Energy 304 (2024) 132038

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

From exergoeconomics to Thermo-X Optimization in the transition to sustainable energy systems

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ARTICLE INFO

Keywords:
Exergoeconomics
Design optimization
Sustainability
UN goals

ABSTRACT

Exergoeconomics has played an important role in the study of new energy systems in the last decades. The use of exergy as a "carrier of value" has made it possible to define an unambiguous criterion for allocating costs among energy systems products. The paper shows how exergoecomic procedures of analytical optimization and design improvement on heuristic basis have been progressively replaced by more efficient procedures aimed at minimizing an objective cost function, leaving exergoecomic cost evaluation as the final step. It also highlights how growing concerns about climate change and the continued growth of inequalities in energy availability have broadened the set of objectives in the search for the optimal integration of the design and operation of energy conversion units and network with intelligent methodologies to reduce energy demands. The objective of the article is twofold: i) present the evolution of the main Exergoeconomic methods and show how they have paved the way for Thermo-X Optimization methods; and ii) outline the path for developing a general model of society's entire energy system that includes a broader set of objectives and constraints in addition to economic ones to help build the energy system of the future with a more sustainable perspective.

1. Introduction

Any study of energy conversion system is accompanied by an economic analysis to determine the desirability and convenience of its construction. Initially the decision goes through the evaluation of energy performance, measured by suitable parameters such as efficiency (ratio of production to consumption, expressed in various forms), specific power, energy density, weight, etc. This requires the contextual consideration of all technological constraints and is followed by the economic evaluation of all construction and operating costs. If costs are deemed too high, design modifications based on experience are proposed to seek a reasonable compromise between performance and cost. This traditional "thermoeconomic" approach may require an iterative procedure to get a satisfactory design, and does not guarantee that the optimal trade-off between performance and cost is obtained at total system level.

To overcome this limitation, many researchers, starting from the pioneering works [1–4] have agreed that the exergy variable could be used, not only to evaluate the components that contribute most to the losses of potential work, but also to the costs associated with these losses, introducing a new field of research, "Exergoeconomics", within the wider field of Thermoeconomics. Using a single variable as commodity of value homogenizes the performance of each system component and supplies a more specific guidance for design modifications in those components affected by higher costs per unit of exergy destruction [5,6].

This paper presents an overview of the transition from exergoeconomic to optimization methods in the search for better-performing configurations of energy systems, as measured by all variables (energetic, economic, environmental, social, etc.) that are involved in the decision about the design and operation of energy conversion systems. It does not pretend to consider extensively all the contributions to the very broad field of "Thermoeconomics" and "Optimization methods", but focuses only on the basic principles of the main exergoeconomic methodologies developed in the literature to explain reasons of its success and limitations, and the evolution towards methods that allow the minimization/maximization of one or more objective functions. About the

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https://doi.org/10.1016/j.energy.2024.132038
Received 1 February 2024; Received in revised form 27 May 2024; Accepted 10 June 2024

latter, the emphasis is on the general formulation, and on the need of enlarging the definition of the objective functions to all aspects affecting the design and operation of energy conversion systems, not only the energetic and economic ones.

In this context, the novelties of the paper are.

- Demonstrate that exergoeconomics has paved the way to the recent design optimization methods and can still be used to obtain more in-depth information for a comprehensive understanding of the optimal design of single energy conversion systems;
- Understand the direction in which newer optimization methods have developed;
- Foresee how these optimization methods may develop in the future to include not only energetic and economic performance aspects of individual systems but also all the other aspects that must necessarily be considered when designing groups of energy conversion systems that fulfil the time-varying demands of multiple users, in larger or smaller geographic areas, through different energy distribution networks.
- Emphasize the need to focus on reducing energy demands, avoiding energy waste in wealthier countries, and instead help increase consumption in poor countries while maintaining a good balance with the environment.

The paper identifies themes and asks questions about these problems without claiming to give exhaustive answers, which are impossible given the complexity and enormity of the problems, which involve virtually all human activities. Rather, it aims to retrace the evolution of research from the first steps of Exergoeconomics to the more advanced design optimization methods to identify lines of sustainable development that are respectful of the developmental needs of individual countries (nations, or other geographical areas), but at the same time narrow their limits to give every human being the same opportunities, not only now but also in the future. The final goal is to present a model of the energy system of the society that includes a broader set of objectives and constraints in addition to economic ones to help build the energy system of the future with a broader and more sustainable perspective.

2. Exergoeconomic methods

Exergoeconomics aims to evaluate the exergetic and monetary costs associated with mass and energy flows in the energy system. The idea is to allocate the input costs of the total system between the internal mass and energy flows of the system, up to the final products, in proportion to the associated exergy flows [1–4]. The principle that exergy is the most appropriate variable for cost allocation actually needs to be supplemented with the definition of the desired exergetic "Product" and the exergetic resources needed to obtain it ("Fuel"). Thus, all exergoeconomic methodologies proposed in the literature suggest allocating the costs of the input streams based on the exergy carried by the Fuel and the Product of the system components. However, this introduces an inherent degree of subjectivity, as the definitions of Product and Fuel that satisfy the energy balance of each component are not unique. The various exergoeconomic methodologies in the literature ultimately differ from each other only in the ways of defining or representing the Fuel and the Product of the components. The "algebraic" approach initially suggested in Refs. [4–6] as well as the "algebraic theory" proposed by Refs. [7,8] leave some degree of freedom on these definitions and their representation, i.e., on the so-called “productive structure”, specifying some rules to avoid other arbitrariness at the system level (e.g., to handle energy losses - "residuals" - of the total system). On the other hand, in all exergoeconomic approaches it was emphasized from the beginning that the “product” is defined according to the “purpose” of the components, and for the large majority of components there is not a big disagreement among different authors about their purpose. The term “desired result” used in Ref. [6] is another term for purpose. The SPECO method, proposed by Lazzaretto and Tsatsaronis [9–13], generalized the definitions of fuel and product, but still based on the principle of “purpose”. The goal is to avoid any ambiguity in the definitions of Fuel and Product by providing specific rules for obtaining them, simply based on the principle that any addition of energy by the considered component belongs to the Product, while any removal belongs to the Fuel. The resulting representation of the production structure is also unique and keeps every interaction between Fuel and Product and the flows of exergy into and out of each component within the boundaries of the component itself, as shown in Fig. 1(b).

A substantially different approach has been proposed by the "Thermoeconomic functional" and ”Engineering functional” approaches [3,15–19], where functions (i.e., product) are defined according to a “purpose” of the component in the system in which it operates, i.e. considering how the single component “serves”, and therefore interacts, with the rest of the system structure (see, e.g., the pump in Fig. 1 (c), which supplies exergy to all system components). In this way, the same component does not have the same "function" independently of the system in which it operates, as the SPECO approach states, but it may have different functions depending on the system in which it is embedded. In this way, the "functional diagram" of the total system has the same logical meaning as the productive structure of the SPECO criterion or other exergoeconomic approaches, but is generally different from it, thus involving a somewhat different cost allocation criterion [14,20–23]. These optimization methods have been assigned the adjective “thermoeconomic,” although they still consider the allocation of input costs among system products based on the exergy carried by material and energy flows (thus, they can still be considered in the “exergoeconomic category”). Note also that the authors often use the terms “purpose” and “function” with the same meaning.

For any functional or production structure, costing requires formulating a conservative balance of the cost streams entering and leaving the component under consideration and formulating auxiliary equations equal in number to the number of exergetic streams leaving the component minus one (since the balance equation is always available). For example, for the k_{th} component receiving a heat transfer ($\dot{E}_{q,k}$) and generating power ($\dot{W}_k$), the cost balance is given by the following Eq. (1) [24].

$$\sum_e (c_e\dot{E}_e)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}_{q,k} + \sum_i (c_i\dot{E}_i)_k + \dot{Z}_k \tag{1}$$

where $\dot{E}_i$, $\dot{E}_e$ and c_i, c_e denote exergy flow rates (kJ/s) and costs per monetary unit ($\$/kJ$), respectively, at the inlet (i) and exit (e) of the k-th component, $\dot{Z}_k$ is the amortization cost for the investment and maintenance and $c_{w,k}$ and $c_{q,k}$ are costs per monetary unit of the work and heat, respectively.

Auxiliary equations are formulated according to the F and P rules [7,10–12]. Referring to the SPECO approach, the F rule states that the exergy removal in a component occurs at the average unit cost at which the exergy removed was supplied in the upstream components, whereas the P rule states that every exergy unit belonging to the product has the same unit cost (Fig. 2).

The result is an overall picture of the exergetic or monetary cost flows associated with the different mass and energy flows in the system. In particular, this makes it possible to estimate product costs, showing that products of components further downstream in the energy conversion system are loaded with higher costs as they are affected by all the irreversibilities generated by upstream components. Regardless of the differences between the different methods, which are generally quite small, they have had the merit of calculating the least ambiguous possible cost of the different energy products of a system, and thus of being able to make comparisons about the ability of different systems to generate products at higher or lower costs.

All mentioned authors applied the respective Exergoeconomic methods to single energy conversion systems (generally power or

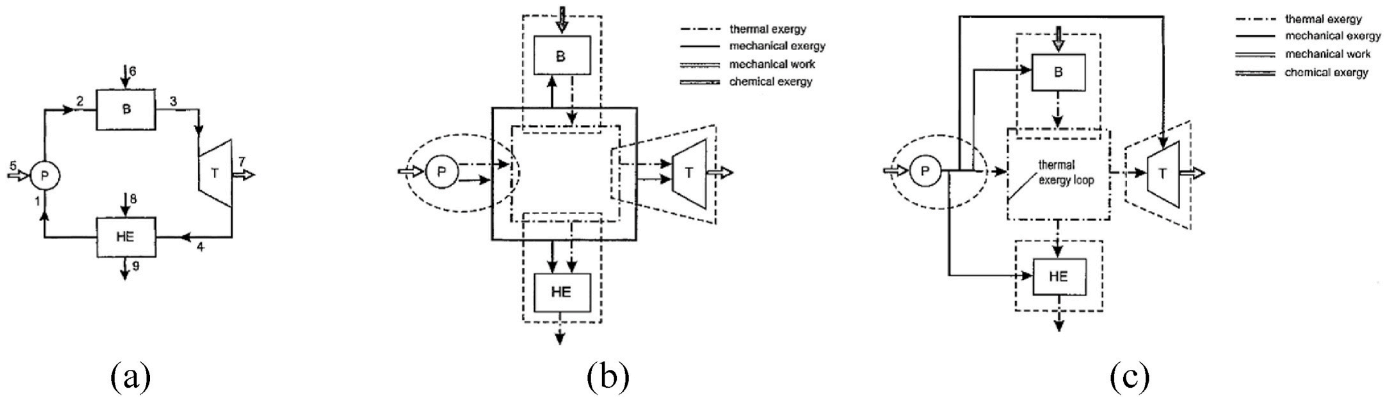

Fig. 1. Simplified physical structure of a steam power plant with "hot" heat exchanger (a) and corresponding productive structures according to the SPECO (b) and Functional (c) approaches [14].

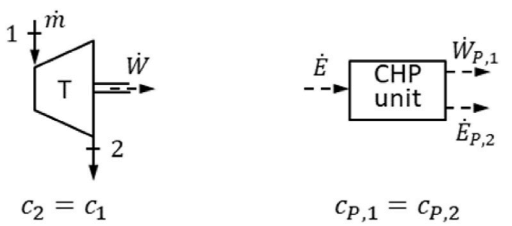

Fig. 2. Auxiliary equations deriving from the application to a turbine of the F rule (left) and the application of the P rule to a CHP engine (right).

combined-heat-and-power plants). An interesting attempt to enlarge exergy accounting criteria to wider systems (such as countries, or "societies") was proposed by Sciubba and co-authors, who suggested to perform the Extended Exergy Accounting [25,26]. This method expresses the primary production factors, (Labour and Capital, Materials and Energy) and the Environmental Remediation Cost in units of "prime resource exergy equivalent", i.e., in kilo joules of primary exergy. The challenge is to evaluate the primary (extended) exergy costs of measures to reduce our degree of unsustainability, given that more sustainable solutions may require in some cases greater resource consumption than the less sustainable ones. The conceptual basis is similar to that of the Emergy Analysis [27–29] although the algebra is different, as shown in Ref. [30].

Going back to single energy conversion systems, the method of design improvement proposed in Ref. [6] and subsequently included in Ref. [24] is based on finding the best efficiency-cost trade-off at the component level, so as to create an overall picture of the main sources of irreversibility and costs in the various components of the energy system. The method proposes to intervene first on those components with the highest values of the sum of depreciation costs and energy destruction costs, and then to act according to the values of other exergoeconomic indicators that properly weight the effect of exergy destruction and relative increase in each cost term for each component. This method may require some iteration steps to improve the system design, driven by the designer's ability to choose the appropriate performance modification of the components responsible for the highest destruction of exergy and cost.

In this context, starting from the beginning of 2000s onward, Tsatsaronis and co-workers introduced the concepts of "avoidable" and "not available" exergy destruction to understand the actual margins of improvement achievable in the iterative design based on the calculation of exergoeconomic variables [31]. Moreover, they suggested overcoming the problem associated with the mutual interdependence of the components behavior by splitting the total exergy destruction within a component into its endogenous and exogenous parts [32]. The former refers to the exergy destruction occurring within the component when all other components operate in an ideal way, whereas the latter is the difference between total and endogenous exergy destruction in the same component. In spite of the interesting conceptual approach, the practical applicability of this exergy splitting is not trivial. Tsatsaronis and Morosuk wrote several papers in the last years on these advanced exergy-based methods for developing, evaluating, understanding and improving energy conversion systems. A good review of these approaches is supplied in Ref. [33].

On the other hand, the Lagrangian analytical approaches [3,15–19] that were proposed to optimize the system design starting from the 70s search for the minimum unit cost of the total system product as objective function. Compared with the design improvement criterion proposed by Tsatsaronis and co-workers [6,24], this approach has the advantage of finding the optimal values of the system design variables (pressures, temperatures, flow rates) without the need for iterations, but at the expense of a quite difficult search for the analytical solution. Lagrange multipliers in this case take the meaning of marginal costs at the point of optimality found. However, setting up and solving an optimization problem with an analytical method limits the use of this approach to relatively simple system configurations, or requires strong simplifying assumptions. Moreover, the iterative approach assumes that the investment costs of the components are not available as functions of the decision variables, whereas the Langrangian approach needs and uses such functions. For this reason, there have been several applications of the exergoeconomic iterative approach, but very few applications of the Langrangian approach to complex real systems. In the iterative approach, it is assumed that a cost engineer provides the component costs at any required design point (i.e. at any iteration), an approach that is much closer to the approaches used in the industry for optimizing energy conversion plants.

An evolution of this approach was the "Environomics", which, in addition to the exergetic and monetary costs of mass and energy streams in the system, considers the costs associated with the consumption of other resources and the emission of pollutants [34]. The total cost of the system is still used as objective function with the addition of one or more terms, which depend on: the environmental and social costs of undesired emissions [35]; on the pollution costs associated with system manufacturing and dismantling system equipment; the costs associated with resource preparation and transport [36]. Since all these terms are costs, the objective function is still economic (in this sense, the abbreviated term thermo-enviroeconomics would be more appropriate, as recognized by Frangopoulos [34]), with penalties applied according to the pollution generated. A variant of the environomic approach is used in Ref. [37], where the objective function considers a carbon tax on CO_2 production as a penalty term and includes the costs of pollutant abatement devices and CO_2 sequestration in the cost of equipment. A different penalty term linked to operational inefficiencies is considered in

Ref. [38].

Other important developments of exergoeconomics have also been made in the diagnosis of energy systems malfunctions. Tsatsaronis and Winhold in Ref. [6] first evaluated the effects on the total fuel consumption of variations of the exergy destruction in a component. Valero and co-workers [39] applied later this criterion to evaluate the system-level effects of malfunctions, understood as changes in efficiency or product in a component relative to the design condition. Reini in 1994 [40] fully formalized the calculation of the "impact" on the fuel of the total system due to changes in the efficiency or product of its components for any system configuration. Torres et al. [41] introduced the concepts of malfunction and dysfunction to distinguish between variation of the component behavior that depend on the component in hand or originate in other components.

However, as already in the iterative design improvement procedures mentioned earlier [6] the main drawback in the application of exergoeconomics to the search of malfunctions lies in the dependency relationship between the exergetic performance variables (exergetic efficiency and exergetic product) of different components. This implies that a variation in one of these variables due to changes in one of more operating variables (pressure, temperature, mass flow rate.) generally results in induced changes in the exergetic variables of other components as well, thus “hiding” the “real” malfunctions and making their identification difficult. To overcome this intrinsic drawback, Toffolo and Lazzaretto [42] suggested a fundamentally different approach to detect malfunctions, based simply on identifying components that vary their characteristic curve. This variation is evaluated by means of an exergetic indicator that accounts for the changes in the derivatives of irreversibilities at the design point of this curve with respect to the independent variables of the component under consideration. They also reviewed all exergoeconomic diagnostic methodologies to highlight their strength and limitations [43]. A good synthesis of different points of view on the use of exergoeconomics in the detection of malfunctions and evaluations of their effects is presented in Refs. [44,45].

The cited disadvantages of the exergoeconomic method for design improvement, diagnosis of malfunctions, or Langrangian optimization have subsequently been only partly overcome by the introduction of new optimization algorithms that have enabled researchers to use a mathematical optimization technique to solve well-formulated optimization problems of the design and operation of power conversion systems, as illustrated in Sections 4 and 5. In this case, there is no need of exergoeconomics to find the optimum design and operation, but there is still the need of component cost functions of the design variables of the system, which are rarely available, particularly when new components are included in the system.

3. Critical aspects and limitations of the exergoeconomic methods

Exergoeconomics is based on concepts and assumptions that have a certain degree of subjectivity, which is reflected in the results obtained and in their utilization for improving the design and operation of energy conversion systems. The critical issues associated with this subjectivity are discussed in the following, separating those associated with simple cost accounting from those involved in the use of exergoeconomics for the design improvement according to the criteria proposed by Tsatsaronis and co-workers [6,24].

3.1. Cost accounting

As shown in the Introduction, the cost balance and the auxiliary equations obtained by the F and P rules allows calculating the exergetic and monetary costs associated with mass and energy streams. Given that the F and P rules require the definition of Fuel and Product of each component, these definitions become crucial for an effective and unambiguous cost allocation criterion [9–12].

The criteria for defining Fuel and Product, and consequently the exergetic efficiency (ratio of Product to Fuel), have been extensively discussed in the literature and converge toward the general idea that the Fuel and Product of a component consist of the decreases and increases, respectively, in each form of exergy between the input and output of that component. This general criterion and the very few exceptions to it are discussed in detail in Refs. [11,12,46]. On the other hand, the F and P rules used to define the auxiliary equations are essentially based on the principle that every unit of exergy removed or added by the component has the same cost. Although consistent with the idea that exergy is the “carrier of value”, this principle is arbitrary and does not take into account the fact that exergy is the maximum work "ideally obtainable" from a mass or energy stream, which differs from the maximum work actually obtainable from such streams. In particular, the exergy destruction to Product ratio associated with real world processes, decreases as the temperature of the process decreases, more than what expected by theoretical thermodynamics. Accordingly, a unit of thermal exergy does not have the same "value" in reality as a unit of mechanical energy, so that units of thermal exergy at lower temperatures have less "value" than those at higher temperatures or, even more, units of mechanical work (Fig. 3).

Moreover, this allocation criterion is normally applied at design conditions, whereas more reliable results could be obtained considering the hour by hour operation, throughout the year, as only few papers in the literature highlighted [47,48]. However, the hour-by-hour operation requires to be predicted in advance, and this implies several assumptions, the inaccuracies of which can only be partially overcome using reliable stochastic approaches to manage the uncertain variables (such as solar irradiance, wind velocity, market cost and prices, etc.). On the other hand, other equally meaningful allocation criteria than the exergoeconomic one could be used for multi-product systems, as shown in Refs. [30,49].

3.2. Design improvement

As reported in the Introduction, the picture of the costs associated with the individual components employed in the procedure of design improvement [6,24] provides information for design improvement that does not allow to obtain the best design in a single iterative process. This is because the improvement in either the exergetic or exergoeconomic performance of one component does not necessarily result in a corresponding improvement for the overall system, since it may have a worsening influence on the exergoeconomic performance of the other components. In fact, there is a dependency link between the exergetic variables of the different components, and thus between the costs associated with them, since exergy values depend, to a greater or lesser extent, on the set of values of the independent design variable set (including temperatures, pressures, flow rates) on which the designer has the ability to act (Fig. 4).

Moreover, the need to guide the different iterations by the designer’s "experience" limits the applicability to the more experienced designers in the exergoeconomic field. Furthermore, as already pointed out about cost accounting, the scope of these exergoeconomic procedures concerns the behavior of the plant under design point conditions only, because of the major complication that would result with an application under off-design operation.

However, these limitations do not negate the usefulness of exergoeconomic accounting and exergoeconomic design improvement procedures, but suggest a partially different use for them, as shown in Section 7.

4. Single or multi-objective design optimization of individual energy conversion systems

This section briefly describes why, starting in the late 1980s-early 1990s, some papers on the design of advanced energy conversion

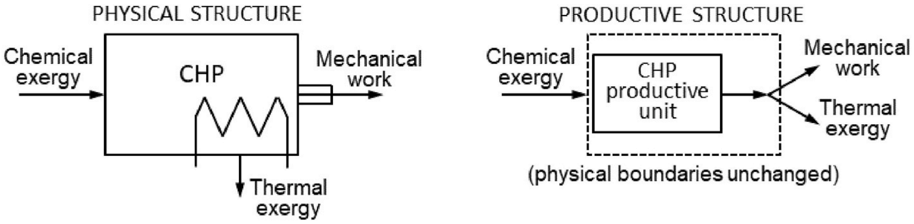

Fig. 3. According to exergoeconomic accounting methodologies, a unit of thermal exergy at the outlet of a CHP engine has the same exergetic cost of a unit of mechanical work.

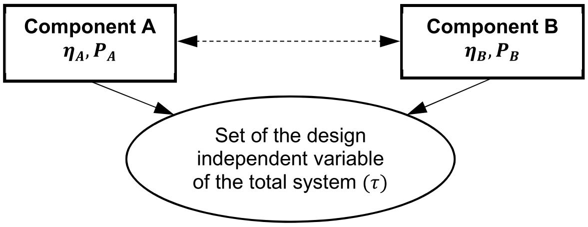

Fig. 4. In general, the exergetic performance variables of different components (e.g., η_A, P_A and η_B, P_B) depend on the set of independent variables of the total system (τ), so that they depend on each other (dotted line).

systems shifted from the iterative exergoeconomic design improvement described in Section 2 to the numerical optimization approach. At that time, the difficulty of setting up and executing design constrained optimization with the Lagrangian analytical method was overcome first with the development of efficient descent optimization algorithms and then with the new and more efficient genetic algorithms. However, it is still necessary to have the cost formulas of the system components as a function of their design variables, which can rarely be available or reconstructed from the market costs of specific components, given the wide variety of component types and sizes. Thus, simplifying assumptions are required to obtain these functions, which affects the accuracy of the results. For this reason, many of the applications to real plants have maintained an iterative approach to design improvement, techno-economic at the industrial level, exergo-economic at the research level.

4.1. Single economic objective

The work of Lazzaretto and Macor [21] showed that, unlike the Lagrangian approach used up to that time for thermoeconomic design optimization, the search for the economic optimum can be separated from the cost accounting by first setting up and solving the following optimization problem, and then calculating the costs in the optimum.

$$\text{Find } \mathbf{x}^* \in \mathbb{R}^n \text{ that minimizes } f(\mathbf{x}) \tag{2}$$

$$\text{subject to } \begin{array}{l} g_i(\mathbf{x}) = 0, i = 1, \dots, p \\ k_j(\mathbf{x}) \geq 0, j = 1, \dots, q \end{array} \tag{3}$$

where $f(\mathbf{x})$ in Eq. (2) is the objective function, the equality and inequality constraints in Eq. (3) represent the energy system model including mass and energy balances of its components and the equations describing the properties of the working fluids, and $\mathbf{x}$ is the set of the design decision variables including pressures, temperature, mass flow rates and fluid properties.

The objective function $f(\mathbf{x})$ is the total cost flow rate ($\dot{C}_{total}(x)$) associated with the amortization of the investment and maintenance costs and of the costs for the fuel utilized by the system (Eq. (4)).

$$\dot{C}_{total} = \dot{C}_{fuel}(x) + \dot{C}_{inv+maint}(x) \tag{4}$$

4.2. Multi-objective optimization: energetic, economic, environmental

Multi-objective optimization techniques have been introduced into energy system design optimization since the end of 1990s-early 2000s, with the concomitant development of evolutionary algorithms. In particular, the paper [50] expands the perspective of traditional thermoeconomic optimization, by applying a multi-objective approach to evaluate the complete spectrum of solutions that satisfies both the economic and energetic objectives. In fact, a “pure” single-objective approach that considers only the economic objective or only the thermodynamic one is able to find one of the two extreme points on this spectrum of optimal solutions: the minimum of the cost objective function, or the maximum of the efficiency objective function. In Ref. [50] the Pareto approach is used to find the optimal set of design variables, since the concepts of Pareto dominance and optimality are straightforward tools for determining the best trade-off solutions between conflicting objectives. An evolutionary algorithm is then chosen to carry out the search for the Pareto optimal solutions (Fig. 5 [50]) for the cogeneration gas turbine considered in Ref. [54], since evolutionary optimization techniques were conceived to deal with a set of solutions (a “population”) to pursue their task. Consequently, a multi-objective Pareto-based evolutionary algorithm is able to make the population converge to the entire set of optimal solutions in a single run. For instance, Fig. 5 [taken from 50] shows the Pareto optimal set of solutions and the influence of the unit cost of fuel (in \$/MJ) on this set. The original unit cost of fuel (0.004 \$/MJ) was first increased by 50 % and then doubled. Results show that the economic minimum at higher unit costs of fuel did not shift upwards as expected, but it also shifted towards higher exergetic efficiencies (from 0,5065 at 0.004 \$/MJ it increased to 0.5146 at 0.006 \$/MJ and 0.5187 at 0.008 \$/MJ). On the other hand, the rightmost branches of the three Pareto fronts tend to converge with each other.

The paper [51] shows how the design of the same cogeneration gas turbine in Fig. 5, as well as that of any thermal system, modifies if the optimization capabilities of the multi-objective approach are further exploited by adding an environmental objective function to the energetic and economic ones. The work compares and discusses the three-objective approach with a single-objective thermo-economic optimization and a two-objective energetic and economic optimization. In particular, the energetic, economic and environmental objective functions were defined as in Eqs (5)–(7), respectively:

$$\text{Energetic } \varepsilon = \frac{\dot{W}_{NET} + \dot{m}_{steam}(e_9(x) - e_8(x))}{\dot{m}_{fuel} \cdot e_{fuel}} \tag{5}$$

$$\text{Economic } \dot{C}_{total}(x) = \dot{C}_{fuel}(x) + \sum\nolimits_i \dot{Z}_i(x) \tag{6}$$

$$\text{Environmental } \dot{C}_{env}(x) = c_{CO_2}(x)\, \dot{m}_{CO_2} + c_{NO_x}(x)\dot{m}_{NO_x} \tag{7}$$

The environmental objective function is expressed in terms of cost, weighting carbon dioxide and nitrogen oxide emissions according to their unit damage costs. Thus, a three-dimensional spectrum of optimal solutions can be extracted from the space defined by the three objective functions by an evolutionary algorithm (Fig. 6).

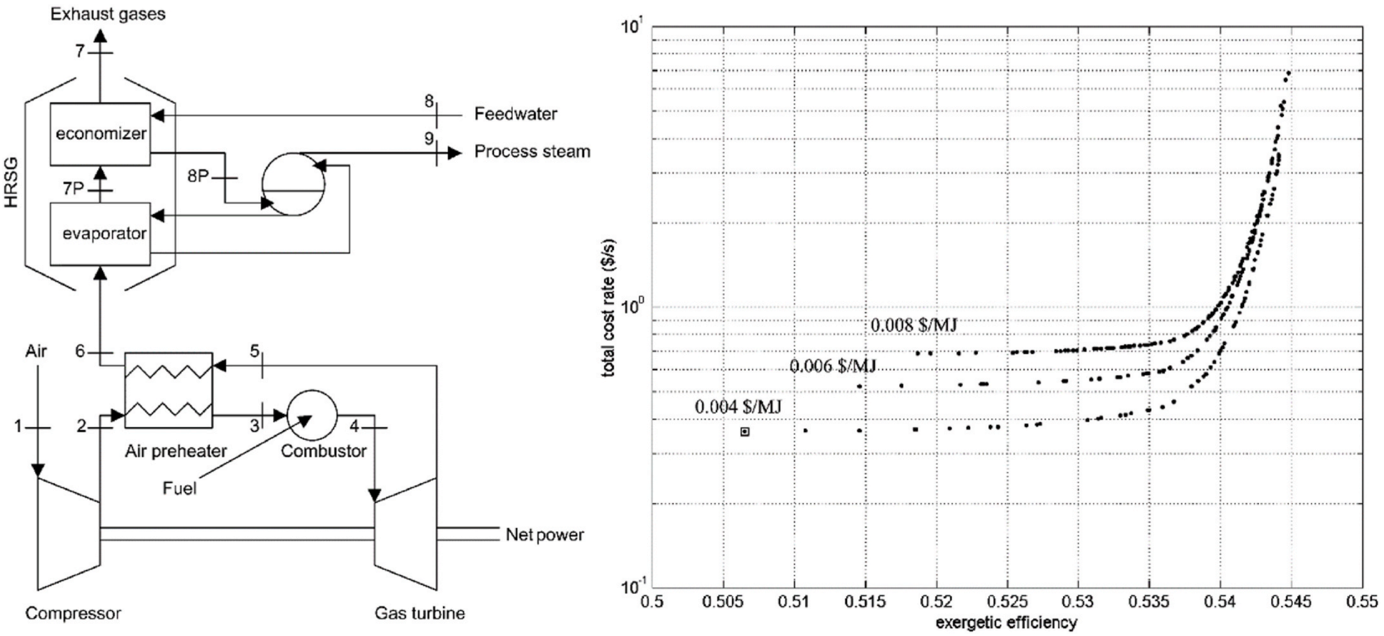

Fig. 5. Pareto front (on the right) for different unit costs of fuel of a cogeneration gas turbine (on the left) [50] considering the total system cost rate ($/s) and the exergetic efficiency as objective functions.

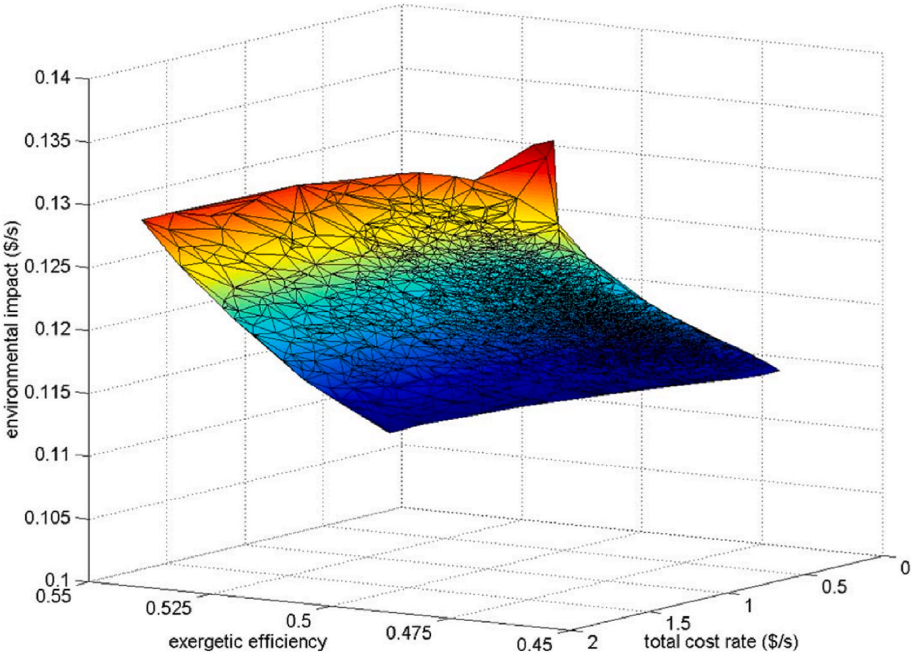

Fig. 6. Optimal values of the three-objective functions (Pareto front) in Eqs (5)–(7) [51].

The main novelty in that paper consists in considering the environmental impact no longer as a limitation to be met, according to legal regulations, but as an objective to be pursued. Thus, referring for instance to the results in Fig. 6, the maximum exergetic efficiency is 0,539, whereas the exergetic efficiency that minimizes the total cost rate (0.362 $/s) is 0,5065 and that minimizing the environmental impact (0,1142 $/s) is 0,485. These results show that searching for the minimum environmental impact corresponds to a significantly higher exergetic penalty than minimizing the total cost rate (more details can be found in Ref. [51]). This paradigm shift, however, requires the correct formulation of the environmental objective function. Equation (7) indicates that on the one hand it is necessary to consider local pollution related to toxic emissions, and on the other hand the impact on the atmosphere of elements that have a high global warming potential. In the design procedure this environmental goal is only partially independent of that of maximum efficiency, because achieving too high temperatures is environmentally pejorative. Of course, considering environmental impact as an objective instead of a constraint leads to a general rethinking of objective functions, as discussed below.

A deep analysis and discussion of theoretical and practical problems in applying optimization technique to energy systems of various complexity, using single and multi-objective approaches and exergoeconomic principles is presented in Ref. [55].

5. The need of proper objective functions for the whole society

Section 4 showed how the design of energy conversion systems has naturally moved toward goals other than just maximum efficiency or maximum profit/minimum cost. Indeed, the use of the design and operation of these systems have implications that go far beyond these goals. Thus, some questions naturally arise:

“Are cost or profit the best goals? Is efficiency the best goal from the energetic point of view? or is it instead absolute energy consumption? Are thermo-economic analyses sufficient, or should we better move toward thermo-X analysis? What are the right environmental goals? Is decarbonization the best one? Is it sufficient to measure the environmental impact?”

As much as conversion technologies continually evolve over time, many of those involving the bulk of global consumption, and particularly those using fossil fuels, have reached levels close to the maximum achievable ones relative to unavoidable physical constraints (e.g., the Second Law of thermodynamics in case of thermal systems). Thus, it is reasonably not conceivable that further developments in technologies could contribute to efficiency gains for these systems that are relevant to the overall system. Moreover, the introduction of more efficient technologies often leads to the so-called “rebound effect” that, in turn, can offset, at least partially, the reduction in primary energy consumption associated with the efficiency gains [56]. On the other hand, it is certainly desirable that there be major increases in the efficiency of technologies based on renewable sources, but it is hardly conceivable that these can really become complete replacements for fossil fuels in a short time. Following the 2015 Paris Agreement on climate change mitigation actions adopted at the 21st Conference of the Parties [57], the legislations of the most technologically advanced states have evolved in the direction of promoting the development of renewable sources, and they have certainly been successful in terms of total installed capacity. However, the share of renewable energy consumption is struggling to grow significantly still remaining in the minority worldwide due to the concomitant increase in overall consumption together with the inherent low capacity factor of renewable sources (solar, wind, hydro in some cases). We can therefore state that,

"*From an energy perspective, the goal of efficiency should be considered concurrently with that of reducing overall consumption.*"

Without this reduction, it will be difficult to achieve the increase in renewable share stated by the legislations, as, for instance, the European Green Deal [58], which aims at reaching carbon neutrality for European countries in 2050. Thus, the limitedness of the atmosphere and of every other natural element involved in energy generation (water, raw materials, …) must necessarily direct us towards the search for new consumption patterns that reduce the overall energy consumption, which is the primary cause of changes in environmental balance.

The focus must then shift to the whole of society, no longer to the individual conversion plant, seeking the best interaction between different energy conversion and storage systems according to the objectives we want to pursue. Therefore, starting from the consideration that our society requires a complex multi-energy system and its associated energy distribution networks, we certainly cannot proceed only with a "plant-by-plant" optimization, and we must necessarily ask the following question:

"*Which are the objectives of the society*?"

Fig. 7 shows for instance a block scheme (superstructure) of the Italian energy system [52]. The blocks included in the red-dotted box represent different types of energy conversion units, energy storage capacities and energy transport infrastructures. In the left side of the box, all categories of renewable and traditional energy sources are shown, while in the right side, all the energy demands. The energy conversion units and networks of this very complex system can be modeled with the desired level of detail depending on the number and type (linear, bi-linear, non-linear) of the utilized equations, and all these sub-models included in a database [59]. The “superstructure” of the whole energy systems (Fig. 7) is then built by connecting in all possible ways the energy conversion and storage units. The design optimization of this superstructure allows identifying type, number and size of the energy conversion units to include in the system in order to minimize (or

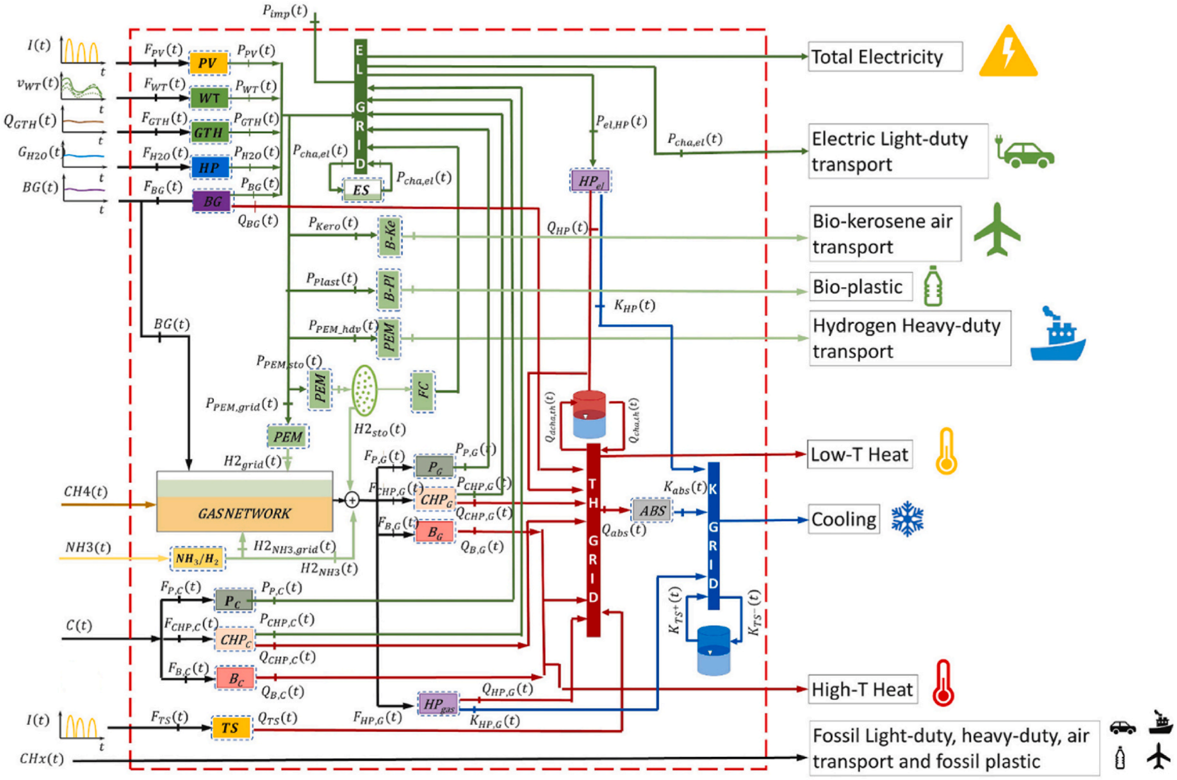

Fig. 7. Superstructure of a multi-energy system representing the Italian energy system [52].

maximize) a single objective function or multiple objective functions. The model must be flexible to include as many constraints as possible to allow a reliable prediction of the design and operation of what the future system might look like, in relation to variations of the boundary conditions (demands, costs, legislation, …) that depend on different human activities and more or less predictable changes in the availability of energy resources. Assumptions may be different depending on the problem to be solved. For instance, energy demands may be assumed to be known (either in a deterministic or probabilistic way), the total share of renewable energy consumption or the total emission levels can be imposed according to regulatory policies, the maximum cost for the total system can be fixed to limit overall expenses, etc.

A representation like the one in Fig. 7 could be made for any country, region, city, industrial or housing district in the world. However, certainly, this model would be very different from zone to zone. How might it look, for example, for a developing country? Again, some questions arise, which are not easy to answer:

"*What are the most sensible objective functions to consider for those countries that barely achieve survival conditions for the majority of the population?*"

"*Are there universal goals toward which every state should converge?*”

Certainly, the goals may remain the search for maximum efficiency or minimum cost of the total system. In the latter case, it is still necessary to have reliable cost functions of all energy conversion systems, which can be expressed in terms of their product, as well as the other variables in the total system model, as described by Rech in Ref. [59]. However, the objectives of maximum efficiency and minimum cost must generally be enlarged, and the total model must also include other constraints than those strictly associated with energy conversion (e.g., social and political), as well as the evolution of these constraints over time (dynamic optimization). Fig. 8 shows the well-known seventeen goals of the United Nations [53] stated in 2015 as part of the 2030 Agenda for Sustainable Development. Those most directly related to energy conversion and consumption are the seventh (affordable and clean energy) and twelfth (responsible consumption and production). All the others are actually closely related to them because of any interaction with the environment and the socio-economic conditions of humanity. All 17 goals are well summarized, in the following three: **end poverty, protect the environment and ensure prosperity for all** [60]**.**

The question is:

"What can researchers, and particularly engineers, do to find realistic solutions to make the overall energy system as consistent as possible with these three general goals?"

A certain and unambiguous answer is impossible, and would require investigating and establishing the meaning of "prosperity" and "poverty," as well as knowing in a general sense what are the best criteria for truly defending the environment. What is certain is that some problems (poverty eradication) have a much higher priority than others, and this requires innovative models of intervention and development, which can also develop within market logic [61], and certainly a comprehensive global view of energy and environmental problems. On the other hand, it is equally certain that in every country, region, area of the World, there is the need to satisfy the current energy demands with appropriate energy conversion systems [62].

Fig. 8. UN sustainable development goals [53].

However, different countries have different "energy needs" and more or less urgent actions to undertake. We can measure prosperity with the Human Development Index [63], and increase this Index by increasing availability and consumption of energy of poor countries while keeping their already existing good equilibrium with environment. Conversely, to drastically reduce the environmental impact of "rich" (developed) countries, with high HDI but too high energy consumption, we must first rationalize the usage of energy to decrease the absolute value of primary energy consumption. This can be done by pushing low-consumption/low-environmental impact technologies [64]. This necessity requires us to ask several questions, including:

"What does it mean to “waste" energy?” “How can the "minimum waste" goal (objective function) be defined?”

Are there criteria for defining the minimum/proper energy needs of a human being regardless of location? What are the acceptable levels of consumption for the planet? "

Independently of the definition, the “waste objective function” must be minimized everywhere to meet the three general objectives mentioned above (end poverty, ensure prosperity for all, protect the environment).

Dealing with an *energy conversion process*, a *waste* can be defined as *the use of an excess of energy compared to the minimum required to fulfill a specified energy demand or to obtain a certain product*. For these processes, maximizing efficiency is equivalent to minimizing waste. However, this is true for energy conversion only, and does not consider the demand side, that is the way in which energy is consumed by the end users. Clearly, it has little effectiveness to seek waste reduction in energy conversion without seeking waste reduction in the use of energy itself. This issue obviously invokes the need to evaluate without conditioning or mistaken habits the ways in which energy is actually used, questioning the uses that are "not properly necessary" because they are overabundant compared to real needs. As such, they cannot be proposed to everybody, because they would not be bearable by the ecosystem. Spreng [65] proposed a primary energy consumption target of 2000 W per capita (“*the 2000 W/capita society*”) to be applied worldwide and that can be sustainable for both environment and society. However, this target is utopian for the Author himself.

This paper was written a few years ago, but this still open problem has subsequently been only much discussed but little addressed, thus greatly lengthening the energy transition towards a renewable system. The delay in becoming aware of the impossibility for the environment to bear an excessive consumption of energy (and consumer goods in general) now leads to the need to intervene "immediately" to avoid even catastrophic consequences [66]. However, this is not rationally possible due to the long installation times of the plants generating the huge renewable energy needed to replace all fossil energy, and requires first considering those interventions that have the best impact on the environment and society as a whole. Given the complexity of the problem, experts from the various disciplines involved propose different recipes, including the need to accept these catastrophic events, or to return to technologies already abandoned for safety and health reasons (nuclear) [67].

In the final analysis, it is a matter of considering the energy problem as a global problem involving all humanity, where the excessive consumption of some leads to energy shortages for others, and thus results, if nothing else, in a "lack of respect" toward them. Of course, these considerations cannot disregard the "models" of societies of individual countries. Many countries have acquired the so-called "western" model based on the search for GDP growth as the only criterion for increasing the individual’s wealth, although often disregarding adequate wealth distribution criteria. Is this the way? Certainly, this approach has led to an enormous improvement in the well-being of many people, and of entire countries as a whole. However, at the same time, it can be certainly be improved to ensure a more equitable distribution of energy use and the benefits that come with it. Can "prosperity for all" be ensured by increasing GDP, regardless of appropriate distribution criteria and regardless of the fact that there are other cultural and developmental patterns of individual countries? Interesting ideas on this issue have been proposed and applied by a former president of Uruguay, Mujica (see for example his speech to the United Nations General Assembly on September 24, 2013 [68]). Moreover, some Authors proposed to integrate social science in energy research and energy policy (see, e.g., Sovacool et al. [69] and Spreng [70]). In any case, this issue must shift the attention of engineers to the "consumption" side, as highlighted in Section 6.

6. From engineering of “energy conversion” to engineering of “energy utilization”

Most of the discussion in Section 5 focused on the critical need to reduce overall energy consumption, while improving the efficiency of individual energy conversion systems, with an effort to achieve as much as possible the three general principles enunciated in that section: end poverty, ensure prosperity for all, and protect the environment."

Having established that the generation efficiency of individual energy conversion systems is generally very difficult to improve for most existing systems, attention must necessarily shift to what might be the most effective actions to reduce our society’s total energy consumption. Below we try to list some of them.

1) A better integration of individual conversion and storage units to take advantage of potential generation synergies between them, thereby optimizing the design and operation of multi-energy systems that supply energy to our society [71–73];
2) Aggregation of different local generation and demand loads of energy users into "energy communities" to reduce demand peaks and thus the required power to be installed [74–78]. Consequently, also the efficiency of fossil fueled systems and their environmental impact in the operation would be improved, as they it would work at more constant load.
3) A more efficient coupling of the entire generation system with the entire "demand system" [62] to size and deploy each plant in the most efficient, least costly, and least impactful way for the entire generation-demand system.
4) Search for a reduction of the absolute value of demand, through appropriate price- and incentive-based demand-response programs [79,80], or appropriate incentive policies, public awareness and education on proper energy use starting from elementary school training levels.
5) Actions to limit the maximum amounts of energy available for individual use should not be ruled out either, since it is quite inconceivable that a reduction in overall consumption (particularly, but not only, of fossil fuels) could take place without limitations on the consumption of individuals. However, it should be considered that these limitations on direct energy consumption (for individual use, as heating, cooling, etc.) would still not include all indirect energy consumption, associated with the purchase of goods (and even devices that use renewable energy but are not "strictly necessary," still involve energy consumption for construction and disposal of materials).

The actions listed above can be summarized as the search for the best possible integration among the elements that make up a society’s energy system, namely the energy conversion plants, the networks that distribute it, and the users who consume it. This integration requires a substantial paradigm shift in the overall design and management of the energy system. The system based on individual production facilities for individual users must be replaced by a system designed to serve the whole society, and the whole society must constitute itself as a community of people who consume energy to improve (or maintain) a better living condition. The design of the system must therefore be unique and optimized for the common good. This vision, which is reasonably utopian, can nevertheless be a reference to be pursued.

Actions 1), 2) and 3) in the list above are on young engineers shoulders, who are expected to manage in a “smart” way the design and operation of the overall integrated systems for energy conversion and consumption using complete models such the one presented above. Actions 4) and 5) are on users’ and politicians’ shoulders, and are reasonably the most important ones. In fact, even with the best systems in terms of efficiency and integration between energy conversion/storage units and energy networks, we might not be able to reach the high degree of sustainability in the short time that is necessary to avoid unexpected and uncontrollable climate change effects. Conversely, actions 4) and 5) may lead to a consistent reduction in the consumption of resources and pollutant emissions, with immediate positive effects in terms of sustainability. Increasing the awareness on the need to create a new energy system in “harmony” with nature is the key to success, and this has to start from the primary schools. Energy education is therefore crucial to mitigate the effects of climate changes and, why not, to finally solve this problem. On the other hand, education has consequent effects also on the politicians who decide policies for transition. In this respect, actions concerning aggregations of users into energy communities certainly go in the right direction. We stress the importance of aggregation as a key element for a prosperous future of society. In this regard, actions should start from local communities. Local governments should rank different utilities (i.e., energy users acting as consumers or prosumers) to identify those with the greatest synergies and coupling possibilities. The energy “demand system” could then consists of the aggregation of these local communities, rather than being composed of individual utilities, with the ultimate goal of achieving an overall energy demand curve that is more consistent with the total renewable availability curve, and at the same time, leading to a net reduction of the total consumption. This would have the added benefit of reducing the need for energy storage, resulting in lower costs for the system as a whole. The search for mechanisms ensuring a fair distribution of benefits from user aggregations, as well as a fair distribution of costs associated with the installation of new renewable plants among those who benefit from them, must therefore become a central theme of research in the field of energy conversion systems. Efforts in this direction have been already the subject of several researches [75,76], and may also benefit from allocation criteria based also on exergoeconomics analysis [49]. It is natural to think that every place in the world is different in habits, religions, customs, but every place can benefit from aggregation and interaction, while respecting and recognizing individual specificities. Energy policies must therefore seek universal means of aggregation, such as the identification of the most suitable energy users that could participate into energy communities, fair criteria for the distribution of profits resulting from aggregation, and compensation mechanisms for those who may suffer damages as a result of aggregation itself, or for those who may not be able to fulfill their commitments due to force majeure (e.g., illness).

7. The dynamic optimization model of the society or of its portions

The need for an integrated design and management of the whole energy system, including generation and storage plants, energy distribution networks and users (with different habits and customs), requires the development of tools that allow modelling this complex system in its totality by considering in it all variables involved, and especially those on which actors from different disciplines (i.e., engineering, economics, sociology, philosophy, politics) can intervene. The models should take into account contextually, on one hand, all the laws of physics, thermodynamics, and chemistry that govern the energy processes and, on the other hand, the design and operational constraints related to the above-mentioned disciplines, and the laws of the countries in which the energy systems operate. Eventually, these models represent the society in its entirety because of their capability to describe the relationship between energy problems and society [81].

Given the potentially huge size of the optimization problem, the degree of detail of the models will necessarily have to decrease as the size of the geographical area under consideration increases. Thus, if the size is that of an entire country or region, plants of the same type may be aggregated into categories, users may be aggregated by types (e.g., low-temperature thermal, high-temperature thermal, electric), and networks may be considered by common characteristics (e.g., high, medium, and low-pressure gas network, or high-, medium-, low-voltage electric networks). Conversely, if the size of the geographic area is smaller, such as housing or industrial districts, all individual energy systems (i.e., energy conversion and storage units) and interconnections (i.e., electric, thermal and gas grids) can be modeled precisely, without approximations. For municipal governments, the boundaries of analysis could be whole municipalities or parts of them, in which it will be possible to model in detail not only the associated plants and distribution networks with each specific existing constraint, but also the utilities, proposing aggregation mechanisms to create benefits for both individual members and the community.

In such a complex reality, it is certainly useful for the individual (or entity, company,..) to decide on the "energy interventions" that are most convenient locally, but it is difficult to think that these local interventions can always be consistent with the search for the overall optimum of the society in which they are implemented.

Thus, there is a clear need to operate both locally and globally, so that local interventions are consistent with those of a global nature, i.e., relating to the region-state, or in general to the overall context/society in which they are carried out.

This coherence highlights the pressing need to start from global models, which give the general guidelines for appropriate energy policies, within which local interventions fit.

Several questions can be asked here as well:

What kind of structure, equations, variables, and what kind of evaluations can this model perform? Is it possible to construct models that include all the variables involved without becoming overly complex and such that they take too long to compute, preventing their simple use, and such that they allow immediate evaluation of the benefits that can be obtained at the overall level? What are the objectives in using these models and what is the actual usefulness of the evaluations produced?

Below an attempt to answer.

- The overall model must certainly include sub-models that are capable of evaluating the behavior of all the conversion and storage systems included in them, both under design and off-design conditions. These sub-models include mass and energy balances of these components and the chemical and physical properties of the fluids involved, and should be included in databases that can be used by the overall model.
- The model arranges these sub-models so that the individual conversion and storage units can be aggregated not only with each other but also with the distribution networks in order to form the model of the overall system;
- The model must include time series of users' energy demands, evaluated on a deterministic or stochastic basis when necessary. The model must also be capable of "managing" these demands according to utility aggregation criteria [82] and demand-response programs [83].
- The overall model is part of an optimization problem that must be solved by an algorithm capable of considering different sets of decision variables.
- The model must consider also all constraints other than energy-technology ones, i.e. those associated with the economic environment (investment costs, costs and prices of different forms of energy and their variability over time,..) and the natural and regulatory environment (limitations on emissions, incentives,..), as well as arising from social issues (acceptability and acceptance and consequent time for installation, use of labor, working conditions, etc ….).
- Goals (objective function(s)) should be clearly established and properly expressed in mathematical terms.

Fig. 9 shows the conceptual scheme of a computational platform (named here "Catharsis") capable of building an energy system model that includes the above-mentioned features.

The platform builds the model of the considered system starting from a superstructure (red part in the center) containing (in a database) all available conversion and storage units in the considered geographical area. The platform chooses the optimal number, type, and size of these units and builds the network to connect them together and distribute power to users according to the optimal value (minimum or maximum) of one or more target functions. The same central part (red) of the superstructure includes the optimization procedure driven by an appropriate algorithm capable of evaluating the objective function for each set of values of the system's independent/decision variables. The construction of the model requires setting all constraints arising not only from the technological-energy limitations of individual conversion and storage facilities, but also economic (investment costs, costs and prices of energy consumed and sold, …), environmental (limitations on emissions, materials to be used …), social (acceptability of renewable and fossil fuel based plants, occupation of areas intended for other uses, …), political-legislative (restrictions imposed by legislation, incentives, taxes, …) constraints. The nature of the model is dynamic, since all variables involved are time-dependent. This feature is crucial given the need to shape the energy system of the future, especially in the "energy transition", by progressively choosing the energy conversion units that best fit to a specific location at a specific time. The model has a Mixed-Integer Linear Programming formulation, where integer variables are used to decide the inclusion or exclusion of conversion and storage units in design problems, and their activation or deactivation in operation problems. General features of the models have been presented in Refs. [59,84]. The last stage in the development of the platform concerns the contextual search for the optimal configuration of the energy generation and storage system and the configuration of the networks that distribute the energy produced [85,86]. This comprehensive view of the system can also include utility management, through organization into energy communities or membership in demand-response programs. Once the optimal configuration and design variables of the generation/accumulation units and energy networks are defined, a final exergetic, exergoeconomic, environmental or life-cycle assessment of the overall system [87] can be performed to obtain a complete picture of its performance and environmental compatibility (bottom right in Fig. 9). In this way, the platform stands as an essential tool for designing and managing the energy system, from generation to demand for the portion of "society" under consideration.

8. Conclusions

This paper is an attempt to trace in a simple way the extraordinary evolution in the research on energy conversion systems that has taken place in recent years. In particular, the purpose was to see how exergoeconomic analyses have played a pioneering role in expanding energy-only analyses toward the whole set of disciplines that are necessarily involved in the design and use of an energy system, starting with economics. The initial focus on increasing the exergetic efficiency of large fossil fuel plants that supplied almost all of the energy for end uses necessarily shifted to the simultaneous search for the best trade-off between this increase and cost reduction, taking into account all the

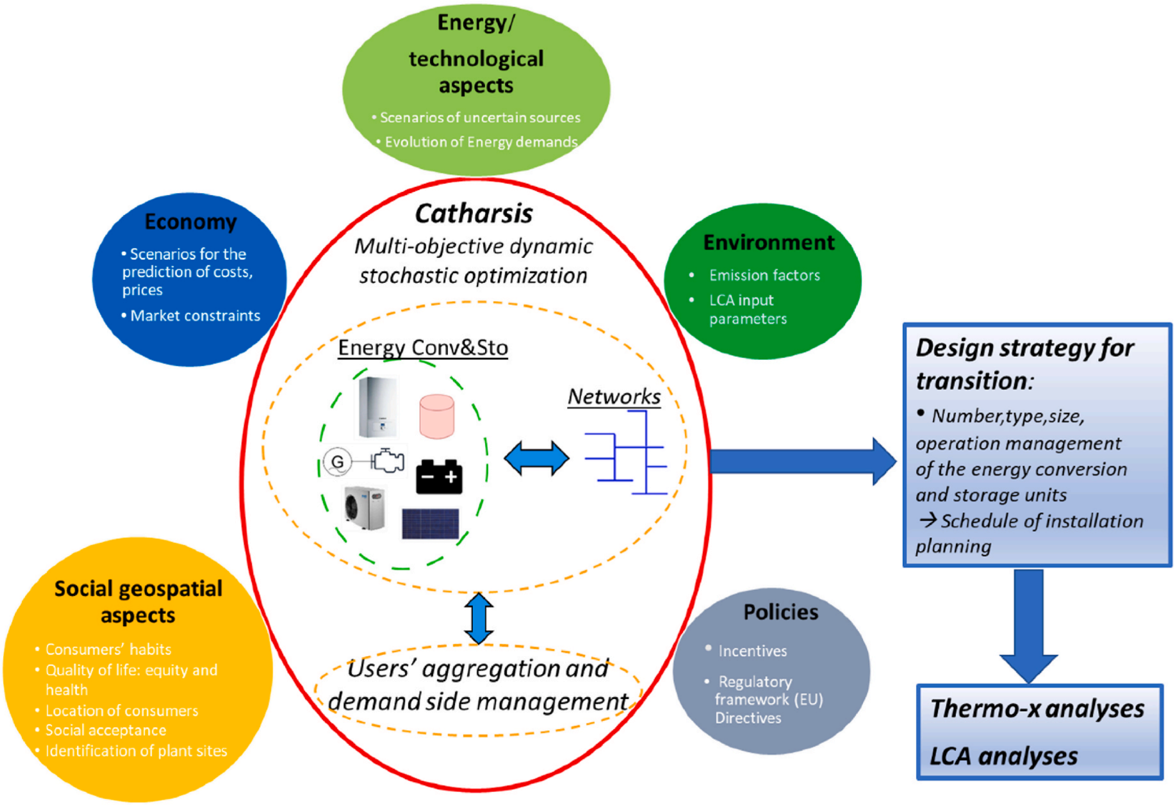

Fig. 9. Calculation platform for planning the installation of new energy conversion/storage systems and the grid in the future.

environmental issues involved in the conversion and use of the energy generated. It is precisely this necessary consideration of the "environment," understood not only as "nature" but also as "humanity" inhabiting the world, that has shifted the focus from the individual plant to larger geographic portions where there are different individuals with different energy needs. These portions of the universe, and ultimately the whole world, require a design the overall energy system of the future in the most sustainable way possible, to give future generations the same opportunities for consumption and well-being as existing ones. To this end, the work of the energy engineer must be concerned with all energy conversion units and energy distribution newtworks included in the geographical portion under consideration taking into account all external constraints. Accordingly, the paper shows that other types of "X" analyses should be added to the exergoeconomic ones to include all aspects involved in energy use, with the ultimate goal of reducing overall consumption and distributing it more evenly around the world as the only means of achieving a truly sustainable system. In this direction, the paper also demonstrates the importance of forecasting models that are capable of predicting and optimizing the design and operation of the energy system of the future by considering the real physical processes involved along with all the external constraints, while maintaining a simple structure. This feature allows useful and realistic results to be obtained quickly and in a way that is easily understood even by non-"insiders." In the future, the ambition is to make these models in common use, especially in public administrations and private companies, to build the overall system of the future as consistent as possible with the sustainability needs of society as a whole.

CRediT authorship contribution statement

Andrea Lazzaretto: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Massimo Masi:** Writing – review & editing, Supervision, Formal analysis. **Sergio Rech:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Gianluca Carraro:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Piero Danieli:** Writing – original draft, Validation, Methodology, Formal analysis. **Gabriele Volpato:** Methodology, Formal analysis. **Enrico Dal Cin:** Writing – original draft, Visualization, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Nomenclature

c	cost per monetary unit ($\$/kJ$)
$\dot{C}$	total cost flow rate ($\$/s$)
CHP	Combined Heat and Power
e	specific exergy (kJ/kg)

$\dot{E}$	exergy flow rate (kJ/s)
$\dot{m}$	mass flow rate (kg/s)
MINLP	Mixed-Integer Non-Linear Programming
$\dot{W}$	mechanical power (kW)
$\dot{Z}$	amortization cost flow rate ($\$/s$)
ε	energetic efficiency
η	exergetic efficiency

Subscripts and superscripts

$e, 2$	exit
F	related to a fuel stream
$i, 1$	inlet
k	related to k-th component
P	related to a product stream
q	heat
w	work

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