Thermoeconomic analysis of Earth system in relation to sustainability: a thermodynamic analysis of weather changes due to anthropic activities

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Thermoeconomic analysis of Earth system in relation to sustainability

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Abstract

Recently, a new bioeconomic indicator has been introduced in order to avoid the difficulties in evaluating the process and technologies for sustainability. Indeed, the indicator has been based on the exergy and irreversibility analysis. The aim of this paper is to highlight how this new indicator could be used for the analysis of climate and weather changes. To do so, the thermoeconomic bases of the indicator are developed in order to link them to the thermodynamic analysis of the Earth system. The result is to describe analytically the effect of the anthropic activities on the Earth system, related to the variation of the Earth internal energy. So, this internal energy variation is linked to the increase of the intensity of the present rainfalls, by using the concept of mass of water vapour present in the dry air, used in the thermodynamic analysis of moist air. It is possible to point out the effect on the increase of mass of water vapour in the atmosphere, due to the increase of the mean Earth temperature and the related partial saturation pressure of water vapour itself.
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Keywords: Entropy; Economic indicator; Entropy generation; Weather and climate; Bioeconomy.

Nomenclature

Latin letters

B	Non-flow exergy accumulation [J]
c	Specific heat [J kg^{-1}K^{-1}]
E	Energy [J]
EI	Energy Intensity [J \$$^{-1}$]
F	Heat power surface density [W m^{-2}]
I	New indicator for sustainability
J	Flow energy [W]
LC	Labour cost [\$ s^{-1}]
p	pressure [Pa]
$\dot{Q}$	Heat power [W]
$\dot{S}_g$	Entropy generation rate [W K^{-1}]
t	time [s]
T	Temperature [K]
U	Internal energy [J]
$\mathbf{v}$	velocity [m s^{-1}]
V	Volume [m^3]
W	Mechanical or process work [J]
$\dot{W}$	Mechanical or process power [W]

Greek letters

ρ	density [kg m^{-3}]
τ	finite time of the process [s]

Subscripts

0	environment
ex	exergetic
λ	lost
Q	thermal

1 Introduction

Nowadays, the human development has come to a crossroad. We have the consciousness that our choices and relative actions have implications for the future generations and for the whole Earth system [1], this is just the core of the *Brundtland Report* [2] sustainable development definition. As a matter of fact, today, a socio-economic system of despair has been generated as a consequence of the complex dynamics due both to the increase in poverty distribution and to the growing amount of ecosystem degradation. Moreover, it appears very difficult to be able to escape from this particular state of human *evolution* [3]. A possible response to these problems can be represented by some substantial progresses in healthcare and access to basic services, and the growing awareness on the ecosystems concerns [4].

What represents a non-sense is that humanity started to impact largely on the world ecosystem when Europe became a technological society and expanded its power by means of colonization. The inconsistent use of technologies generated the needs of energy and the faster use of the resources. Nowadays, we have gained the knowledge [5–13] for the comprehension of consequences on the ecosystems, and we must change our viewpoint in order to avoid the increase of this degradation. In particular, the composition of the Earth's atmosphere allows us to gain information on the state of the whole Earth system [14].

Earth's system is continuously maintained in a thermodynamic non equilibrium state as it has been highlighted by Lovelock in 1965 [15]. Just Lovelock introduced the hypothesis that this non-equilibrium state was related to the life itself. Then, it was pointed out that the biotic activity was able to modify the geochemical reaction times [16], and to introduce new biochemical reactions: life and Earth system are in a continuous interaction with a related dependence [17].

The primary Earth's source of energy is the inflow of the electromagnetic waves from the Sun, while the cooling origin is the outflow of infrared thermal energy from the Earth to Universe.

All these findings hold to the study of the causes of this Earth non-equilibrium state. Indeed, incoming solar radiation carries thermal energy which characterises a state far from thermodynamic equilibrium with the temperature, related to the absorption and re-emission of the electromagnetic radiation [14]. The disequilibrium is the consequence of the temperature difference between the emission temperature of the radiation and the temperature at which radiation is absorbed. Consequently, inside the Earth system, this non-equilibrium state is the cause of the kinetic energy associated with the fluid fluxes due to pressure gradients and the heat transfer, which generate dissipation for friction (erosion fluxes, sediment transport, etc.). In the atmosphere, there is also a disequilibrium of the carbon cycle which generates differences in CO_2 concentration between the atmospheric CO_2 and the concentration in the mantle and in organic carbon [14].

The thermodynamic analysis of the Earth system, as a whole, must take into account that any process on our planet occurs at different time scales. In this context we must highlight that the common effect of the Earth process, from atmospheric to geological ones, from biological to chemical-physical ones, is the transport of energy and mass [14]. In particular, we must consider that any human activity alters the behaviour of our planet atmosphere, lands and water [18–20].

Thermodynamic analysis requires the definition of the control volume. We consider the Earth-system in terms of non-equilibrium thermodynamics, with particular regards to the transformations of energy and mass, and their flows.

Any change in the Earth stationary state is caused by some variations in the balance of the inflow and outflow of energy through the boundary of the Earth system [21, 22].

The aim of this paper is to develop a thermoeconomic analysis of the Earth systems in relation to the recent weather (ot climate) changes in any region of the Earth. In particular, we suggest the use of a thermoeconomic indicator recently introduced [9, 23–25] in order to consider the irreversibility and to take into account the target of the industrial processes. The result will be a link between the weather (or climate) changes and the Earth global temperature variation due to the irreversibility of the anthropic activities.

2 Theory

In the analysis of the Earth system, first we define the control volume by defining its boundary. In order to develop our analysis, we consider the top of the atmosphere. In this case, the fundamental energy flux is the radiative one [18]. Trough this choice of the control boundary, the Earth can be considered as a closed system, with the consequence that we can ignore the inner mass flows.

In relation to this boundary, the first law of thermodynamics can be written as:

$$\dot{Q} - \dot{W}_\lambda = \frac{dU}{dt} \tag{1}$$

where $\dot{Q}$ is the heat power exchanged through the boundary, $\dot{W}_\lambda = T_0 \dot{S}_g$ is the power lost for irreversibility, with T_0 reference temperature (the environmental temperature of the system, in our case the Universe temperature) and $\dot{S}_g$ the entropy generation rate [6, 7, 13, 26–31], and U is the internal energy of the control volume. The evaluation of the power lost can be done considering that the Earth exchange heat with the Sun, so that, considering the Gouy-Stodola theorem, it is possible to write [18, 32]:

$$\dot{W}_\lambda = T_0\, \dot{Q} \left(\frac{1}{T_{Earth}} - \frac{1}{T_{Sun}} \right) \tag{2}$$

where $T_0 = 3$ K is the temperature of the Universe around the Earth, $T_{Earth} \approx 288$ K is the mean temperature of the border of the control volume, $T_{Sun} \approx 5760$ K is the mean temperature on the Sun surface.

Consequently, the internal energy rate results:

$$\frac{dU}{dt} = \dot{Q} - \dot{W}_\lambda = \dot{Q} - T_0\,\dot{Q}\left(\frac{1}{T_{Earth}} - \frac{1}{T_{Sun}}\right) = \dot{Q}\left(1 + \frac{T_0}{T_{Sun}}\right) - \dot{Q}\,\frac{T_0}{T_{Earth}} \quad (3)$$

In relation to this result, we can highlight that the more the mean Earth temperature increases the more its internal energy increases. This represents a difficulty because the internal energy is the energy that the Earth system uses to internal work, useful to maintain the life conditions, the slow internal energy transfer (winds, tides, etc.). Indeed, an increase in the mean Earth temperature increases the dissipation.

Recently, we have introduced a new thermoeconomic indicator which takes into account the interaction between technical, economical and social topics, defined as:

$$I = \eta_\lambda \cdot EI \cdot LC \quad (4)$$

where $\eta_\lambda = 1 - \eta_{II}$, where $\eta_{II} = W/Ex_{in}$ is the second law efficiency, $EI = E_{in}/GDP$ is the Energy Intensity, E_{in} is the energy used to obtained the value of GDP, and the GDP is the Gross Domestic Product which represents the wealth of a country or a productive system, $LC = GDP/n_w$ is the labour cost, with n_w the total number of work hours.

The new indicator has been generalised as:

$$I = \frac{T_0\,S_g}{f} \quad (5)$$

where f is the required sustainable effect.

These last physical quantities can be obtained by a classical thermodynamic approach. Indeed, according with the first law of thermodynamics for the open systems, any energy variation within the thermodynamic control volume can be due to the transferring of:

1. Flows of matter through the system's control surface, that mean variations in internal, chemical, potential, kinetic and other forms of energy;

2. Heat through the system boundaries;

3. Work which is performed by or on the system.

So, for any process, interaction, cycle, etc. can be defined the lifetime of the phenomenon itself: the definite time τ in which the phenomenon occurs. Thus, for any process inside the Earth system, it is possible to obtain the exergy balance as follows [31]:

$$W = \Delta B + \sum_{\alpha} J_{ex,\alpha} + \sum_{\beta} Ex_{Q,\beta} - T_0 S_g \tag{6}$$

where:

- W is the net work performed during the process;
- $\Delta B = E + p_0 V - T_0 S$ is the non-flow exergy accumulation;
- $J_{ex} = \int_0^{\tau} \dot{m}\big(e - T_0 s\big) dt$ is the flow exergy caused by the matter flow;
- $Ex_Q = Q\big(1 + T_0/T\big)$ is the flow of exergy caused by heat transfer;

and the subscript 0 means environment, while p and V respectively represent the pressure and the volume.

Now, considering the relations (3) and (5) it is possible to obtain the relation between the internal energy of the Earth and the new indicator as follows:

$$I = \frac{\dot{Q}_{lost}}{f} = \frac{-\dot{W}_{\lambda}}{f} = -\frac{T_0\,\dot{Q}}{f}\Big(\frac{1}{T_{Earth}} - \frac{1}{T_{Sun}}\Big) \approx -\frac{T_0\,\dot{Q}}{f}\,\frac{1}{T_{Earth}} \tag{7}$$

because $T_{Sun} >> T_{Earth}$ and the negative sign of the work lost to irreversibility is related to the sign considerations of the heat transfer from the Earth towards the Universe [14, 19, 32, 33]. This result highlights how our indicator is strictly related to the global behaviour of our planet. It is possible to highlight that:

- $\dot{Q}$ is the inflowing power from the Sun, and it can be considered constant;
- dU/dt is the internal energy variation rate;
- Greater is the Earth temperature greater is the indicator, in accordance with the behaviour of the indicator related to its lower value in correspondence to the more sustainable process.

So, the indicator proposed is strictly related to the thermal effects of the anthropic activities on the Earth system, considering the natural processes constant.

3 Results

The fundamental result of this paper is the link between the new indicator for sustainability, recently introduced in bioeconomy [23, 24], and the climate conditions of the Earth. This result is mathematically expressed in the relation (7). Indeed, this relation presents:

- The required effect of the process under analysis, which can be considered as a constant if the process is defined;
- The energy fluxes from the Sun, which can be considered constant in relation to the human activities;
- The internal energy variation, which is the fundamental quantity related to the Earth internal fluxes, that are causes of the Earth climate and local weather modifications.

Indeed, considering the fluid systems on the Earth, there exists a gravitationally unstable top-heavy density distribution due to the processes of expansion and contraction of the fluid itself which are caused respectively by the fluid heating, which takes place at the bottom of the system, and by its cooling which occurs at the top [34, 35]. To this particular density distribution is associated a potential energy that is caused by the differential heating, resulting in the conversion of the heat into work [36]. There is a difference temperature threshold value above which fluid convective motions start their development and the system becomes unstable against low perturbations [34].

When the convective phenomenon begins, the fluid motion, due to the potential energy of the gravitational field, transports energy in the form of heat, and therefore the related total heat flux increases. The conversion of the potential energy into the kinetic energy of the fluid occurs and subsequently this energy is dissipated by viscous dissipations into heat [34, 35]. In a steady state, the rate of the potential energy is balanced by the viscous dissipation rate [34]. Thus, the heat inflow rate should be equal to the outflow rate. In this steady state, the entropy generation S_g, produced in a time τ, is [37]:

$$S_g = \int_0^{\tau} dt \int_V \frac{1}{T} \left[\frac{\partial(\rho\, c\, T)}{\partial t} + \nabla \cdot (\rho\, c\, T\, \mathbf{v}) + p\, \nabla \cdot \mathbf{v} + \nabla \cdot \mathbf{F} \right] dV \qquad (8)$$

where T is the absolute temperature, ρ is the fluids density, c is the specific heat at constant volume, $\mathbf{v}$ represents the velocity of the fluid, p is the pressure, V is the volume of the fluid system, Ω is the surface which surrounds the system, and $\mathbf{F} = \dot{\mathbf{Q}}/\Omega$ is the heat power surface density, defined as positive outward.

The motion of the fluids has been proven to be related to climate, and in particular that the Earth entropy generation is related to the internal energy variation of the fluids on the Earth [14, 18–20]. Consequently, we can point out that:

- All the climate processes are controlled by the fluid fluxes and the entropy generation;
- The entropy generation is related to the sustainable indicator introduced;
- The indicator allows us to take into account the following effects:
  - The link between economy and engineering;
  - The optimisation opportunity by using the thermodynamic analysis of fluxes [26–28, 31];
  - The effects of the anthropic activities on the Earth climate, due to well known relation between the vertical acceleration of the atmospheric air mass fluxes and the Earth internal energy variation due to thermal effects [35].

4 Discussion

Albert Einstein considered thermodynamics as the “only physical theory of universal content” [33]. This statement allows us to introduce a thermodynamic analysis of the Earth system in relation to sustainability. Indeed, entropy generation represents a fundamental quantity in relation to efficiency, because entropy generation allows us to evaluate the exergy lost by any system in any process [38].

So, we have introduced an indicator based just on the definition of entropy generation. In this paper we have pointed out how this indicator could take into account the weather variation due to anthropic activities.

Indeed, following Kleidon [19] and Volk *et al.* [39], entropy generation has been used to evaluate the thermodynamic analysis of many Earth system processes, with particular regards to the atmosphere thermal fluxes.

Moreover, we have highlight that the increase of the Earth temperature determines an increase of the Earth internal energy. In a simplified, but effective thermodynamic approach, the intensity of extreme rainfall is related to the capacity of the atmosphere to hold water, by following the equation of saturation pressure of water vapour as a function of absolute atmospheric temperature T [40]:

$$\omega = 0.622\,\frac{\varphi p_{sat}(T)}{p - \varphi p_{sat}(T)} \tag{9}$$

where ω is the mass of water vapour per kg of dry air, φ is the ratio of the gas constant for dry air to that of water vapour, p is the atmospheric pressure, $p_{sat}(T)$ is the saturation pressure at the temperature T. The saturation-specific humidity increases by around the 7% per degree at 0°C and around 6% per degree at 24°C. If we consider a constant relative humidity, p_{sat} increases with temperature increase, so ω increases, which means that also the mass of water per kg of dry air increases [41]. Consequently, the mass of water increases in relation to the raise of the Earth temperature, that it is related with the increase of the Earth internal energy. In Figure 1, it is represented a numerical evaluation of the ratio of the mass of water vapour between two states:

- The Earth mean temperature increase of temperature up to 5°C, which corresponds the mass of water vapour $\omega(T)$;
- The Earth present state ($\approx$ 15°C), , which corresponds the mass of water vapour ω(288 K).

In this Figure the evaluation has been developed for four different relative humidity (φ = 30%, φ = 50%, φ = 80%, and φ = 100%): it is possible to point out the effect on the increase of mass of vapour in the atmosphere, due to the increase of the Earth mean temperature (and of the related partial saturation pressure of water vapour).

This theoretical result is fundamental to point out how the indicator introduced could represent a response to the requirement of analysing the anthropic processes as a quantitative basis for the decision makers on sustainability.

5 Conclusions

Energy production and transformations are the fundamental quantities for all the transformations and transitions within the system [42, 43]. During the social and economic development humans must increase their knowledge about the technologies related to the useful processes, as recently developed in more sustainable researches [44–51]. Spreng [52] introduced the evaluation of the economic activities in relation to the importance of their output by a measure of their information and their efficiency.

Consequently, we wish to highlight that the choice among alternative technologies can be based on entropy, because entropy is the thermodynamic quantity related both to information and to efficiency [23].

In this context, we have introduced a new indicator, related to the optimisation approach in engineering thermodynamics, in accordance with the recent researches on sustainability based on Constructal Law [53–61]. Here we have pointed out the link between this indicator and the climate or whether conditions. The result is to highlight a new view point introduced by this indicator:

- To analyse the production system as an open thermodynamic system;
- To consider the exergy lost by the production system and evaluate it in relation to the aim of the production system;
- To use the entropy generation which is a quantity used in the engineering thermodynamic approach to optimisation and, consequently, to improve the plants and the production system, from an energy point of view;
- To introduce an indicator which takes into account the climatic issues;
- To use an indicator which can be expressed also in monetary way, by choosing a monetary energy reference (for example the electricity cost).

The approach proposed is a global approach, so that its limit is to be unable to obtain local forecasting for weather changes, but only global weather or climate changes.

We wish to highlight how this model is interesting for evaluation on global scale in order to develop policies of developments based on evaluation of sustainability.

Conflict of interest

The authors declare that they have no conflict of interest.

Authors contributions

UL developed the thermophysical approach. GG developed the engineering thermodynamic considerations. UL and GG developed the thermodynamic application on whether. D.F. and G.G. developed the green economy considerations. All authors contributed to the main manuscript text and reviewed the manuscript.

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Figure 1: Numerical evaluation of the ratio of the mass of water vapour between the increased Earth mean temperature and the present state, in the scenario of a range increase of temperature up to 5°C, starting from the present Earth mean temperature of 15°C (288 K). The evaluation has been developed for three different relative humidity ($\varphi = 30\%$, $\varphi = 50\%$, $\varphi = 80\%$, and $\varphi = 100\%$).