PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

From thermoeconomics to environomics and beyond

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Abstract:
Modern energy systems are more and more based on integrated technologies in a world evolving towards increasing concerns not only for economics but also for environmental issues with a growing focus on resources and emissions. In parallel, information technologies including advanced simulation and optimization algorithms develop at a rapid pace. Thermoeconomics based on either the First Law or exergy, together with cost factors distributed through its equipment, also evolved during the last 30 years. However modern muti-objective evolutionary optimization techniques, extending the capacity to tackle optimization considering a growing number of parameters including the internalization of the costs of emissions of whole systems has also emerged. The latter is called environomics. So far, the supply of energy services was essentially dominated by fossil-based resources with a high focus on operational costs. The new trends towards renewable energies requires a growing need to consider the embedded exergies since renewable energy, like solar energy, is economically free and operational costs are inherently low. While economic factors can vary over a broad spectrum throughout the years of operation, the embedded exergies are more stable values, particularly because the systems are built in a known economic and energetic environment. A new class of methods is only emerging to deal with more complete exergy approaches to formulate more holistic exergy life cycle analyses. Those should provide a lower bound of the expected exergy payback over the lifetime of the systems to be compared with thermoeconomic or environomic optima. It is still a huge challenge ahead to provide practical tools to do it.

Keywords:
Thermodynamics; Exergy; Environomics; Thermoeconomics; Second Law.

1. Introduction

The world is facing major challenges regarding environmental threats and resource constraints at a time where geopolitics tends to have a growing influence and globalization is questioned. In this context there is a growing need for efficient integrated systems. Apart from technical progress, engineering methods have to constantly evolve to account for energy efficiency, economic viability and environmental constraints, taking in particular advantage of progress made in optimisation schemes and data processing.

During the early days of thermoeconomics, with pioneers like Tribus and El-Sayed referred to in Frangopoulos [1], as well as Tstsaronis [2], Valero [3], and von Spakovsky [4], a strong emphasis was put on thermodynamic formulations that would favour the decentralisation of the optimisation of each component due to the lack of available adequate algorithms. In terms of Second Law of thermodynamics each component of a system has to "pay" for its inefficiencies, that is for the entropy it created, and the cost associated with its dumping to the environment. The earlier energy systems considered were primarily fossil based and for systems in steady-state conditions.

The broad name of thermoeconomics includes both energy analyses and optimisation based on the First Law with costs minimisations, while a narrower approach considers only exergy consideration with cost minimization.

Quickly the need for developing methods accounting for the increasing complexity of investment and operation of real energy systems arose to deal in particular with:

- Environmental emissions both local and global (environomics).
- Time dependent operating conditions.
- Reliability constraints implying both active and passive redundancy for example.
- Global resource considerations including considerations of the embedded exergy of components.

https://doi.org/10.52202/069564-0005

2. Competing methods

While the Second Law fundamentals with the exergy theory were rarely questioned two different methodology paths were pursued.

- The mathematical approach with the continuous development of Second Law based thermoeconomics [5] in parallel to First Law thermoeconomics, and
- The graphical approach using a simplified second Law approach, called pinch technology, with an emphasis on minimizing the costs linked to the heat transfer exergy losses. The latter is a clever graphical application of the Second Law to optimize the energy integration of industrial processes [6-10].

Ultimately all benefitted from the considerable progress made by the optimisation algorithms with, in particular, evolutionary algorithms able to reliably tackle problems with non-linear and even discontinuous solution spaces. With such computational capabilities the need for decomposition of the problems to allow easier optimisation faded somewhat. Methods based on non-linear mono- and later multi-objective optimisation emerged allowing to deal with both design and operation factors, even for expected changes in operation over the lifetime of the energy systems [11,13].

2.1 Second Law and environmental aspects

One problem in trying to include environmental pollutants with the Second Law approaches of exergy-based thermoeconomics is that the detrimental effects of local pollution are generally not linked to the entropy of the substances in the environment. Therefore, the need to express the cost of emissions with complementary factors was identified and Frangopoulos coined the term environomics [1] for methods dealing with the internalization of the specific individual costs of pollutants. This allowed to do sensitive analyses on specific pollutants and the economic penalties when having to reduce the emissions. Individual pollutant costs could even be modelled with functions accounting for the distance between the pollutant source and the density of the population directly affected [14] as illustrated in [15-16]. The impact of pollutant could also be accounted for when dealing with downstream pollutant capture as shown for the optimisation of combined cycle plants with or without considering pollutant costs by Pelster et al. [17]. The internalisation of pollutant costs is important in the context of the introduction of taxes like the CO_2 tax. It can also be of great help in assessing new measures for decision makers or in studying the potential financial risk differences between competing designs. Pareto frontier representations of the solutions developed with environomic bi-objective optimisation is a powerful tool as shown in Figure 1. This illustrates the trade-offs related to the design of District heat system [11] and their effects, among others on the temperature of heat distribution. These results nicely complement the mono-objective optimisation initially made by Curti [15-16].

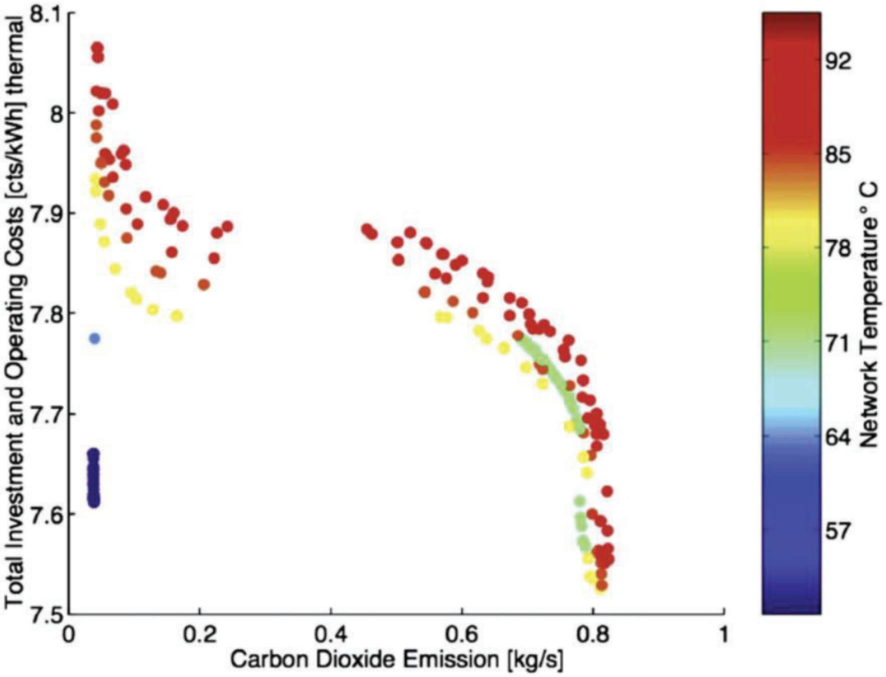

Figure 1. Solutions for a District Heating network with both centralized and decentralized heat pumps. Each dot represents a configuration of components both centralized and decentralized in individual buildings [11].

https://doi.org/10.52202/069564-0005

It particularly highlights the switch that can be observed in District heating networks from central plant with relatively high distribution temperatures to networks operated at “ground temperature levels” with decentralized heat pumps in each building (blue dots on the left). These low temperature networks, sometimes called District Energy Networks of fifth generation or anergy networks, not only increase the synergy between providers and users of energy services but also allow direct air-conditioning services with simple heat exchangers. Operating networks at low temperatures limits the need for thermal insulation and opens the opportunity to capture all kind of waste heat. It further favours some seasonal storage with, for example, fields of shallow geothermal wells. District heating and cooling networks (DHC) are expected to grow fast in the light of the enhanced decarbonization policies.

In Figure 1 the most cost-effective solutions but with the highest emissions are shown on the right and correspond to a central plant with a heat pump for 50%, a cogeneration gas turbine for 20% and ancillary gas boilers for 30% of the heat demand. In this particular case, the peak heating power considered was 63 MW, the specific electricity price was 0.13 $/kWh for a natural gas cost of 0.05 $/kWh. A NOx pollution cost of 13$/kg and a CO_2 cost of 0.03 $/kg [11] was also considered. It is easy to see on the graph that the recent increase of energy prices, that is likely to be maintained in the search for regional independence in energy supply, will further improve the importance of the electric heat pump only solutions.

2.2 Thermoeconomic analysis of time-dependent processes

Obviously, energy systems must be designed for a proper adjustment over time between the needs of the users and the constraints of the suppliers. Hence the need for multi-period/multi time optimization as described in [12,18]. This can be approached with sequential optimization inside the more global optimization. Employing typical operating time periods, like typical days throughout the season, is often the way to reduce the computational efforts. The introduction of energy storage components often generates alternatives to the strategies based on the power modulation of oversized supplying technologies that need to be compared with. Seasonal storage needs often to consider synthetic fuels easy to store over long periods of time. This is part of the actual discussion occurring around energy and cost intensive synthetic fuels compared to the investments in an overcapacity of power production like was favored previously by France with nuclear or Germany with coal plants.

In process engineering a hybrid approach between pinch technology and evolutionary algorithm optimization was proposed by [19] for batch processes including graphical representation of the solutions with multi-storage tanks.

Needless to say that these brief comments are by no means exhaustive and further methodological improvements of these broader thermoeconomic approaches accounting for time variations are needed.

2.3 Thermoeconomic optimisation accounting for reliability

It is imperative for many energy systems to provide reliability guaranties and liabilities could be quite costly during operation. Therefore, including elements like active or passive redundancies of components might significantly modify the thermoeconomic or environomic optimisation of designs. Examples applied to waste incineration plants are shown in [12,13], where increasing the number of furnaces that is less economic at first sight can finally be among the most adapted options.

For all the above requirements a first phase based on exergy considerations is required to build the super-structures (or super-configuration) on which the optimisation problems are based.

3. Influence of the current energy system trends on the thermoeconomic methods

With increasing concerns about greenhouse gases and following the Paris international agreement, the trends are going for an increasing pressure to improve the efficiency of systems and rely more and more on renewables. While the present thermoeconomic or environomic methods based on exergy are already adequate for efficiency, new considerations regarding resources and the increasing ratio between investment versus operational cost with renewables modify the relative importance of the different factors.

If, as mentioned above, the polluting emissions are not directly linked to entropy, the material resources are linked to the concentration of the elements in the Earth crust and therefore to entropy. So, at a time where humans increase the use of most parts of the Mendeleev chart of elements, all the present efforts to account for this in exergy approaches should be pursued. The Second Law approaches for processes, from the early work of [20] to the deeper considerations of materials in [21] represent valuable background approaches that are well initiated. The recent update of [22] adequately complement the methodological aspects on how to deal with resources with the Second Law in mind. Those approaches provide a methodological answer to the crucial problem of the scarcity of materials, like the Rare Earth Elements, in the development of renewable energies and the efficiency improvements links to the growing electrification of our societies. This cannot be

https://doi.org/10.52202/069564-0005

dissociated from the recycling processes or even the material substitutions that follow the fast growth of specific storage components like those used in the electric batteries, often with a significant time delay.

When it comes to graphical approaches the earlier work on extended composites in [8] provides some examples on how embedded exergies of components could be accounted for. Figure 2 illustrates the extended composites related to the implementation of an industrial heat pump in a drying process together with a gas engine (410 kW) to provide the power (265 kW) needed for the compressor of the heat pump as well as the power (145kW) requested by the various fans of the dryer tunnel. It relies on two related diagrams, the main one related to pinch technology approach completed by a second one (electric power versus a pseudo-Carnot factor to illustrate the exergy losses including embedded exergy linked to the compressor of the heat pump. It has also the advantage of visualizing the electricity balance in each process. The exergy losses in the evaporator and condenser of the heat pump are directly shown in the main pinch composite diagram while the exergy losses linked to the engine are shown in the top diagram with a pseudo-Carnot factor superior to one.

A similar diagram was made in [9] for the dryer equipped only with gas furnaces and the exergy losses with the retrofit solution given in Figure 2 were reduced from 1725 kW to 1040 kW.

Note that the notion of embedded exergy losses is strongly inspired by the earlier of work of Bejan [23] when discussing the optima in heat exchangers accounting for heat transfer, friction losses and embedded energy losses.

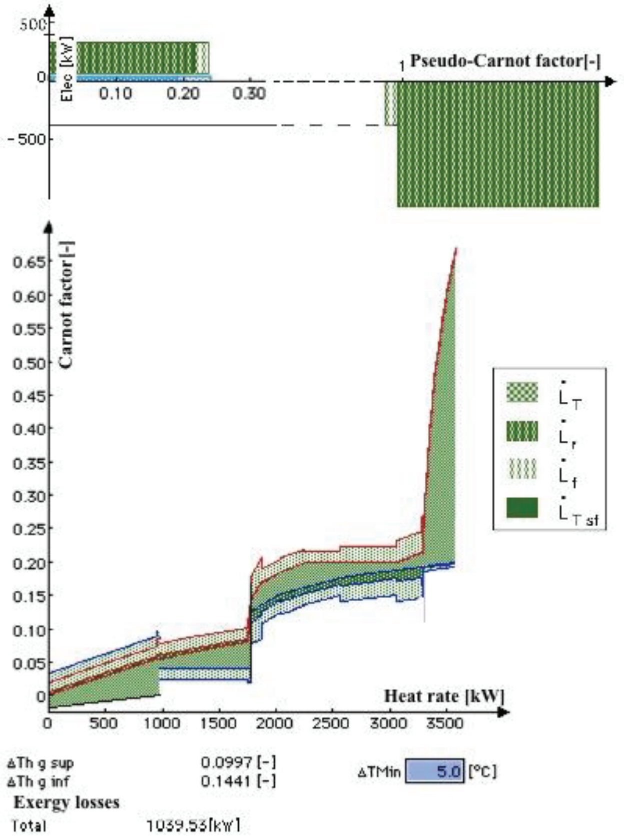

Figure 2. Extended composites proposed in with a visualisation of the exergy losses of heat transfer $\dot{L}_T$, friction $\dot{L}_F$ and embedded exergy losses $\dot{L}_f$ for a plaster drying case with gas engine and heat pump [9]

Contrary to fuel-based approaches, for many renewable technologies like solar or wind the actual resource is free and the embedded exergies together with the implementation, the maintenance and disposal costs are to be accounted for. One earlier paper [24] advocates that the best way to deal with such renewable is to include the rate of embedded exergy divided by the expected lifetime of the equipment among the exergy losses to be taken into consideration. This is particularly valid for solar and wind where the resource does not cost anything. The situation is more complex for biomass for which the resource has a cost and a hybrid approach needs to be taken.

The major hindrance when it comes to embedded exergies is the large inventories of data on materials and processes that are often to be considered. There is a place for advanced methods of data mining in this context.

https://doi.org/10.52202/069564-0005

The extension of exergy-based methods including exergy LCA aspects is particularly interesting in the present context of the implementation of Carbon Capture and Storage or utilisation technologies [25]. The exergy of diffusion of CO_2 in the atmosphere as expressed in [26,27] is providing an absolute minimum of exergy (work) required to extract CO_2 from the atmosphere as is promoted by some companies. It allows an immediate comparison with the extraction from flue-gas pipes in advanced concepts like published in [28]. In the latter CO_2 extraction can be made at negligeable exergy requirements. However, introducing the embedded exergy in the components would allow a much better estimates when comparing these technologies, since the amount of heat exchanger surfaces is high. Synergies with the recent efforts in so-called exergoenvironmental methods [25,29] should be exploited. Nevertheless, optimization based on exergy life cycle analyses can only provide a minimum value that always needs to be compared with economically based optima. They are however much more robust knowing that monetary costs are subject to significant variations linked to geopolitical influences and potential speculation on resources among others.

4. Conclusions on the future of thermoeconomics or environomics

In spite of the interest of “narrow” thermoeconomic approaches, that also include exergoeconomics, from an academic thermodynamic standpoint, the future lies in extended environomic approaches ideally including embedded exergy considerations in connection with broader use of exergy LCA analysis. Furthermore, researchers should be encouraged to further develop graphical tools for easier interpretation of the optimized results. Researchers should also question the results of their methodological approaches when the optimized solution only vary in the range of uncertainties of the major variables. There is also a major effort to be made to try to simplify the approaches and tools, for engineers in practice to be able to concentrate on innovation with new integrated concepts, rather than on the development of sophisticated computer formulations.

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