	0.15	0.76	0.79
η_{ex}	0.41	0.39	0.34	0.47	0.79
c [€/GJ]	11.53	15.50	8.71	12.93	3.48
IRR [%]	8.99	17.34	12.7	11.4	12.2
PI	1.539	2.469	1.547	1.884	3.05
s_{air}	3.71	1.75	0	0.95	0
s_{water}	2.35	1.33	0	0	0
Tr [seJ/J]	1.50E+05	1.79E+05	1.45E+05	9.83E+04	6.70E+04
ESI	9.42E-02	2.21E-07	11.9	4.56E-01	9.46

A “friendly” representation of the results have been proposed (Mirandola et al., 2000), where the indicators are opportunely scaled in order to have values ranging from -1 (worst quality) to 1 (best quality); 0 is the value assumed by the scaled indicators if performance is equal to reference ones, expressing current technology behavior. In this way, a comparison of performance with respect to different viewpoints is simplified, and a global overview of different plant characteristics is more perceptible. Figure 4 shows the results for the plants analyzed.

These results give the analyst the tools to choose the best plant among the ones analyzed, the one whose operation (in this example all the plants already exist) must be preferred.

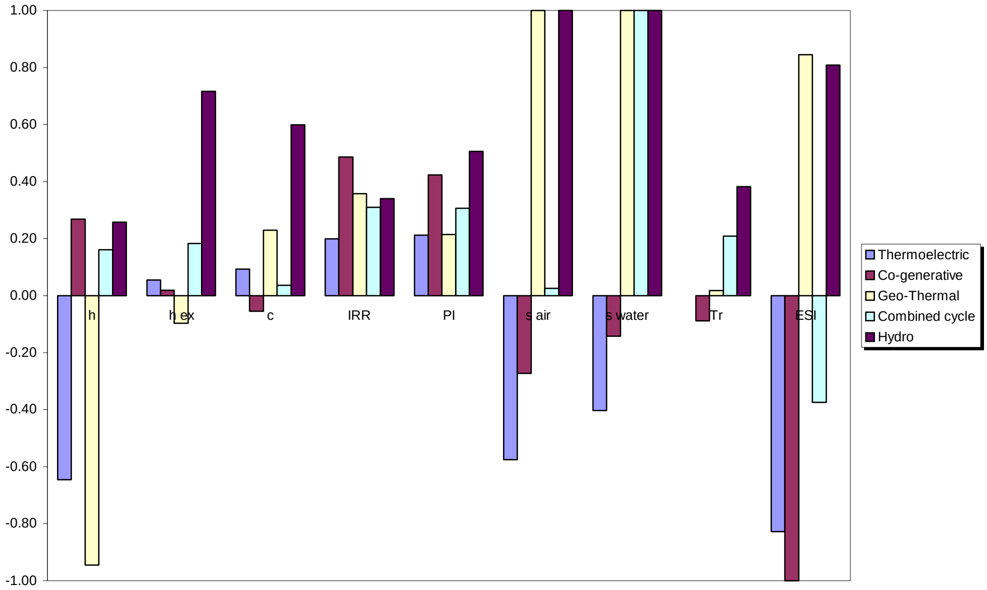


Figure 4. Graphic representation of the results for the case studies.

5. Conclusions

An iterative procedure has been described, aimed at improving energy system performance based on energetic, economic and environmental aspects. It can be used to both optimize the configuration and the control criteria of an existing or planned plant (inside→outside approach, very useful for designers and plant operators) and choose the most sustainable energetic strategy in a given local context (outside→inside approach, suitable to be used by policy makers). The method is very flexible in order to meet the analyst's requirements and could be further extended by adding new evaluation parameters. The parameters and the indicators illustrated in this work do not have an "absolute" value for every case: the analyst or the policy maker can select the most suitable ones according to the targets to be reached, i.e. according to his/her priorities.

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Nomenclature

B	Exergy [J]
D	device contribution to product cost[c€/s]
E	Energy [J]
Em	Emergy [seJ]
ESI	Emergy Sustainability Index
F	Fuel [J, seJ]
I	Irreversibility (I= F–P) (J)
Inv	Initial Investment [€]
IRR	Internal Rate of Return [%]
L	In-force emission limits
NPW	Net Present Worth [€]
NR	Non-renewable Resources [seJ]
P	Product [J, seJ]
PI	Profit Index
R	Renewable Resources [seJ]
S	Emission level
Tr	Transformity
Z	Device capital cost
c	cost per exergy unit [€/J]
i	discount rate [%]
s	emission indicator
in	input
η	First Law efficiency
η_{ex}	Second Law efficiency

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