A contribution to the discussion on the Future of Thermoeconomics

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Abstract:

'Thermoeconomics' was introduced and its foundations were laid down by Tribus, Evans and El-Sayed in the late 1950's – early 1960's as a method that combines Thermodynamics (in particular Second-Law quantities) and Economics for the analysis, evaluation and optimization of thermal systems. Since that time, many researchers throughout the world taking various roads helped in developing Thermoeconomics from theoretical point of view and applying it in a variety of systems, thus establishing it as a particular field.

Today, questions such as the following may be posed:

- Is there room for further theoretical development of Thermoeconomics?
- Are there areas where Thermoeconomics has not been applied yet, however its application would be beneficial?
- What additional features should Thermoeconomics have, in order to be applied to these areas?
- Is it possible to introduce other considerations, in addition to thermodynamic and economic, in a more holistic approach? If yes, which are they?

In this paper, the authors present in brief their own approach to Thermoeconomics and then they attempt to give answers to the questions, without any claim of completeness.

Keywords:

Thermodynamics; Economics; Thermoeconomics; Second-Law analysis; Optimization.

1. Introduction

'Thermoeconomics' has been coined by M. Tribus as a name for the technique that combines thermodynamic with economic considerations for the analysis and optimization of thermal systems. As it is written by El-Sayed [1], the first landmark of work on thermoeconomics was by Tribus and Evans [2,3] and dealt with seawater desalination processes. The seeds of this work, however, are found in an earlier report by Tribus and co-workers [4], while Evans and El-Sayed developed it further [5-7] and extended the application to thermal systems in general. Significant contributions along these lines in the US were made also by R. Gaggioli and W. Wepfer [8,9].

As it is written by R. Gaggioli [10], the idea of using exergy (availability in the US) for costing energy products appeared in the US in the 1930's:

'… Keenan, who refers to the costing idea in the appendix to his 1932 paper [11]. *(As others have informed us, while teaching at Stevens Institute, Keenan had informed a perplexed cost accountant from a local cogeneration utility, how to charge fuel costs to its steam and electricity products).'*

The idea of combining second law (and exergy, in particular) with economics appeared also in Europe in the same period with thermoeconomics. It is interesting to quote a statement written in a paper by Z. Rant published in Slovenian [12] and translated in English:

'The existing method for energy pricing (accounting) in combined plants on the basis of used enthalpies is fundamentally wrong. It has to replace with pricing (accounting) on the basis of used exergies, which is the only proper way.'

It is worth noting that the word 'exergy' ('eksergij' in Slovenian) appears already in this article, one year before Rant's landmark article [13], where he explains how he coined the word 'exergy'.

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Important contributions in these early years in Europe were made also by Szargut [14,15], Beyer [16], Borel [17] and Fratzscher [18].

As written by El-Sayed [1], thermoeconomics rises on three main pillars:

1. Improved thermodynamic analysis (includes second law of thermodynamics quantitatively rather than qualitatively).
2. Improved costing analysis (a closer look at the interaction between fuel and equipment).
3. Enhanced optimization (interdisciplinary approach: thermodynamics, design, manufacture, economics).

In the decades following the early years, the interest in thermoeconomics has increased internationally, a variety of methods have been developed and many applications have demonstrated the usefulness and importance of thermoeconomics.

Today, questions such as the following may be posed:

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- What additional features should Thermoeconomics have, in order to be applied to these areas?
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In the following, the authors present in brief their own approach to Thermoeconomics and then they attempt to give answers to the questions, without any claim of completeness.

The structure of the paper is as follows. The main methodologies are mentioned in Section 2 with emphasis on the functional approach developed by the authors. Section 3 presents thermoeconomics with additional aspects at an early stage and the needs of further development. In Section 4, further considerations and application areas of thermoeconomics are presented together with needs for proper methodological development. The paper closes with remarks regarding the aforementioned four questions and a more or less comprehensive list of references.

2. Progress to date

2.1. Thermodynamic and economic considerations

Several schools of thought have been evolved in the last four decades [1,19], each one characterized by the particular approach it follows, such as the exergoeconomic analysis [20], thermoeconomic functional analysis [21-25], structural theory [26], specific exergy costing (SPECO) [27,28].

2.2. Environmental considerations in addition to thermodynamic and economic

The concern for the depletion of energy / exergy resources led to the development of the aforementioned methods, in an attempt to save energy / exergy by proper analysis and optimization of energy systems.

Soon became evident that energy-related activities cause depletion of other scarce natural resources, in addition to energy, as well degradation of the environment. In order to take these effects into consideration, thermoeconomics had to broaden its basis and methods such as the following appeared in the literature: Cumulative Exergy Consumption [29-31], Thermo-ecological Analysis [31-34], Extended Exergy Accounting [35-37], Environomics [38-41], Exergo-environmental Analysis [42].

Since other contributors to the development of thermoeconomics participate in the discussion about its future, the presentation in this section is not intended to be a general review of thermoeconomics and, therefore, only certain characteristic publications are cited, while more emphasis is given to the functional approach developed by the authors.

2.3. Thermoeconomic functional analysis and optimization

2.3.1. The basic formulation

The basic formulation of thermoeconomic functional analysis (TFA) appears in [21-22]. In TFA, it is considered that the system consists of a set of inter-related units, with each unit having one particular function (purpose or product). Functional analysis is the formal, documented determination of the function of each unit and of the function of the system as a whole.

The functional diagram is a picture of the system consisting of geometrical figures representing the units and a network of lines representing the distribution of the unit functions (Figure 1). Junctions connecting the functions of two or more units and branching points distributing the function of a unit to two or more units are additional features of the functional diagram. The functions of units are quantified by means of second-law properties such as exergy and negentropy.

Since the beginning, TFA is formulated so that it can be applied for analysis, evaluation, product costing [44] and optimization of energy systems. If needed, decomposition of the system into subsystems facilitates the

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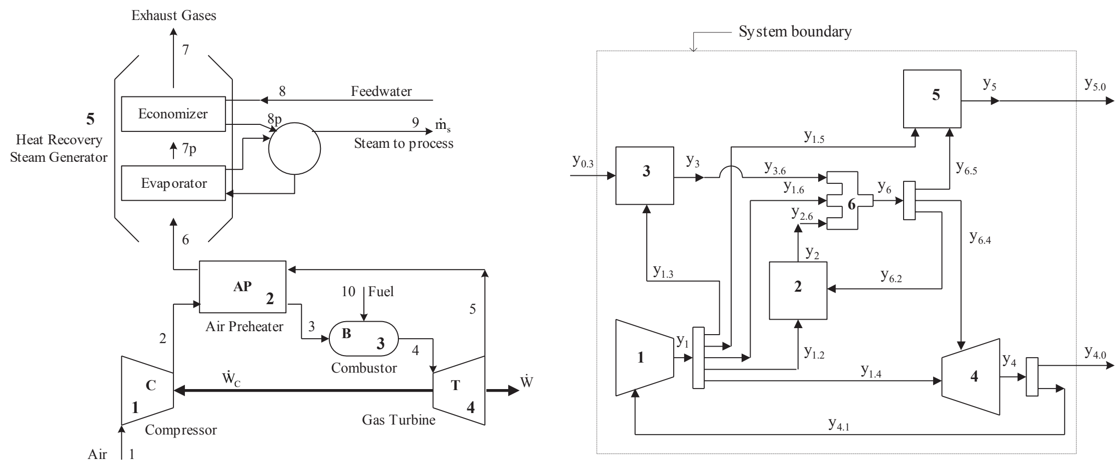
solution of the optimization problem [23]. Even though the formulation is such that physical economics can be used (every cost is measured in physical units such as exergy), the method has been applied with monetary economics.

It is interesting to note that the productive structure introduced later on by Valero and his co-workers is based on the functional diagram, as written in Ref. [45].



(a) (b)

Figure 1. Example of a functional diagram: a) flow diagram of a gas-turbine cogeneration system, b) the functional diagram of the system [43].

2.3.2. The intelligent functional approach (IFA)

Optimization can be considered at three levels (Figure 2): synthesis (components and their interconnections), design (nominal technical characteristics of each component and of the whole system) and operation (operating state at each instant of time): SDO optimization. If complete optimization is the goal, each level cannot be considered in isolation from the others. Thus, the optimization problem can be stated by the following question:

> *What is the synthesis of the system, the design specifications of the components as well as of the whole system and the operating state at each instant of time that lead to the overall optimum?*

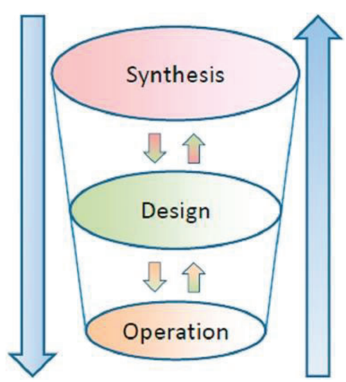


Figure 2. The three interrelated levels of optimization.

Thus, TFA was further developed, in order to address this complex optimization problem [46,47]. The name ‘intelligent’ is due to (i) the information (‘intelligence’) obtained by the analysis and during the optimization procedure in the form of proper indexes (e.g. Lagrange multipliers) and (ii) the intelligent (guided by intellect, rational) use of this information for the solution of the optimization problem. The superstructure approach is followed for the synthesis optimization.

Of course, if the synthesis of the system is given, the optimization determines the optimal design and operation. If both the synthesis and design are fixed, operation optimization is performed. IFA can be applied for any of these problems.

2.3.3. Environomic functional analysis and optimization

IFA was further developed, in order to take into consideration environmental aspects quantitatively, in addition to the thermodynamic and economic considerations [38-41].

Pollution indexes and degrees of abatement of the various pollutants are defined, and pollution abatement equipment is included in the system. Thus the total cost consists of the (i) installed cost of components including pollution abatement equipment, (ii) cost of resources, (iii) environmental and social cost due to pollution. Complete optimization (synthesis, design, operation) can be performed. The degrees of abatement are among the independent variables of the optimization problem, which determine the design and operation characteristics of the pollution abatement equipment.

The costs to the environment and the society due to damages caused by pollutants emitted from energy conversion systems are called ‘external costs’ (external to the system) or ‘externalities’. It is noted that damages are caused not only in the vicinity of the system, but also in distant areas, even in other countries, that are in the trajectory of pollutants dispersion. Methods for estimation of these costs and publications with first results are mentioned in [48], while joint systematic research at the European Union level led to the development of a method for environmental impact analysis [49] and estimation of externalities [50] supported by related software. More information and an application are presented in [51]. It has to be recognized, however, that this is an effort that has to be continued for improving the methods and decreasing the uncertainty of the results.

Numerical examples including sensitivity analysis demonstrated that, in spite of the uncertainty, it is prudent to take environmental and social costs into consideration in the analysis and optimization of energy systems, than to ignore those.

2.4. Other approaches to the thermoeconomic optimization of synthesis, design and operation of energy systems

The SDO optimization of energy systems requires the derivation of the system configuration either through the automated synthesis during the optimization process or by the definition of a generic super-configuration – consisting of all possible alternatives examined – with the optimal one determined as the output of the optimization procedure. The former approach has been followed in [52,53], while the latter was used in [54-57]. Further, the complex optimization problem of three levels (SDO) can be reformulated in two levels: (A) synthesis and design, and (B) operation. The solution is obtained by iteration between the levels A and B [54-56]. This improves significantly the computational cost of thermoeconomic optimization allowing for complex models of systems and cost functions to be used.

The works presented in [54-56] introduced thermoeconomic optimization in marine energy systems for cruise ships and LNG carriers. In further works, thermoeconomic optimization was applied to Organic Rankine Cycles for low temperature waste heat recovery from ship energy systems [57] and to a marine combined cycle system [58]. In [59] the complete SDO optimization problem is tackled at a single step, with no need of reformulating it in the aforementioned levels A and B. Of course, higher computer capabilities are required for such an approach.

Further developments appear in [60-61] with the introduction of dynamic and intertemporal optimization in the SDO optimization. Dynamic and intertemporal optimization describes situations where subsequent decisions are affected by decisions taken earlier in the time horizon of the optimization problem. Coupling this class of problems to thermoeconomics allows for a wider and more realistic range of energy systems applications to be addressed.

The application of thermoeconomic SDO optimization to ship energy systems is an important contribution to the extension of thermoeconomic approaches due to the complexity of the marine environment. Ship energy systems are isolated (sailing at sea), resource constrained, and highly interconnected with many space, weight and safety constraints. Further, they have many operational modes and wide mission profiles. Therefore, the thermoeconomic methodologies and optimization algorithms often need special adaptation to be successful in marine applications, as the referenced works suggest.

2.5. Achievements not possible without thermoeconomics

The use of thermoeconomics in the analysis and optimization of energy conversion systems acts as a “common denominator” in identifying the sources of losses and their impact on efficiency and costs throughout the system. The major achievement of thermoeconomics lies in to having a methodology that can attribute both costs and energy / exergy efficiency to components and products of a system in a rational and

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uniformly applicable manner. This increases the objectivity, trust and transparency of the engineering decision making process when assessing, comparing and optimizing various design and technology alternatives.

Thermoeconomics also uses correlations, i.e. cost functions, of the capital expenditure for the various components of an energy conversion system with their respective design characteristics and performance figures. This is a unique way to assess the impact of technology both in the performance and energy efficiency as well as the cost of the products per unit of energy or exergy. More simple technoeconomic analyses often fail to reveal the dependency of technology with performance and cost of useful products. Therefore, thermoeconomics offers the means for a more robust and informed decision-making process when considering the synthesis, design and operation of energy conversion systems.

3. Thermoeconomics with additional aspects at an early stage of development

Formulations and applications of thermoeconomics with reliability analysis, risk analysis and control of energy systems are presented in brief here. These are interesting subjects but they are at an early stage of development with very few publications. Further development of methodologies combined with more applications would be more than welcome.

3.1. Thermoeconomics with reliability analysis and optimization

In optimization of energy systems it is usually considered that the equipment is not subject to failure and, consequently, it is available for operation at any instant of time, except of predetermined periods of maintenance. Redundancy is provided empirically and as a consequence the configuration of the system may be non-optimal. Let it be mentioned that the reliability and availability of energy systems is a critical economic and efficiency factor.

In [62], reliability and availability are introduced in the thermoeconomic model (IFA formulation) of the system and optimization of synthesis, design and operation under time-varying conditions is performed. The IFA facilitates the solution. A numerical example with a cogeneration system shows that the introduction of reliability leads to an entirely different optimal solution for each one of the three levels (synthesis, design, operation), while profits from selling the products of the system (electrical and thermal energy) are overestimated, if reliability aspects are ignored. More recently in [63], thermoeconomic optimization is coupled with availability considerations for the assessment of a compressed air storage system. Though no optimization is attempted, the differences in expected cost of electricity and profits are assessed with and without reliability considerations highlighting important differences.

Incorporation of reliability into thermoeconomics requires methodological advances on the reliability modelling of energy systems. The most suitable approach, the state-space-method appearing in [62], exhibits an exponential computational burden when the number of system components is increased. There is need of developing reliability assessment methodologies that have significantly lower computational cost and, at the same time, are capable of describing the multiple states of partial failures and reduced output that the whole system may encounter.

In addition, reliability considerations need to be also coupled with the individual component cost functions allowing for increased time between failures or reduced time to maintain a system component, factors that affect the capital cost per unit of time. A revision is also needed on how the maintenance operational expenses are considered up to now, incorporating the mean time to repair as a component of the maintenance costs.

3.2. Thermoeconomics with risk analysis – Thermorisk

Combined quantitative risk and exergy analysis is proposed in [64-65], in order to assess impacts from major accidents in energy systems. Impacts on human health are considered. The method is used to minimize damages of major accidents by proper energy system design. An application example is presented in [64] that minimizes the specific risk (risk per unit exergy of the plant product) of a geothermal drilling plant connected to an organic Rankine cycle system.

In [66], a power and fresh water cogeneration system is studied, consisting of a Rankine cycle, an organic Rankine cycle and a reverse osmosis module. Exergy, economic and risk analyses are performed, followed by multi-objective optimization of the system with the total cost rate and the total specific risk as objective functions.

The work initiated in [64-66] introduces an important dimension in thermoeconomic analysis. In real-world applications the decisions affecting the selection, design and operation of a system also address the total cost of ownership (TCO). The present forms of thermoeconomics account for many of the TCO dimensions such as capital expenditure, operational, maintenance and environmental costs. However, the implicit costs due to safety, major accidents, regulatory compliance and loss of production due to spares availability are not addressed in a thermoeconomic context up to now. These dimensions are typically assessed via risk assessments methodologies either qualitatively or quantitatively.

The expansion of thermoeconomics towards incorporating risk assessment elements and results will allow for a more holistic framework of analysis, insight and optimization of energy conversion systems. The main extensions required are in the areas of correlating the probability (likelihood) and severity with cost incurred to the system and its components. Then the well-established thermoeconomic methodologies can incorporate and correlate these costs with exergy flows and technical characteristics of the components of the system. Such an extension of thermoeconomics with risk assessment elements will further increase the applicability of the methodology to realistic decision making processes.

3.3. Thermoeconomics with control of a system

Only few publications are mentioned here, but they are adequate for understanding the current state of development.

In [67,68] the thermoeconomic approach is used to evaluate compare and improve the performance of alternative control strategies. An exergetic cost and a monetary cost are associated with the control system. Application to a gas turbine unit driving a generator shows that, with proper control, fuel consumption and operational cost at part load can be significantly reduced in comparison with typical control strategies.

In [67] the effects of the control system on the thermoeconomic diagnosis of a power plant are studied. The role played by the control system on the propagation of malfunctions is analyzed. The control system sometimes forces the plant to operate in a less efficient mode, inducing inefficiencies and malfunctions in the components. In order to avoid these effects, thermoeconomic diagnosis is applied that takes the control system behavior into consideration in the analysis directly. The procedure is applied to a gas turbine cogeneration system.

A review of applications of the second law of thermodynamics to control of energy systems is given in [69], primarily in the building sector. Out of 58 papers reviewed, only three papers apply thermoeconomics / exergoeconomics. In [70] an economic analysis of the exergy-efficiency control strategy of a geothermal district heating system is performed and it is estimated that the new controller (PID) has a payback period of 3.8 years. In [71] the structural theory of thermoeconomics is applied in order to determine the optimal load allocation strategy of the HVAC system of an airport terminal. In [72] energy-based, exergy-based and exergoeconomic-based control strategies of an HVAC system in the built environment is performed and it is shown that the last one could reduce the annual operation costs by up to 23%.

It is noted that in the literature, the words ‘control’ and ‘dynamic’ are used with two different meanings: (a) control of multi-stage operation with steady state in each stage; it sets the operating point of a system at each stage as the conditions (load, environmental temperature, etc.) change from stage to stage, without taking into consideration the transients; (b) control of transients; it specifies the trajectory that a system will follow, in order to go from a steady state to another one. References [67,71-73] belong to the first category, while Refs. [68,70] belong to the second category. In the following, the word will be used with the meaning ‘control of transients’, while setting the operating point of a system in each stage of a multi-stage process is covered by the intertemporal SDO optimization. Needs of further development are presented in brief.

Thermoeconomic control optimization can be considered either in isolation, i.e. optimization of the transient(s) only, or integrated with the intertemporal SDO optimization of the system. In both cases the control unit itself is subject to SDO optimization. There are several configurations of controllers depending on the required control action such as on-off, proportional (P), integral (I), derivative (D) and combinations of those (e.g. PID). The optimal configuration of the control unit is requested (synthesis). For each configuration, the optimal specifications of the components have to be determined (design), followed by optimal adjustment of characteristics (e.g. time constant, gain, damping ratio) in particular periods (operation).

Of course in order for the optimal control to be thermoeconomic, a proper objective function has to be defined. An example of such a function is formulated as follows. During a transient operation along a trajectory specified by the control unit, exergy is used by the whole system including the control unit. Minimization of this exergy is desirable, but such a control action may overstress certain components of the system, thus increasing the frequency and cost of maintenance and/or decreasing their lifetime; the last one causes an increase of the capital cost per unit of time. The total cost (exergy+maintenance+capital) is a very proper thermoeconomic objective function. With appropriate selection of the additive terms, such a function can be defined for the optimization of a single transient operation or for the optimization of the whole period of operation, including transients, as written in Subsection 4.2.

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4. Further considerations and application areas of thermoeconomics with proper development of methodology

4.1. Social aspects in thermoeconomics

Currently, thermoeconomics includes thermodynamic, economic and environmental considerations. In the last one, the cost to the society due to emission of pollutants and depletion of natural resources is included either in physical units (exergo-environmental analysis, extended exergy accounting) or in monetary units (environomics). However, the construction and operation of energy systems has not only adverse effects but also benefits to the society. Therefore, an interesting and important extension of thermoeconomics is to include both cost and benefit to society.

Evaluation of projects for their effect on the society with criteria such as job creation, general welfare, standard of living, etc., is widely performed, but the quantitative inclusion of these aspects in thermoeconomic analysis and optimization needs to be developed. Hints of how this can be performed are given by the following publications (indicative only).

In [74] a system of forest-based biorefineries and biofuel supply chain is studied and a multi-objective optimization is performed with three objective functions: (i) maximization of newly created jobs, (ii) maximization of the net present value, and (iii) maximization of the GHG emission savings compared to the current supply chain.

Closer to the energy systems studied by thermoeconomics is the work presented in [75]. Optimization of a thermal-solar-wind combined power system is performed with two objectives: (i) Minimization of economic cost (construction, operation and maintenance, CO_2 cost) and (ii) maximization of social benefits that consist of consumer surplus, government revenue and environmental benefits brought by CO_2 reduction.

The effort is still at its infancy and there is need of significant methodological development for inclusion of social aspects in thermoeconomic analysis and optimization of energy systems.

4.2. Thermoeconomic dynamic optimization of synthesis, design and operation including transients

Even though very few, there are publications on thermoeconomic SDO optimization with multi-stage operation or on optimization of transients, but the complete problem of thermoeconomic SDO optimization addresses the whole life of an energy system taking the complete operating profile into consideration that consists of interrelated periods (stages) of practically stead-state operation as well as transients.

The only publications known to the authors with such an approach are two papers [76,77], where optimization of the energy system of an aircraft that includes the phases of take-off, flight and landing is presented. Each phase is described by a different system of differential and algebraic (DAE) equations and the optimization must be performed for the whole trip. The method is open to further improvement and adaptation to other applications.

The required simulation model of an energy system may contain hundreds even thousands of differential and algebraic equations, making it computationally heavy and very time consuming. Therefore for practical applications there may be need of developing reduced models that are fast, yet with satisfactory accuracy. Examples of methods for developing reduced models are given in [70,78].

4.3. Thermoeconomic SDO optimization of energy systems including synthesis of the working fluids

In the preceding, the optimization of energy systems refers to the components, their interconnections, the technical specifications and the operating state at any instant of time, while the working fluids are selected in advance. If there are several fluids appropriate for the particular system, optimization is performed for each fluid in separate and the one with the best performance is selected.

In [79] computer-aided molecular design (CAMD) of the working fluid in an ORC system is applied that makes it possible to optimize the fluid and the thermodynamic system simultaneously in a single CAMD-ORC framework. The fluid is synthesized during the optimization procedure using several molecular groups (e.g. –CH3, –CH2–, =CH2, =CH–, etc.). The thermodynamic properties of the fluid are calculated by the group-contribution equation of state, SAFT-γ Mie, while critical and transport properties such as thermal conductivity, dynamic viscosity and surface tension are estimated using empirical group-contribution methods. The aim of the optimization is to determine the optimal combination of the molecular groups and thermodynamic variables that maximize the power output generated by the ORC for specified heat source and heat sink.

In a subsequent paper [80], the same system is studied, and two optimization problems are solved: (a) single-objective, minimization of the specific investment cost, and (b) double-objective, minimization of the specific investment cost and maximization of the power output generated by the ORC.

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In these works, the synthesis of the system is fixed and operation is considered at the nominal power. It would be very interesting to extend the method by applying thermoeconomic analysis and optimization of synthesis, design and operation under time varying conditions.

It should be mentioned that the term ‘thermoeconomic optimization’ is used in [80], but neither exergy is used, nor the second law is mentioned explicitly. This fact raises the question as to whether the use of the word ‘thermoeconomic’ is justified.

4.4. Thermoeconomic SDO optimization with variable synthesis through time

The recent decarbonization concerns for land-based and marine energy systems introduce new fuels, technologies and energy improvement measures to be considered. International and regional decarbonization regulations are introduced in gradual manner, becoming stricter and stricter over time. This entails that the environmental performance of a system has to gradually improve, usually staying below a regulatory trajectory over time. Therefore, a system that is compliant and cost effective now, may not be any more at some point during its economic lifetime. The question that arises is when to invest or re-invest in energy efficiency measures and environmental technologies in order to optimize the system throughout its lifetime.

This question becomes even more important under the new requirements for environmental performance goals with stricter limits (trajectories) over time. Thermoeconomic optimization methodologies should be adapted to identify the optimal point in the economic life of the system, in which a suitable technology is introduced. This needs to be extended also to the selection of the right type of technology or measure from a set of available and feasible technologies. Examples of technologies and measures that affect the environmental performance of energy systems are carbon capture systems, alternative fuels like hydrogen or ammonia (and their auxiliary systems), fuel cells, advanced waste heat recovery.

A further cause of complexity, especially in marine systems, is that some technologies cannot be introduced (retrofitted) later in the lifecycle of the system, unless the system is suitably prepared (becomes “ready”) during construction to accept this technology afterwards. For example, introducing a carbon capture system in a ship is significantly less costly if there is an initial provision of space, strengthening of structures and sizing of the energy conversion system to deliver more thermal and electric energy when needed by the carbon capture system.

The above considerations indicate that the standard formulations of thermoeconomic optimization problems need to be revised to account for variable investment points in the time horizon. In addition, the synthesis part of the optimization becomes more important with larger sets of available technology alternatives.

4.5. Low and zero carbon fuels and cryogenic systems

In close relationship with the Subsection 4.4, decarbonization concerns have introduced new fuels, technologies and systems that require analysis, assessment and optimization. Although thermoeconomics has proven its general applicability, there is need for a refinement of methodologies in conjunction with decarbonization considerations.

The decarbonization of land-based, offshore and ship energy conversion systems introduces a multitude of new fuels with low or zero carbon footprint such as hydrogen, ammonia, methanol and synthetic gas or liquid fuels. The actual emissions footprint of these fuels depend on their production, storage, transportation and energy conversion processes. Each of these stages consumes energy and has an inherent efficiency that affects the carbon footprint, the efficiency and cost of the fuel. Introducing exergy analysis and thermoeconomics to the assessment of the value chain of the production, delivery and use of the fuels will significantly enhance the rational and uniform evaluation of their value chain impact on greenhouse gas emissions and overall costs – including the effect of capital expenditure of production and storage infrastructure. Further, the introduction of novel fuels with novel production methods like hydrogen and ammonia poses some challenges with respect to their exergetic analysis and reference state selection that need to be revised and updated accordingly.

Furthermore, most of these new fuels require cryogenic transportation, permanent or temporary storage and fuel gas handling systems. This is also true for liquified natural gas with its global transportation and use intensified due to the recent geopolitical developments. The thermoeconomic analysis of cryogenic and refrigeration systems, although it is well established, poses some challenges related to states below the reference [81,82]. One additional complexity is also related to the muti-component mixtures, with real gas behavior that need to be assessed in vapor-liquid equilibrium conditions, often appearing when assessing the cryogenic storage and handling of the new fuels.

Finally, in terms of component cost functions, there is a significant gap in research and literature. Namely, cryogenic heat exchangers and equipment, natural gas and hydrogen compressors, and many of the associated auxiliary equipment cannot be described or extrapolate their cost functions from conventional power generation ones, used in most of the literature. Efforts should be made to develop representative cost functions describing new equipment and technologies associated with these decarbonization options.

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Closure

In a discussion on the future of thermoeconomics, the fundamental question that can be posed is: “does thermoeconomics have a future?” After the fundamental question, other questions such as the four questions written in the Introduction can be posed.

In order to help in answering the four questions, the preceding sections give arguments regarding the necessity of applying thermoeconomics and a few suggestions regarding the introduction of considerations in addition to thermodynamic and economic, areas where the application of thermoeconomics can be extended, and needs of further development of thermoeconomics. Of course, the whole subject is open to additional ideas and suggestions.

After the aforementioned, the answer to the fundamental question is clear: “Yes, thermoeconomics has a future”.

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