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A Thermo-Economic Measure of Sustainability

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Abstract: Recently, an improvement of the United Nations Human Development Index (HDI), named the Thermodynamic Human Development Index ($THDI$), has been introduced to link socio-economics to environmental and technical pillars of sustainable development. In this paper, the $THDI$ is linked to the Kaya identity to bring out the quantities useful in energy economics and to obtain a clearer tool for the evaluation of sustainability. Moreover, the $THDI$ has been normalized for use as an index for the analysis of sustainability. The component related to environmental emissions, which is included in the $THDI$, can be linked to the Kaya identity. This linkage allows us to use the $THDI$ for the analysis of scenarios, which is useful for evaluating the possible impacts of any future actions on the development of countries.

Keywords: bio-economy; sustainability; thermodynamics; happiness; wealth; human development index

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1. Introduction

In 1974, Richard Ainley Easterlin developed the first study on happiness in economics, introducing a paradox that can be summarized by the following statement [1]: at a certain point, happiness varies directly with income, both within and among countries; however, over time, happiness does not grow as income increases. This means that higher incomes do not produce greater happiness over time [2,3]. The original study was based on the United States' data from 1946 to 1970, and this evidence was confirmed in a later analysis of 21st century data, not only from the USA but also from other industrialized or socio-economically transitioning countries.

Two possible explanations have been conjectured:

- The effect of additional money is not related to the personal wealth condition but rather to a comparison of the condition among different people [4];
- The effect of additional money is related to obtaining holdings, but it is not able to determine an increase in personal well-being [5].

Some criticisms have been leveled at the Easterlin paradox. In particular, these include:

- The time series in happiness and income were not related [6–8];
- Some data show no evidence of a threshold in contrast to the hypothesis that the happiness trend occurs after some minimum level of income [9,10].

Against these criticisms, Easterlin has highlighted that the analyses used to comment on his paradox are based on insufficient observations to establish the real trend [2].

Recently, there has been continuous growth in interest in measuring both quality of life and well-being due to the recognition that the Gross Domestic Product (GDP) is solely an economic indicator, offering only a partial perspective on the different facets of people's lives [11].

Furthermore, recently, a definitely unheard-of consensus among world scientists has emerged regarding the cause–effect relationship between human activities and global warming [12,13], even though climate change has continued to attract a great deal of discussion and disagreement [14,15]. Moreover, the urgent need to reduce anthropic-based greenhouse gas emissions was recognized in the legally binding international treaty on climate change, too. The treaty was adopted by 196 parties during the 21st Conference of Parties (i.e., the Paris Agreement [16]). Because of the negative effects of GHG emissions on the environment (i.e., the one required by organisms to live), the need to also consider environmental aspects within measures of human well-being arises.

Thus, some considerations must be introduced in relation to greenhouse gases and pollutant emissions, but they are related to air pollution due to human activities. Indeed, air pollution is a mix of some substances emitted into the air from:

- Human activities, such as vehicle emissions, fuel oils and natural gas for heating homes; by-products of manufacturing and power generation; and fumes from chemical production, etc.;
- Natural phenomena, such as smoke from wildfires (when caused by self-combustion, otherwise, these can also be due to human acts); ash and gases from volcanic eruptions; gases emitted from the decomposition of organic matter into soils, etc.

Air pollution is responsible for more than 6.5×10^6 deaths each year globally [17], with some other adverse health consequences [18], such as cancer [19–22], cardiovascular diseases [23], respiratory diseases [24], etc.

Moreover, air pollution related to human activities is mainly caused by the emissions of traditional air pollutants, including carbon monoxide (CO), nitrous oxides (NO_x), sulphur dioxide (SO_2), black carbon (BC), ammonia (NH_3), organic carbon (OC), and non-methane volatile organic compounds (NMVOCs), while the climate-change-related air pollution is caused by the emission of greenhouse gases (GHGs) from fossil fuels and other resources, with particular regards to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and halocarbons [25]. To quantify the latter emissions, the concept of carbon dioxide equivalent (CO_{2-eq}) has been introduced. It represents a metric measure useful to compare the emissions from various greenhouse gases based on their global warming potential (GWP), by converting amounts of other gases into the equivalent amount of carbon dioxide with the same global warming potential. The GWP is a greenhouse-gas-relative potency, molecule for molecule, that considers how long a GHG remains active in the atmosphere [26]. The present reference time interval is 100 years, so carbon dioxide is taken as the reference gas with a given 100-year GWP of one. In this context, the need to evaluate the CO_{2-eq} emerges. To evaluate this, the Kaya identity can represent a powerful approach [27].

1.1. The Kaya Approach

The Kaya identity is a mathematical relation that links the total emission level of the GHGs with the product of four factors: (i) human population, (ii) GDP per capita, (iii) energy intensity per unit of GDP, and (iv) carbon intensity (i.e., the emissions per unit of energy consumed). The Kaya identity is useful for evaluating emissions on the basis of the available data in any country, pointing out the elements of the global economy on which any country can act in order to reduce emissions. Moreover, this relation is used in the formulation of future emissions scenarios by the IPCC in the Special Report on Emissions Scenarios, on the basis of a range of conditions introduced for each of the four considered quantities in a future perspective, with the aim of predicting the future carbon dioxide concentration and the evolution of the global warming. The Kaya identity was proven from its estimation of the CO_2 emissions by comparing its evaluation with accurate data among 215 countries for the period from 1990 to 2011 [27]; indeed, the result obtained has been that the Kaya identity can predict 80% of the future emissions around the world. The Kaya identity can be summarized as follows: $\dot{m}_{CO_{2-eq}} = P \cdot GDP_{pc} \cdot IE \cdot CI$.

This identity can represent a tool for evaluating GHG emissions, in terms of CO_{2-eq} ($\dot{m}_{CO_{2-eq}}$), related to fuel consumption and fuel type for a given year. Moreover, it also considers the four aforementioned different factors driving fuel consumption:

- Population (P), whose growth represents one of the significant factors for carbon dioxide emissions, with particular regard to developing countries;
- Economic development, estimated in the Kaya identity, by the Gross Domestic Product per capita (GDP_{pc}), which represents a measure of the overall economic output of a country per citizen;
- Energy intensity (IE), which represents a measure of the energy efficiency of a country's economy or the amount of energy consumed per unit of GDP;
- Carbon intensity (CI) represents the relative amount of carbon emitted per unit of energy or fuel consumed. Usually, a country presents a lower value on its carbon intensity if its energy mix presents a high share of renewables and biomass sources and nuclear power, and, as concerns fossil fuels, if gas gives a higher percentage than carbon in the energy mix.

However, during the last decades, some limits of *GDP*, *actually* used for any decision on country development, have been pointed out. In the next subsection, an overview of some of the most well-known indicators of well-being and/or including aspects of sustainability adopted over the years are summarized.

1.2. Summary of Some of the Measures Proposed among the Years toward Sustainability

During approximately the last fifty years, indicators and indexes have been introduced by researchers and international organizations in order to give information and support decision making toward sustainability. At the beginning, the focus was more oriented toward overcoming the sole use of *GDP* as a unique reference for all of the aspects related to human well-being/national welfare (which is not the aim of *GDP* itself), by using a monetary approach [28]. Subsequently, aspects related to environmental sustainability were included as well by means of composite indexes, subjective evaluation, etc. In this context, a brief summary of some of the available indicators is presented:

- The Measure of Economic Welfare (*MEW*) is considered one of the first versions of a modified National Income Index, which was introduced in the 1970s by Nordhaus and Tobin [29] to overcome the use of *GNP* as representative of citizen's well-being and to better reflect the economic welfare, by introducing modifications on its accounting by means of: (i) reclassification of expenditures into consumption, investment, and intermediate; (ii) different services (consumer capital, leisure, and household activities); and (iii) correction for dimensions as urbanization and industrialization [30].
- The Index of Sustainable Economic Welfare (*ISEW*) was presented by Cobb in 1989 [31] as a possible alternative to the Gross Domestic Product (*GDP*). Afterwards, Cobb modified the 1989 version of *ISEW* [32], with the aim of providing both a more reliable monetary indicator of welfare and sustainability by means of the Genuine Progress Indicator (*GPI*). It is constituted by the sum of personal consumption, public non-defensive expenditures, capital formation, and services from domestic labor and the subtraction of private defensive expenditures, costs of environmental degradation, and the depreciation of natural capital [33]. It was evaluated as a too-ambitious proposal as it enclosed a lot of different information within a single index [34].
- The Ecological Footprint (*EF*) was introduced in the first half of the 1990s by Rees and Wackernagel [35] aiming to easily measure the human impact on the environment by introducing the concept of "appropriate carrying capacity" [36]. In particular, they evaluate the anthropic demand on natural capital at its current consumption versus the land's biocapacity; moreover, it can be calculated locally, within a region or a country [37]. The *EF* is still used to assess different kinds of sustainability performance, as developed in Refs. [38–42]. The strength of this indicator has been identified as its intuitive definition and easy calculation tools. However, the same strength has also been interpreted as a source of criticism against it [43].

- The Genuine Savings Indicator (*GSI*) was introduced to measure national wealth in both human and natural terms [44], based on the "Hartwick rule" for the re-investment of rents from the depletion of natural resources into reproducible forms of capital [45]. It considers the sum of gross domestic savings and education expenditures, from which the costs of pollution, depletion of non-renewable resources, and damages related to GHG are subtracted [46].
- The Human Development Index (*HDI*) was introduced in 1990 by the United Nations Development Programme [47,48]. It is a multidimensional index to measure the advancement of a country, based on a socio-economic standpoint. It was built to change the focus from a solely economic-based to a more human-centered development [48,49].
- The Environmental Sustainability Index (*ESI*) was introduced to provide an environmentally oriented decision-making tool characterized by a national environmental performance and to evaluate environmental sustainability by means of twenty environmental and socio-economic indicators. These were in turn combined with between two and eight variables [50,51]. Then, this composite index was modified, with a focus on a smaller set of environmental concerns regarding governments by designing the Environmental Performance Index (*EPI*) [52]. The EPI identifies economic and social driving forces, and environmental pressures, considering the reduction in environmental stresses on human health and the protection of the environmental ecosystem [52,53].
- The Happy Planet Index (*HPI*) was introduced in 2006 by the New Economic Foundation aiming to include both human and ecosystem well-being. It is a composite index, which aggregates information on human-well being, education, life-expectancy, and environmental footprint, ranking countries by taking into account additional aspects related to sustainable development. However, several criticisms have been made against this indicator; many are due to its hybrid components (both objective and subjective) [54] and the fact that embodying an adaptation issue is not taken into account [33].
- The United Nations Development Goals (SDGs) constitute a dashboard by which to measure international efforts toward sustainability up to 2030. The 17 main Sustainable Development Goals are further subdivided into 169 targets, with more than 230 indicators.

1.3. The Focus of This Paper

In this paper, we introduce some considerations related to a recently developed indicator, the Thermodynamic Human Development Index (*THDI*), which in turn is based both on thermodynamic-related considerations and on the aspects considered within the Human Development Index (*HDI*).

The latter is a composite index, developed by the United Nations (the UN), which measures the socio-economic conditions of a country by means of the the geometric mean of three different indexes: the Expectancy of Life (LE), the Education Index (EI), and the Income Index (II). This index was developed to consider more aspects of human well-being and to give information more representative than GDP concerning human well-being.

A deeper analysis of the HDI highlights that this index does not consider any consequence on the environment.

For this reason, in recent years, the index has been improved by introducing a measure of the environmental impact of processes and by measuring their irreversibility concerning the expected beneficial effect. Thus, the Thermodynamic Human Development Index, $THDI$, was built by introducing the Gouy–Stodola theorem and the entropy generation related to pollutant emissions.

In summary, the $THDI$ is composed of the following aspects:

- The Expectancy of Life at birth, related to a healthy life, related to the health care system, to access to water and food, etc.;
- The Education Index, related to the schooling years and knowledge abilities;
- The Income Index, related to the sustenance of a decent life in a country;

- The environmental impact, related to the efficiency of a productive system associated with GHG emissions.

Concerning the last component, the need to quantify GHG emissions emerges.

Consequently, in this paper the Kaya approach is proposed to obtain an evaluation of the carbon dioxide emissions, by introducing this identity within the $THDI$, using the Kaya-modified carbon dioxide emissions within the Thermodynamic Human Development Index. In this way, the $THDI$ can be improved to forecast future scenarios related to sustainable development.

Moreover, to show the effects of the quantities considered within the $THDI$ compared to HDI, the normalization of the $THDI$ has been proposed, obtaining a value in the same range (from 0 to 1) as the one for the HDI, the so-called normalized Thermodynamic Human Development Index ($THDI_n$).

The article is structured as follows: In the Introduction section, the need to dispose of well-being and sustainability indicators different from the solely economic-based GDP is highlighted, together with the requirement to consider environmental aspects jointly with human well-being. As concerns the environmental assessment of GHGs, the well-known Kaya approach is introduced. Then, a brief summary of the main indicators of well-being that have been proposed over the years is presented, together with the recent Thermodynamic Human Development Index, which is the tool that this paper aims to improve.

In Section 2, both the bases of the HDI and $THDI$ are presented, together with the normalization of the $THDI$, to show the different types of information that can be obtained from the two indexes. Then, the proposal to introduce a Kaya-like approach within the *THDI* for use with GHG scenarios is presented.

In Section 3, an example of the use of the indicators for some countries is developed in order to show the different information that can be obtained from the $THDI_n$. In the last section, some comments and conclusions are provided.

2. Materials and Methods

Some key enablers of sustainable development are represented by sustainable consumption of resources, changes in production systems, and energy policies [55]. The increasing request for bio-based industrial raw materials necessitates reorganizing the energy and industry chains, which implies technological choices with related measurements of their environmental, social, and economic consequences.

New indicators are needed to assess sustainable policies and to combine economic, technological, and social aspects while also considering citizens' well-being. Moreover, the requirement of disposal of indicators of sustainability was already set within the Agenda 21 [56], looking for the inclusion of all relevant aspects that affect human life, including the environmental ones.

However, the effects of human activities on the environment must also be considered. So, the Human Development Index, HDI, may be improved by introducing some engineering thermodynamic considerations, to contemplate also the thermodynamic optimization approach and its link to socio-economic and environmental consequences.

2.1. The Human Development Index (HDI)

The Human Development Index (HDI) is a composite index centered on three main dimensions [57]: the possibility of leading long and healthy lives (taken into account by the life expectancy at birth), the opportunity to reach an adequate level of knowledge (taken into account by the mean and the expected years of schooling), and the opportunity to achieve a decent standard of living (taken into account by gross national income per capita). It is defined as [58,59]:

$$HDI = \sqrt[3]{EI \cdot LEI \cdot II} \tag{1}$$

for which [57,60]:

$$EI = \frac{1}{2} \cdot \left(EYSI + MYSI\right) \tag{2}$$

where EI is the Education Index, $EYSI$ is the Expected Years of Schooling Index, and $MYSI$ is the Mean Years of Schooling Index, and for which [58,61]:

$$LEI = \frac{LE - 20}{65} \tag{3}$$

where LEI is the Life Expectancy Index and LE is the Life Expectancy at birth. Lastly:

$$II = \frac{1}{\ln(750)} \ln\left(\frac{GNI_{pc}}{100}\right) \tag{4}$$

where II is the Income Index and GNI_{pc} is the gross national income per capita [61–63] at purchasing power parity (PPP) [47].

2.2. A Brief Overview of the Gouy–Stodola Theorem

The definition of the Human Development Index, HDI, does not consider the technological and environmental level of the considered country. Therefore, a new indicator, the Thermodynamic Human Development Index, $THDI$, has been proposed to improve the HDI, starting from the Gouy–Stodola theorem [64], a very powerful theorem for engineering optimization. Indeed, this theorem allows us to evaluate irreversibility. Following the Second Law of Thermodynamics, irreversibility is the phenomenon that prevents us from performing the complete conversion of heat or energy into useful work. Thus, part of the work, W_λ, is always lost due to irreversibility caused by friction, dissipative processes, *etc*. The evaluation of this work is fundamental in engineering and the Gouy–Stodola theorem links it to the entropy variation [65]:

$$W_\lambda = \int_0^\tau dt\, \dot{W}_\lambda \tag{5}$$

where $\dot{W}_\lambda$ is the power lost by irreversibility, defined as:

$$\dot{W}_\lambda = \dot{W}_{max} - \dot{W} \tag{6}$$

and $\dot{W}_{max}$ is the maximum work transfer rate (maximum power transferred), which exists only at the ideal limit of a reversible operation, and $\dot{W}$ is the effective work transfer rate (effective power transferred). The entropy of the whole system, composed by the open system and the environment, is defined as:

$$S = \int \left(\frac{\delta Q}{T}\right)_{rev} = \Delta S_e + S_g \tag{7}$$

where S_g is the entropy generation, defined as:

$$S_g = \int_0^\tau dt\, \dot{S}_g \tag{8}$$

and $\dot{S}_g$ is entropy generation rate defined as:

$$\dot{S}_g = \frac{\partial S}{\partial t} + \sum_{out} G_{out} s_{out} - \sum_{in} G_{in} s_{in} - \sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} \tag{9}$$

where ΔS_e is defined as the entropy variation that would be obtained exchanging reversibly the same heat and mass fluxes throughout the system boundaries, G is the mass flow, the terms *out* and *in* mean the summation over all the inlet and outlet port, s is the specific entropy, S is the entropy, $\dot{Q}_i, i \in [1, N]$ is the heat power exchanged with the $i-$th heat bath, T_i its temperature, and τ is the lifetime of the process which occurs in the open system. Then, the term due to irreversibility, the entropy generation S_g, measures how far the system is from the state that will be attained in a reversible way. The Gouy–Stodola theorem states that, in any open system, the work lost for the irreversibility W_λ and the entropy generation S_g are related each other as follows [66]:

$$W_\lambda = T_0 \, S_g \tag{10}$$

where T_a is the ambient temperature. To prove this statement, we consider the the First and Second Laws of Thermodynamics for open systems, from which the maximum power transferred results as follows:

$$\dot{W}_{max} = \sum_{in} G_{in} \left(h + \frac{v^2}{2} + g\,z + T_0\,s \right)_{in} - \sum_{out} G_{out} \left(h + \frac{v^2}{2} + g\,z + T_0\,s \right)_{out} - \frac{d}{dt}(E - T_0\,\dot{S}) \tag{11}$$

while the effective power transferred results as follows:

$$\dot{W} = \sum_{in} G_{in} \left(h + \frac{v^2}{2} + g\,z + T_0\,s \right)_{in} - \sum_{out} G_{out} \left(h + \frac{v^2}{2} + g\,z + T_0\,s \right)_{out} - \frac{d}{dt}(E - T_0\,\dot{S}) - T_0\,\dot{S}_g \tag{12}$$

where h is the specific enthalpy, v the velocity, g the gravity constant, z the height, and E is the instantaneous system energy integrated over the control volume. Considering the definition of the power lost, $\dot{W}_\lambda$, it follows that:

$$\dot{W}_\lambda = T_0\,\dot{S}_g \tag{13}$$

from which, integrating over the range of the lifetime of the process, the Gouy–Stodola theorem can be obtained.

$$W_\lambda = \int_0^\tau dt\,\dot{W}_\lambda = T_a \int_0^\tau dt\,\dot{S}_g = T_a\,S_g \tag{14}$$

2.3. The Thermodynamic Human Development Index (THDI)

The Thermodynamic Human Development Index results as follows [67]:

$$THDI = \sqrt[3]{\frac{LEI \cdot EI}{I_T}} \tag{15}$$

where [68]:

$$I_T = \frac{T_0\,\dot{m}_{CO_{2-eq}} s_{CO_{2-eq}}}{\dot{W}\,GNI_{pc}} = 0.01 \cdot \frac{T_0\,\dot{m}_{CO_{2-eq}} s_{CO_{2-eq}}}{\dot{W}} \cdot 750^{-II} \tag{16}$$

where $\dot{W}$ is the useful work obtained (the product), s is the specific entropy related to the carbon equivalent dioxide emissions, T_0 is the environmental temperature, and $\dot{m}_{CO_{2-eq}}$ is the carbon dioxide flow, i.e., the emission of equivalent carbon dioxide in the time interval considered.

Consequently, the $THDI$ results as a bio-economic indicator, which also considers a society's technical and environmental level; moreover, it introduces the consequences of the irreversibility of the processes on the sustainability measurement. Indeed, reducing irreversibility is fundamental to making a process more sustainable. As happens for the HDI, a higher value of the $THDI$ entails higher human well-being, including also the interactions of the population with its environment, considered in terms of carbon dioxide equivalent emissions.

Concerning its definition, the $THDI$—as expressed in Equation (15)—is not a normalized quantity, while the HDI is the product among normalized indexes, resulting a normalized index itself. Thus, we firstly must normalize the $THDI$. Considering the aim of the definition of the $THDI$, it must follow the same structure as the HDI, so it must result in a product of normalized quantities. Therefore, it follows that the quantity to be normalized is I_T^{-1}. To achieve this, it is possible to express I_T as follows:

$$I_T = \frac{I}{GNI_{pc}} \tag{17}$$

where $I = T_0\, \dot{m}_{CO_{2-eq}} s_{CO_{2-eq}} / \dot{W}$. As a consequence of the definition of the $THDI$, we must normalize I^{-1} and GNI_{pc}. To achieve this, considering the relation between GNI_{pc} and II, it is possible to normalize GNI_{pc} as follows:

$$GNI_{pc,n} = \frac{GNI_{pc}}{GNI_{pc,max}} = \frac{100 \cdot 750^{II}}{75000} = 750^{II-1} \tag{18}$$

Then, following the the approach of the proof of the Gouy–Stodola theorem [64], it is possible to obtain:

$$\dot{W}_{id} = \dot{W} + T_0\, \dot{S}_g \tag{19}$$

where $\dot{W}_{id}$ is the maximum useful power that can be produced. Thus, in the approach here used, it follows that:

$$\dot{W}_{id} = \dot{W} + T_0\, \dot{m}_{CO_{2-eq}}\, s_{CO_{2-eq}} \tag{20}$$

Consequently, it is possible to normalize I by using the following relation:

$$I_n = \frac{I}{I_{max}} = \frac{\dfrac{T_0\, \dot{m}_{CO_2-eq}\, s_{CO_2-eq}}{\dot{W}}}{\dfrac{T_0\, \dot{m}_{CO_2-eq}\, s_{CO_2-eq}}{\dot{W}_{id}}} = \frac{\dot{W} + T_0\, \dot{m}_{CO_{2-eq}}\, s_{CO_{2-eq}}}{\dot{W}} \tag{21}$$

so,

$$I_n^{-1} = \frac{\dot{W}}{\dot{W} + T_0\, \dot{m}_{CO_{2-eq}}\, s_{CO_{2-eq}}} \tag{22}$$

Consequently, the normalization of $I_{T,n}^{-1}$ results:

$$I_{T,n}^{-1} = \frac{\dot{W}}{\dot{W} + T_0\, \dot{m}_{CO_{2-eq}}\, s_{CO_{2-eq}}} \cdot 750^{II-1} \tag{23}$$

obtaining the normalized Thermodynamic Human Development Index:

$$THDI_n = \sqrt[3]{\frac{LEI \cdot EI}{I_{T,n}}} \tag{24}$$

The $THDI$ explicitly takes into account the emissions of the considered country. When a process is analyzed, weighting its CO_{2-eq} contribution concerning the total carbon dioxide emission of the country in which the process occurs is useful. Indeed, progress has always been associated with economic growth and with a related increase in energy production needs. Even today, energy production has been made mainly by the combustion of fossil fuels, with a related increase in air pollutants and the emission of greenhouse gases, such as CO_2. Consequently, today, one of the main issues in industrialized and developing countries is the management of CO_2 emissions, a current problem for production systems [69,70], although these CO_2 emission could also represent an opportunity to promote high-efficiency design in both conventional and new technological plants.

2.4. A Possible Approach to Evaluate CO_2 Emissions

The Kaya approach can represent a powerful tool to be adopted within the $THDI_n$, and this can be carried out considering the definitions both of the Kaya identity and of the normalized Thermodynamic Human Development Index. To adopt the Kaya approach, we must first introduce the original Kaya Identity [71]:

$$\dot{m}_{CO_{2-eq}} = P \cdot GDP_{pc} \cdot IE \cdot CI \tag{25}$$

where:

- P is the population, i.e., the number of people in a country;
- $GDP_{pc} = GDP/P$ [\$ person^{-1}] is the per capita Gross Domestic Product, a measure of a country's economic output per person, frequently related to the prosperity of the country;
- $IE = E/GDP$ [J \$$^{-1}$] is the Energy Intensity, a measure of the energy inefficiency of an economy, which expresses that high energy intensities indicate a high price or cost of converting energy into GDP;
- $CI = \dot{m}_{CO_{2-eq}}/E$ [kg$_{CO_{2-eq}}$ J^{-1}] is the Carbon Intensity, a measure of the emission rate of a given pollutant relative to the intensity of a specific activity or an industrial production process, converted into CO_{2-eq}.

Now, we introduce the Kaya identity to evaluate the carbon dioxide emission, obtaining:

$$I_{T,n}^{-1} = \frac{\dot{W}}{\dot{W} + T_0\, P \cdot GDP_{pc} \cdot IE \cdot CI\, s_{CO_{2-eq}}} \cdot 750^{II-1} \tag{26}$$

with the consequence of pointing out the different terms of sustainability in the $THDI$, which finally results:

$$THDI = \sqrt[3]{LEI \cdot EI \cdot \frac{\dot{W}}{\dot{W} + T_0\, P \cdot GDP_{pc} \cdot IE \cdot CI \cdot s_{CO_{2-eq}}} \cdot 750^{II-1}} \tag{27}$$

3. Results

In this paper, we have suggested measuring sustainability by improving an existing UN socio-economic indicator, the HDI, by introducing a thermodynamic evaluation of irreversibility and obtaining the $THDI$. This improvement considers the environmental impact of technologies used in human activities in relation to the energy used to obtain well-being. In order to evaluate environmental impacts, the CO_{2-eq} must be considered. To consider this, the Kaya identity is taken into consideration and used in the analytical relation obtained. Here, the $THDI$ has been normalized in order to use it as an index for analysis of sustainability. The term related to the Kaya identity allows the $THDI$ to be used for scenario analyses, which is useful for decision-makers to consider the possible impact of any action of developments based on socio-economic as well as environmental evaluation.

Indeed, the Thermodynamic Human Development Index ($THDI$) aims to add information related to environmental aspects to the well-known Human Development Index (HDI), which is carried out by introducing a term related to irreversibility due to GHG, by means of the Gouy–Stodola theorem. The latter allows us to link emissions with the average technological level of a country, with irreversibility minimization serving as an engineering optimization tool based on an unavoidable law of nature: the Second Law of Thermodynamics.

In order to show the additional information enclosed within the $THDI$ when compared to the HDI, it has been normalized, as expressed in Equation (24), obtaining a value in the interval from 0 to 1. As an example, in Table 1, the 2019 values both of the well-known HDI and of the $THDI_n$ are presented for some countries, and these data have been represented in Figure 1.

Thus, in Figure 1, it is possible to point out the behavior of the HDI (in blue color) and $THDI_n$ (in orange color) values for the following countries: Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Ghana, India, Italy, Japan, Mexico, the Netherlands, Norway, Senegal, South Africa, Spain, Sweden, the United Kingdom, and the United States, for a given year (2019).

Table 1. HDI and $THDI$ values for Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Ghana, India, Italy, Japan, Mexico, Netherlands, Norway, Senegal, South Africa, Spain, Sweden, United Kingdom, and United States.

Year 2019			
Country	**Code**	HDI	$THDI_n$
Argentina	ARG	0.852	0.589
Australia	AUS	0.941	0.829
Belgium	BEL	0.936	0.848
Brazil	BRA	0.766	0.480
Canada	CAN	0.937	0.815
China	CHN	0.762	0.483
Denmark	DNK	0.946	0.877
Finland	FIN	0.939	0.833
France	FRA	0.905	0.783
Germany	DEU	0.948	0.855
Ghana	GHA	0.631	0.305
India	IND	0.645	0.327
Italy	ITA	0.897	0.755
Japan	JPN	0.924	0.774
Mexico	MEX	0.779	0.522
Netherlands	NLD	0.943	0.864
Norway	NOR	0.961	0.920
Senegal	SEN	0.513	0.219
South Africa	ZAF	0.736	0.439
Spain	ESP	0.908	0.752
Sweden	SWE	0.947	0.870
United Kingdom	GBR	0.935	0.807
United States	USA	0.930	0.870

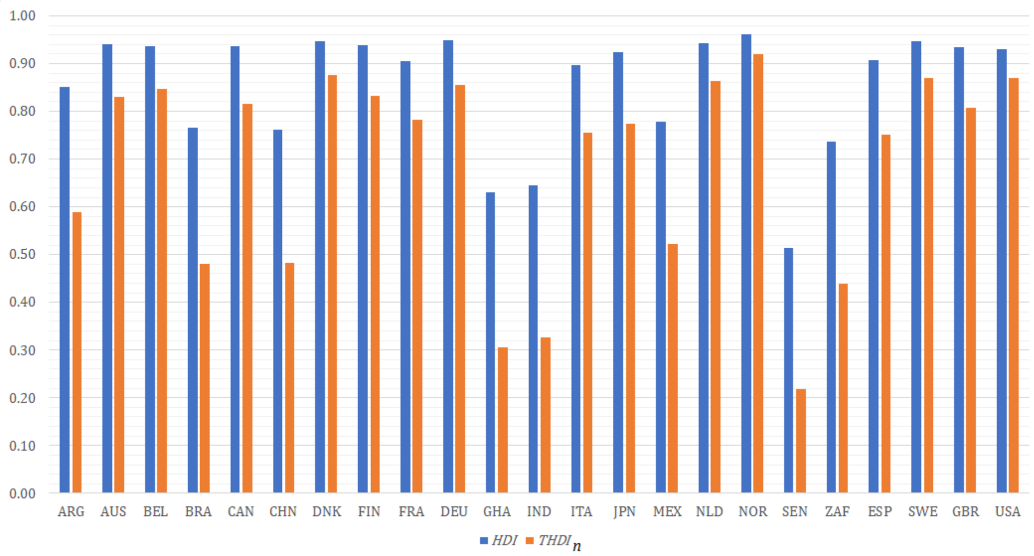

Figure 1. HDI and $THDI_n$ values in blue and orange, respectively, for some countries (Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Ghana, India, Italy, Japan, Mexico, Netherlands, Norway, Senegal, South Africa, Spain, Sweden, United Kingdom, and United States) in 2019. The data used to perform the calculations are available in different databases [72–74].

The $THDI_n$ always presents lower values than the HDI because it considers irreversibility, too. Furthermore, it can be observed that a country's rank may differ among the two indexes due to its technological level, which is related to its environmental impact. Among these countries, Norway presents the highest value considering both human well-being and human well-being and environmental aspects together (HDI value: 0.961 and $THDI_n$ value: 0.920, with a relative difference among values of 4.3%), meaning that virtuous approaches have been developed by this country to optimize its technical systems. However, there are other countries that present a relative difference among the HDI and $THDI_n$ of higher than 30%, such as Argentina (30.8%), Mexico (33.0%), China (36.7%), Brazil (37.4%), South Africa (40.4%), India (49.3%), Ghana (51.7%), and Senegal (57.4%), meaning that significant improvements should be developed in order to reduce their technological impact level.

We also point out that the $THDI_n$ can be linked to the Kaya identity, as expressed in Equation (27), meaning that it may be used together with the carbon dioxide emission scenarios, which in turn are built just considering this identity. The advantage of including the environmental aspects in the $THDI_n$ remains with respect to the same relation. Indeed, the $THDI$ was introduced [67,68] just to link socio-economic and engineering quantities to build a tool for sustainable evaluation based on joint considerations of the environmental and socio-economic impacts of human activities [67]. Thus, Equation (27) also maintains the aim of measuring the three main pillars of sustainable development. However, expressing the $THDI_n$ as in Equation (27) brings the use of quantities adopted into the well-known HDI, and expression of the $\dot{m}_{CO_{2-eq}}$ through the Kaya identity, allows us to introduce four common socio-economic and energy economics quantities. So, by introducing a Kaya-like approach, the improvement of the analytical formulation of the $THDI_n$ allows us to explicitly introduce fundamental econo–physical quantities, usually adopted in energy economics, which are known and used by many researchers and institutions. In particular, these quantities can be grouped into three sets:

- Economic quantities:
  - GDP and GNI: GDP stands for Gross Domestic Product, which represents the value of the finished domestic goods and services produced within a nation's borders, while GNI stands for Gross National Income, which represents the value of all finished goods and services owned by the country's citizens, whether or not those goods are produced in that country. GDP is an indicator of the local or national economy, while GNI represents how its nationals contribute to the country's economy; it factors in citizenship but overlooks location, and, consequently, GNI does not include the output of foreign residents. Both indicators are considered by dividing their value for the total population of the considered nation (per capita);
  - Energy intensity (IE): This is a "hybrid" quantity used in energy economics. It is the ratio between the energy consumed and the GDP of a given year, and it represents a measure of the energy inefficiency of an economy. High values of IE correspond to a high price or cost of converting energy into GDP, and *vice versa*. Countries with low energy intensity values tend to have labor-intensive economies;
- Physical quantities:
  - Environmental temperature T_0: This thermodynamic quantity represents a constraint from a thermodynamic viewpoint, being the temperature of the environment in a country (or of a local site) related to the Carnot efficiency, which is the higher value of thermodynamic efficiency. Of course, it conditions the energy consumption both concerning technical efficiency and civil uses;
  - Specific entropy generation, $s_{CO_{2-eq}}$: This quantity depends on the environmental temperature, and it is related to irreversibility. So, it allows us to measure the efficiency of a productive system. The lower the entropy generation is, the higher the energy use efficiency is;

    - Carbon Intensity (CI): This is a "hybrid" quantity measuring the emission rate of GHG in relation to GDP;
- Social quantities:
    - Education Index (EI): This was introduced in the Human Developed Index (HDI) by the UN to measure the schooling years. Recently, an improvement related to EI has been proposed [75] by introducing considerations on the measure of the abilities to solve complex problems and developing reasoning results fundamental for the ability and productivity of the future workforce of a country, to organize the production sites, depending on the technological skills required. Indeed, this is all the more concerning as work requirements shift due to the needs of people to adapt to change and conceptualize complex ideas in a multidisciplinary setting [76–81];
    - Life Expectancy Index LEI: This is a social-related quantity linked to a long and healthy life, and the results are related to people's possible access to social and health care services.

4. Discussion and Conclusions

In this section, we wish to present some considerations regarding the Thermodynamic Human Development Index to highlight its usefulness in relation to the link between socio-economic and thermodynamic quantities, to represent a possible measure of sustainability based on all its pillars.

Environmental conditions have been recognized as resources for sustainable development [82]. This evidence pointed out the need to link processes to the consumption of natural resources, environmental conditions, and social inequity [83]. Consequently, the concept of Human Sustainable Development was introduced by the United Nations Development Programme, based on the requirement to consider also the environmental variable in evaluating the link between growth and development [84].

The first analytical contribution to the link between economic growth and the natural system has been developed by Meadows et al. [85], who first discussed the constraints of the scarcity of natural resources concerning economic growth, with particular regard to economic and social well-being.

Some criticisms have been directed toward the Meadows approach, particularly regarding the role of technological and scientific developments in supporting economic growth and the increase in natural resources, introducing the concept of dynamic equilibrium [86].

A new viewpoint on sustainable development emerged within the Brundtland Report [87]. Indeed, the concept of preserving natural resources for future generations was pointed out. Following this approach, Max-Neef [88] introduced the threshold hypotheses. He highlighted how an increase in people's well-being is related to economic growth only in the first period of the growth itself, while a continuous growth in economics generates a corresponding decrease in human well-being. Consequently, there exists a time when economic growth must be accompanied by attention to social well-being [89].

These historical steps pointed out the need to measure sustainable development together with human well-being, to evaluate a method to foresee the threshold to: (i) identify what is sustainable, (ii) identify the reference system for growth, and (iii) optimize the growth process itself.

In this context, many interesting methodologies and approaches have been developed during the last decades, such as:

- The Life Cycle Assessment (LCA), which is a methodology to quantify the potential environmental impacts of each stage of the life cycle of commercial products, processes, and services [90]. Therefore, the development of an LCA requires a comprehensive inventory of the energy and materials used in the processes, from raw materials acquisition through production, use, and disposal, in order to evaluate the related emissions into the environment; consequently, LCAs assess cumulative potential environmental impacts. The procedures for conducting LCAs are set in the 14000

series of environmental management standards of the International Organization for Standardization (ISO), particularly regarding ISO 14040, concerning principles and framework, and ISO 14044, concerning requirements and guidelines. The LCA method and approach have sometimes been criticized, both in general and about the consistency of its methodology, especially concerning system boundaries. In this study, the focus is related to a global description of sustainability, so, no criticisms are considered. However, as concerns the LCA, the limit of not considering the social and economic conditions of people may be highlighted;
- The atom economy, a concept which moves the practice of minimizing waste to the molecular level. Green chemistry and atom economy introduce a new approach to reaction chemistry: designing reactions such that the atoms present in the starting materials end up in the product rather than in the waste stream. This concept provides a framework for evaluating different chemistries, and an ideal to strive for in new process and formulation chemistry [91].

Moreover, many indicators have been proposed with the aim of switching the viewpoint associated with the concept of development from a solely economy-based perspective toward a more human-oriented one (including the environment), going beyond GDP. Indeed, concerning GDP as a measure of economic and social progress, some limitations have been identified, highlighting that a high or rising level of GDP is often associated with increased economic and social progress, but it has also been shown that an increase in GDP does not necessarily lead to a higher standard of living, particularly concerning healthcare and education. Due to the characteristic of aggregate quantity, economic well-being measured by GDP is not able to describe the right distribution of incomes among people.

Therefore, in 1990, the United Nations introduced the Human Development Index (*HDI*), a multidimensional index with a socio-economic perspective, to assess a country's development and well-being level by considering its economic growth as well as its citizens' educational level and life expectancy [48,49,92]. The HDI was introduced as an alternative measure to the mono-dimensional GDP, to include both economic and social aspects for the assessment of the development level of a country, emphasizing the primary role of people's well-being and quality of life [61,93]. Indeed, human development was defined by the United Nations as *the process that enlarges people's choices* [92]. So, this index aims to evaluate a country from a more human-oriented standpoint, not only related to a merely economic one [49,94,95].

Recently, this index has been improved to include information on resource consumption and the environmental impact of human activities as well. The result has been the so-called Thermodynamic Human Development Index ($THDI$) [67,68], an indicator that considers both well-being and anthropic-related environmental impacts.

Now, we wish to highlight that different methodologies may be adopted to assess the carbon intensity of a process, such as:

- The life cycle assessment (LCA), which includes the CO_2 emissions due to a specific process and those due to the production and end-of-life of materials, plants, and machinery. However, this represents a quite complex method, requiring a big set of variables;
- The well-to-wheel (WTW) analysis, which is commonly used in the Energy and Transport sectors. It is a simplified LCA approach and considers the emissions due to the extraction and refining of the materials and fuel used, without any evaluation of the emissions due to the production and end of life of productive systems;

As concerns $THDI$, the introduction of the Gouy–Stodola theorem highlights the meaning of the Second Law of Thermodynamics, the natural constraints present in any process and transformation, i.e., the impossibility of avoiding irreversibility and dissipation. So, its use allows the decision-makers to support the efforts in improving the efficiency of the systems based on optimization approaches and research. Moreover, it should be highlighted that an improvement in the Education Index embedded within the $THDI$ was proposed [75], aiming to include the OECD-PISA program results. This inclusion seeks to assess the abilities acquired by students during their schooling journey, to evaluate their job prospects in the near future, and to assess their abilities to be prepared for these opportunities and the advancement of technologies in sustainable development, which will increasingly require more technical competences. The issue related to the calculation of this improved education index is related to the time availability of data, while the other quantities needed for the $THDI$ are usually available yearly. While the OECD-PISA assessment is conducted every three years, it also takes additional time for the OECD to analyze and process the results. However, including the output of the educational pathway, which means considering the skills acquired during the educational pathway, is fundamental to the knowledge needed for future generations. In this paper, the normalization of the $THDI$ has been proposed, together with its link to the Kaya identity, which is usually adopted to develop previsions and scenarios. In the context of the $THDI$, this characteristic may be very interesting because it allows the $THDI$ to support policymakers to "design" their decision to comply with international agreements on the environment. This consideration encompasses socio-economic implications, underscoring the consequence of considering all of the pillars of sustainability, summarized in only one index. In particular, the $THDI$ results in an indicator that expresses the effect of all of its components, with particular regards to:

- The social condition concerning education, expressed by the EI index;
- The social condition concerning life quality and health, expressed by the LEI index;
- The economic condition concerning purchasing power, expressed by the II and GDP_{pc} indexes;
- The technological condition concerning power generation efficiency, expressed by the ratio $\dot{W}/\dot{W}_{id}$ index;
- The environmental condition concerning irreversible processes and GHG emissions, expressed by the $T_0\, s_{CO_{2-eq}}$ component;
- The social condition concerning population, expressed by the P component;
- The techno-economic condition concerning energy inefficiency and economy, expressed by the IE index;
- The environmental condition concerning GHG emissions, expressed by the CI index;

In conclusion, the normalized Thermodynamic Human Development Index represents a socio-economic and technological indicator, with the advantage of linking together the environmental, technical, and socio-economic measures of the production system of a country, introducing a weighted system to reduce the limitation of the single use of indicators.

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