EXERGY, ECOLOGY, AND DEMOCRACY-CONCEPTS OF A VITAL SOCIETY OR A PROPOSAL FOR AN EXERGY TAX
30 YEARS AFTER,
Part 2 – Exergy and UN Sustainable Development Goals

by

Michele TRANCOSSI[a,b,c*]***, Jose PASCOA***[a]***, and Tiziano CATELLANI***[d]

[a] Universidade da Beira Interior, Covilha, Portugal
[b] Atlantic International University, Honolulu, Hi., USA
[c] ENEXERGY Ltd, London, UK
[d] Circolo Carlo Cattaneo, Parma, Italy

Original scientific paper
https://doi.org/10.2298/TSCI220907020T

Thirty years ago, Wall published "Exergy Ecology Democracy - Concepts of a vital society or a proposal for an exergy tax". This paper discusses this milestone contribution by Wall. It has traced a path toward economic, environmental and societal sustainability and proposed exergy as a robust indicator for measuring progress. This paper is divided into two parts. The first focuses on better understanding Wall's role in today's scenario. This second part presents different methods that allow using exergy to assess the sustainability of economic, industrial and societal processes. First, it presents an example showing the inadequacy of domestic material consumption (DMC) in evaluating the sustainability of import-export operations. Second, how exergy can apply to increase the significance of DMC has been discussed. A new indicator that allows coupling with DMC has been defined to improve the information delivered by DMC and make it a more effective sustainability indicator. Third, some ecological indicators are discussed. The use of exergy to integrate DMC and assess lifecycle and polluting emissions into the environment has been discussed. Finally, an effective exergy tax proposal is presented as an instrument for stimulating an effective transitionward sustainability of consumption and people's habits.

Key words*: sustainability, sustainability development goals, globalisation, sustainability indicators, DMC, exergy impacts*

Introduction

Wall [1] presented *Exergy, ecology and democracy: concepts of a vital society or a proposal for an exergy tax*. It has defined a robust framework for sustainability. After thirty years, it has maintained fundamental importance also in today's scenario.

In light of Wall's pioneering vision, Part 1 [2] of this paper evidences that the UN sustainable development goals (SDG) [3] and Paris Agreement [4] are not declarations of principles but necessary and demanding processes. In addition, the transition measures deployed by national governments and industrial and commercial companies remain insufficient to create a sustainable society [5], which can reduce the menaces for humankind caused by climate change and global warming. Sustainability remains a problem that interferes with national and

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[*] Corresponding author, e-mail: mtrancossi@gmail.com

economic interests. Therefore, it is essential to rethink and redefine economic models, globalization, agriculture, energetic and industrial production, logistics and waste management [6, 7].

Bartelmus [8] has analyzed the indicators of prosperity and well-being and their effects on the necessary measures for supporting the development of the economy, environment and society. He has shown that the data and the consistency of indicators adopted by decision-makers present evident problems. Societal and environmental indicators affect economic activity, quality of life and environment, and prosperity of people and nations. The UN SDG and Paris agreement require observing that incomplete or inadequate information leads to insufficient estimations and limits the effects of political decisions [9, 10].

Bartelmus [11] has evidenced the need to improve policy guidelines and adopt effective and coherent accounting methods to analyze and revise political procedures toward sustainable social and economic development. The persisting polarization of the debate between environmentalists and economists is often a misleading element in the path toward a more sustainable society with the capability of integrating the principles from the environmental sciences and the economy.

Wall [1] has demonstrated that thermodynamics can define a third way in the debate toward sustainability and reduction of climate change [12-14]. The thermodynamic way allows a rigorous assessment of the impacts, which can be complementary to the economic analysis, and provides the necessary elements usually neglected in governmental estimations [9, 10].

Part 1 of this paper [2] critically analyses SDG 12 Sustainable consumption and production and the related indicators and, in particular, the *resource productivity index* introduced by the EU [15]. It is the leading indicator toward a European *resource efficiency* roadmap. It evidences that material consumption (MC) is the ratio between gross domestic product (GDP) and DMC. It seems evident that this definition misses essential information that allows for verifying the environmental footprint. The DMC does not consider the resources and the impacts outside the considered economy [16] (import and export). Hence, it leads the national governments to an evident underestimation of the impacts that may affect footprint indicators, including material, energy, and GHG emissions.

This second part will verify the inconsistency of DMC in estimating the environmental impacts and discusses a typical example related to globalized production. The example shows how different production and logistic plans affect the environmental impacts of production. At the same time, DMC misses any possibility of estimating the indirect effect caused by transport and misses the opportunity of attributing a measurable value related to the environmental quality of the materials.

The limits in the analysis based on DMC are evident because it is limited to mass balance, and mass is not a consistent sustainability indicator. On the other hand, exergy analysis can avoid these limits [17, 18], according to the first part of this paper [2]. Hence, the samples determine how mass balance can be integrated by energy and exergy, producing a valuable activity of analysis, design and verification for the measures toward sustainability and reducing the effects of climate change.

Exergy analysis shows that social fluxes and processes (energy conversion systems, industrial plants, transport systems*, etc.*) can be analyzed using the second law of thermodynamics [13, 14]. The Second law recognizes the irreversibility of real processes. In particular, it can be observed that irreversibility depends mainly on the degradation of materials and energy over time. As Wall [1, 8, 9] and Gaggioli [15] show that there is a scale of energy quality, which can be quantified in terms of availability analysis (exergy), and this scale can be expressed both intrinsically and economically.

Materials and methods

Resource productivity and domestic material consumption

The resource productivity index underpins the economic productivity of DMC. It is defined as the GDP divided by DMC [11]:

$$RP = \frac{GDP}{DMC} \tag{1}$$

where DMC is the amount of resources directly used by an economy:

$$DMC = M_\mathrm{D} + M_\mathrm{I} - M_\mathrm{E} \tag{2}$$

where M_D is the total raw materials extracted from the domestic territory, M_I – the all physical imports, and M_E – the exports. In Newtonian physics, the mass balance cannot describe the problem entirely. However, DMC misses information in terms of masses and their impacts. In addition, when a transformation occurs, it is necessary to apply the laws of thermodynamics to the problem.

Material flow analysis

More rigorous computations of the principle of conservation of mass have been formulated by Hendriks *et al.* [19], Brunner and Rechberger [20], and Baccini and Brunner [21]. They have formulated the concept of material flow analysis (MFA). It is the *systematic assessment of the flows and stocks of materials and their societal pathways within a system defined in space and time.* Therefore, MFA is a tool that applies the principle of conservation of mass to complex physical processes. It describes the flows of materials considering inputs, stock transports, and outputs. It is then evident that it provides an accurate analysis of the flows and stocks of substances.

The MFA identifies inputs and outputs inside the relevant societal, industrial and biological processes. The MFA method produces an inventory analysis for the material flows and stocks of the system. It produces an effective mass balance of the anthropogenic processes and systems intricately linked to time and space. It can be associated with information, energy, exergy, environmental and societal impacts. Brunner and Rechberger [20] define the following terms and procedures:

- Systems are the thermodynamic domain in which natural, industrial and societal processes occur. They are limited portions of the physical universe characterized by material and energy flows entering, exiting, passing through, transforming, or stocking.
- System boundaries for real irreversible processes must be discussed in detail, with particular reference to the time boundary that describes the time the system of interest needs to be studied. It is highly variable depending on the nature of the process ranging from milliseconds to thousands of years. In addition, the spatial boundaries are highly variable, from the dimension of a cell up to the ones of the entire planet.
- Materials are the resources, substances, goods and products characterized by uniform properties (or units) and economic values (positive or negative).
- Processes relate to material changes, including transport, transformation, or storage of materials. They are considered black boxes, so the relevant information regards only the inputs and outputs from the box. Any process can be subdivided into any arbitrary number of subprocesses (black boxes) to describe the evolution of a system with the desired level of detail.
- Flows connect the sources and the processes and are described by mass-flow through the process.

– Transfer coefficients (TC) describe the amount of a material or a substance within a process. They are defined as the amount of each material or substance necessary to produce the final products of the process. The TC are substance-specific values and give the amount of a substance (percentage) transferred to a product or the waste for its production. They can be extended to account for energy, exergy, emissions and wastes.

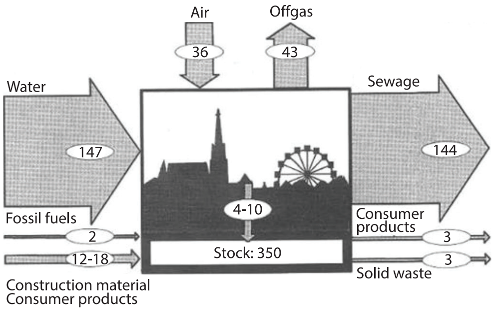

Figure 1. Schematics of material flow analysis for the city of Vienna (flows in tonnes per capita/year) [15]

Figure 1 presents a sample of the flows in the city of Vienna.

Figure 1 clearly shows that MFA could be a precious instrument for sustainability analysis because it presents the schematic representation of the relevant flows that feed the city of Vienna.

Evolved societal metabolism model

A system can be modelled as a coupled socio-economic and thermodynamic system which can be formulated by considering the societal metabolism models by Fischer-Kowalski [22, 23] and Bringezu *et al.* [16]. By considering Trancossi *et al.* [17] and Wang *et al.* [18], the societal metabolism model can be extended by the thermodynamic laws involved in the processes, fig. 2.

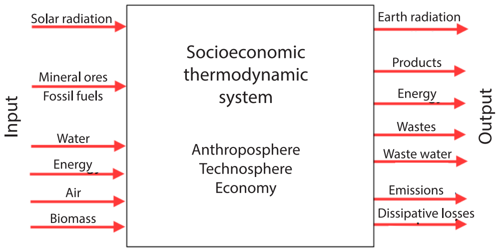

Figure 2. Basic scheme of the socio-economic system exchanges

According to Wall [1, 18, 24], fig. 1 has introduced solar radiation and Earth radiation, which are often not introduced in analogous schemes from sociotechnical engineering. Solar radiation allows accounting for solar-derived renewable sources, including photovoltaic, thermal, and wind energy, which would otherwise be excluded. This scheme applies to different scale problems. Otherwise, information from mass balance is limited and does not give an accurate snapshot of the considered system's sustainability and environmental impacts.

Cumulative exergy consumption and societal metabolism thermodynamics

Szargut [25] and Szargut and Morris [26] have introduced the concept of cumulative exergy consumption (CExC). The sum of the exergies dissipated inside a process or a physical system is a fundamental indicator for impact assessment. It describes how a process reduces the quality of the available resources [27]. The CExC includes all the necessary exergies for assessing the quality of energy demand and includes both the exergy from energy carriers and materials. Bosch [28] has defined CExD as a valuable indicator of exergy and the quality of the environmental resources extracted to produce a particular product.

Furthermore, CExD quantifies the total depletion of resources and exergy and related environmental impacts. In particular, it is measured in [MJ] and is expressed:

$$CExD = \sum_i m_i B_{(\mathrm{ch}),\mathrm{i}} + \sum_j e_j \beta_{ex/e(k,p,n,r,t),j} \tag{3}$$

where m_i [kg] is the mass of material resource i, $B_{(\mathrm{ch}),i}$ [MJ-eqkg^{-1}] – the chemical exergy per kg of substance i, e_j [MJ] – the amount of energy from energy carrier j, $\beta_{\mathrm{ex}/e(k,p,n,r,t),j}$ – exergy factor (or exergy to energy ratio) of energy carrier *j* and are reported in Part 1, tab. 3 [2]. Cumulative exergy consumption can be referred easily to fig. 2 in [2] and societal metabolism.

Results

Effect of localization of production facilities on the environmental impacts

An industrial case is considered. It is the production and transport of one-litre bottles made of polyethylene terephthalate (PET) with high density polyethylene (HDPE) lids and polypropylene (PP) labels. Different cases are considered for a functional unit of 1000 one-litre still water bottles:

- local production,
- plastic granulates for the bottle, lid and label produced in China and bottling operations locally, and
- plastic, granulates for the bottle, lid and label made in China, transported to Turkey along different paths, and bottling operations are performed in Turkey.

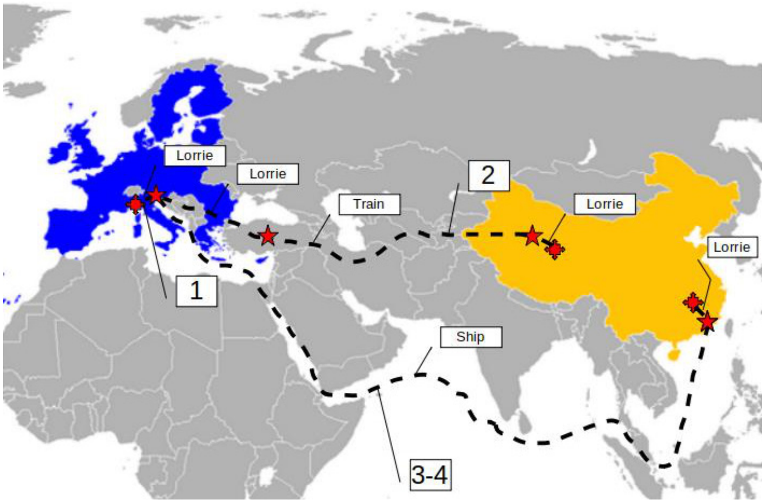

Figure 3. Map of different logistic cases

Identical bottles are considered. Two transport scenarios are analyzed for plastic granulates from China: train and ship, fig. 3. In Cases 1 and 4, bottles are formed and filled in the same country in which they are sold. Local transport is assumed by road transport. In Cases 2 and 3, filled bottles are transported from Turkey by road transport. It is possible to assume and evaluate the problems related to materials accounting evidenced by Wiedmann *et al.* [9] and how exergy allows avoiding them. The mass of the plastics is supposed to be 0.065 kg (0.05 kg in the PET bottle, 0.01 in the HDPE cap, and 0.005 kg in the PP lid). The mass of the filled bottle is 1.065 kg.

Exergy analysis extends to the impacts over the entire lifecycle. The consequences regard exergy disruption and consequent climate change contribution, resource depletion, water acidification and eutrophication, human toxicity, and ozone layer depletion. The entire production chain for PET, HDPE and PP is considered. In addition, the transport processes are analyzed because they have a variable impact dependent on the different means of transport and distances. Papong *et al.* [29] have compared the lifecycle impacts of PLA and PET drinking water bottles. In addition, Russo *et al.* [30] and Ortego [31] have produced the exergy analysis of multiple plastic materials. They have verified that exergy is a helpful instrument for measuring resource consumption during the life cycle of polymers. In particular, they have analyzed the production chains of different polymers. The production cycle is represented in fig. 4.

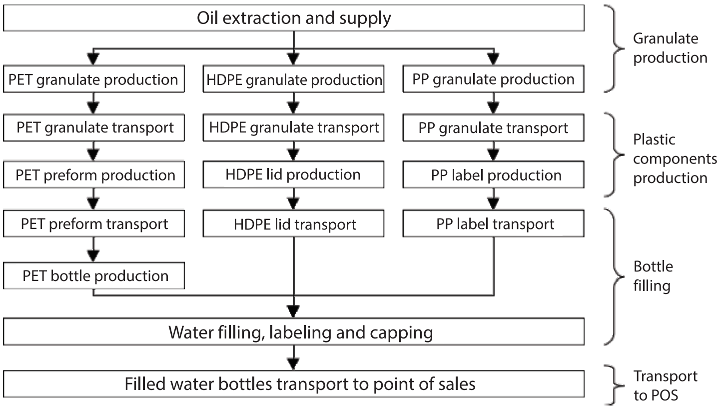

Figure 4. Process schematics derived [29]

Table 1. Embodied exergy of materials for 1000 bottles, [30, 31]

Commodity plastics	Production process	Exergy for production* [MJ/kg]	Embodied exergy* Raw material [MJ/kg]	Embodied exergy* Used material [MJ/kg]
HDPE	Addition polymerization of ethylene gas from cracking of petroleum	74.00	77-85	≈35-45
PP	Addition polymerization of propylene (C_3H_6) from cracking of naphtha	72.30	75-83	≈35-45
PET	Polymerization of terephthalic acid (PTA) or dimethyl terephthalate (DMT) and ethylene glycol (EG)	101.64	79-88	≈60-64

* At standard atmospheric conditions (15 °C, P_0 = 100315 Pa).

Table 2. Sample cases studied

	Unitary mass	Case 1		Case 2		Case 3		Case 4	
Activity	kg	Vehicle	km	Vehicle	km	Vehicle	km	Vehicle	km
Granulate production	0.065	–		–		–		–	
Granulate transport	0.065	Lorry	200	Lorry	300	Lorry	300	Lorry	300
				Train	5000	Ship	13000	Ship	13000
Preform, lid and cap prod.	0.065	–		–		–		–	
Preform lid and cap transport	0.065	Lorry	200	Lorry	200	Lorry	200	Lorry	2600
Filling, labelling and capping	1.065	–		–		–		–	
Transport to the point of sale	1.065	Lorry	200	Lorry	2600	Lorry	2600	Lorry	200

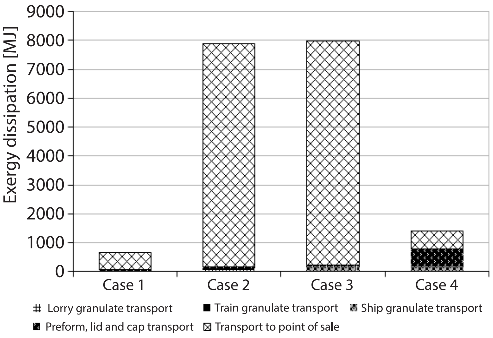

Figure 5. Exergy dissipation by transport in the different cases, calculated [37, 38]

Accurate verifications have been performed. The exergy requirements and exergy content of raw and used materials have been estimated according to Vučković [32].

Table 1 estimates the exergy needed for producing 1000 bottles and the embodied exergy in standard atmospheric conditions (15 °C, 100315 Pa). They are obtained by multiplying the obtained values by the mass of bottles, lids, and caps.

Osterroth *et al.* [33] and Osterroth and Voight [34] have experimentally assessed the energy consumption of industrial electrical bottling machines. Coupling these results with the ones by Trancossi *et al.* [35, 36], the exergy disruption of the bottling plant can be calculated. The four hypotheses described in fig. 4 and detailed in tab. 2 have been estimated. Cases 3 and 4 are identical but differ because of the location of operations.

The exergy requirements for production and exergy content of the materials of raw and used materials have been estimated. In addition, the exergy consumed by transport has been calculated, according to Trancossi [39]. Therefore, the ideal hypothesis of the maximum payload on the transport vehicles has been assumed for this evaluation. Therefore, a ULCC class tanker, a dense freight electric train and an average intercity truck are assumed from Trancossi [39].

Exergy disruption by transport in the different cases is presented in fig. 5. In addition, the total estimated exergy disruption is shown in fig. 6. It is essential to observe that the exergy for production and bottling is almost constant, with low variability. In particular, they can be considered equal if the plants are identical.

Table 3. Critical data of the estimated vehicles

Vehicle	Exergy	Emissions	Mass at full charge	Exergy per ton	Emissions per tone
	MJ/km	Kg(CO_2)/km	Tone	MJ/t km	g(CO_{2e})/t km
Tanker, ULCC class	59404.28	5650.41	419200	0.173	0.016
Train, Dense freight	177.16	16.85	1300	0.236	0.022
Truck, avg. intercity	108.98	10.37	55.00	2.79	0.266

Table 4. Exergy estimation for transport of 1000 bottles

		Unitary mass	Case 1		Case 2		Case 3		Case 4	
Activity		kg	Vehicle	MJ	Vehicle	MJ	Vehicle	MJ	Vehicle	MJ
Granulate transport	Lorry	0.065	Lorry	36.27	Lorry	54.41	Lorry	54.41	Lorry	54.41
					Train	76.7	Ship	146.19	Ship	146.19
Preform lid and cap transport	Lorry	0.065	Lorry	36.27	Lorry	36.27	Lorry	36.27	Lorry	471.51
Transport to point of sale	Lorry	1065	Lorry	594.27	Lorry	7725.51	Lorry	7725.51	Lorry	594.27
Transport			Total	666.81	Total	7892.89	Total	7962.37	Total	1266.37

The difference in exergy disruption depends mostly on transport, tab. 3. The considerations by Wiedmann *et al*. [9] allowed for verifying the inconsistency of DMC estimations. Case B and C, which require the transport of filled bottles by lorries, are the one that produces the maximum impact in term of transport, tab. 4. A similar analysis can be performed in terms of the different effects. However, for brevity, the study is limited to GHG emissions. The results are reported in figs. 6 and 7.

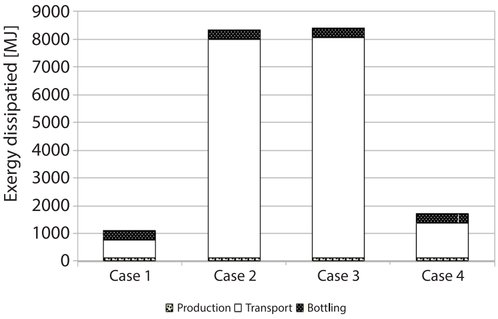

Figure 6. Total exergy disruption in the different Cases

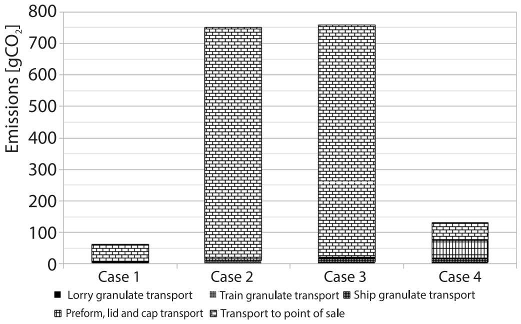

Figure 7. The CO_2 emissions in the considered transport cases

Exergy consumption in the food preservation industry

In this second part, the production of jam marmalade is considered [40] a fundamental food conservation technique for elongating the shelf life of fruits. Different sub-processes will be estimated, such as fruit drying, canning and processing.

The material should be composed fruit (~9% dry matter), sugar syrup and water are mixed to dissolve the sugar. Then it is heated up to around 65 °C under a 0.0866-0.9 MPa vacuum for 15 minutes to achieve the final marmalade (65-70% dry matter). Before adding pectin and acid, a final heating process brings the product to 85-90 °C before adding pectin and acid.

Conventional systems consume fuel or electricity to produce the required thermal energy. As demonstrated later, these processes have second law efficiencies in heat transfer. These losses depend on inefficiency and irreversibility. The production and pasteurization of jam marmalade require the dehumidified fruit to be agitated and heated inside a vacuum vessel at an average temperature of 65 °C. The vessel can be heated through water or heating oil heat transfer fluid (HTF), which is electrically inside the jacket of the vessel or an electrical inductive heater.

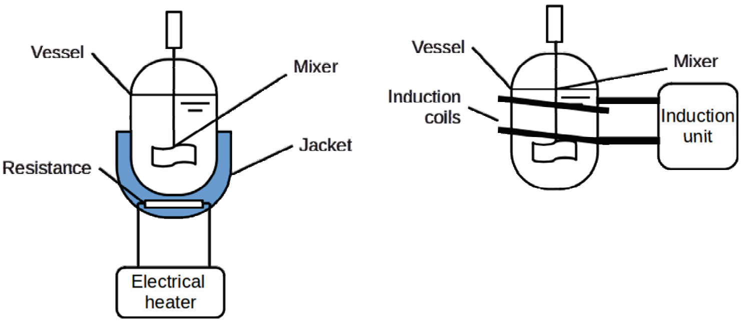

Figure 8. The HTF jacket vessel and induction coil vessel

The exergy disruption of the two systems has been derived from Tsatsaronis [41], Yilmaz *et al.* [42], and Wang *et al.* [43]. The results are in line with Todorović [44] *et al.* One-ton marmalade unit has been considered. In particular, the equations of the system are reported in tab. 5. The thermodynamic states of considered materials are given in tab. 6.

Table 5. Equations of the considered system

	Liquid	Induction
Conservation of mass	$m_p = \text{const}, m_l = \text{const}$	$m_p = \text{const}$
Conservation of energy	$\dot{Q} - \dot{W} = m\left(u_e - u_i\right)$	$\dot{Q} - \dot{W} = m(u_e - u_i)$
Exergy disruption	$\dot{B}_{\text{dest}} = \dot{W}_{\text{tot}} + \left(\dot{B}_p - \dot{B}_l\right)_i - \left(\dot{B}_p - \dot{B}_l\right)_e$	$\dot{B}_{\text{dest}} = \left(\dot{B}_{p,i} - \dot{B}_{p,e}\right) - \dot{Q}_b\left(1 - \dfrac{T_0}{T_b}\right) - \dot{W}_{\text{tot}}$
Exergy efficiency	$\varepsilon = \dfrac{\dot{W}}{\left(\dot{B}_p - \dot{B}_i\right)_i - \left(\dot{B}_p - \dot{B}_i\right)_e}$	$\varepsilon = \dfrac{\dot{c}_{p,i} - \dot{B}_{p,e}}{\dot{W}_{\text{tot}}}$

Table 6. Thermodynamic states of considered materials

				Water		HTF		Induction		
Material	m [kg]	T [°C]	P [bar]	u [kJkg^{-1}]	b [kJkg^{-1}]	u [kJkg^{-1}]	b [kJkg^{-1}]	m [kg]	u [kJkg^{-1}]	b [kJkg^{-1}]
Fluid	157	25	1	104.9	–	104.9	–	0	104.9	–
Jam	547	25	1	1107.7	–	1107.7	–	547	1107.7	–
Jam	547	25	–	1107.7	0	1107.7	0	547	1107.7	0
Jam	547	110	–	1256.4	208	1256.4	208	547	1256.4	208
Fluid	157	25	1	105.0	0	105.0	0	0	105.0	–
Fluid	157	90	1	377.0	26	377.0	9.9	0	377.0	–

The HTF energy efficiency has been calculated between 82.5% (HTF) and 93.5% (water). In addition, with induction heating and energy efficiency is around 95%.

Considering the different cases, comparable results in energy consumption, fig. 8, and energy efficiency lead to very different results regarding exergy disruption, figs. 9 and 10. In particular, it is determined that the batch system with an induction heater needs lower energy than conventional ones. In particular, it destroys less exergy input than traditional electrical heater systems to provide the same desired output. It is evident by considering the exergy efficiencies, fig. 11.

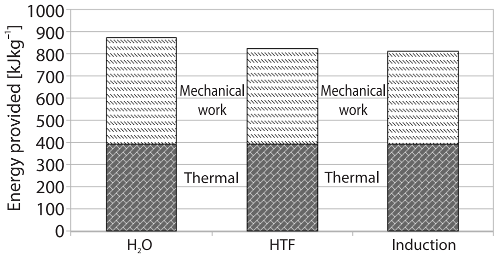

Figure 9. Energy provided to different plants

The induction heating process has several advantages against conventional fluid heating by H_2O and HFC. In particular, it lowers energy and exergy losses for a specific production.

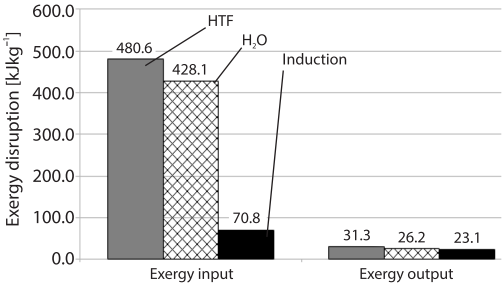

Figure 10. Exergy disruption expressed in terms of exergy input and output of the process

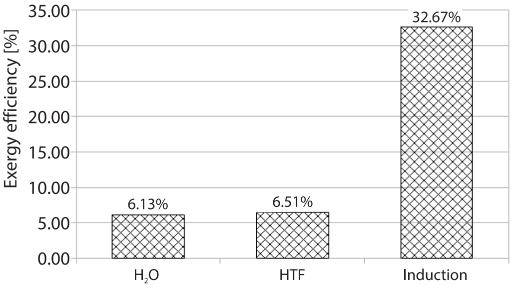

Figure 11. Exergy efficiency

Discussion

Critical analysis of the obtained results

The proposed cases have been presented to explain the effects of energy and exergy analysis. The first one studies a product for which transportation impacts are much higher than any other. Therefore, optimizing the production cycle requires assessing the optimal locations for industrial activities. The example shows the evident effects of transportation on the final products.

The transportation of the filled bottles causes higher energy consumption, exergy disruption and environmental impacts. The result demonstrates the findings by Trancossi [37, 38], who analyzed the impacts of transport by considering the ones which can be attributed to the vehicle and the ones attributed to the payload for different vehicles. The energy consumption and exergy disruption depend on the weight transported, the vehicle used and the distance. A heavier payload transported for a long distance (*i.e.* in Cases B and C) produces a higher impact. For the specific product, the effect of the manufacturing process is very low, but the transport impacts assume fundamental importance. In this case, increasing the efficiency of the process requires acting on the transport. For example, importing materials from China has a low impact on the process, while the bottling process in Turkey generates a very high impact on the final product.

The analysis demonstrates that DMC accounting, as evidenced by Wiedmann *et al.* [9], cannot estimate the impacts of transport operations. Therefore, this indicator must be supplemented by the implications for producing and transporting the masses of materials. The process efficiency can be improved, and the environmental impacts can be reduced by exergy analysis. However, the investigation has been limited to exergy disruption and GHG emissions. More accurate ones may also be extended to other critical environmental indicators.

These considerations may benefit by considering the end of life of the products. The reuse and recycling processes can be evaluated in the proposed elementary case. Considering tab. 4 and Schmidt *et al.* [45], it is evident that used bottles keep a consistent exergetic value. The complete lifecycle must be considered. It includes the end-of-life collection, reuse and recycling process. It could be interesting to extend this study to complete the end of the PET life cycle by having the recycling process chain. For example, the model adopted in Germany for PET bottles could be sounding [46]. The PET bottles produced in Germany are charged by a refundable deposit which will be given back when the used bottle is given back. Therefore, the environmental impacts of the bottles coming from Turkey would be even higher than those produced locally with materials from China.

The second example shows a process that may be substantially improved in production technologies. It clearly shows that the industrial process may change in terms of both energy and exergy analysis depending on technological choices. It shows evidence that traditionally fluid-heated vessels have much higher energy consumption and exergy disruption than vessels with induction heating coils. It is also evident that the requirement for mechanical energy necessary for agitating the product is nearly independent of the adopted heating technology.

The example shows the influence of the different technological choices on the environmental impacts. In particular, it suggests the opportunity of renewing the existing plants by adopting induction heating because of the much higher efficiency. This second example could be further developed by improving traditional fluid heating with thermal solar plants, even if it is outside the scope of the actual research. Solar energy plants could be interesting for similar productions, such as concentrated tomatoes and sauces, which use similar operating temperatures.

This case is much more efficient from an exergy point of view. Commercial tomato paste plants with a double-effect evaporator show that the critical element of the production plant is the boiler. The 82% of the total destroyed exergy in the plant occurred in the boiler combination as the main component wasting exergy. In particular, exergy analysis also effectively optimizes the performance of multiple-effect evaporation systems employed in the food industry.

Definition of new sustainability indicators that couple with today's economic indicators

Over time many scientists have worked on economically based sustainability indicators and methods for sustainability assessment. However, the results, as we have seen in both the first part [2] and this second part of the present paper, may produce results missing a realistic estimation of the environmental and climate change impacts.

Therefore, some further consideration can be developed by assuming as a reference the preliminary discussion as introduced in figs. 1 and 2. In particular, the balance expressed in fig. 2 can be modified to consider the different categories that Wall defines [1]. Finally, the results have been presented in fig. 12.

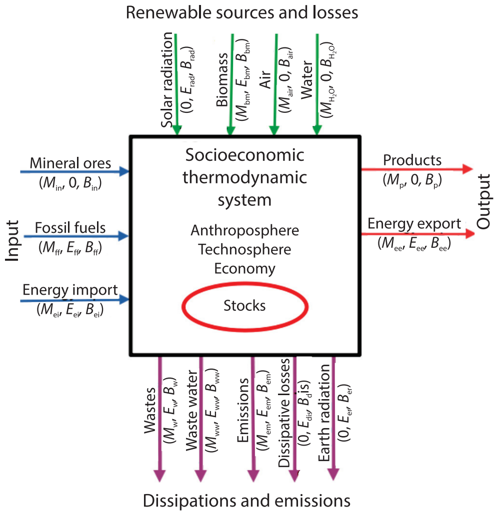

Figure 12. Revised scheme of the socio-economic system exchanges

The different inputs and outputs can be expressed in terms of conservation equations and second law inequality:

– Conservation of mass

$$\sum_{\text{in}} M_{\text{in}} - \sum_{\text{out}} M_{\text{out}} - \sum_{\text{w}} M_{\text{w}} = \sum_{\text{st}} M_{\text{st}} \tag{4}$$

where M_{in} is the input masses, M_{out} – the exiting masses, M_{w} – the masses of wastes, and M_{st} – the masses stocked.

– Conservation of energy

$$E_{\text{sol}} + \sum_{\text{in}} E_{\text{in}} - E_{\text{em}} - \sum_{\text{out}} E_{\text{out}} - W - \sum_{\text{w,in}} E_{\text{w,in}} - \sum_{\text{ww,in}} E_{\text{ww,in}} - \sum_{\text{st}} E_{\text{st}} = 0 \tag{5}$$

– Second law inequality

$$CE \times D_{\text{in}} > CExD_{\text{out}} + CE \times D_{\text{w}} + CE \times D_{\text{st}} \tag{6}$$

where CExD is defined in eq. (3).

Therefore, eq. (6) becomes:

$$\begin{gathered}\underbrace{\sum_{\text{in}} m_{\text{in}} b_{(\text{ch}),\text{in}}}_{\text{chemical exergy in}} + \underbrace{\sum_{\text{in}} e_{\text{in}} \beta_{\text{ex}/e,\text{in}}}_{\substack{\text{exergy for}\\ \text{managing import}}} > \underbrace{\sum_{\text{out}} m_{\text{out}} b_{(\text{ch}),\text{out}}}_{\text{chemical exergy out}} + \underbrace{\sum_{\text{out}} e_{\text{out}} \beta_{\text{ex}/e,\text{out}}}_{\substack{\text{dissipated exergy out}\\ \text{for managing chemical}\\ \text{processes}}} + \\ + \underbrace{\sum_{\text{w}} m_{\text{w}} b_{(\text{ch}),\text{w}}}_{\substack{\text{chemical exergy of}\\ \text{emissions, wastes,}\\ \text{and waste waters}}} + \underbrace{\sum_{\text{w}} e_{\text{w}} \beta_{\text{ex}/e,\text{w}}}_{\substack{\text{exergy for managing}\\ \text{wastes}}} + \underbrace{\sum_{\text{st}} m_{\text{st}} b_{(\text{ch}),\text{st}}}_{\substack{\text{chemical exergy}\\ \text{stocked}}} + \underbrace{\sum_{\text{st}} e_{\text{st}} \beta_{\text{ex}/e,\text{st}}}_{\substack{\text{exergy stocked,}\\ \text{energy for managing}\\ \text{stocked exergy}}}\end{gathered} \tag{7}$$

where b is the specific exergy [$b = B/m$].

Exergy and economy

Economic issues have a fundamental role in assessing and developing economic and industrial systems. Designing successful and efficient products and industrial production plants requires a significant multidisciplinary effort. The design activity requires combining fundamental physical disciplines (in particular thermodynamics), specific technical fields related to the specific sector, and the economy to optimize the system effectively.

As noticed by van Gool [47] and Wall [48] and exhaustively formulated by Rosen [49], today's energetic consumptions are not formulated appropriately. Today's accounting system is based on energy, which makes no sense because energy is not fully available. Hence, it does not refer to the useful part of the energy, which can be transformed effectively but to a theoretical amount that does not refer to the effective work it may produce. Exergy is fundamental if applied to economic systems because it allows accounting for the measure of energy that can be utilized. Scientific literature presents several methods for exergy accounting as identified by Tsasaronis [50]. In particular, Tsatsaronis determines four primary methodologies for exergy-based cost accounting. They are exergy-economic cost accounting, exergy-economic calculus analysis, exergy-economic similarity number, and product/cost efficiency diagrams.

Referring to scientifically correct models, the exergo-economic methods assume exergy as the commodity value to be accounted for rather than energy because final users could effectively transform only exergy. Therefore, they determine costs and/or prices for exergy. The main result of such accounting methods would encourage the economic system to effectively optimize the financial resources to optimize system design and operations and obtain the system's highest possible profitability while respecting the environment.

Jaber *et al.* [51] advance the hypothesis of using exergy as the commodity in a price-driven economic model, which is respectful of thermodynamic laws and the environment. In particular, exergy allows a more effective cost and benefit analysis. It will enable to distribute better the costs of the inputs among the outputs and benefits produced. Therefore, exergy is a consistent measure of economic value. Usually, this is not true for energy because some of it is not useful (entropy) and cannot be used.

Rosen and Dincer [52] analyze the possible general relations between thermodynamic losses and capital costs. They analyzed economic and thermodynamic data related to mature devices and determined that empirical correlations exist between capital costs and exergy losses for devices. Such a correlation has been verified for energy conversion power plants. Rosen and Dincer have also determined that the fundamental mature subsystems in power plants respect a particular value of the exergy loss rate to capital cost, reflecting that they have approached a high degree of optimization and technological maturity.

On the proposal for an exergy tax

The aforementioned considerations on the economic value of exergy open a discussion scenario related to the national taxation criteria. Taxes are inevitable because they allow the survival of the States and the necessary services to be delivered to the citizens. Therefore, what governments tax is only a convention and can be moved from one asset to another. Today, the national government conventionally relies mainly on the taxes imposed on three simple assets: personal and corporate income taxes; payroll taxes (Social Security and Medicare). Taxes on sales, excises, and properties.

Such structured taxes can affect the economy by discouraging work, savings, entrepreneurship and investment. Moreover, Repetto *et al.* [53] show that taxes distort the market, the general economy and economic decision-making.

Today emergencies caused by climate change and global heating open multiple questions on the conventional way of applying taxes. They reduce to one only. Can tax revenues be generated in a more ethical and valuable way. Repetto *et al.* [53] recommend adopting *green fees* such as pollution, waste, and congestion charges. In today's scenario, shifting existing taxes to green fees would positively affect society by producing a cleaner environment, increasing the transition a greener economy and reducing the economic disincentives created by today's taxes on income, profits, and work and entrepreneurship. Such paradigm change could make the economy more robust and socially responsible. Such a taxation model can generate an effective paradigm shift from taxing *goods* to taxing *bads*, as auspicated by Repetto *et al.* [53].

The very first model of exergy tax has been defined by Hirs [54]. He introduced exergy loss or entropy added as a basis for energy taxing because it can be accounted objectively for all energy and materials input and output in its different forms and qualities: electricity, fuel, feedstock, product and heat of high as well as low temperature. Hirs has hypothesized the name entropy added tax (EAT) and discussed its advantages and disadvantages. The main advantage of EAT is that it could be a strong incentive for investors to operate toward increasing sustainability and reduce the consumption of energy resources without any interference with free markets. On the other hand, the main disadvantage is supposed to be might be the risk that governments use EAT to increase the total tax burden instead of substituting existing taxes.

In line with energy-economic modelling, Wall [1] has formalized the hypothesis of introducing a tax on exergy disruption. The cases analyzed in this paper evidence clearly how they can be applied.

The first paradigmatic case shows that the localization of production for the final market is a fundamental element of exergy disruption. Therefore, the exergy tax could be computed by considering the dissipation of exergy between the case of water bottling coincident with the final point of sale and the excess of exergy caused by transport. Furthermore, this case shows that remote import-export of products with a low exergy (or human creativity) value is environmentally detrimental.

The second case shows how the industrial plants' efficiency differences cause exergy dissipation. In this case, the exergy tax could be applied to the difference of exergy destroyed between the real process and the best possible theoretical case (the Carnot cycle operating between the same temperatures).

As Wall [1] stated, the exergy tax can be fundamental in promoting sustainable choices and more sustainable globalization. Therefore, an exergy tax can be computed by accounting for the exergy dissipated by the complete industrial process (including transport).

Typical results of the exergy tax and the consequent paradigm shift from taxing *goods* to taxing *bad*s could lead to significant advantages:

- an effective improvement of the efficiency of the industrial processes, a reduction of costs and encouraging process improvements in terms of a substantial reduction of environmental impacts,
- massive adoption of renewable energy sources,
- Encouraging environmentally friendly behaviour in both nations, industry, services, and transport,
- a more robust and attractive economy which increases its competitiveness and its sustainability, and
- attracting investments, intelligence, and skilled workers.

However, the excess exergy depletion against the one corresponding to the best practices can be carefully verified for the relevant processes. In particular, it focuses on the relevant environmental impacts, including wastes and emissions in the environment, which must be necessarily accounted for in any process.

As Wall [1] states, *an exact relation is impossible to find for all substances and all environmental conditions, but a simple exergy estimation could be one to tax pollution*. Therefore, more accurate exergy tax computation methods have been proposed by several authors, including Wall and Gong [24], Dincer [55], and Traverso *et al*. [56].

The definition of an exergy tax as a substitute for personal taxes has been performed by Szargut [57]. He clearly states that taxes should not be a kind of penalty for positive effects of human activity (productivity, invention) but should burden adverse effects, like the production of dangerous wastes and the depletion of natural resources, and harmful impacts on society and the environment. In particular, he defined a rigorous method that accounts for the detrimental effects on the societal and natural environment. It includes accounting for maintenance of the instruments and buildings and the impact of importing foreign manufactured products. Stanek *et al*. have commented on and explained the model [58].

Conclusions

This paper aims to discuss the thirty-year-old milestone paper by Wall [1], *Exergy Ecology Democracy - Concepts of a Vital Society or A Proposal for An Exergy Tax*, according to today's scenario. Wall's work has been a fundamental step in analyzing relevant environmental impacts and abuse of resources. Today, it is much more actual in the light of UN sustainable development goals. After analyzing shortly the path toward UN. The SDG and some inherent inconsistencies of the currently adopted indicators to measure the progress toward the realization of an effective transitionward a more sustainable society. This transition requires solving the three societal dilemmas enunciated by Wall [1]: misuse of physical resources, the environment, and the abuse of human intelligence.

Despite the increasing mitigation actions, climate change and the continuous growth of the effects of global heating show the limits and inconsistencies of economically based sustainability accounting. It evidences the necessity of introducing more objective parameters that can effectively describe the resources wasted in our society. A helpful parameter is proposed. Exergy describes the maximum useful work produced by a process, a flux of matter, energy, and any substance in nature. Dissipating exergy means reducing the potential of Earth to produce useful work and causing a depletion of available energy [58].

From this consideration, Abu-Rayash and Dincer [59] have proposed adopting exergy analysis as an effective instrument for accounting for sustainability and understanding and compensating for the damages that anthropic processes produce to the ecosystem.

The exergy disruption by different processes differing only for production location must be considered. It relates to water bottles in four different cases. The example has demonstrated that the amount of exergy dissipated by industrial processes is often much lower than the one related to transport. In particular, it has been evidenced that the distance between the bottling plants and the final point of sale is an important cause of unneeded exergy dissipation. In addition, the economic value of exergy and the possible introduction of an exergy tax are considered substitutes for the existing economically deleterious taxation system.

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Paper submitted: September 7, 2022
Paper revised: October 1, 2022
Paper accepted: December 15, 2022