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The Gouy-Stodola Theorem—From Irreversibility to Sustainability—The Thermodynamic Human Development Index

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Abstract: Today, very complex economic relationships exist between finance, technology, social needs, and so forth, which represent the requirement of sustainability. Sustainable consumption of resources, production and energy policies are the keys for a sustainable development. Moreover, a growing request in bio-based industrial raw materials requires a reorganization of the chains of the energy and industrial sectors. This is based on new technological choices, with the need of sustainable measurements of their impacts on the environment, society and economy. In this way, social and economic requirements must be taken into account by the decision-makers. So, sustainable policies require new indicators. These indicators must link economics, technologies and social well-being, together. In this paper, an irreversible thermodynamic approach is developed in order to improve the Human Development Index, *HDI*, with the Thermodynamic Human Development Index, *THDI*, an indicator based on the thermodynamic optimisation approach, and linked to socio-economic and ecological evaluations. To do so, the entropy production rate is introduced into the *HDI*, in relation to the CO_2 emission flows due to the anthropic activities. In this way, the *HDI* modified, named Thermodynamic Human Development Index *THDI*, results as an indicator that considers both the socio-economic needs, equity and the environmental conditions. Examples of the use of the indicator are presented. In particular, it is possible to highlight that, if environmental actions are introduced in order to reduce the CO_2 emission, *HDI* remains constant, while *THDI* changes its value, pointing out its usefulness for decision makers to evaluate *a priori* the effectiveness of their decisions.

Keywords: gouy-stodola theorem; human development index; irreversible thermodynamics; sustainability

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1. Introduction

It was the XIII Century, when St. Thomas Aquinas (1225–1274) introduced in Philosophy the consideration of the impossibility for an effect to be stronger than its cause [1]. This is an implicit statement on the effect of irreversibility in Nature. St. Thomas shows how the concept of irreversibility had always been clear in the history of humans.

In 1803, Lazare Carnot (1753–1823) developed the analysis of the efficiency of some pulleys and inclined planes [2], obtaining a general approach to the conservation of mechanical energy. Twenty-one years later, in 1824, his famous son Nicolas Léonard Sadi Carnot (1796–1832) introduced a reference model for the thermal engine and obtained its maximum efficiency, which, against any expectation, always results in being less than 1, and depends on the high and low working temperature [3]. In particular, for a defined heat source (constant high temperature), the environmental temperature plays a fundamental role in the inefficiency of any engine, but also of any process and transformation [4–6].

Real systems are very different in relation to the Carnot engine; indeed, they are finite-size devices and operate in a finite-time, characterised by dissipation and friction [7–11]. Consequently, theoretical and experimental attempts have been developed in order to evaluate the efficiency of the real systems [12–23] but they always confirm the Carnot general conclusion about the existence of an upper limit for the conversion rate of the heat into the mechanical energy [24].

Now, in the history of the concept of thermodynamics, two scientists appeared, showing a new analytical approach to evaluate the irreversibility, by considering a global analysis of a general system (closed or open): the French physicist Louis Georges Gouy (1854–1926) [25] and the Slovak engineer and physicist Aurel Boleslav Stodola (1859–1942) [26,27]. Indeed, in 1889, Gouy proved that the exergy lost in a process can be calculated by the product of the environmental temperature and the entropy generation [28–31]—the entropy due to irreversibility [24]. Then, in 1905, Stodola, independently, obtained the same result in designing a steam turbine [32], giving an experimental proof, too. The Gouy-Stodola theorem is the result of a continuous improvement of thermodynamics, started when Clausius [12] introduced the concept of entropy, just to analyse the dissipative processes [16,24,33].

Today, this theorem, in addition to being a powerful way to evaluate irreversibility in real processes and systems, could play a new role in sustainability. Indeed, this theorem is useful for optimizing the processes [17,34] in engineering design, but optimisation means also a decrease in the CO_2 emissions and pollutants, and a decrease in the environmental and ecological impact of anthropic activities. Indeed, since the 1970s, when Georgescu-Roegen developed his analysis of the conflict among individual, social, and environmental values [35], the Second Law of Thermodynamics was shown to be a fundamental approach to evaluating the dependence of humans on energy availability, with particular regards to available energy [36]. Moreover, the Nobel laureate Joseph Stiglitz has recently highlighted the unsustainability of the present growth, due to its impact on the environment—a change in our economic and productive system is required to assess economic and social performances [37].

In order to monitor and assess the performance of sustainable policies, indicators have been introduced in socio-economic and ecological analysis [38]. Therefore, to support decision-making towards sustainable development, organizations and researchers have proposed indexes and indicators for sustainable development. In 1989, the Index of Sustainable Economic Welfare *ISEW* [39] was introduced to replace the Gross Domestic Product *GDP*, and, later, it was improved [40] to obtain a more detailed analysis of welfare and sustainability. But some criticisms have been made of this indicator, because of its attempt to enclose too many different information into a single index [41]. In the 1990s, the Ecological Footprint *EF* [42] was developed in order to take into consideration the biologically productive land, required to support a given population [43] at its current level of consumption [44–49]. Criticisms against this indicator have been developed against its bases [50], in relation to its calculability. The Environmental Sustainability Index (*ESI*) is composed of twenty different indicators, which are combined with two to eight variables [51] and assesses sustainability by using environmental and socio-economic indicators. Its improvement is the Environmental Performance Index (*EPI*), which identifies economic and social driving forces and environmental pressures, in order to assess the impacts on human health and on the environment [52]. Since 1990, the United Nations Development Programme (UNDP), has introduced the Human Development Index (*HDI*) [53,54], as a multidimensional index to measure the development of a country from a socio-economic viewpoint, with the aim to switch the focus from a pure economic development to a more human-centred standpoint [54,55]. This indicator combines three dimensions together:

- Life expectancy at birth;
- Education, represented by years of schooling;
- The gross national income *per capita* at purchasing power parity rates.

Since 2010, *HDI* has been improved in relation to the new needs emerging in relation to sustainability, as deeply analysed in Refs. [55–57]. Stanton has highlighted the following two fundamental roles played by the HDI [58]: on one hand as a tool to understand human development in relation to human well-being, and, on the other hand as an alternative to GDP_{pc} in order to measure and compare the levels of development of countries. In Table 1, the previous indicators considered are summarised in relation to their chronological introduction.

Table 1. Main indicators of sustainability introduced in the Introduction Section.

Year	Indicator	References
1989	Index of Sustainable Economic Welfare (*ISEW*) first version	[39]
1990	Human Development Index (*HDI*) first version	[53,54]
1992	Ecological Footprint (*EF*)	[42–50]
1994	Index of Sustainable Economic Welfare (*ISEW*), updated version: Green National Product	[40,41]
2007	Environmental Sustainability Index (*ESI*)	[51]
2010	Human Development Index (*HDI*) updated version	[55–57,59]
2013	Environmental Performance Index (*EPI*)	[52]

The HDI is a statistic composite index of life expectancy, education and per capita income indicators. A country scores a higher HDI when its lifespan is higher [60] but this index does not take into account any ecological impact and it is not related to any physical quantity used in engineering in order to also evaluate the technological level of a country.

So, a new approach is required to evaluate human activities in relation to sustainability; indeed, the present economic indicators are not able to take into account the sustainable requirements and some new social and economic issues are also becoming relevant in energy and industrial engineering. Consequently, the requirements related to sustainability remain without any overall answer [61–74].

In this paper, in order to suggest a response to this problem, we develop an approach based on irreversible thermodynamics, introducing the measurement of pollution and anthropic footprint into the Human Development Index, in order to obtain a new indicator for sustainability, the Thermodynamic Human Development Index (*THDI*), which takes into account the social, economic and ecological requirements, but is also linked to the optimisation approach to engineering systems.

2. Materials and Methods

The Human Development Index is an indicator of the developing level of a country in relation to education, health and salary conditions [75]. It is the geometric mean of three normalised indices representative of each dimension [53] and its analytical definition is [76]:

$$HDI = (LEI \cdot EI \cdot II)^{1/3}, \tag{1}$$

where LEI is the Life Expectancy Index, EI is the Education Index and II is the Income Index. The Life Expectancy Index LEI is defined as [59,76]:

$$LEI = \frac{LE - 20}{85 - 20}, \tag{2}$$

where LE is the Life Expectancy at birth, which indicates the overall mortality level of a population. It corresponds to the years that a newborn is expected to live at current mortality rates [77]. Therefore, in order to normalise the Life Expectancy at birth, the UNs have set its minimum and maximum values to 20 and 85 years, respectively [76]. Indeed, in the XXI century there are no countries with a life expectancy at birth lower than 20 years, and, on the other hand, the value of 85 years is set as a realistic aspirational target [76].

The Education Index EI, is defined as [76]:

$$EI = \frac{MYSI + EYSI}{2}, \tag{3}$$

where $MYSI = MYS/15$ is the Mean Years of Schooling Index and $EYSI = ESI/18$ is the Expected Years of Schooling Index [76].

The Normalised Income Index II, is defined by the United Nations, as follows [60]:

$$II = \frac{\ln(GNI_{pc}/100)}{\ln(75000/100)}, \tag{4}$$

where GNI_{pc} is the gross national income per capita at purchasing power parity (PPP), with minimum and maximum value set by the United Nations [76] as \$100.00 and \$75,000.00, respectively. The choice of \$100, as the GNI_{pc} minimum value, is due to the difficulty in capturing the amount of the unmeasured subsistence and non-market production, within the official data of the economies close to the minimum [76]. While, the maximum GNI_{pc} value of \$75,000 has been chosen as threshold because, for higher values, there has been shown no gain in human development and well-being [76,78]. But, this index does not take into account of the technological and ecological level of a country.

Recently, with the aim of considering the technological level, a thermoeconomic indicator has been introduced, in order to link economics to a technical approach [79]:

$$I = \eta_\lambda \cdot ExI \cdot LP = \frac{\dot{W}_\lambda}{n_w \cdot n_h}, \tag{5}$$

where η_λ is the inefficiency [80]:

$$\eta_\lambda = \frac{\dot{W}_\lambda}{\dot{Ex}_{in}}, \tag{6}$$

where $\dot{W}_\lambda$ is the power lost due to irreversibility, and ExI is the Energy Intensity related to the power really used,

$$ExI = \frac{\dot{Ex}_{in}}{GDP}, \tag{7}$$

where $\dot{Ex}_{in}$ is the exergy rate [24], GDP is the Gross Domestic Product and represents the well-being of a country or a productive system, LP is the Labour Productivity, defined as [81] $LP = GDP/n_{wh}$, where $n_{wh} = n_w \cdot n_h$ is the total number of worked hours needed to obtain the GDP, with n_h number of worked hours and n_w number of workers. Now, considering the Gouy-Stodola theorem, the power lost due to irreversibility is related to the entropy generation [24,82,83]:

$$\dot{W}_\lambda = T_0\, \dot{m}_{CO_2} s_g, \tag{8}$$

where $\dot{m}_{CO_2}$ is the CO_2 mass flow rate emitted for obtaining the required effect $\dot{W}$ and s_g is the specific entropy generation due to the process developed.

In order to improve the HDI by also using the indicator of Equation (5), now, we consider that the total number of workers is strictly related to the Gross National Income per capita, GNI_{pc}, and we combine its expression in relation to the Income Index, Equation (4), obtaining:

$$I_T = \frac{T_0 \dot{S}_g}{\dot{W} \cdot GNI_{pc}} = 0.01 \cdot \frac{T_0 \dot{S}_g}{\dot{W}} \cdot 750^{-II}. \tag{9}$$

Now, we propose a Thermodynamic Human Development Index by introducing the following definition:

$$THDI = \left(\frac{LEI \cdot EI}{I_T}\right)^{1/3}. \tag{10}$$

As a result, the $THDI$ improves the usual HDI by also considering the technical and ecological level, introducing the CO_2 flows and the s_g quantities, evaluated in the I_T.

3. Results

In this paper, we have introduced the Thermodynamic Human Development Index ($THDI$), which is an indicator related:

- To the physical quantities—the entropy generation due to the anthropic activities with its related environmental impact;
- And to the socio-economic quantities—life expectancy, education, and per capita income indicators,

all considered as the basis for sustainable development. In particular, as presented in Equation (9), we have considered the irreversibility due to the anthropic carbon dioxide emissions and the Income Index. Subsequently, we have calculated the $THDI$, as presented in Equation (10).

First, we wish to highlight that a fundamental requirement to define an indicator is the accessibility to the updated data of countries, in order to be able to continuously monitor their performances [84].

Here, in order to make use of the indicator *THDI*, the following countries are considered as examples—Algeria, Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Greece, India, Italy, Japan, Mexico, Norway, South Africa, Spain, Sweden and the United States of America. This analysis considers 1990 as a reference year, as defined by the United Nations [53], which is also the same reference year used for the global carbon dioxide emissions targets [85].

Thus, in Figures 1–3, for each country considered, the following quantities are represented for the years 1990, 2000, 2010, 2019, respectively:

- The Human Development Index (HDI), data retrieved from [86];
- The Thermodynamic Development Index ($THDI$), calculated with Equation (10), considering the primary energy supply as the useful effect $\dot{W}$ [87];
- The anthropic carbon dioxide emissions, data retrieved from [88].

During the period 1990–2019, an overall rise of the HDI has occurred. The increase of this quantity from 1990 up until today can be assessed respectively as: 31% for Algeria, 18% for Argentina, 8% for Australia, 15% for Belgium, 25% for Brazil, 9% for Canada, 53% for China, 17% for Denmark, 19% for Finland, 15% for France, 17% for Germany, 17% for Greece, 50% for India, 15% for Italy, 12% for Japan, 19% for Mexico, 13% Norway, 13% South Africa, 19% Spain, 15% Sweden and 7% United States of America. We can highlight that the countries with 1990 HDI lower values present a higher percentage variation of HDI, in time [89]. Among the countries with a high level of HDI in 1990 (higher than 0.790), the Northern European countries have shown the higher percentage increase.

In order to consider the national environmental footprint at a global scale, the total carbon dioxide emissions, due to anthropic activities, have been considered. In Figure 3, it is possible to observe that, during the period 1990–2019, different behaviours in carbon dioxide emissions have occurred, for the countries considered, depending on their starting development level, too. Only a few of them have reduced their emissions: −17% in Belgium, −27% in Finland, −19% in France, −40% in Denmark, −23% in Italy, −33% in Germany, −19% in Greece, −4% in Japan, −25% in Sweden . On the contrary, most of them have increased their environmental footprint, mostly due to their need for quick social and economic growth (124% for Algeria, 60% for Argentina, 48% for Australia, 125% for Brazil, 25% for Canada, 320% for China, 38% for Mexico, 20% for Norway, 53% for South Africa, 9% for Spain, 3% for United States of America).

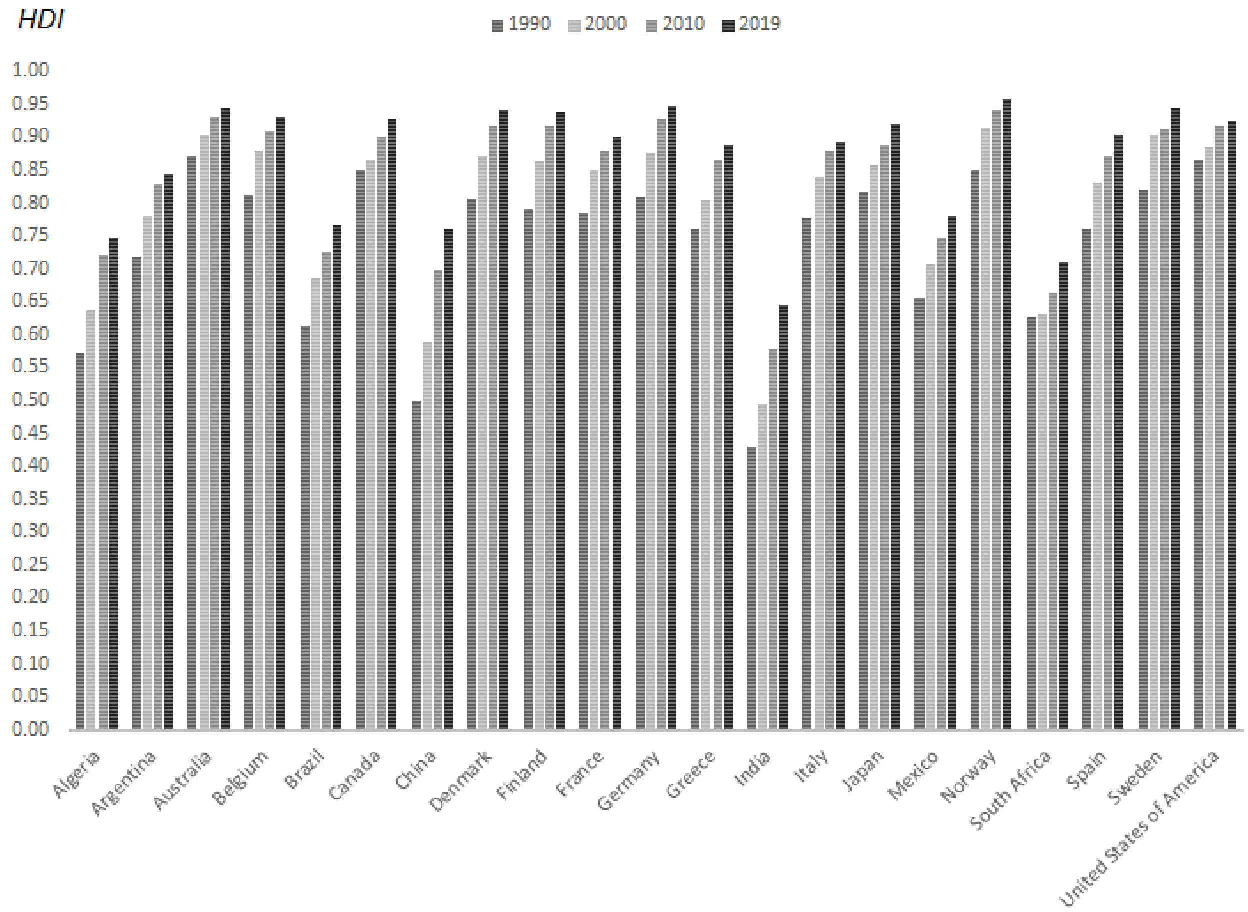

Figure 1. The Human Development Index (*HDI*) (data from [86]) is represented for four years (1990, 2000, 2010 and 2019) for a set of countries (Algeria, Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Greece, India, Italy, Japan, Mexico, Norway, South Africa, Spain, Sweden and United States of America), chosen as an example.

$THDI$ has been calculated by Equation (10) , considering the primary energy supply as the useful effect $\dot{W}$. The values of the Life Expectancy Index and of the Education Index have been directly taken from the United Nations data [90,91]. In order to calculate I_T (Equation (9)), the data of the Gross National Income per capita GNI_{pc}, based on purchasing power parity (PPP), referred to 2017, have been taken into account [92]. The GNI_{pc}, based on purchasing power parity (PPP), is an economic indicator, converted to international dollars by using the purchasing power parity rates. So, this quantity allows us to compare the income of different countries, considering the same standards of living. For each country, the mean environmental temperature T_0 has been evaluated by considering the data reported by the World Bank [93]. Then, we can obtain the power lost due to irreversibility $\dot{W}_\lambda$ by using Equation (8), where the carbon dioxide emissions [88] and the properties of carbon dioxide (entropy per unit of mass s_{CO_2} for the calculated mean temperature) have been considered.

In accordance with the United Nations indicator, also for $THDI$, the higher the value of the indicator ($THDI$) is, the more sustainable is the process considered.

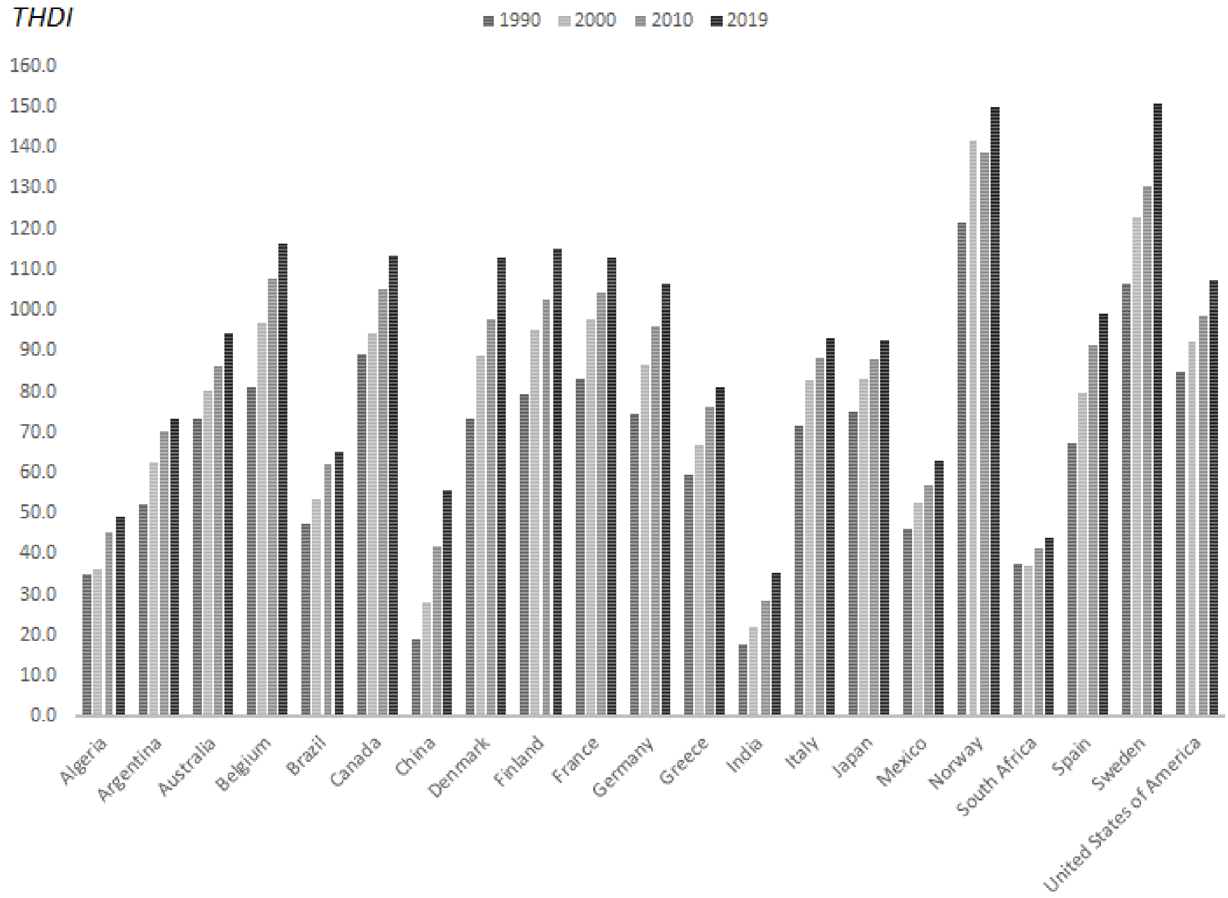

Figure 2. The Thermodynamic Human Development Index ($THDI$), calculated by Equation (10), is represented for four years (1990, 2000, 2010 and 2019) for a set of countries (Algeria, Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Greece, India, Italy, Japan, Mexico, Norway, South Africa, Spain, Sweden and United States of America), chosen as an example. The useful effect, $\dot{W}$, that has been considered is the total yearly energy supply for each country.

As for the HDI, all countries have increased their Thermodynamic Human Development Index in percentage, from 1990 to 2019. The relative variation of $THDI$, during this time period, has been respectively of: 40% for Algeria, 40% for Argentina, 29% for Australia, 44% for Belgium, 37% for Brazil, 27% for Canada, 189% for China, 54% for Denmark, 45% for Finland, 36% for France, 43% for Germany, 36% for Greece, 100% for India, 30% for Italy, 23% for Japan, 37% for Mexico, 23% Norway, 17% for South Africa, 48% for Spain, 42% for Sweden, and 26% for United States of America. However, the absolute value of the indicator, presents significant variations among the different countries, as shown in Figure 2. Indeed, the indicator considers the environmental footprint, in terms of carbon dioxide emissions, that has been produced to obtain the improvement on their HDI. So, the Thermodynamic Human Development Index considers the negative effect on the global environment, required in order to improve the national well-being. By considering the exergy losses due to irreversibility, it is possible to obtain a measure of the technological development of each country.

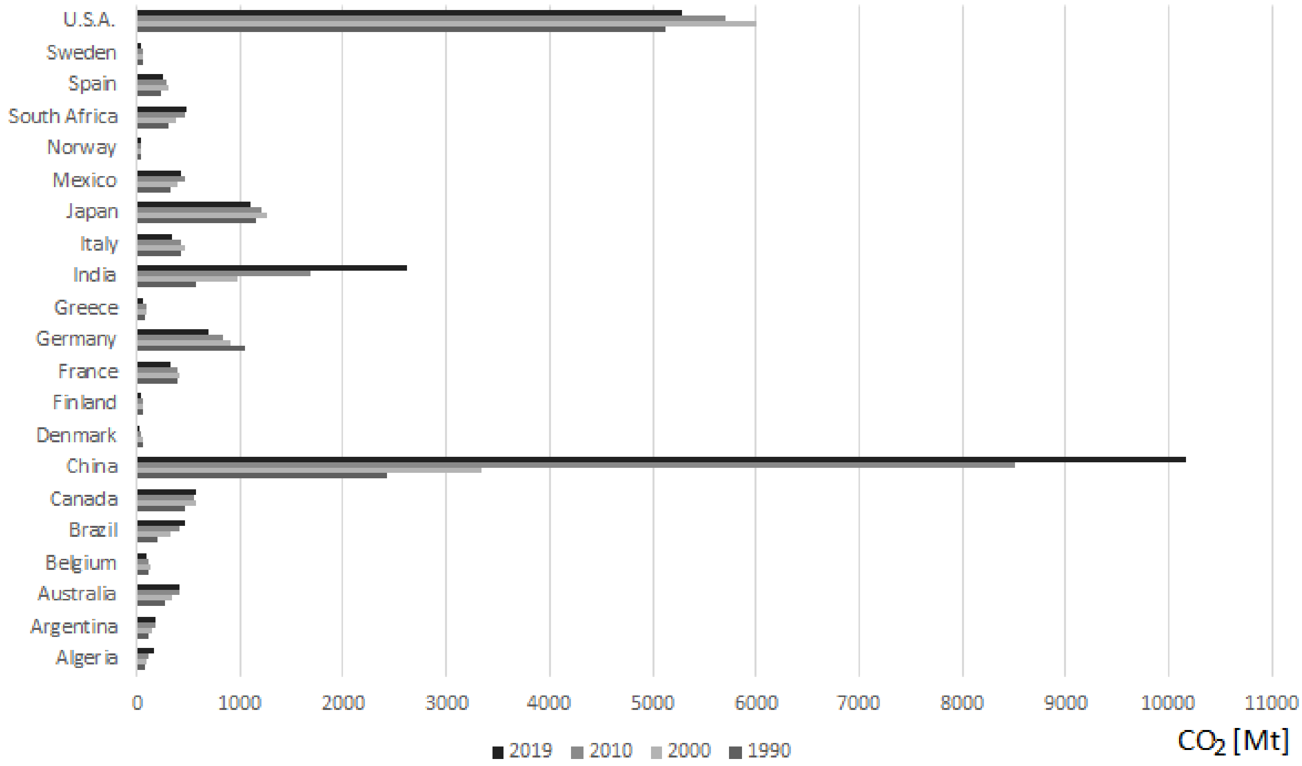

Figure 3. The total carbon dioxide emissions, in [Mt] (data from [88]), are represented for four years (1990, 2000, 2010 and 2019) for a set of countries (Algeria, Argentina, Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Greece, India, Italy, Japan, Mexico, Norway, South Africa, Spain, Sweden and United States of America), chosen as an example.

In Figure 2, the variation of the Thermodynamic Human Development Index is represented in the years 1990, 2000, 2010 and 2019, for the above listed countries, in relation to their carbon dioxide emissions and to their Human Development Index. We can highlight that:

- In relation to Central and South America, Argentina, Brazil and Mexico have increased their HDI, but with a different environmental impact; indeed, the CO_2 emissions of Brazil and Mexico are greater than that of Argentina—in accordance with previous considerations, the $THDI$ of Argentina results are greater than those of Brazil and Mexico. The $THDI$ values of these last two countries are comparable;
- In relation to Australia, Canada, Japan and the United States, all these countries have improved their HDI, maintaining about the same level of CO_2 emissions; consequently, the $THDI$ presents a small growth;
- In relation to China and India, the HDI has grown as well as their environmental impact; consequently, for these countries, the $THDI$ presents lower values;
- In relation to Europe, all the countries present a comparable increase of $THDI$, highlighting a common decrease in carbon dioxide emissions (Figure 3) and a comparable increase of their HDI;
- In relation to Algeria and South Africa, HDI and CO_2 values have increased for both countries. Algeria has increased by three times the HDI value of South Africa, with the result of achieving a comparable HDI to South Africa, and $THDI$ summarizes this result.

Considering the European targets on climate policy strategies, a reduction of at least 40% of the greenhouse gas emissions—from 1990 levels—is expected by 2030 [94]. Thus, in Figure 4, HDI and $THDI$ are represented for 1990 and 2019; furthermore, their evaluation, based on 2019 data but considering the European target of CO_2 reduction, has been introduced—it is represented by the series named *2019 mod*. We can point out that $THDI$ varies between 2019 and 2019 mod, due to the reduction of the carbon dioxide emissions, while HDI is not affected by this environmental action and maintains constant its value. So, we can highlight that $THDI$ represents an improvement of HDI, because it includes the information of HDI, adding the environmental component, too.

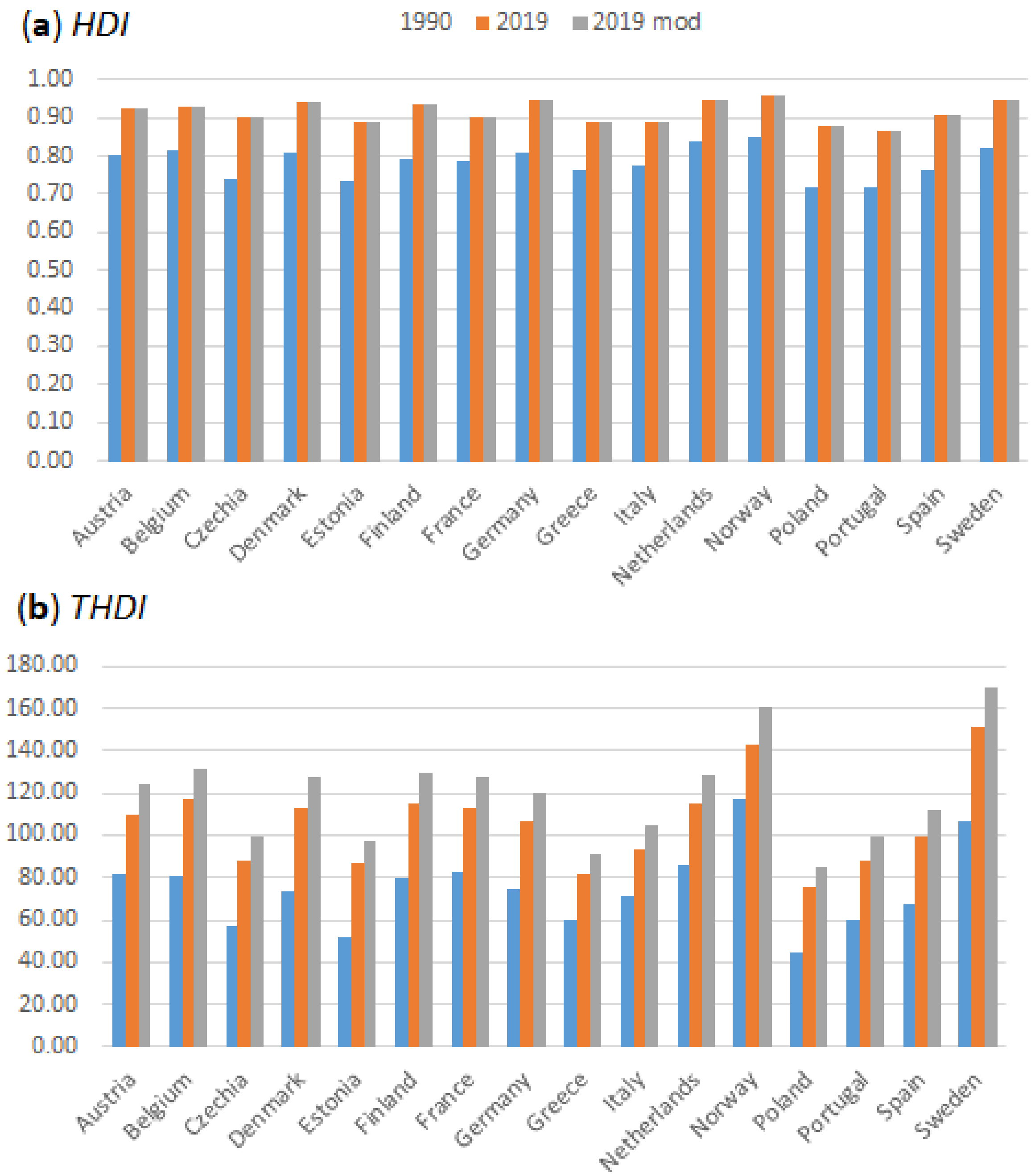

Figure 4. The HDI (**a**) and the $THDI$ (**b**) values are illustrated for the following European Countries: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Portugal, Spain, Sweden. The years considered are 1990 and 2019. Furthermore, the series *2019 mod* has been calculated with the values related to 2019 but, taking into account the carbon dioxide emission targets of the European Commission, modifying the 2019 CO_2 values, with those obtained considering a linear reduction of CO_2 emissions from 1990 to 2030 of 40%.

In summary, the Thermodynamic Human Development Index is an indicator related to the evolution of a process, due to its close link to the entropy generation, the thermodynamic quantity used to describe the spontaneous evolution of the natural processes [95–98]. Moreover, entropy and entropy generation represent the bases of the modern engineering thermodynamics and optimisation methods [24].

Up until now, social, environmental and technical systems have always been taken into account separately, but it is clear that they are in continuous interaction. The results obtained go beyond this limit and suggest a holistic indicator, which takes into account of economics, social, technical and environmental requirements, together. A process results sustainable, if the value of the indicator is as high as possible.

4. Discussion and Conclusions

Huge efforts have been made by the United Nations to build an indicator, which measures the human progress, and the well-being of a country, by taking into account not only the merely economic growth, but also other fundamental social requirements, such as the educational level (knowledge), and the life expectancy (population's longevity). However, some criticisms of the Human Development Index have been raised, due to the lack of information about the effects, on the environment and the related responsibilities [55,99–103]. These effects must be considered to assess the level of development both for the present and the future generations [104].

The evaluation of the resource consumption can be obtained by the exergy flows [105] but, on the other hand, there is not a reference quantity to quantify socio-economic parameters and natural capital, with the consequence of maintaining the evaluation of sustainability as a present open problem [105].

The present requirement is to understand how to evaluate resources, industrial activities and services in order to consider them as forms of capital [106], for their best use for human well-being. Moreover, the environmental issues result fundamental for sustainable development. But, irreversibility plays a fundamental role in all human activities. So, it must be taken into account in any indicator for sustainability.

Here, we have obtained the Thermodynamic Human Development Index, an indicator which links together the entropy generation rate, related to optimisation and the Human Development Index, related to people well-being. This indicator contains all the information of the HDI, also considering the anthropic environmental impact. In this way, we respond to the above mentioned requirements of an indicator for sustainability.

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