# *EXERGY, ECOLOGY, AND DEMOCRACY – CONCEPTS OF A VITAL SOCIETY OR A PROPOSAL FOR AN EXERGY TAX* 30 YEARS AFTER, Part 1 – Generalities

by

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*Goran Wall's "exergy, ecology, and democracy – concepts of a vital society or a proposal for an exergy tax" has come a long way since its presentation in 1992. Wall has extended the thermodynamics to the sustainability analysis of economic, environmental and societal models. The authors of this paper aim to discuss Wall's intuitions in today's scenario. Governments are assuming increasing measures against climate change and toward sustainability. However, these measures do not affect the concentration of GHG and global heating. It is an evident failure from a thermodynamic point of view. The economic indicators used by governments to measure the progress toward UN. Sustainability development goals and the Paris agreement reveal a scarce consistency. One of the most used is "domestic material consumption". It accounts for the mass balance of the materials entering or exiting a national economic system. However, it lacks consistency and delivers insufficient information because it neglects the impacts of import-export. As Wall shows, more effective and consistent indicators are necessary to account for sustainability. The most relevant is exergy, which has been presented and discussed widely.*

Key words: *exergy, society, economy, impacts, sustainability, sustainable development goal, domestic material consumption, Paris agreements, indicators, globalization, import-export*

## Introduction

Wall [1] published *Exergy, ecology and democracy – concepts of a vital society or a proposal for an exergy tax* three decades ago. In this milestone paper, Wall has observed that traditional economic models have failed to create a vital, sustainable, and participative society.

In particular, it has evidenced the three fundamental dilemmas of our society:

- *misuse of physical resources*, derived from a poor understanding of scientific concepts such as exergy and availability, which allow understanding of how resources are extracted, transported, transformed, used, disposed of, recycled or reused, optimizing the societal processes,
- *misuse of nature* because of the ignorance of natural laws. It produces devastating effects, including pollution, waste accumulation, deforestation, soil erosion, poor air quality, undrinkable water, respiratory illnesses*, etc.* It has negative impacts on quality of life and health, and

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- *misuse of human intelligence* at different societal levels: lack of democracy, inequalities, over-exploitation of the workforce, inadequate work conditions, limited access to knowledge and information, scarce formation, censorship, limitations to personal freedom, criminality, corruption*, etc.*

These considerations show that Wall [1] has prefigured the principles of the UN. Sustainable development goals (SDG) [2] and the Paris Agreement [3]. In addition, Wall [2] has intuited the limits of economically driven paths toward sustainability. Economic laws fail to respect the laws of physics and natural sciences that govern natural, industrial and societal processes. Therefore, scientifically coherent methods must be adopted to estimate the progress toward sustainability. Finally, Wall [4, 6] has indicated exergy as the fundamental indicator for societal sustainability.

Exergy is the maximum work which can be extracted by a substance or a process in disequilibrium with the environment. Exergy describes any process and estimates the paths toward increasing efficiency and sustainability, including thermal, radiant, mechanical, chemical, biochemical, nuclear, electric, and magnetic processes, fig. 1. In addition, it applies at different scales, including globe, nations, regions, cities, transport networks, industrial plants and building systems, biological ecosystems, vehicles, biological organisms, metabolism, and chemical reactions.

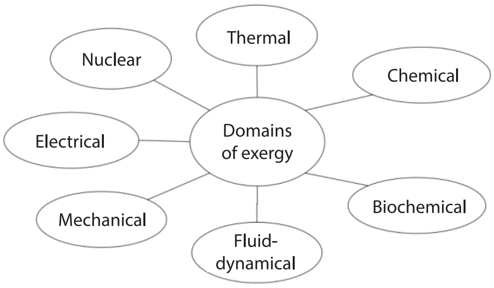

**Figure 1. Domains of exergy analysis**

## Scenarios: Today’s transitionward sustainability

### *Societal warnings and political actions against climate change*

After WWII, the necessity for social and economic reconstruction favoured the diffusion of the myths of unlimited progress and economic growth [7]. The result has been a poorly governed globalization with improved wellness, lifestyles and living conditions in a limited part of the world. However, the costs have been high: environmental disruption, reduction of available resources, and economic inequalities. On the other side, the global population was rapidly growing with a proportional increase in resource demand and environmental stresses. The result has been an unsustainable economic growth [1, 8], producing a set of irreversible damages to the planet:

- excessive exploitation of fossil and energetic resources limiting their future availability,
- increasing industrial emissions, wastes, and environmental pollution of air, land and water,
- irresponsible deforestation, excessive exploitation of land, reduction of the quality of soils,
- sea over-exploitation, fish reduction, and pollution,
- increasing emissions of GHG,
- global warming, extreme climatic events, desertification, and reduction of the glaciers,
- increase of seawater levels and submersion of more vulnerable coastal areas, and
- growing inequalities between different geographic areas, poverty, abuses and massive migrations.

The energy crisis of the 1970's was the turning point in political and scientific activity toward reducing the consumption of energy, fossil and natural resources [5, 9, 10]. In the 1980's, Reganomics diffused the illusion of unlimited economic growth and the availability of resources [11]. As a result, some of society assumed unsustainable lifestyles, while others promoted the Green movements. The societal division encouraged the studies on climate change and sustainability [12], leading to two milestone documents, UNEP *State of the environment: environment and health* [13] and UN. *State of the environment* [14] in 1986. They promoted a mobilizationward sustainability and a large spread of fundamental studies, which had a limited influence on policy-makers.

International organizations and opinion leaders launched important warnings about climate change in the last decade. IPCC reports [15, 16] have highlighted the following key points:

- the growth of GHG emissions accelerated despite mitigation policies from 2000-2010,
- stabilizing the temperatures within the 21st century requires radical actions,
- considerable technological, economic and institutional challenges are necessary for limiting the temperature growth to 2°C relative to pre-industrial levels, and
- less ambitious goals (2.5-3 °C) involve similar challenges on an extended time scale.

Pope Francis's encyclical letter Si [17, 18] invites humankind to renew the relationships with *our common home*. In particular, it criticizes today's economic models for their dangerous effects on climate change, global heating, depletion of energy and natural resources, air pollution, land and water, drinking water scarcity, depleting biodiversity*, etc.* Thunberg [19] and *Fridays for future* have moved youths to fight against climate change, asking for sustainable policies and environmental defence [20]. Moreover, this massive movement has encouraged many corporations toward more sustainable products and production keep the support of young generations.

### *The UN Sustainable Development Goals and the Paris agreement*

The UN SDG [2] have stated seventeen synergic goals for global actions toward a more sustainable and inclusive society to be achieved over the following decades. The UN SDG are reported in tab. 1.

**Table 1. The UN sustainable evelopment goals**

| | | |
|---|---|---|
| Goal 1: No poverty | Goal 2: Zero hunger | Goal 3: Good health and well-being |
| Goal 4: Quality education | Goal 5: Gender equality | Goal 6: Clean water and sanitation |
| Goal 7: Affordable and clean energy | Goal 8: Decent work and economic growth | Goal 9: Industry, innovation and infrastructure |
| Goal 10: Reduced inequality | Goal 11: Sustainable cities and communities | Goal 12: Responsible consumption and production |
| Goal 13: Climate action | Goal 14: Life below water | Goal 15: Life on land |
| Goal 16: Peace and justice strong institutions | Goal 17: Partnerships to achieve the goal | |

It emerges the centrality of goals from 6-15 in the path toward environmental sustainability. Goals 7, 9, 11, and 12 are fundamental toward achieving goals 3, 6, 13, 14, and 15. They refer to the concepts of exergy, availability and use of resources, whatever their nature.

The Paris Agreement [21] has traced the general guidelines for international climate policies [22]. It has recognized the importance of domestic policy and defined a framework for voluntary national actions. It allows countries to set their specific mitigation measures, which can be compared and reviewed internationally inside a system of climate accountability and cooperationward decarbonizing the global economy. This framework risks failure because national governments tend to express sounding aspirations but avoid drastic measures. The progress could be verified by a *pledge and review* mechanism, which requires international mobilization, consistent and measurable indicators, domestic pressure and political momentum for climate remediation policies.

### *The UN SDG 12 Responsible consumption and production*

The UN SDG 12, responsible consumption and production, has a fundamental role in the path toward sustainability [23]. First, it involves resources, their transformation and distribution, lifestyles and people's acceptance. It involves accessibility and distribution of global resources, wellness conditions, and diffuse inequalities between different areas of the planet. Finally, it regards managing and using natural and fossil resources to shape humanity's enduring well-being. Sustainable consumption and production (SCP) objectives are reported in tab. 2. They couple future economic growth with responsible use of natural resources by tracing new development trajectories, reducing environmental degradation and improving resource efficiency.

**Table 2. Targets of UN SDG 12, SCP**

| | |
|---|---|
| 12.1 | Implement the 10 year framework of programmes on SCP |
| 12.2 | Sustainable management and efficient use of natural resources |
| 12.3 | Halve per capita global food waste and reduce food losses |
| 12.4 | Environmentally sound management of chemicals and all wastes |
| 12.5 | Reduce waste generation through prevention, reduction, recycling and reuse |
| 12.6 | Encourage companies to adopt sustainable practices and integrate sustainability information in their reporting cycle |
| 12.7 | Promote public procurement practices that are sustainable |
| 12.8 | Rationalize inefficient fossil-fuel subsidies |

Goal 12 has direct consequences on human wellness and the economy. It involves thermo-dynamic concepts such as exergy, availability, use of natural resources and the environment. It couples economic growth with responsible use of natural resources, environmental degradation reduction, and efficiency of production processes and lifestyles [24]. However, decades of poor governance of global economic processes have dramatically affected unemployment, reduced families' spending power, and populism. In addition, the resistance to sustainability policies and global inequalities leads to political instability, nationalism, corruption, criminality and wars. Therefore, new development models are necessary to recover the damages of past development models [25].

Multiple indicators can assess SDG and the 2030 Agenda and monitor the progress toward more sustainable development. For example, the UN projections [26] estimate that the global population has been growing fast and could reach 8.5 billion in 2030 and 9.7 billion in 2050. Keeping actual lifestyles could require three planets. Therefore, according to UN, it is necessary to lower the consumption of natural resources and environmental degradation. In addition, UN projections show a contradictory panorama [27]. Today, the exploitation of biosphere deposits and lithosphere funds has grown to unprecedented levels in the industrialized world [27]. These excesses have implied a consequent resource depletion and environmental disruption. The results are evident from the UN reports and relate to the causes of anthropic effects on climate change and global warming.

### *Resistances against the measures toward sustainability negative and positive outcomes*

As Trancossi *et al.* [28] have observed, inconsistent scientific or governmental estimations risk having relevant impacts on the consensus and feeding the populism against scientific objectivity and measures toward social and environmental responsibility. Any lack of consistency can increase the strength of fake news. Typical examples of negating anthropic contributions to climate change derive from the interests of corporations and governments oriented to business-as-usual [29, 30]. Sustainability policy regards how society and political regimes could survive [31]. In line with the societal evolution models by Giddens [32], Russia and other countries (*i.e.*, US Trump's administration and Brazil) have tried to avoid the risks and reinstate traditional societal structures through de-modernizing and over-exploiting natural and human resources.

In developed countries, the opposition environmental policies [33] is conducted on social media. It is visible in the narration of radical movements in Europe and the USA. This opposition is similar to the no-vax movement during the Covid pandemic [34]. It acts in three directions: stressing excesses, ambiguities and uncertainties by scientists, producing direct attacks on scientists, and overestimating the possible negative social impacts on occupation and purchasing power.

China has recognized, with some delay, the necessity of the transitionward sustainability and fighting climate change. Initially, China considered economic development the leading guide toward the future and took a conservative position on climate change [35]. Trump's deregulation has made environmental quality a new source of legitimacy for the Chinese government, which started proactive action on environmental problems. The announcement of the carbon neutrality target marked a new era in China's climate governance [36]. Even if the start of effective measures has been delayed to 2030, it starts the ambitious objective to reach carbon neutrality by 2060. However, notwithstanding the initiatives, problems seem to emerge in transferring the measures from central to local authorities.

## Material and methods

### *The inconsistency of indicator 12.2 Absolute material footprint and DMG*

Wiedmann *et al.* [37] have analyzed global governmental data on resource productivity and consumption. These data present a relative decoupling (the consumption of natural resources grows slower than economic growth) or an absolute decoupling (the consumption of natural resources decreases over time). Wiedmann *et al.* [37] have verified governmental data against materials associated with global production and consumption flows. They recalculate the material footprint of 186 nations, including raw material equivalents of international trade. The effective decoupling of advanced economies has resulted in much lower than reported or even non-existent. They have also evidenced a diffused trend. As national welt grows, consumed materials increase, and the national extraction of materials reduces, with higher impacts on transport and logistics.

They observe that multiple indicators can account for the sustainability of resource use and support decision-making. Domestic material consumption (DMC) is the most used indicator at the governmental level. It accounts for material flows but neglects essential data related to import and export. The EU has adopted the *resource productivity* index as the headline indicator toward a *resource efficiency roadmap*. Resource productivity (RP) allows for underpinning the economic productivity of DMC by being defined as the gross domestic product (GDP) divided by DMC:

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

The RP increases when DMC decreases. According to the paradigm of globalization, governmental documents estimate DMC as the amount of resources directly used by an economy and neglect the impact of import, export and related transportation:

$$DMC = M_D + M_I + M_E \tag{2}$$

where $M_D$ is total raw materials extracted from the domestic territory, $M_I$ – the physical import and $M_E$ – the export. Equation (2) neglects the resources related to imports and export from outside the considered economy. Therefore, the national resources accounting is usually underestimated and can affect other footprint indicators, including material footprint, energy footprint, and GHG emissions.

Allen *et al.* [38] have observed that the success in implementing SDG relies upon well-suited national plans for the objectives. They have suggested a method based on scenario analysis and the best practice literature review. In addition, they proposed an interactive framework for supporting national SDG planning and presented several scenario modelling case studies. The given scenarios show a fundamental fragility: materials and energy (including waste, losses and emissions) are physical magnitudes and their extraction, transport, and transformation are well-defined physical processes through the adopted plants and equipment. Different plants realize processes with different efficiencies and impacts, which may vary individually or in terms of national average values.

The presented scenarios seem inconsistent with the related laws of physics, such as conservation of mass and energy and entropy increase at least. No physical phenomenon can exist outside their simultaneous necessary validity. A question arises: how can footprint models be consistent if they are not consistent with the fundamental laws governing the phenomena they claim to estimate?

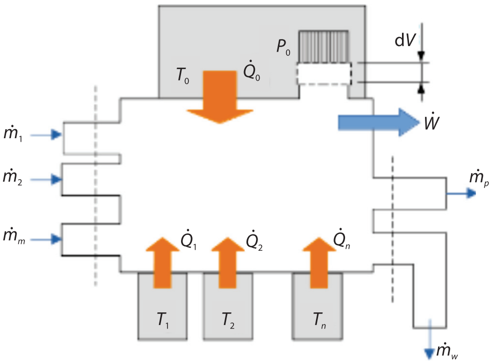

**Figure 2. Sample thermodynamic domain**

### *The First law of thermodynamics (conservation of energy)*

The energetic crisis of the 1970's has been a turning point for thermodynamics. It has allowed understanding limits of the First law of thermodynamics in the case of real and irreversible phenomena. The first law of thermodynamics (energy conservation) compares the initial and final states.

Assuming an arbitrary domain, mass-flows of different substances enter and exchange heat and work with the surrounding environment and heat with various heat sources, and masses of useful products and waste exit. By considering fig. 2, it is possible to express the law of conservation of energy. It is presented in terms of power by eq. (1).

### *The Second law of thermodynamics (entropy generation analysis)*

Equation (1) gives a minimal amount of information regarding the effects of the irreversibility of real transformations. According to Lucia and Grazzini [39], the missing physical information in the balance can be obtained from the second law. In particular, second law analysis can be performed in entropy (or entropy generation) and exergy. Entropy is the function of state that defines the second law. It is increasing and never negative. Bejan allows localizing the source of inefficiency inside the processes and determining the upper limits of efficiencies. The expression in terms of entropy generation (the speed of entropy creation):

$$\dot{S}_{\mathrm{gen}} = \frac{\mathrm{d}S}{\mathrm{d}t} = \frac{Q_0}{T_0} + \sum_{i=1}^{n} \left( \frac{\dot{Q}_i}{T_i} \right) + \sum_{j=1}^{\dot{m}} \dot{m}_j s_j + \dot{m}_{\mathrm{p}} s_{\mathrm{p}} + \dot{m}_{\mathrm{w}} s_{\mathrm{w}} \tag{3}$$

where $s$ is the specific entropy of the materials that enter or exit the system. Equation (3) is the total entropy generation rate. It must satisfy the second law inequality. Minimizing the entropy generation rate and the waste is advantageous. Furthermore, it reduces the irreversibility of the process. These results may be achieved by varying one or more quantities along the system boundary.

This method allows an accurate optimization of a system toward achieving the expected results in terms of sustainability. Lucia and Grazzini [39] demonstrate that it describes both industrial systems (minimum entropy generation) and biological and living systems (maximum entropy generation).

### *The Second law of thermodynamics (exergy analysis)*

Exergy is the maximum work a system can perform with respect to the external environment. It closely relates to entropy. It has the dimensions and order of magnitude of energy and work and is not a variable of state. It is a relevant thermodynamic magnitude. The exergy concept dates back to the origin of modern thermodynamics. It was implicit in Carnot [40], who determined the maximum conversion efficiency of heat to work (ideal Carnot cycle). It depends on the temperature $T_H$ of the heat source and the temperature $T_0$ of the surrounding environment:

$$\eta_{\max} = 1 - \frac{T_0}{T_H} \tag{4}$$

The work of the Carnot cycle is the maximum theoretically available work and becomes:

$$W_{\max} = \eta_{\max} Q = \left( 1 - \frac{T_0}{T_H} \right) Q \tag{5}$$

It is the exergy relative to a thermal source at temperature $T_H$ and the environment at temperature $T_0$. Increasing the efficiency requires growing $T_H$ and reducing $T_0$. Rant [41] has extended the definition of exergy as the useful energy of a substance, a process or a flow, whatever its nature.

In addition, Wall [42] has defined the exergy $B$ of a system in a large environment:

$$B = T_0 \left( S_{\mathrm{eq}}^{\mathrm{tot}} - S^{\mathrm{tot}} \right) W_{\max} \tag{6}$$

where $T_0$ is the temperature of the environment, $S_{\mathrm{eq}}^{\mathrm{tot}}$ – the entropy of the system in equilibrium with the external environment, when the system is in equilibrium with the external environment, and $S_{\text{tot}}$ – the entropy of the total system at a specific appropriate deviation from equilibrium. Therefore, ($S_{\text{eq}}^{\text{tot}} - S_{\text{tot}}$) is the deviation from the equilibrium of the negentropy (minus the entropy) of the system and its environment when the system evolves from the reference equilibrium state to any arbitrary state. For example, the exergy of a closed system exchanging energy and mass can be determined from Gibbs energy according to [43]:

$$B = S\left(T - T_0\right) - V\left(p - p_0\right) + \sum_i n_i\left(\mu_i - \mu_i, 0\right) \tag{7}$$

where extensive parameters are entropy, $S$, volume, $V$, and number, $n_i$, of moles of substance $i$, and the intensive parameters: $T$ – the temperature, $p$ – the pressure, and $\mu_i$ – the chemical potential of substance $i$. The subscript 0 indicates the reference environment. Equation (7) allows evaluating the difference between Exergy and Gibbs energy [44-47]. Gibbs free energy describes a reversible system in equilibrium with the environment [47, 48]. Exergy refers to irreversibility. It is the maximum amount of work extracted from a system going in equilibrium with its environment and reaching the maximum entropy state. In addition, the exergy of a biological, living and open thermodynamic system can be expressed according to [49-51]:

$$B = \frac{U}{U_{\text{eq}}} + p_0\left(V - V_{\text{eq}}\right) - T_0\left(S - S_{\text{eq}}\right) - \sum_i \mu_i\left(n_i - n_{i,\text{eq}}\right) \tag{8}$$

where $U$ is the internal energy, eqs. (7) and (8) show that exergy measures thermal, mechanical and chemical transformations. In addition, eq. (8) applies to open systems, including living and biochemical ones. Terms for gravity, electricity, magnetism, and radiation can be considered. It is possible to subdivide exergy into four contributing parts:

$$B = B_k + B_p + B_{\text{ph}} + B_{\text{ch}} \tag{9}$$

where $B_k$ is the kinetic exergy reflecting the velocity of a flow, $B_p$ – the gravitational or electro-magnetic potential exergy, $B_{\text{ph}}$ – the physical Exergy or thermal exergy, and $B_{\text{ch}}$ – the chemical exergy.

Physical exergy $B_{\text{ph}}$ is the work which can be obtained by taking the system through reversible physical processes (compression, expansion and heat exchange) to the temperature and pressure of the environment. It is the work that could be extracted from an ideal (reversible) heat engine operating between the system and its environment. Chemical exergy, $B_{ch}$, is the work obtainable by a subsystem with the same temperature and pressure as the environment, reversibly to the same chemical composition of the environment. The versatility of exergy is evident in representing systems of different nature and their capability to produce work, tab. 3.

Dincer and Rosen [52] evidence that exergy analysis is an instrument for improving efficiency and sustainability. Szargut [53] have observed that exergy applies to energy and matter flows and transformations of any nature.

### *Exergy as an instrument for better resources accounting*

Wall [1, 35] has presented a method to account for exergy in natural, mineral and energy resources in human society and proposed exergy analysis to calculate the total exergy use of materials, products, services, nations, or the entire planet. He evidenced the necessity to define a model of Earth's resources. He pointed out that the world is a limited thermodynamic system exchanging radiant energy with the surrounding Space.

**Table 3. Work, exergy and exergy rate of change of different elementary processes**

| | Work or energy [J] | Exergy [J] | Exergy rate of change [W] |
|---|---|---|---|
| Mechanical work | $W$ | $W$ | $DW/\mathrm{d}t$ |
| Friction (1, 2) | $mfgl = mfgvt$ | $mfgl = mfgvt$ | $mfgv$ |
| Aerodynamics (1, 2, 3, 4) | $0.5\ C_D A\rho v^3 t$ | $0.5\ C_D A\rho v^3 t$ | $0.5\ C_D A\rho v^3$ |
| Fluiddynamic (3, 4) | $0.5\ Kmv^2$ | $0.5\ Kmv^2$ | $0.5\ K\mathrm{d}m/\mathrm{d}tv^2$ |
| Potential (1, 2) | $mg\Delta z$ | $mg\Delta z$ | $\Delta z = \mathrm{const}\ g\Delta \mathrm{z}\ \mathrm{d}m/\mathrm{d}t$ or<br>$m = \mathrm{const}\ mg\ \mathrm{d}z/\mathrm{d}t$ |
| Kinetic (1, 2) | $0.5\ mv^2$ | $0.5\ mv^2$ | $v = \mathrm{const} \Rightarrow 0.5\ v^2\ \mathrm{d}m/\mathrm{d}t$<br>or $m = \mathrm{const} \Rightarrow mv\ \mathrm{d}v/\mathrm{d}t$ |
| Heat | $Q$ | $Q\ [1 - (T_0 - T)]$ | $\mathrm{d}Q/\mathrm{d}t\ [1 - (\mathrm{T}_0 - T)]$ |
| Electrical (5) | $I\Delta Vt$ | $I\Delta Vt$ | $I\Delta V$ |
| Chemical (6) | $m\Delta gG$ | $m[\mu - \mu_0 + \mathrm{R}T_0 \ln(c/c_0)]$ | $\mathrm{d}m/\mathrm{d}t\ [\mu - \mu_0 + \mathrm{R}T_0 \ln(c/c_0)]$ |
| Radiation (7) | $P = e\sigma(T^4 - T_0^4)At$ | $e\sigma[T^4 - (4T^3\mathrm{T}_0)/3 + T_0^4/3]At$ | $e\sigma[T^4\text{-}(4T^3T_0)/3 + T_0^4/3]A$ |

Notes: 1 – Dewulf and Van Langenhove (2003), 2 – Trancossi (2016), 3 – Herwig and Schmandt (2014), 4 – Trancossi *et al.* (2021), 5 – Rosen and Bulucea (2009), 6 – Wall (1977), and 7 – Petela (1964)

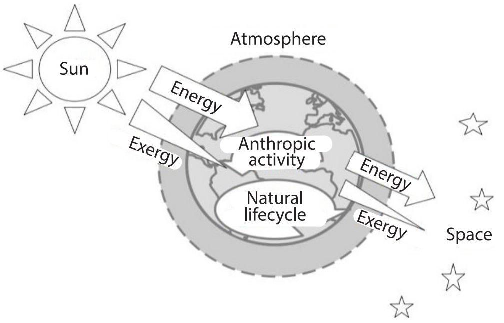

**Figure 3. Earth system, with energy and exergy exchanges**

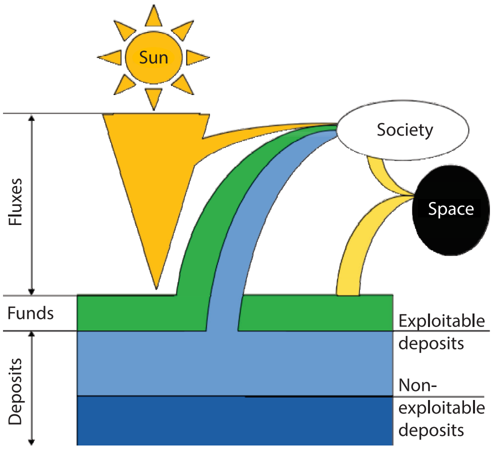

**Figure 4. Energy and exergy flow related to human society**

Energy (and exergy) come from the Sun (light radiation), is transformed in the biosphere by the natural cycle, and is emitted toward Space. The proposed model , figs. 3 and 4, differs from the one by Wall [1]. It considers anthropic activity separate from the natural lifecycle because it is necessary to evaluate how resources (exergy) extracted from the soil and the biosphere are transformed.

Wall has classified the resources according to their origin, but not their use, as fluxes, funds and deposits. *Fluxes* are constituted by energy and materials transported to the biosphere and society, where they are transformed through natural or anthropic processes. *Funds* originate from the solar flux (plants, cultivations, crops, *etc.*). They are renewable within a reasonable time (months or years) and develop in the biosphere. Deposits are materials and energy resources extracted from the lithosphere. Deposits are disposable if existing technologies can exploit them or not disposable if their extraction is expensive, technically impossible, or limited by political decisions, tab. 4.

**Table 4. Exergy factors for different energy sources**

| Energy source | Exergy factor (or exergy to energy ratio)* |
|---|---|
| Mechanical energy | 1.0 |
| Electrical energy | 1.0 |
| Chemical energy | 0.8-1.0 (depending on the chemical reaction) |
| Oil petroleum products | 1.04 |
| Natural gas | 1.03 |
| Coal | 1.05 |
| Coke | 1.06 |
| Wood (20% humidity) | 1.13 |
| Nuclear energy | 0.95-1 |
| Sunlight (the whole spectrum) | 0.93 |
| Thermal radiation | $1 + (1/3)(T_0/T)^4 - (4/3)(T_0/T)$ |
| Heat at temperature, $T$ | $1 - (T_0/T)^{**}$ |
| Hot steam (600°) | 0.6 |
| Hot water (90°) | 0.2-0.3 |
| Thermal energy at room temperature | 0-0.1 |
| Physical energy | $Ex = (h - T_0 s) - (h_0 - T_0 s_0)$ |
| Pressure of an ideal gas at $T_0$ | $Ex = n\mathrm{R}T_0 \ln(P/P_0)$ |

* from Wall (1993), Staine and Favrat (1996) and revised according to De Wulf *et al.* (2008)
** when $T < T_0$ is negative because the resulting exergy flow is in the opposite direction of the energy flow

It is opportune to overcome the traditional distinction between energy and other resources. For example, oil is classified as energy, and wood is a construction material. This distinction makes no sense. Oil is also a material for producing plastics and other materials. At the same time, wood and vegetables are used for multiple energetic uses, from direct combustion fuel production. In addition, wastes from agriculture, industry and human life must be adequately accounted for as resources or energy sources. Again, this distinction makes no sense if it does not consider the final uses.

## Results: Exergy and consistent accounting of environmental impacts

### *Exergy and assessment of environmental impacts*

Energy and materials are necessary to satisfy human needs and improve quality of life, but they lead to environmental impacts. The UN SDG [4] indicate the necessity of effective atmosphere-recovery strategies. They involve energy conversion processes to increase efficiency, reduce the impacts, and optimize the energy mix and renewable energies inside a path toward reduced $CO_2$ emissions.

Exergy analysis combines the first and the Second law of thermodynamics. It includes the laws of conservation of mass and energy (First law of thermodynamics) and the law of entropy increase (Second law). Exergy is the most appropriate way of connecting thermodynamics with sustainability and environmental impacts [8, 9]. The reference environment regarding temperature, pressure, and chemical composition always determines it. It measures the distance between the system's state and the environment's state [54]. The exergy of a system depends on the state of the system and environment. It is zero only when the system is in equilibrium with its environment.

Exergy allows an evaluation of more meaningful efficiencies than the ones estimated by energy analysis since exergy efficiencies are a measure of the approach to the ideal [55]. Exergy analysis is valuable for analyzing, designing, and improving physical systems and processes. It flows at a different level of detail because it applies to the entire system, its modules, sub-modules and components. Moran [56] shows that it allows identifying the wastes and losses at different scale levels, their magnitude, their locations, their causes, and the possible improvements to reduce them. It determines the available margin of improvement for designing more efficient energy systems.

Lucia and Grazzini [39] show that exergy allows a better comprehension of the relevant energy-related processes and improvement of engineering systems by limiting the irreversibility and living biological systems by maximizing the irreversibility. Increasing exergy efficiency for industrial and energy plants and processes reduces waste exergy emissions and internal exergy disruption. Exergy contributes to better understanding and reducing environmental impacts. There is a relation between exergy and the environment revealing the effects of processes and understanding the environmental damages. On one side, the exergy analysis of the natural processes allows effective ecological modelling and understanding of the effects of large-scale environmental impacts.

Increasing energy efficiency (First law of thermodynamics) can reduce environmental impacts by reducing energy losses. However, a much higher reduction of impacts can be achieved through exergy analysis and optimization with a consequent increase in exergy efficiency and reduced exergy losses in terms of both waste exergy losses (wastes) and internal exergy consumptions. Multiple relationships between exergy and environmental impacts exist, according to Rosen and Dincer [57].

### *Exergy is a measure of order*

The increase of disorder or the disruption of order is a form of environmental damage. It produces an increase in entropy and a decrease in exergy. While entropy measures disorder, exergy measures order. In particular, a society that makes an enormous amount of poorly managed waste destroys much more exergy than a society in which reuse, reduction and recycling of wastes are the praxis. The exergy that is destroyed when wastes are chaotically produced is much larger than the one destroyed in an ordered scenario. To swift from chaotically displaced wastes to an ordered system in which the wastes are managed to minimize their impact on the environment requires work. Exergy measures the minimum work necessary to convert a chaotic system to an ordered one. It is an ideal measure because it applies only if ideal reversible phenomena are used. Real phenomena require much higher work. Similar considerations apply to global warming. For example, the melting of glaciers requires a considerable amount of thermal energy, but their reconstruction requires a much higher amount of energy, demonstrating the irreversibility of the phenomenon. It is then evident that the amount of necessary exergy by the icing process is higher than that required for the melting process.

### *Exergy is a measure of environmental disruption*

The degradation of natural resources in natural and anthropic processes produces a detrimental disruption of the quality of environmental resources. According to Kestin [58], resources are natural and artificial materials in a state of disequilibrium with the surrounding environment. This disequilibrium is measured in terms of exergy. Chemical properties, including composition and reactivity, characterize resources. For example, reactivity is a typical characteristic of fuels that describes the impetus that allows a chemical substance to react with other substances releasing energy. When a substance degrades, reactivity changes, generally reducing but sometimes increasing. In addition, degradation usually reduces the exergy content of a material, and the reinstatement of the material's original properties requires spending a further amount of exergy. The degradation of the resources is essential because the living matter does not respond to the usual law of minimum entropy generation. Still, it evolves according to the law of maximum entropy generation [59-62]. Therefore, the survival of living systems requires a large amount of exergy to be dissipated. Thus, reducing the available exergy through the degradation of the resources minimises the possibility of survival for humankind and living organisms.

Two general approaches are adopted to reduce the environmental impact associated with the degradation of resources. The first relates to increasing the efficiency of the processes. It allows for preserving exergy by reducing the necessary exergy for realizing an anthropic process. It reduces the environmental damage that the process may cause. As a result, energy and pollutants emissions are reduced together with the related environmental injuries. The second regards using involuntary exergy (and energy) sources, for example, solar energy. It is possible because Earth is a limited open thermodynamic system receiving energy and exergy from the Sun, which generates renewable sources. Limiting the cementation and overbuilding of the soils and incrementing the green areas with a preference toward increasing the available solar exergy from the Sun. The environmental damages can be repaired by taking advantage of radiation exchanges with the Sun and the universe. Today, these exchanges are altered by the increasing presence of greenhouse gasses, which creates a barrier and limits the openness of Earth's thermodynamic system. In particular, the increase of greenhouse gasses limits the thermal dissipation from Earth toward Space. Therefore, it makes the planet more degraded by increasing the temperature and, consequently, the entropy.

### *Exergy is a measure of the disequilibrium caused by pollution*

Waste exergy emissions result from the unstable equilibrium between natural and anthropic systems with the environment. Hence, they represent the potential to cause a change. When emitted into the environment, the gaseous, liquid and solid wastes are quantified in terms of their potential to change and damage the environment. Emitted pollutants react and come to equilibrium with the surrounding environment, with both negative and positive effects [63, 64]. Usually, the typical effects of waste and pollutants emissions produce irreversible environmental damage. The results are killing or causing illnesses in animals, fishes, plants, and humans by dangerous emissions that react with air, water, and living cells. The advantages refer to thermal emissions in water because of cooling-water outlets from thermal power plants, which usually generate grow-rates of fish and vegetation. In addition, exergy emissions of $CO_2$ and other GHG, to the environment can interfere with both solar radiation coming to Earth and the outcoming one.

Filtration plants or $CO_2$ capture systems may be evaluated even if they could reduce the efficiency of the plants and processes and produce a consequent exergy disruption. Therefore, it is necessary to estimate their use carefully through accurate balances. They are convenient for measuring subtracted exergy by those systems. Subtracted energy is not lower than the exergy needed to remove the pollutants from the environment. In this way, it is necessary to develop an accurate design of plants to reduce inefficiencies. The exergy impacts of different economically and socially relevant anthropic processes are analyzed in the next part of the paper [65].

### *Exergy as a useful LCA modelling tool*

Exergy is a useful LCA tool because it is capable of estimating sustainability. Figure 3 shows that physical resources are classified into natural exergy flows, exergy funds and exergy deposits. Natural exergy flows derive directly or indirectly from solar radiation. Renewable resources are resources that can be regenerated in a reasonable time. Depleting exergy funds (deforestation, overbuilding, land and water pollution and contamination, unsustainable agricultural exploitation, land impoverishment, waste landfilling, *etc.*) causes a reduction in renewable resources' benefits. The use of exergy deposits relates to non-renewable resource abuse. Being Earth a limited system, non-renewable resources are not infinite. After a century of excessive and increasing exploitation, their use must be accurately managed to ensure long-term perspectives for future generations [66].

If an economical, industrial, natural or societal process is considered, the total exergy disruption must be estimated to increase the sustainability of society's materials and energy supply systems. The exergy flow through a supply system, such as a power plant or a transport infrastructure, usually consists of different stages. The construction stage destroys exergy for the necessary operations to prepare the required interventions, build the plant and/or the interconnected infrastructures, and put them into operation. Exergy is spent in different ways: extraction of materials, processing and predisposing the necessary semi-finished products, transports, land predisposition, excavation of the ground, manufacturing and finishing the infrastructure and plants. When the plant starts operations, it is necessary to account for the materials and the energy sources to be transformed, the transport processes, the transformation, the final products and the maintenance operations. Finally, it is necessary to evaluate the final dismantling stage, including dismantling, reconversion of the materials and recycling, including the management. These three-stages are identical to the ones used in lifecycle management. According to Gong and Wall [8, 9], the exergy input used for construction, maintenance and dismantling is usually named indirect Exergy $B_{\text{indirect}}$. The exergy of the necessary materials and energy is $B_{\text{in,}}$ and the one of the final products is $B_{\text{pr}}$. In addition, the specific sources in terms of materials and energy sources used for the production must be analysed: the part that comes from deposits is unsustainable, and the part from funds and natural sources is sustainable. They can be balanced to maximize the sustainability of the products. It must be considered that exergy relates directly to entropy. Therefore, the entropy of the final product must be higher than the ones of the plant and the sources. In terms of exergy, it can be expressed:

$$B_{\text{pr}} < B_{\text{in}} + B_{\text{indirect}} \tag{10}$$

Figure 5 shows the exergy flow in the process, which must necessarily respect the inequality (10). The difference between the exergy for production ($B_{\text{in}} + B_{\text{indirect}}$) and the one of the products $B_{\text{pr}}$ is the exergy disrupted by the considered process $B_{\text{disrupted}}$. In particular, $B_{\text{disrupted}}$ includes both exergy reduction during the process, exergy of wastes and exergy of environmental emissions.

It is possible to consider the exergy destroyed in terms of process waste $B_{\text{waste}}$. In particular, assessing the wastes in terms of their final destination is crucial. For example, in some processes, waste can be a valuable byproduct that allows for feeding other processes. In this case, the useful wastes that are reused for other useful processes can be accounted for in the final products. On the other side, the wastes that need to be managed and disposed of are considered wastes. In addition, wastes include the substances dispersed in the environment, such as gaseous emissions. In this case, fig. 5 is modified as in fig. 6.

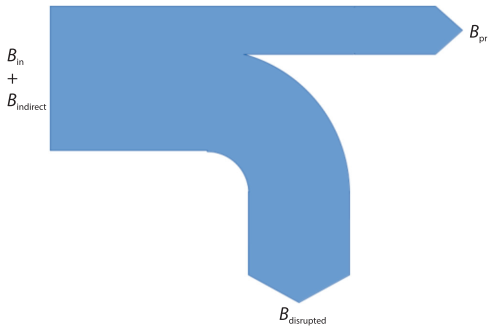

**Figure 5. Exergy flow representation**

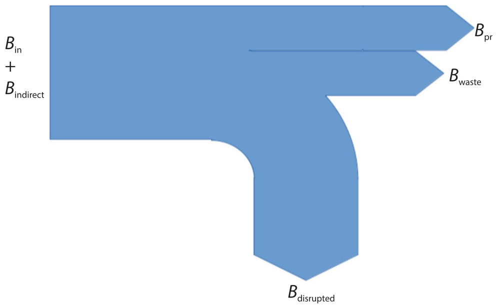

**Figure 6. Exergy flows, including wastes**

*Exergy as an ecological indicator*

Exergy is a fundamental ecological indicator which can be used in both design and estimation of the impacts of the processes. The minimization of the exergy losses in a process usually causes a reduction of the exergy dispersed into the environment. in terms of losses and environmental effects. For example, if a gasoline or diesel vehicle is considered, the gaseous emission generates a certain amount of waste exergy [52, 67, 68]. The exergy flows are described in fig. 7.

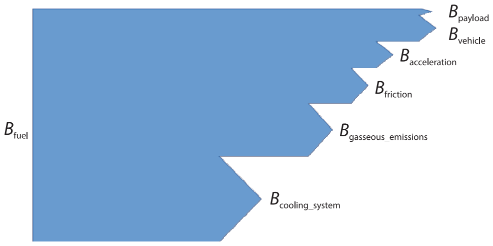

**Figure 7. Exergy disruption in an ICE vehicle moving on a flat plane, derived from [52]**

Figure 7 is the average exergy flow through a vehicle transportation system. Thus, it exemplifies how fuel input is used. This specific example is important for the second part of this paper [68]. Less than 10% of the gasoline or oil introduced for ground vehicles is effectively used to move the vehicle and payload. The remaining exergy is dissipated for converting fuel into work or emitted into the environment (heat and gaseous emissions).

As Wall [1, 8, 9] has observed, exergy analysis presents multiple advantages with respect to traditional energy balance. In particular, exergy analysis allows:

– identifying potential areas of action increase the exergy efficiency and consequently reduce the environmental impacts,
– comparing different alternative processes or materials, verifying the exergy embodied in the emissions and their potential to cause damage to the environment,
– applying the same method to describe multiple processes at different scales, considering all the relevant impacts of the process,
– estimating the useful energy embodied in any material and, therefore, helps to give an environmental value to any material and product, and
– supporting lifecycle analysis of chemical processes because it considers the *hidden energy* of chemical products and polymers.

## Conclusions

*Exergy, ecology and democracy – concepts of a vital society or a proposal for an exergy tax* [1] has been a milestone paper. It has been the first paper to extend thermodynamics and the second law analysis to policy-making in 1993. This milestone paper has demonstrated that thermodynamics and second law analysis can be valuable instruments for effective policy-making toward sustainability. Moreover, it reveals its enduring relevance in the political framework determined by the *UN Sustainability and Development Goals* [2] and *Paris Agreement* [3]. In particular, the paper by Goran Wall [1] is a guideline toward an effective and measurable actuation of the goal *SDG 12, Responsible Consumption and Production*.

*The UN SDG* and the *Paris Agreement* evidence the necessity of sustainability transition, reducing greenhouse gas emissions and limiting the global temperature increase. However, the policy measures on sustainable development have proved to be sounding even if the governmental measures toward an effective transition seem confusing and with scarce efficacy. A significant cause is that the indicators used to assess sustainability and climate-change-driven measures often appear inconsistent. This paper has considered SDG 12, *Responsible Consumption and Production.* This goal has been fundamental in any path toward sustainability [3, 22]. Any measure toward SDG 12 influences resources, their transformation and distribution, lifestyles and people acceptance, accessibility and distribution of global resources, wellness conditions, and the inequalities between different areas of the planet. Exergy analysis is a fundamental indicator of the sustainability of anthropogenic activities and societal development. It provides a rational framework for accounting resources and their uses.

Exergy analysis is an instrument for sustainability accounting that delivers much more helpful information than mass-based indicators such as Domestic materials consumption, which are often adopted at the governmental level even if they present evident problems in terms of consistency.

The importance of exergy has been evidenced. It applies to almost any natural, industrial, and societal process. In particular, it has been discussed how exergy can be used as an effective measure of LCA impacts. Different examples have been discussed, and a more effective clarification of the possible uses of exergy analysis has been discussed.

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