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in Energy and Nuclear Engineering

Master of Science Thesis

Longitudinal analysis between Human Development Index and CO_2 intensity. How development reflects the energy quality of a country

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Summary

1 Abstract

Energy has allowed humankind to reach a high level of wellbeing. Nevertheless, the use of the actual energy technology is having a critical impact on the environment with severe consequences for the biosphere. This thesis aims to investigate through data analysis the linkage between energy and wellbeing to understand how countries can achieve a high level of development through a sustainable path for the environment.

The first part of the thesis contains an extensive literature review on the energy, environment and wellbeing dimensions; the state of the art attempt to review how these three dimensions are quantified in literature employing different indicators and how they have been studied.

From the index literature review, we chose the Human development index (HDI) as wellbeing proxy and the CO_2 intensity index ($CO2_{int}$) as a proxy for the energy and the environment dimensions. Moreover, the interest of analysing the relationship between these two indicators arise from the fact that, at the best of our knowledge, they have never been deeply analysed in the literature on a global scale. The HDI and the $CO2_{int}$ of 96 countries are analysed both in cross-sectional (on 2014) and in longitudinal analysis (from 1990 to 2014).

The results confirm a strong relation between $CO2_{int}$ and HDI that describes the connection between energy quality and development level of a country. Moreover, it is very interesting that a bell curve links these two indexes. Low-HDI and Medium-HDI countries have increased their $CO2_{int}$ by increasing their HDI, High-HDI countries exhibit a transition phase where no a predominant behaviour is identified, and Very-High-HDI countries have decreased their $CO2_{int}$ by improving their HDI level.

The discovery of this relation has been used to formulate four decarbonisation scenarios for 2050: Business As Usual (BAU), Energy Bound (EB) and Energy and $CO2_{int}$ Bound (ECB), both inspired by the 2030 European Union targets, and an Extreme scenario (EX). The results suggest that from 2030 to 2050, a complete decarbonisation described by the Extreme scenario will be necessary to maintain the global warming below 2°C, as recommended by IPCC.

This work offers a new key-point to understand the linkage between energy and wellbeing. The based data-driven approach represents a powerful tool to study and monitor the sustainability of the countries development easily.

2 Introduction

This thesis aims at investigating the energy from a broad perspective, by studying the relation between energy and wellbeing, to offer new guidelines about how the energy system should be planned to maximise the quality of life of people.

It is well-known that energy has led to reaching a high level of wellbeing, and it supports main human activity. Nevertheless, the use of the actual energy technology is generating a critical impact on the environment with severe consequences on the biosphere. This actual condition is not congruent with the sustainable development goals set up by United Nations[1], which aims at reaching a high level of wellbeing and a low environmental impact simultaneously.

Therefore, this work purposes of exploring new determining factors in the linkage between energy and wellbeing, that can help to study and to monitor the sustainable development of the countries.

The thesis is composed of a first part dedicated to studying the state of the art, and of a second part which focuses on data analysis. Firstly, the literature review tries to define a clear picture of the already analysed and individuated key-points that describe the relation between energy and wellbeing. In this part, the aspect less investigated by literature has been individuated, and Human Development Index (HDI) and Carbon intensity index ($CO2_{int}$) have been chosen for the data analysis part. Thus, in the second part, the selected indexes are analysed both in cross-sectional and in longitudinal analysis, by using data from 1990 to 2014 for 96 countries. Then, the drawn results from the data analysis have been used to formulate four scenarios. The scenarios are assessed, in order to understand which would be the consequence, linked to their CO_2 emissions, of different energy use scenarios.

Hence, the thesis analyses the linkage between energy and wellbeing from a sustainability perspective. For that reason, the introduction presents the three main dimensions related to the case study (energy, wellbeing and environment), by discussing the key topics that will be recalled throughout the work.

2.1 Energy

Energy is commonly defined as the ability to do work[2]. This work is implemented to help people to meet their needs for cooling, heating, lighting, etc. For this reason, energy has always been considered as a determining factor for human development[3].

Nonetheless, the energy used for meeting human needs is manifested in its final form. In other words, the energy is initially captured from a natural source. Then it is transformed into a more useful form for human activity, and finally it is consumed by the final users. All these processes defined respectively supply sector, transformation sector and energy-consuming sector, represent the energy supply-chain[2,3]. Thus, the first step of the supply chain is represented by the procurement of the primary energy commodity. An energy commodity is defined as primary when it is directly extracted from natural resource reserves (such as fossil fuel) or captured from a flow of natural resources (such as the energy captured by renewable technology)[2,3]. A primary energy commodity does not undergo a transformation or a conversion, except for the first separation and cleaning process[2]. In statistics, a source is defined primary when it is in the marketable state. The fossil fuels are in the marketable state after the extrapolation and the first separation and the cleaning process. For geothermal and solar panel technology, the primary energy is represented by the collected heat. For hydropower and photovoltaic technology, the primary energy is represented by the generated electricity[2].

After this process, the second step of the supply chain is the transformation sector. In this sector, the energy commodity is converted and transformed into a more useful form, such as electricity and heat. In this process, a part of the energy is lost due to the irreversibility of the transformation, and a part of the energy is used to support the transformation sector[2,3].

After this process, the energy results in a better form and useful for human activity. Therefore, the energy delivered to the users is considered as final consumption, which will be used by the appliance of the users.

Hence, in the supply chain, we can distinguish the primary energy and the final consumption. The final consumption is equal to the primary energy less the energy used to support the transformation sector, less the energy losses during transformation, and minus energy losses during distribution[2].

2.2 Wellbeing

Wellbeing has been often considered as the most important goal of life. Contemporary researches have argued that the pursuit of happiness should be a central goal of the government agenda[4]. Recently, the wellbeing has been more investigated, in order to understand which are the main factors that lead to new wellbeing indexes to go beyond GDP. In fact, GDP has been considered for a long time a misleading index for wellbeing. A demonstration of this new challenge is represented by the commission held by Stiglitz, Sen and Fitoussi[5] (SSF commission). The SSF commission analysed the main wellbeing dimensions and discussed the sustainable development. In this framework, the commission identified nine main dimensions of wellbeing, such as health, education, wealth, environment and so on.

The main criticism on GDP is that it accounts just one dimension of the nine individuated by SSF commission, and it is directly connected with the consumer society, that link happiness to consumption[6]. Easterlin provided the first evidence of the limit of GDP by showing that in several countries from 1946 to 1970, the GDP increased while the perceived happiness maintained constant[7].

Despite this criticism, the GDP theory has gained a lot of success. This success is because the variation of GDP is positively correlated with the improvement of wellbeing for low-income countries[8]. That is because for those countries, the increase of GDP corresponds to the possibility to satisfy basic human needs, such as good quality food and water, access to health care, and educational opportunities[8]. When the basic needs are met, this correlation saturates[9], and GDP increase does not effect wellbeing, namely the overconsumption is unnecessary and it could also be potentially counterproductive[6].

Moreover, a theory connected to the human needs sphere is the capability approach of Sen and Nussbaum[10]. Sen argues that the people should first satisfy their basic needs, and then they can have the capability to develop their wellbeing[11].

In the past decade, the increasing awareness of the environmental damage generated by the actual economic system led to connect the study of wellbeing with sustainability. The concept of sustainability links together human wellbeing, social inclusion and environmental sustainability[8]. In this context, the sustainable development (or sustainable economic system) aims to improve the quality of environment and quality of life[9].

2.3 Environment

The environment is an essential factor for human wellbeing as confirmed by the SSF commission[5], which considers the environment as one of the 9 wellbeing dimensions. In fact, on the one hand, the quality of air and of water directly influences the health condition. On the other hand, people mood is directly influenced by the state of the natural environment[5]. In light of this, the issue of the environment today need particular attention due to the problem represented by global warming.

Since different years The Intergovernmental Panel on Climate Change (IPCC) is responsible for the collection of research and the elaboration of data about climate change and CO_2 emissions. According to the IPCC, the increase of the mean surface temperature of 0.87°C from the pre-industrial level (1850-1900) up to the recent years (2006-2015), is directly connected to the increase of the CO_2 emissions per year[12]. With this in mind, the expected increasing CO_2 emissions will lead to reaching global warming higher than 1.5°.

An increase of the awareness of the climate issue is testified by the recent Paris agreement[13] and the consequently European long-term strategy on climate and energy[14], which aims ay maintaining the global warming well below 2°C. This target could be reached by reducing the greenhouses gases (GHGs) emissions until the achievement of zero net emissions by 2050.

The climate change, in fact, is mainly caused by all greenhouse gases, in this work, in particular, will consider just the CO_2. The choice of this assumption is justified by the fact that CO_2 emissions represent 72% of the total GHGs emissions on 2017[15]. Furthermore, starting from 1970, the CO_2 emissions have been increased by 50%, while the other GHGs have followed a slightly increase[16]. A further reason why the other GHGs are neglected is because CO_2 emissions are more connected with energy.

Several studies have been carried out to understand, which will be the increase of temperature based on the cumulative CO_2 emissions. Among these studies, important information is reported by Meinshausen[17] who analysed different possible scenarios with different cumulative CO_2 emissions between 2000 to 2050, assessing the consequential global warming of each scenario. Meinshausen[17] rsays that cumulative emissions higher than 1500 Gt will increase global warming higher than 2°C, with a probability higher than 50%. On the other side a cumulative emissions of 1000 Gt could maintain global warming below 2°C with a probability of 75%.

These information have been used by Costa[18], who has computed different scenarios. Costa[18] affirms that if the actual trend of CO_2 will be maintained, cumulative emissions will be between 1700 and 2300 Gt. Additionally, he built up a model that can respect a budget of 1000 Gt, starting from the hypothesis that countries with HDI higher than 0.8 can reduce their emissions by improving their wellbeing, while the countries with HDI<0.8 are not able to do the same.

3 Literature review

3.1 Methodology and articles

3.1.1 Research methodology

In this paragraph, it is introduced the search methodology that has led to find the reviewed articles. The principal scope of the literature reviewed is to discover how energy and wellbeing have been studied together with a statistical approach and which are the results of these analyses. Particular attention has been paid to the indexes used in this analysis. The research questions connected to this object are shown in Table 1. The used key-word on the research can be divided into two groups, one regards energy, and the other regard wellbeing (see Table 1). The study has been limited to that article belonging to energy and econometric subject area, and to articles that analyses data at the global scale or at a significant regional level. The articles have been searched in the database of Scival and Scopus.

ENERGY-WELLBEING LITERATURE RESEARCH METHODs	
Object	To figure out how the wellbeing and energy have been studied together with a statistical approach and which are the results of these analysis
Research question	• How have the wellbeing and energy been studied together? • Which indexes of wellbeing and energy have been used? • Which results do they report?
Key-words[1]	((energy index) OR (energy consumption) OR (energy use) OR electri*) AND (welfare OR well?being OR happ* OR (life satisfaction) OR (quality life))
Inclusion criteria	Subject area: Energy, Econometric Study approach: statistical and data analysis Covered countries: global scale, or vast region
Exclusion criteria	Exclusion of subject areas, such as medicine, computer science, agriculture, namely all the rest subject area except social science and philosophy.
Utilised database	Scival, Scopus

Table 1. Method of article search. The table shows the object, the research question, the key-words, the inclusion and exclusion criteria, and the utilised database used in the article research.

[1] The symbols "*, ?" have been used to include any other similar words

3.1.2 Selected articles

14 articles have been selected for the literature review, and they are listed in appendix 7.1. 11 out of 14 articles have carried out the analysis at the global scale, while three of them have focused on a specific group of countries, such as G7 countries[19], BRICS countries[20] and eastern European countries[21].

The articles have been assessed by using the Scopus metric evaluation, especially to evaluate source and author and to considered the number of citation of each article. Figure 1 shows that the articles have been published from 2010 to 2018; in this figure, the source of the articles is specified.

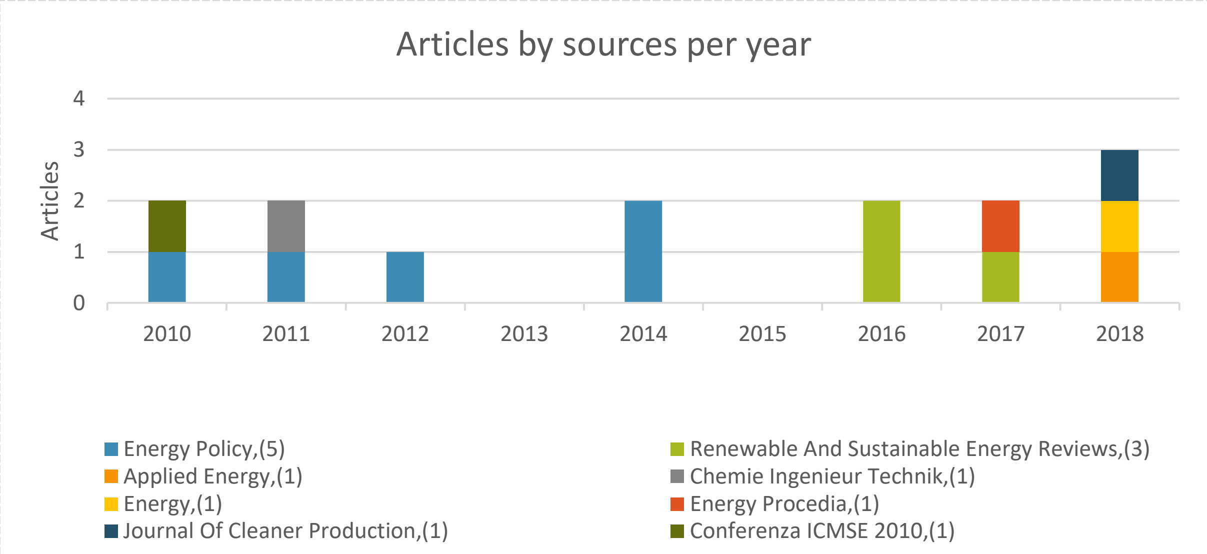

Figure 1. Year of publication of the selected articles

The articles are from 7 scientific journals and the article of Q. Wu and Clulow[22] is from the 17th International Conference on Management Science and Engineering (ICMSE), held in 2010 at Melbourne (Australia). Table 2 shows the 7 journals, by specifying the cite score, the percentile cite rating (provided by Scopus) and the number of the selected articles from each journal. 12 out of 14 articles are form journal with a percentile cite score is higher than 75%, which means that these journals belong to 25% journal more influent within a specific subject field (see Table 1).

JOURNAL	CITE SCORE	PERCENTILE CITE SCORE	NUMBER OF ARTICLES
APPLIED ENERGY	8.44	99%	1
ENERGY POLICY	4.97	97%	5

JOURNAL OF CLEANER PRODUCTION	5.79	97%	1
RENEWABLE AND SUSTAINABLE ENERGY REVIEW	10.54	96%	3
ENERGY PROCEDIA	1.44	73%	1
ENERGY	5.6	99% (civil and structural engineering)	1
CHEMIE INGENIEUR TECHNIK	0.51	44% (industrial and manufacturing engineering)	1

Table 2. Journals of the selected articles. The cite score and the percentile cite rating (provided by Scopus) is reported. The percentile cite score regards to econometric or energy subject area, just two journals are not within these subject area, and their subject area is specified in brackets.

Figure 2 shows the first authors of the articles, by specifying in brackets the h-index (provided by Scopus) of each of them. 6 articles are from authors with an h-index higher than 20.

Figure 2. First authors of the selected articles. For each author is reported the number of its articles belonging to the selected articles. After each author's name, the h-index (provided by Scopus) is reported in brackets.

3.2 Indicators

This paragraph analyses how the articles have studied the linkage between energy and wellbeing, from a statistical point of view. Therefore, this paragraph will introduce the used indexes, it will individuate matching indexes, and it will highlight which methods have been applied.

The indexes have been grouped into three dimensions: energy, wellbeing and environmental. Even if, the main argument of the articles is the relation between energy and wellbeing, some of them have connected to this topic the environment issue. That could be a consequence of the emerging study on sustainability principles.

3.2.1 Energy indexes

Concerning the energy indexes, most articles (13 out of 14) have analysed indexes about energy consumption, while some of them has analysed the electricity, and others have focused on the energy quality of the countries.

Two types of energy consumption indexes have been analysed, one regarding the primary consumption and one regarding the final consumption. The first one counts the consumption of whole energy commodity, including also the losses during transformation and distribution, and the energy used in support to transformation sector, while the second one focuses just on the end-use of energy consumption, neglecting the losses part during transformation and distribution.

11 out of 14 articles have preferred to face the energy consumption by using indexes of primary energy consumption. 7 articles[23,24,22,19,21,25,26] have used the indexes of the IEA, namely the TPES. 4 articles[27,28,29,30] have preferred the index Primary Energy Consumption (PEC) released by the U.S. Energy Information Administration. 2[31,32] out of 14 articles have analysed the energy consumption by using the Total Final Consumption (TFC) of the IEA. In all selected articles, these indexes have been accounted in per capita units.

Two articles have considered the Electricity Consumption per capita (ELC pc), one has used the data from World Bank[23], and the other one has used data from U.S. Energy Information administration[30]. This index accounts the net electricity consumption, which includes the electricity generation less the losses of transmission and distribution, minus the energy consumed by the generating units, plus the electricity imports and minus the electricity exports[30,33]. Instead, one article [28] has analysed the Electrification Level (EL). This index counts the % of the population with electricity access[34].

Lambert[27], in its research, has focused on the quality of energy of a country, by taking into account the Energy Return of Investment (EROI). The EROI counts the energy gained (and useful for the human well-being) from a unit of energy spent in the process of obtaining energy [35]. In this article EROI has been computed at the social level, by elaborating economical and energy information [27].

Lambert[27] himself has elaborating a new indexes, which combines together an index of energy consumption (by using data of PEC per capita of the Energy Information Administration), an index of energy quality (using the EROI), and an index of income distribution as a proxy of energy distribution (by using the Gini-index of income distribution). This index is called Lambert Energy Index (LEI), and it is a geometric mean of the three normalized indexes (see Equation 1).

$LEI = \sqrt[3]{EROI_{soc} \cdot PECpc \cdot (1 - Gini\_index)}$	Equation 1
Where: • The subscript *soc* means that the EROI is computed at the social level	

One article[24] published in the "Journal Cleaner of production", proposes another energy index, the "Total Primary Energy Footprint" (TPEF). This index tries to allocate the energy to the real consumer, by correcting the TPES, which is an index with Production Based Account. According to the article of Akizu-gardoki[24], the consumption of high-income countries appears to be smaller with TPES, because part of it is outsourced and accounted for in other countries. Instead, the TPEF is computed in Consumption-Based Account, by applying the "Global Multi-Regional Input-output methodology"[24].

One article[20] published in the journal "Renewable and Sustainable Energy Reviews", carries out his analysis by considering just the energy produced by alternative energy sources, namely the amount of energy generated from nuclear (measured in % of the total energy use), the electricity production from renewable source (in kWh), combustible renewable and waste (in % of the total energy use). To specify the energy consumption of these sources, the term Alternative Energy Source (AES) is used. For a complete description and definition of all energy indexes, please refer to the Appendix.

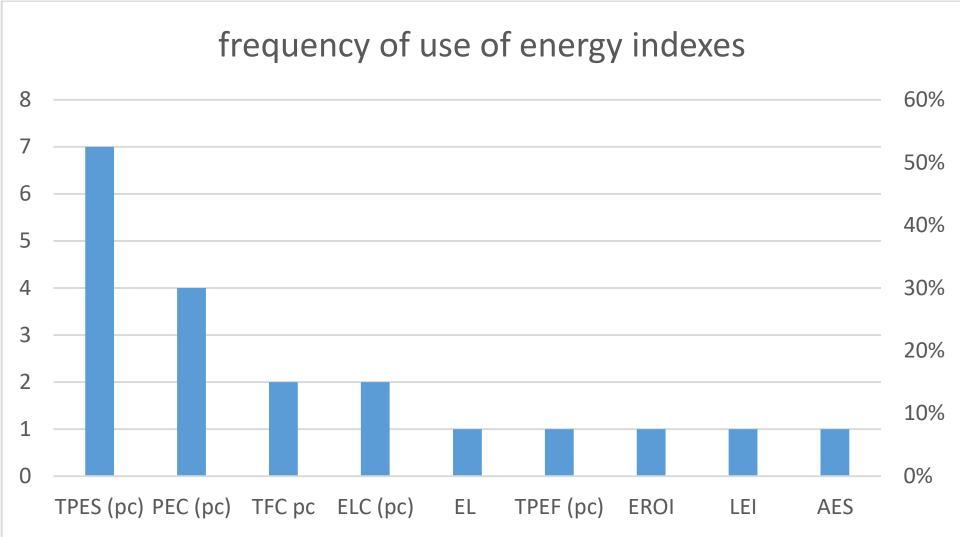

Figure 3 Utilization frequency of all used energy indexes in the selected articles. The x-axis reports all the energy indexes, the left y-axis reports the absolute number of articles that have used the indexes, the right y-axis reports the percentage of use on all selected articles (14). Each bar provides information about each energy index, which are sorted in descending order.

3.2.2 Wellbeing indexes

Often an article has used different indexes of wellbeing, as recommended by various studies on wellness, which suggest to analyse wellbeing by considering different dimensions and variables simultaneously[5]. One single energy index has usually been matched with varying variables of wellbeing.

In this paragraph, the most used wellbeing indexes are introduced, and their frequency of use is shown by Figure 4. And to consider which the articles have more analysed wellbeing dimension, all used wellbeing indexes are grouped into different categories. The categorisation is inspired by the nine dimensions individuated by the Stiglitz, Sen and Fitoussi commission[5]. Figure 5 shows the frequency of use of the wellbeing indexes categories.

Most articles have used the index of Gross Domestic Product per capita (GDP pc). The GDP pc is defined as the sum of value added by all resident producers plus any product taxes (minus subsidies) not included in the valuation of output, and then it is divided by the midyear population. It is counted in Purchasing Power Parity [36]. 9 articles[23,31,32,30,22,19,20,21,27] out of 14 have used this index. However, five articles have used the Gross National Income per capita (GNIpc), two[28,29] of them has used just the GNI, while three[23,32,31] of them have used GNI and GDP simultaneously. The GNI is defined as the sum of value added by all resident producers plus any product taxes (minus subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad. Then it is divided by the midyear population. It is counted in Purchasing Power Parity [36].

The second most used index is the Life expectancy at Birth, which measures the longevity of a country, and it has been used by 9[25,23,28,29,30,21,31,32] articles out of 14 LEB is defined as the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life[33].

The third most used index is the Infant Mortality Rate. It has been used by 7 articles[23,31,32,28,29,30,20] out of 14. This index is defined as the number of infants that die before reaching one year of age, per 1000 live births in a given year [33].

The fourth most used index is the Improved Water Access (IWA) has been used by 6 articles[23,31,32,28,29,27]. The IWA is defined as the % of people with access to at least 20 litres of water a person a day from an improved source, such as piped water into a dwelling, public tap, tube well protected dug wells, and rainwater collection, within 1 kilometre of the dwelling [36]. Anyway, one of these articles has focused on the IWA computed in % of the rural population with water access, and this particular IWA will be specified as IWA(r)[27].

Just 4[23,31,32,28] articles have used the Mean Years of Schooling (MYS). The MYS is defined as the number of years of education received by people ages 25 and older, converted from education attainment levels using official durations of each level[37].

Three articles have used indexes of Subjective Well-Being (SWB). Two articles[25],[26] have used the data collected by Inglehart[38], while the article of Mazur[30] has used the data from World values survey. Both indexes are about self-assessment of the people life-satisfaction, and their score comes from surveys made by people.

Some articles have used a composite wellbeing index, such the HDI, the Index for Sustainable Economic Welfare (ISEW), the index of quality of life (QL) of Pasten and Santamarina[28] and the index of quality of life (QoL) of Nadimi[23].

The HDI is an index used by the United Nations in its initiative "Development Program" to check the improvement of people life instead the increase of their income[39]. This index analyses three wellbeing dimensions, such as health, education and wealth.

The HDI has been used by 5 articles[25,26,27,24,22]. One of these articles[27] has used the inequality-adjusted HDI.

The ISEW has been used by just one article[19]. This type of index represents a previous version of the Genuine Progress Index (GPI), and it has been defined as a sustainable index, which uses a similar structure of GDP but by accounting also the damage of human activity in monetary terms. This index accounts for different element of welfare: the consumption, the public expenditure for defensive, capital growth, unpaid work, depletion of the natural environment, and cost of damage of pollution[19].

One article has used the QL[28], and three articles[23,31,32] have used the QoL. The QL and QoL are multiple wellbeing indexes proposed by Pasten[28] and by Nadimi[23] respectively. These two indexes are similar, in fact, both use as variables LEB, IWA, IMR and the MYS, while QoL also accounts two wealth variables, such as GDP and GNI. In other words, the two indexes are expressed with their variables as following: QL(LEB, IWA, IMR, MYS); QoL(LEB, IWA, IMR, MYS, GDP, GNI). The two indexes use a different model, the QL is structured with a linear model and the QoL is structured with a non-linear model.

To account the frequency of use of the indexes, the QL and QoL have not been considered, and their variables have been counted separately. This choice is motivated by the fact that QL and QoL are not official indexes with available dataset.

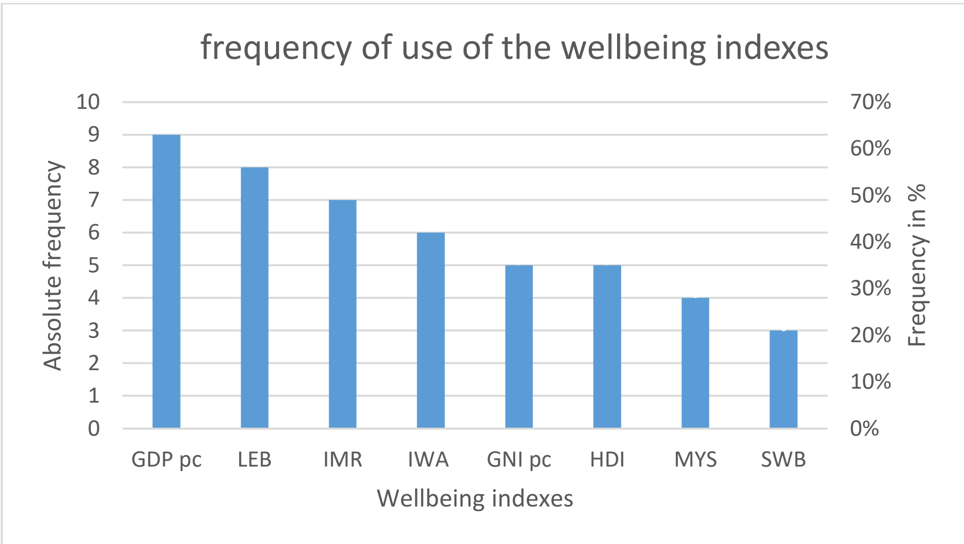

Figure 4 Utilization frequency of the most used wellbeing indexes in the selected articles. The x-axis reports the wellbeing indexes, the left y-axis reports the absolute number of articles that have used the indexes, the right y-axis reports the percentage of use on all selected articles (14). Each bar provides information about each wellbeing index, which are sorted in descending order.

Figure 4 shows that the articles have preferred to analyse mostly the GDP, followed by indexes of health, such as LEB, IMR and IWA.

The indexes have been grouped into the following categories: wealth, health, education, multidimensional index and subjective wellbeing indexes. The multidimensional indexes have been counted two times for the frequency use of the wellbeing categories, once as single indexes and once by considering their variables separately. To highlights how much articles have used multidimensional indexes, and in order to highlight their representative wellbeing dimension. To remind, HDI and QoL analyse variables regarding health, education and wealth dimension, while the QL analyses health and education dimension.

For the frequency of use of the categories, as well as the already cited indexes, also other variables have been considered, to individuate which wellbeing dimension the articles have studied. The following list shows the considered indexes, and they are divided in their category. For the definition of all wellbeing indexes, please refer to the appendix.

- Wealth
  (LEB)
  - Infant Mortality Rate (IMR)
  - Improved Water Access (IWA)
- Education
  - Mean Years of schooling (MYS)
  - Literacy Rate (LR)
  - School enrolment, tertiary (SET)
- Self-report index
  - Subjective Well Being (SWB)
- Multiple indexes
  - Human Development Index (HDI)
  - Quality of Life (QL) (of Pasten)
  - Quality of Life (QoL) (of Nadimi)
  - ISEW

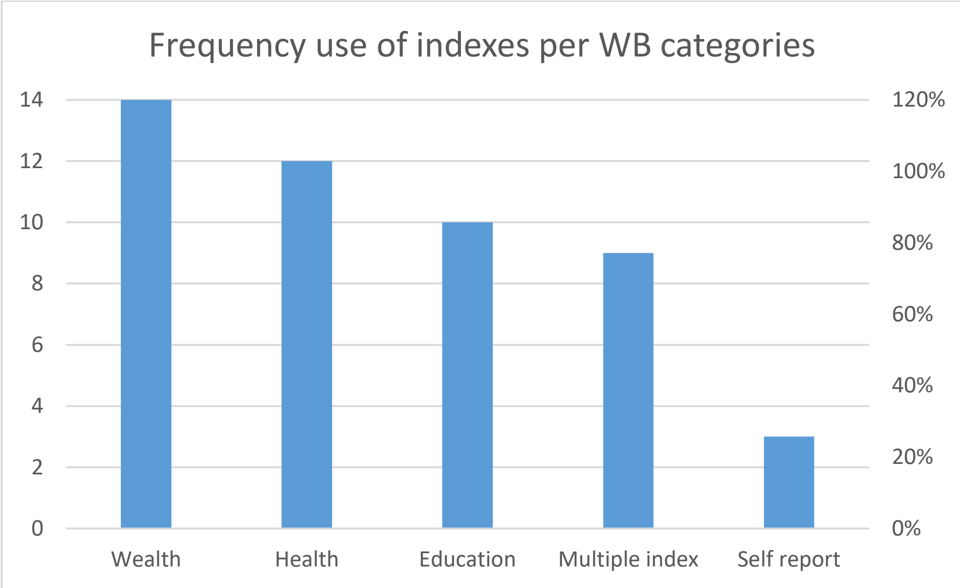

Figure 5 Utilization frequency of the most used indexes per wellbeing categories. The x-axis reports the wellbeing indexes categories, the left y-axis reports the absolute number of articles that have used the categories, the right y-axis reports the percentage of use on all selected articles (14). Each bar provides information about the frequency of each wellbeing indexes categories, which are sorted in descending order.

Figure 5 shows that all articles have analysed indexes of wealth, and the health category was the second class most considered by the articles. Nine articles have utilised multidimensional indexes, following the new tendency of the wellbeing studies. HOWEVER, the commission of Stiglitz, Sen and Fitoussi have individuated others five wellbeing dimension (the ninth is the environment which will be considered for the environment indexes), that have not been considered by the selected articles. It could suggest that the dimensions, such as governance, personal activity and social connection could not be connected with energy.

3.2.3 Environmental indexes

Some articles have also considered the environmental dimension, as recommended by the commission of Stiglitz, Sen and Fitoussi[5].

Even if the majority of articles talks about the importance of environment, just five of them have analysed environmental indexes in their studies.

Among these articles, three articles analyse the CO_2. Two have focused on the emissions from burning fossil fuel and cement manufacturing analysing the data of IEA[31,32], and the other one has focused on the emissions from buildings activity[20].

The CO_2 index of World Bank accounts for the carbon dioxide emissions stemming from burning fossil fuel, counting also the gas flaring, and emissions from the manufacture of cement

The other two articles[25,26] have used the Ecological Footprint per capita (EF pc) of the Global Footprint Network.

The Ecological Footprint counts the global hectare necessary to satisfy the human demand of 1 year. The global hectare is the world-average ability to produce resources and absorb wastes, so it is defined as the sum of the area of all cropland, grazing land, forest, built-up land and fishing grounds required to produce food, fibre, timber, etc., it also considers the bio-capacity needed to absorb CO_2 emissions.

3.2.4 Matching indexes

In this paragraph, the method of analysis of the articles are analysed. It is specified if the articles focused on cross-sectional or longitudinal analysis, and the applied method are highlighted.

5 articles[28,23,31,30,22] out of 14 have studied the indexes both in static analysis and in time series, instead, 4[26,25,32,27] out of 14 have used just the static analysis, and 5[29,24,19,20,21] out of 14 have used just the time series analysis.

Regarding the applied method, the articles could be divided into two groups. The first group of articles analyses energy and wellbeing focusing on regression analysis between wellbeing and energy indexes (see Table 3), and the second group of articles adopts different type of analysis (see Table 5).

8[25,26,23,31,32,30,28,27] articles have studied the correlation analysis. Some of these articles have reported the value of correlation or the determination coefficient among their analysed indexes, and others have reported the graphical representation of the relation of the analysed indexes. In this way, they have highlighted the connection among the indexes in the analysed countries and time (Table 3 shows the main important analysed indexes by each articles, and it specifies the analysed year and countries.

Article	Match index[2]			method	year	Countries	Ecological index
[27]	HDI-PEC	HDI-EROI	HDI-LEI	Correlation in cross-sectional	2009-2010	-	
	GDP-PEC	GDP-EROI	GDP-LEI				
	IWA(r) - PEC	IWA(r)-EROI	IWA(r)-LEI				

[2] All TPES, PEC, TFC, CO_2 and GDP indexes are referred as per capita unit

28	Log(PEC)- IWA	Correlation in cross-sectional	2010	118	
	Log(PEC)-LEB				
	Log(PEC)-Log(IMR)				
	Log(PEC)-MYS				
	Log(PEC)-Log(GNI)				
	Log(PEC)-EL				
	Log(PEC)-QL	Correlation in cross-sectional and in longitudinal	1980-2010		
25 26	TPES-LEB	Comparison value	2007	33	
	TPES-LR				
	TPES-GNP	Correlation in cross-sectional			TPES-EF
	TPES-HDI				
	TPES-SWB				
23	TPES-QoL	Correlation in cross-sectional and in longitudinal	2005-2013	112	
	ELC-QoL				
31	TFC-QoL	Correlation in cross-sectional	2013	112	CO_2
	TFC-QoL-CO_2-PR	Value comparison			
32	TFC-QoL	Correlation in cross-sectional	2013	12	CO_2
	TFC-QoL-CO_2-PR	Value comparison			
30	PEC-LEB	Correlation analysis in cross-sectional and in longitudinal		135	
	ELC-LEB				
	PEC-IMR			21 (industrialized) in cross-sectional, 13 for longitudinal analysis	
	PEC-GDP				
	PEC-SWB				
	ELC-IMR				
	ELC-GDP				
	ELC-SWB				

Table 3 utilised indexes and method of analysis of articles that study the correlation between wellbeing and energy. The used indexes, the applied method of analyses, the year and the countries analysed are shown for each article

Most of the articles of the first group (see Table 3) have analysed the correlation between wellbeing indexes and energy consumption, these indexes matching are shown in Table 4, which also highlights the articles that analysed these indexes matching.

	TFC		PEC		TPES	
	frequency	articles	frequency	articles	frequency	articles
GDP			2	27,30		
GNI			1	28		
GNP					2	25,26
LEB			2	28,30	1	25
IMR			2	28,30		
IWA			2	27,28		
MYS			1	28		
SWB			1	30	2	25,26
Multiple WB indexes (HDI, QoL, QL)	2	31,32	1	27,28	3	25,26,23

Table 4 Match between energy consumption indexes and wellbeing indexes. The table shows how the indexes of energy consumption have been matched with wellbeing indexes, and it shows also the articles that have analysed them.

The articles of the second group have carried out different methods of analysis (see Table 5). Q. WU and Clulow[22] have computed the Gini index for TPES, and they have compared it with the Gini index computed for GDP and HDI. For each index, different Gini indexes have been computed, according to the sorting of countries with different criteria, such as GDP, HDI, energy consumption and energy production. Akizu-gardoki[24] has focused on the decoupling indexes between HDI and TPES and the decoupling indexes between HDI and TPEF. The decoupling indexes is the arctangent of the ratio of two indexes changing (in %) over time. Al-mulali[29] has analysed the bi-directional long-run relation among one energy data (PEC) and wellbeing indexes, such as GNI, IWA, LEB and IMR. This analysis has been carried out by using the canonical cointegrating regression.

The other three articles have studied the causal relationship between the analysed indexes, and they have carried out the analysis for a limit region of countries. Menegaki and Tansel[19] have studied the causal relation by employing a multivariate framework panel data analysis and considering as dependent variables first the GDP and then the ISEW and as independent variables the TPES, gross fixed capital formation, total labour force, research and development expenditure per capita. This article focuses on the G7 countries, which are Canada, France, Germany, Italy, Japan, UK and USA. Zaman[20] has studied the causal relationship between economic growth and variables such as AES, CO_2, IMR, fertility rate, population density and agricultural machinery. The causal relationships among these variables has been carried out by applying a cointegration and Panel unit root and focusing on the BRICS countries (Brazil, Russia, India, China and South Africa). Jorgenson[21] has studied the dynamic causal relationships among the energy intensity and wellbeing variables such as GDP, Gini index, democratisation, health expenditures, manufacturing and exports. The energy intensity has been computed as a ratio between TPESpc and LEB. This analysis has been focused on 12 eastern European countries.

article	Match index[2]	method	year	countries	Environmental index
22	Gini(TPES) sorted per GDP	Gini index for energy consumption based on different sorting criteria; in cross-sectional and in longitudinal analysis	1998-2007	129	
	Gini(TPES) sorted per HDI				
24	Arctan($\frac{\Delta HDI\,[\%]}{\Delta TPES\,[\%]}$)	Decoupling index (longitudinal analysis)	2000-2014	126	
	Arctan($\frac{\Delta HDI\,[\%]}{\Delta TPEF\,[\%]}$)				
29	PEC-GNI	Bi-directional long run relation	1990-2009	198	
	PEC-IWA				
	PEC-LEB				
	PEC-IMR				
19	GDP (TPES, others WB variables[3])	Study on causal relation between sustainable economics and energy consumption in longitudinal by employing a multivariate framework panel data analysis.	1995-2013	G7[4]	
	ISEW(TPES, others variables[3])				
20	GDP(AES, IMR, CO_2, others[5])	Study on causal relation by applying a cointegration and Panel unit root)	1975-2013	BRICS[6]	CO_2 from building
21	Energy intensity(GDP, Gini, others[7])	Study on dynamic relation between energy intensity and economic development (Longitudinal analysis)	1992-2010	12 eastern European countries	

[3] The others are socio-economic variables, and they are: gross fixed capital formation, total labour force, research and development expenditure per capita [$]
[4] The G7 countries are: Canada, France, Germany, Italy, Japan, UK and USA
[5] Others mean variables such as fertility rate, population density, Agricultural machinery
[6] The BRICS are: Brazil, Russia, India, China and South Africa
[7] Others means variables such as democratization, health expenditures, manufacturing and exports

Table 5 utilized indexes and method of analysis of articles that apply a different method of analysis. The used indexes, the applied method of analyses, the year and the countries analysed are shown for each articles.

3.3 State of the art

The selected articles report several information about the relation between wellbeing and energy. In this paragraph, the main points are grouped per similar thematic and discussed. These thematic are the relation between energy consumptions and wellbeing, the relation between energy quality and wellbeing, the energy distribution and wellbeing, and the importance of sustainability path.

3.3.1 Energy consumption and wellbeing

Several articles (most of them are listed in Table 3) have studied the correlation between energy consumption and wellbeing, they have described this relation, and they agree that the energy benefits wellbeing until a certain amount of consumption, after that their linkage saturates. Therefore, it must kept in mind that the results, about at which energy consumption the relation saturates, are depended on circumstance, for example, the cold countries and hot countries may require more energy to reach a comfortable temperature in their building than temperate countries, so the results are drawn by the average value of whole countries[25].

Another point to be considered before to analyse the single results of articles deeply, it is that there is a reciprocal dependence between the increase of energy consumption and the improvement of quality of life. In fact, Al-mulali[29] has studied the bi-directional correlation between these two elements, and he has figured out that for 70% of 198 analysed countries, the energy consumption helps to improve the wellness, and for 65% of 198 analysed countries, the quality of life enhancing leads to an increase of the energy consumption[29]. The reason of this last point is that the high quality of life means a rise of income so to a growth of standard of living, it also leads to an increase of the improved water access, which raises the life expectancy and so the population grows, and all these factors determine an increase of energy demand[29].

The review of the results about energy consumption and wellbeing are introduced below and are grouped per different categories of wellbeing indexes, such as wealth, health, education, subjective wellbeing and multidimensional wellbeing indexes.

Wealth

As shown by Table 4, five articles have analysed the correlation between energy consumption and wealth indexes. Jess in his two articles[25,26] reports that on 2007 for the 33 analysed countries (68% of the global population) the relation between GNPpc and TPESpc is positively correlated, and it is linear until the value of GNPpc of 15,000 $/pers and the value of TPESpc of around 2 Toe/pers. After these coordinates there are two groups of countries, the first that follows the linear trend of the relation, and the second one is more virtuoso, namely they have a very high level of GNPpc while its energy consumption is relative lower than other group, and Jess comments that these countries benefit the positive effect of efficient energy system.

Lambert[27] and Mazur[30] both have analysed the correlation between GDPpc and PECpc, and both have found a positive correlation between them with a small determination coefficient. The study of Lambert[27] reports a determination coefficient (R^2) of 0.16 for the data of 2009 and 2010, while Mazur[30] individuates a slightly higher determination coefficient (R^2=0.35) for 21 industrialised countries in 2006. However, the study of Mazur[30] reveals that this correlation is weaker in longitudinal analysis, fact that testifies the independence of these two variables over time. In fact, for the industrialised countries, the changing of GDPpc and the changing of PECpc from 1980 to 2006 have a determination coefficient (R^2) of 0.078[30].

The article of Pasten[28] shows that GNIpc and PECpc have a positive but no-linear relation on cross-sectional analysis, in fact by analysing data of 2010 for 118 countries the logarithmic correlation (base-10 logarithm) of two indexes reports a determination coefficient (R^2) of 0.81.

Health

Three articles have focused on the correlation between LEB and energy consumption, both of them report that these two indexes are positively correlated in cross-sectional analysis[25,28,30], and two of them highlight that a logarithmic curve represents the relation of these two indexes in cross-sectional[28,30].

Pasten and Santamarina[28] show that, analysing data of 2010 for 118 countries, the correlation between LEB and Log(PECpc) has a determination coefficient (R^2) of 0.68, and a good level of life expectancy could be reached with a PECpc of 0.75 Toe/pers. Similar results are shown by Mazur[30], which reports that a logarithmic fit-curve represents the relation between LEB and PECpc with an R^2 of 0.69, results obtained by analysing data on 2006 for 135 countries. Moreover, Mazur affirms that the countries with a PECpc higher than 3.44 Toe/pers have a

LEB higher than 80 years. Mazur[30] has also analysed the longitudinal correlation between LEB and PEC for industrialised countries, by using data from 1980 to 2006, and this study reports a determination coefficient (R^2) of 0.073, fact that reveals that the two indexes are not correlated over time. Anyway, all industrialised countries have increased their LEB from 1980 to 2006, testifying that the LEB is not saturated and it will continue to increase also independent by the increase of energy consumption[30].

Two articles have analysed the correlation between PECpc and IMR. Pasten and Satamarina[28] have study this correlation for all type of countries, and they found a negative relation, and they report a determination coefficient (R^2) of 0.71 between Log(IMR) and Log(PECpc). While, by analysing data for industrialised countries on 2006, the determination coefficient is lower (R^2=0.09)[30], and also for longitudinal analysis, the correlation is weak(R^2=0.057) [30]. Mazur reports a lower determination coefficient because he has focused on industrialised countries, in fact, himself affirms that the IMR of industrialised countries is lower than that of underdeveloped countries[30], and countries with a PECpc higher than 0.75 Toe/pers have a very low IMR[28].

Two articles have studied the correlation between energy consumption and IWA. Both articles report that PECpc and IWA have a positive correlation, and a logarithmic curve better represents it. Lambert[27] reports that PEC and IWA(r) have a correlation with R^2=0.33, and Pasten[28] report an R^2 of 0.67 between IWA and Log(PECpc). Both articles agree that IWA and PECpc have a logarithmic relation, and in particular, countries with a PECpc higher than 0.75 Toe/pers have an IWA close to 100%[28], while countries with a PECpc higher than 2.38 Toe/pers have an IWA(r) higher than 75% [27].

Education

Three articles have studied the relation between energy consumption and education. Nadimi[23] have used the MYS as a variable of his index (QoL), and he affirms that MYS could increase by improving the sanitation at school, and the sanitation at school is positive dependent on energy use, which helps to provide adequate light and comfortable temperature in school building and to provide transportation educational media and communication facilities. Pasten[28] affirms that PECpc and MYS are positively correlated, but with a logarithmic relation, in fact, the correlation between MYS and Log(PECpc) is characterised by an R^2=0.72. However, Mazur[30] has discovered that for industrialised countries, there is no-correlation between PECpc and SET (School Enrolment, tertiary) (R^2=0.078).

SWB

Three articles have studied the correlation between energy consumption and SWB. Jess in his two articles affirms that the relation between TPESpc and SWB is characterised by diminishing marginal utility effect, in other words, an amount of energy consumption of 2 Toe/pers allows to reach a very high level of happiness, and more energy consumption does not lead to any improvement in happiness[25,26]. Mazur[30] reveals that for industrialised countries, the PECpc and the SWB have a low determination coefficient (R^2=0.1) in cross-sectional analysis, and this correlation is lower in the longitudinal analysis (R^2=0).

Multidimensional wellbeing indexes

Seven articles have studied the correlation between energy consumption per capita and a multidimensional index of wellbeing. These articles have used different multi-dimensional indexes, such as HDI[25–27], QL[28] and QoL[23,31,32]. The conclusions that come from the analysis of one of these wellbeing indexes could be extended to the others because these three indexes report a reciprocal linear correlation with an R^2 always higher than 0.89 [23].

Both articles affirm that the relation between these wellbeing indexes and the energy consumption is characterized by the diminishing marginal utility effect[23,25–28,31,32]. Jess[25] and Nadimi[23] agree that for the developing countries, the relation between TPESpc and wellbeing is linear, instead, for developed countries, the positive effect of the energy consumption saturates. Furthermore, Nadimi[23] reveals that neither for underdeveloped countries there is a linear relation, by affirming that these countries do not benefit from energy consumption until to reach a TPESpc of 0.5 Toe/pers.

As a consequence of the diminishing marginal utility effect that characterises the relation between energy consumption and wellbeing, some articles have individuated the level of consumption of saturation point. Nevertheless, these articles report no-coincident saturation points because they use different indexes and analyse different countries and year.

Jess[25], by analysing data of 2007 for 33 countries, affirms that the relation between TPESpc and HDI saturates with an energy consumption of 2 Toe/pers. Lambert[27], by analysing data of 2009 and of 2010, affirms that the relation between PECpc and HDIia (HDI inequality adjusted) saturates with a PECpc of 3.58 Toe/pers. Pasten[28], by analysing data of 2010 for 118 countries, affirms that the relation between PECpc and QL saturate with a PECpc of 3.77 Toe/pers. Nadimi[23], by analysing data of 2013 for 112 countries affirms that the saturation between energy consumption and QoL occurs for the developed countries, which countries have a TPESpc higher than 5.47 Toe/pers. Instead, Nadimi himself, by using the TFCpc, affirms that the developed countries have a TFCpc higher than 2.45 Toe/pers[31,32].

Furthermore, the correlation between energy consumption and QL is not strong in longitudinal analysis, in fact, from1980 to 2010 the majority of the countries have improved their QL while they have maintained constant their energy consumption[28].

3.3.2 Quality of energy and wellbeing

Some articles have analysed the relation between energy and wellbeing by focusing on the quality of energy. About the quality of energy, it has been considered electricity, as the most useful energy form[23,28,30], and the affordability of energy commodity[27].

The electricity is considered a high-quality energy form, because it is versatile and useful for the actual technology[30], and the electricity allows to substitute heavy labour with the automated system. Thus it improves industrial, commercial and residential sectors, whose development is connected with a high level of well-being[23].

For industrialized countries, there is not a good linear correlation between electricity consumption per capita and wellbeing, in fact, Mazur[30] reports that, for these countries, ELCpc has a low determination coefficient with GDPpc and SWB and a very low one with SET and LEB in cross-sectional analysis (respectively R^2=0.38, R^2=0.3, R^2=0.14, R^2=0.02), and in longitudinal analysis these correlations are weaker. Instead, by analysing ELCpc and LEB at the global scale, their relation is better represented by a logarithmic curve (R^2=0.7), and it testifies that also electricity consumption per capita and wellbeing are characterised by saturation in cross-sectional analysis[30]. As a consequence of this type of relation, Mazur affirms that countries with an ELCpc of 0.5 Toe/pers have a LEB higher than 80 years. As a consequence, for the underdeveloped countries there is more chance to improve their quality of life by increasing their electricity consumption, while for developed countries this relation has reached the saturation[30].

The other indexes used as a proxy of the quality of life is the EROI (Energy Return Of Investment). According to the study of Lambert[27], EROI reports a correlation with wellbeing indexes similar to that reported by energy consumption per capita. Thus, EROI is considered another key point to study the correlation between energy and wellbeing[27]. This means that countries with an easier access to energy commodity, for example, the energy producer countries, and countries that benefits from energy commodity with higher energy content or that benefits from technology that allows exploiting better the potential of the resource, have a higher EROI and all these factors are connected with higher quality of life[27]. However, the correlation between EROI and quality of life is also characterized by the diminishing marginal utility effect, and value of EROI at the social level around 25:1 is enough to guarantee high level of HDI, GDPpc and IWA(r)[27].

3.3.3 Energy distribution

Another critical aspect that influence that relation between energy and wellbeing is the energy distribution. Several articles affirm that an equal distribution of energy will improve the quality of life at global scale[22,27]. However, the actual global situation does not show equal energy distribution. In fact, just almost 5% of the global population accounts for almost 24% of the total energy consumption, and almost the 17% of the world population consumes almost the 48% of the total global energy consumed in one year[22,28,32]. In contrast, almost 15 % of the population has a low level of HDI (HDI<0.6) and accounts for just almost 3% of the total global energy consumed in one year[22]. Nevertheless, Q. WU and Clulow[22] showed that from 1980 to 2007 the distribution of energy consumption tends to become equally distributed, even if the actual situation is far from the condition of equality.
Lambert[27] affirms that energy distribution represents another important key point for the relation between energy and wellbeing. In fact, she define a new energy index, which considers simultaneously the quantity of energy consumption, the quality of energy (represented by the EROI at social level), and the income distribution as a proxy of energy distribution[27]. This index is defined Lambert Energy Index (LEI), and its mathematical structure is defined in the previous paragraph by Equation 1. The LEI has reported a better correlation with HDI, GDPpc and IWA (for rural population) than PECpc and respect to EROI at the social level. This high correlation testifies that the relation between energy and wellbeing should be studied by looking at consumption, quality and distribution energy of a country simultaneously[27].

3.3.4 Sustainability

Many articles have connected the argument "energy and wellbeing" with the thematic of sustainability. In fact, they have followed the new path of economic, which is interested in sustainable wellbeing[19]. Some of them have suggested how sustainability should be studied when energy and wellbeing are analysed together, while others have illustrated which could be the path to create a sustainable society.

The necessity to follow and actuate the sustainable principle is motivated by an expected increase of the energy demand, and by the dependence of the actual economy to the fossil fuel, whose reserves are diminishing[28]. Jess[25] affirms that if the relation between HDI and TPESpc will not change over time, and considering the increase of population, the global primary energy demand will increase until on 2050 it will be more than 35% of the 2007 level.

The prevision made by Pasten[28] is more drastic, in fact, they affirm that the maintenance of the status quo will lead to having a global primary energy consumption of 19.1 GToe on 2040, which means a 50% increase from the 2010 level. However, Jorgenson[21] is optimistic about the chance to reach a more harmonious relation between development, human well-being, and the natural environment.

Two articles suggest that the sustainability path could be not traced by considering the GDP as a wellbeing index. In fact, Menegaki and Tansel[19] have discovered that from 1995 to 2013, the G7 countries have increased their GDP, while their ISEW (indexes of sustainable economic growth) have not improved. Furthermore, the energy consumption is positively correlated with GDP, but it contributes negatives to sustainable economic wellbeing[19]. Zaman[20], which has studied the causal relationship between the main pillars of sustainable growth, which are economic, health, environment and energy, for the BRICS countries from 1975 to 2013, has discovered that environmental variables have a deleterious effect on GDP growth of these countries. The results shown by Zaman confirms what states by Hueting[40], namely that environmental protection represent a limitation for economic growth based on monetary account. So a changing of perspective should be necessary to highlight the importance of the environment for human beings.

Some articles have tried to monitored the sustainability path by analysing environmental indexes. Jess[25] has investigated the feasibility of a meeting point between happy people and happy planet by analysing the Ecological Footprint (EF) with HDI and TPESpc. The EF allows us to consider the equivalent amount of planet Earth necessary to satisfy human needs and to absorb pollution produced by human activity. On 2007 the global EF reveals that 1.3 Earth has been necessary, and with the hypothesis that on 2050 all countries reach a high level of HDI, and that they consume a TPESpc of 2 Toe/pers (minimum amount of energy to guarantee the high level of HDI with actual technology), and considering that a global population of 9 billion of persons, 2 Earth will be necessary to support all that[25]. Thus, the necessity of more than one Earth means that in one year it will be used part of the ecosystem that should be used for next year, or by the next generation, hence the results of Jess[25] shows a society that does not respect one of the fundamental principle of sustainability. Instead, Nadimi[32] has compared the average value of CO_2 emissions per capita and the average value of TFCpc of three different groups of countries, which are developed, developing and underdeveloped countries. Due to the CO_2 emissions per capita of the developed countries is more than double of the developing countries level, which in turn have a CO_2 per capita four times more than that of underdeveloped countries level, Nadimi[32] recommended different policy implementation for each group in order to achieve a sustainable world. It should be necessary an eco-sufficiency policy for developed countries, an eco-efficiency policy for developing countries, and a poverty reduction policy for underdeveloped countries[32].

Others articles have studied the sustainability by combining a wellbeing index with an energy consumption index. Akizu-garfoki[24] has computed the decoupling index as a proxy of sustainability. The decoupling index is a ratio between the changing (in percentage) over time of HDI and the changing (in percentage) over time of the TPES pc. Jorgenson[21] has computed the energy intensity, dividing the TPES pc by the LEB. According to the decoupling index, the countries follow the sustainability path when the percentage of wellbeing increase is higher than the percentage of the energy consumption changing [24]. According to the energy intensity, sustainability improves when the energy intensity decreases, namely when the same wellbeing is achieved with less energy use [21]. Akizu.gardoki[24] has discovered that from 2000 to 2014 both developed and underdeveloped countries have decoupled their wellbeing from energy. Jorgenson[21] has discovered that the eastern European countries from 1992 to 2010 have improved their LEB and increased their GDP, while their energy consumption remained constant or decreased a little. So these countries have focused on economic activities that involve less energy consumption[21]. And Menegaki and Tansel[19] suggest that in long-run the G7 countries can reduce their energy consumption and so improving their sustainability, while they maintain constant their wellbeing.

In conclusion, these articles agree that the sustainability path should be represented by action about decarbonisation and the reduction of consumption. In other words, the decarbonisation should be reached by an energy transition toward renewable technology, and the consumptions should be reduced by avoiding over consumption and improving energy for-life efficiency [23]. Some of these articles recognise the responsibility of policy, which should adopt and respect sustainability policy agenda [20], it should promote the development and installation of clean technology and renewable energy and guarantee the implementation of energy-efficient technology [28], and it should eliminate subsidies for fossil fuel [19].

Jess[25], Pasten and Satamarina[28] agree that the countries should not consume more than the minimum amount of energy per capita that guarantee a high level of wellbeing. Pasten and Santamarina[28] affirm that fixing a maximum for primary energy consumption at 2.77 Toe/pers, which would guarantee a high level of wellbeing with the actual technology, the consumption on 2040 will be the same of the 2010 level. As well as overconsumption, the global CO_2 emissions should decrease until to reach 50% of the 2007 level, in order that happy people and happy planet can coexist [25].

In conclusion, a sustainable society should offer the safeguard of the natural environment and improvement of the quality of life, by reducing pollution and environmental risk for human health[31,32].

3.4 Selected indexes for this work

For analysing the wellbeing dimension, the choice of the index has been focused on multidimensional indexes, in according to wellbeing study[5], and some papers about wellbeing indexes evaluation have been consulted. The HDI has been chosen because it has been largely used in statistical approach for studying the quality of life[41], it accounts for three wellbeing dimension by combining just four variables, which means that the HDI is a simple and strong index[42]. Other wellbeing indexes have been individuated in literature, such as Social Progress Index (SPI) and Legatum Prosperity Index (LPI), which both report a high correlation with HDI[43,44,41], the fact that testify that these indexes report the same info of HDI[42]

The state of the art shows that articles have studied the relation between energy and wellbeing by focusing intensely on energy consumption. However, still few points have been analysed regarding the energy quality. Therefore, the analysis of energy quality and wellbeing could represent an potential opportunity to discover new information. The other emerging investigated point from literature is represented by sustainability and by the object of decarbonisation, and this point has led to consider into the analysis also the CO_2 emission as an environmental index. So the CO_2 intensity ($CO2_{int}$) has been individuated as an energy quality index that could also be suitable to face the investigation on decarbonisation process.

The $CO2_{int}$ is an index that describes the environmental impact, namely the CO_2 emissions, produced by one unit of primary energy of the supply chain of a country[45]. This index analyses simultaneously the energy dimension and the environmental dimension, because it considers the TPES of a country and its CO_2 emissions produced from the combustion of fossil fuel and cement manufacturing[45]. This index has been considered as a suitable index to study the decarbonisation process and the sustainable development[46], in fact, the $CO2_{int}$ has better explained the high reduction of CO_2 of Sweden from 1970 to 2011[46].

A first investigation about the relation between HDI and $CO2_{int}$ has been carried out by Pîrlogea[47], who has analysed data of some European countries from 1997 to 2010. By agreeing with Costa[18], Pîrlogea[47] affirmed that countries with HDI>0.8 could reduce $CO2_{int}$ by improving their quality of life, while countries with HDI<0.8 are not able to do it.

An interesting review upon the $CO2_{int}$ of the main sources used in electricity production has been carried by IPCC[48], which has considered the entire life cycle. IPCC[48] reports that renewable energy sources have a very low value of $CO2_{int}$, and a high value of CO2int characterises the non-renewable sources. Among the non-renewable sources, the natural gases are characterised by a lower value of $CO2_{int}$ than oil and coal, and coal has the highest $CO2_{int}$ value.

4 Dataset and materials

The analysed indexes in paragraph 5.1 are the HDI and $CO2_{int}$. The HDI is a wellbeing index, whose data are annually released by United Nations Development Report[37]. The index is a combination of normalised indicators, for that reason, the data of different year can be compared just referring to the same edition of the report. In this thesis, the data of last available edition (of the year 2018) have been used. This edition reports data from 1990 to 2017 for 142 countries in 1990 and 189 countries in 2017 (see Table 6). The $CO2_{int}$ is an index of energy quality. In this thesis, the database released by World Bank[45] has been used. The database reports data from 1960 to 2014 for a variable number of countries each year (see Table 6). The $CO2_{int}$ database of World Bank collects data from: International Energy Agency, Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee and United States[45].

INDEX	TYPE	COUNTRIES	YEARS	SOURCE
HDI	wellbeing	142-189	1990-2017	37
$CO2_{int}$	Energy quality	24-168	1960-2014	45

Table 6. Database of the analysed indexes. The type of index, the covered countries and yea, and the data source are specified for each index.

By matching these available datasets, the analysis has been carried out for the largest time-span, namely from 1990 to 2014, and for the largest number of countries, namely 96 countries. The sample of 96 countries represents 81.95% of the world population in 2014, and 82.91% of the global TPES in 2014 (see Table 7). Data of United Nations population divisions[49] give the value of the population. The value of the sample TPES is obtained from World Bank database[50], the data of the global TPES is from data of IEA[51].

	population (2014) [billion]	TPES (2014) [GToe]
Sample (2014)	5.981	11.3
World (2014)	7.298	13.6
% on world value	81.9%	82.9%

Table 7. population and energy consumption of the sample on 2014, in comparison to the world population and global energy consumption.

4.1 Longitudinal analysis assumption

The indexes have been analysed in cross-sectional analysis (the year 2014) and in the longitudinal analysis (from 1990 to 2014). In the longitudinal analysis, the variation of these two indexes over time have been first analysed graphically, then their average variation has been deeper studied. The average variation has been computed by using the line represented by Equation 2, whose slope is specified by Equation 3. To verify the precision of this approximation, a margin of confidence of the 30% for Equation 2 is considered. According to these criteria, 84 on 96 analysed countries (namely 87.5% of the sample) respects the confidence criteria.

$$CO2_{int}(y) = m * [HDI(y) - HDI(1990)] + CO2_{int}(1990)$$	*Equation 2*
where: ➢ m is the slope of the line, whose value is given by Equation 3 ➢ y is the generic year	

$$m = \frac{\Delta(CO2_{int}(2014) - CO2_{int}(1990))}{\Delta(HDI(2014) - HDI(1990))}$$	*Equation 3*
Where: ➢ m is the slope of the line of Equation 2	

4.2 CO_2 emission scenarios by 2050

In paragraph 5.2, four future scenarios have been constructed, whose produced cumulative CO_2 emissions from 2000 to 2050 have been computed and compared with a budget of 1000 Gt.

Each scenario is built on the future estimation of the average behaviour of four groups of countries, in other words, on the estimation of the average value of HDI, of TPESpc and of $CO2_{int}$ of each group. The countries have been divided into four groups based on their belonging development level on 2014. The four development levels are specified in Table 8.

For each scenario, the prevision of the population of each country is provided by the United Nation population division[49]. United Nation population division has made different previsions for the global population, considering different growth rate. Here the prevision made with the medium variant criteria has been considered. The scenarios have been built for those countries, whose data are provided both for their population and for their HDI of 2014. As a consequence, each scenario considers 188 countries which represent 99% of the global population.

The scenarios consider different estimation for $CO2_{int}$ and TPESpc, but equal estimation for HDI. For the estimation of HDI, the historical data from 1990 to 2014 has been used. In other words, the mean HDI of each group has been computed by considering the variations reported by Table 11, where it is specified the different variations for each development level.

In Business As Usual scenario, the estimation of $CO2_{int}$ has been computed by using the historical data from 1990 to 2014. In other words, the mean $CO2_{int}$ of each group has been computed by considering the different variations in each development level (see Table 11). In Business As Usual scenario, the TPESpc has been computed considering the curve fitting of the correlation of HDI and TPESpc (see Figure 6). The regression analysis has been carried out with data of 2014 and for 132 countries, whose data are available simultaneously for both indexes. The data have been fitted by using a power-law curve, and the quality of fitting is represented by an $R^2=0.98$. It is assumed that this relation remains constant throughout the timespan. This criterion is valid just until an HDI=0.88 (mean value of the VH group in 2014), after this value it is supposed that countries maintain constant their TPESpc value by increasing their HDI. This hypothesis is confirmed by the studies of Mazur[30] and of Ya Wu[52], which reveal that the energy consumption of the Very-High-HDI countries has saturated, even if they have improved their wellbeing in recent decades.

The individuated values of mean TPESpc in Figure 6 are obtained by intercepting the values of the curve corresponding to mean HDI.

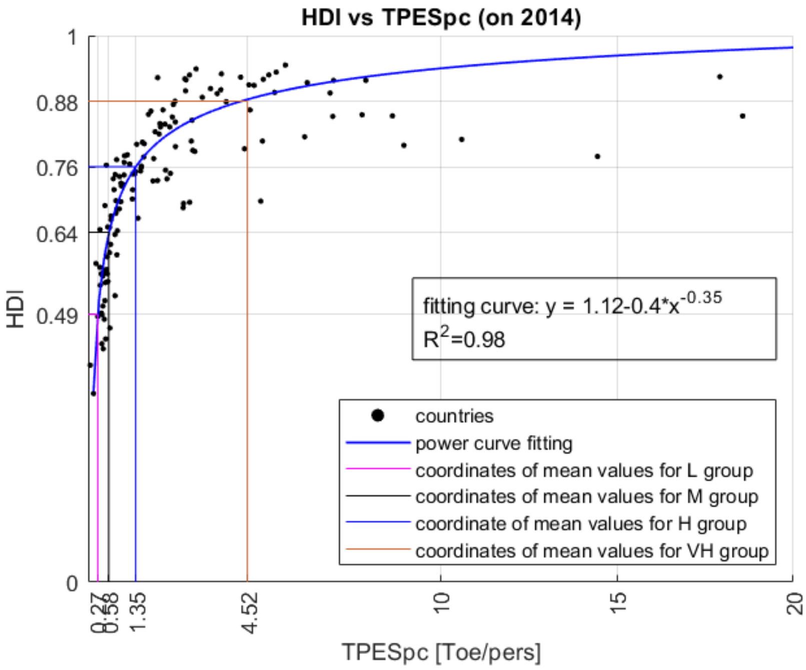

Figure 6. Correlation between HDI and TPESpc in 2014. The data refers to 132 countries. The x-axis reports the values of TPESpc (in kg/kgoe) of each country, the y-axis reports the value of HDI of each country. The black dots individuate the meeting of the coordinates for each country. The blue curve is the fitting of the regression, which is obtained with the power-law equation shown in the figure. The straight lines of different colours represent the coordinates corresponding to the HDI mean of the L group (purple line), of the M group (black line), of the H group (blue line), and of the VH group (brown line).

In each scenario the annual global CO_2 emissions is calculated by multiplying the estimation of TPES of each country by the estimation of the mean $CO2_{int}$ of the country's group (see Equation 5). The estimation of TPES of each country has been computed by multiplying the estimation of each country population by the estimation of the mean TPESpc of the country's group (see Equation 4).

$TPES_{ji}(t) = TPESpc_{mean\ j}(t) * Pop_{ji}(t)$	*Equation 4*
Dove: ➢ The subscript *j* refers to the four groups of countries ➢ The subscript *i* refers to the countries of group *j* ➢ Pop refers to the population of the countries	

$CO_{2\ ji}(\mathrm{t}) = \mathrm{CO}_{2int\ mean\ j}(t) * TPES_{ji}(t)$	*Equation 5*
Where: ➢ The subscript *j* refers to the four groups of countries ➢ The subscript *i* refers to the countries of group *j*	

The cumulative CO_2 emissions produced by each scenario from 2000 to 2050 has been computed by considering the historical cumulative CO_2 emissions between 2000 and 2014 (obtained from the data of World Bank[53]) and adding to it the contribution of the annual CO_2 emitted by each country from 2015 to 2050 (look at second term of Equation 6). The historical cumulative CO_2 emissions between 2000 and 2014 is 462 Gt (according to World Bank).

$$CO_{2\,budget} \geq \sum_{ji} \left(\int_{2015}^{2050} CO_{2\,ji}(\mathrm{t})\, dt \right) + CO2_{\mathrm{historic}} \qquad \textit{Equation 6}$$

Where:

- The subscript *j* refers to the four groups of countries
- The subscript *i* refers to the countries of group *j*
- $CO2_{\mathrm{historic}}$ refers to the cumulative emissions from 2000 to 2014
- $CO2_{budget}$ refers to the limit of cumulative emissions to maintain global warming below 2°C

5 Results and discussion

5.1 Change in CO_2 intensity at each development level

This paragraph analyses the relation between the development of a country, represented by the HDI indicator, and the quality of energy used within the country, meaning the amount of CO_2 emissions per unit of primary energy consumed, represented by $CO2_{int}$. These two dimensions are analysed in this paragraph by the cross-sectional and the longitudinal analysis.
The development levels of countries are specified by UNDP[37] using a classification based on the HDI score as shown by Table 8:

Development Level	Acronym	HDI score
Low-HDI	L	HDI < 0.55
Medium-HDI	M	0.55 < HDI < 0.7
High-HDI	H	0.7 < HDI < 0.8
Very-High-HDI	VH	0.8 < HDI

Table 8. Countries development levels according to different HDI scores [37]

The cross-sectional analysis, carried out with data of 2014 for the 96 analysed countries, is shown in Figure 7, where each blue dot represents the coordinates of HDI and $CO2_{int}$ for a country. The value of $CO2_{int}$ of the analysed countries ranges from 0.16 kg/kgoe (value of the Democratic Republic of the Congo) to 3.88 kg/kgoe (value of Mongolia), and the mean value of $CO2_{int}$ of all the sample is 2.13 kg/kgoe, summarized in Table 9. The relation between $CO2_{int}$ and HDI in the cross-sectional analysis is not linear as the data are distributed along to a bell curve. Nevertheless, we can notice a positive correlation among the two variables for countries with an HDI lower than 0.75, in fact,, the countries belonging to this group show a high HDI for high value of $CO2_{int}$; while countries with a, HDI higher than 0.75 have a negative correlation with the $CO2_{int}$, as the higher the HDI the lower is their $CO2_{int}$.

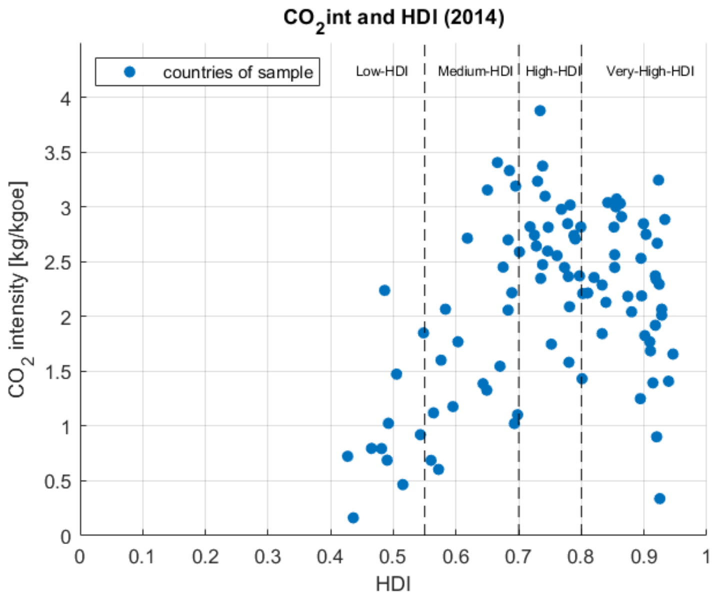

Figure 7. Correlation between $CO2_{int}$ and HDI in cross-sectional analysis in 2014 for the 96 analysed countries. In the x-axis the HDI values of each country are reported, in the y-axis, the $CO2_{int}$ values (in kg/kgoe) of each country are reported. Each blue dot individuates the meeting of the coordinates of each country. The three black dotted lines delimit the four development levels (introduced by Table 8), which are specified on the top of the figure.

As a consequence, the countries with HDI value around 0.7 are characterized by the highest mean value of $CO2_{int}$ among all the counties. In fact, the countries showing the lowest value of $CO2_{int}$ belong to the Low-HDI level, as any countries of this level have a value of $CO2_{int}$ lower than 2.24 kg/kgoe; while the Very-High-HDI countries have a value of $CO2_{int}$ tendentially lower than the High-HDI countries. Nevertheless, Very-High-HDI countries cover a large range of $CO2_{int}$ values, from very low values such as Iceland (with 0.34 kg/kgoe) and Sweden (with 0.9 kg/kgoe), up to countries with an elevated $CO2_{int}$, such as Hong Kong (with 3.24 kg/kgoe), Cyprus, Poland, Malta and Emirates (both with a value around 3 kg/kgoe).

Variables	Development level	Minimum	Maximum	Mean
$CO2_{int}$ [kg/kgoe]	Whole sample	0.16	3.88	2.13
	Low-HDI	0.16	2.24	1.01
	Medium-HDI	0.6	3.40	1.93
	High-HDI	1.58	3.88	2.67
	Very-High-HDI	0.34	3.24	2.22
HDI	Whole sample	0.43	0.95	0.75
	Low-HDI	0.43	0.548	0.49
	Medium-HDI	0.56	0.698	0.64
	High-HDI	0.701	0.799	0.76
	Very-High-HDI	0.801	0.939	0.88

Table 9. The minimum, maximum and mean value of HDI and $CO2_{int}$ on 2014 of all 96 countries of the sample, and of the group of countries dived for their development level.

The correlation between $CO2_{int}$ and HDI in longitudinal analysis is shown in Figure 8, which shows the evolution of Figure 7 over the time span from 1990 to 2014 at intervals of 5 years. Each broken line represents the path that a country has covered from the coordinates of the year 1990 to the coordinates of the year 2014. Since all countries in this time span have increased their HDI, it follows that their trajectory goes from the left to the right of the graph. In the longitudinal analysis, the countries are grouped and referred according to their development on 2014.

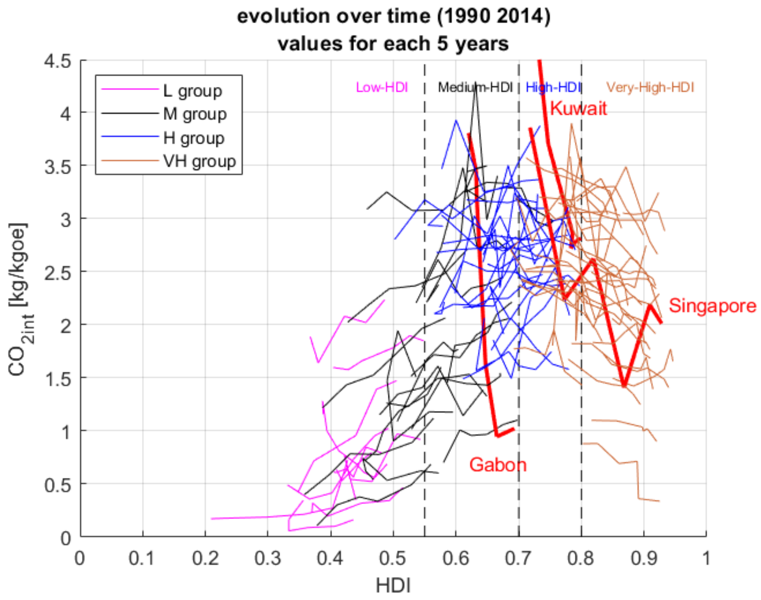

Figure 8. Correlation between $CO2_{int}$ and HDI in longitudinal analysis from 1990 to 2014 at intervals of 5 years for the 96 analysed countries. In the x-axi,s the HDI values of each country are reported, in the y-axis, the $CO2_{int}$ values (in kg/kgoe) of each country are reported. The trajectory of each country is represented by a broken line coloured accordingly to their development level by the 2014 Low-HDI (purple), Medium-HDI(black), High-HDI (blue) and Very-High-HDI (brown). The three black dotted lines delimit the four development levels, which are specified on the top of the figure. The countries highlighted in red are considered as exceptional. the coordinate of Kuwait of the year 1990 are not shown (which have a value of $CO2_{int}$ of 5.6 kg/kgoe), because the figure maintains the same scale of the other figures

In Figure 8 three countries have been highlighted (with red colour) as they have decreased their $CO2_{int}$ much more than any others for exceptional reason. Indeed, Gabon, Kuwait and Singapore have reduced their $CO2_{int}$ of 2.79 kg/kgoe, 2.78 kg/kgoe and 1.85 kg/kgoe respectively, in comparison to the reduction of 1.02 kg/kgoe of Brunei. The reason of the high reported value of $CO2_{int}$ of Kuwait on 1990 is most likely attributed to the suffered military invasion by Iraq on 2nd of august 1990 which ended with the liberation of Kuwait on 25th of February 1991[54]. In fact, from 1989 to 1990 in Kuwait there has been an increment of the $CO2_{int}$ from 1.52 kg/kgoe on 1989 to 5.6 kg/kgoe on 1990, and then the $CO2_{int}$ has decreased again until 2.39 kg/kgoe on 1992, according to the data of the World Bank[45]. The decreasing of $CO2_{int}$ in Gabon occurred mostly from 2000 to 2010, in fact, according to data from World Bank, the

TPES of Gabon has increased from 1.47 MToe/year on 2000 to 5 MToe/year on 2010, while its CO_2 emissions has changed a little, going from 4.7 Mt on 2000 to 4.81 Mt on 2010. This decoupling between energy consumption and carbon dioxide emissions could be linked to the increase of the renewable commodity share, which has increased from 72.8% of TPES on 2000 to 85.9% of TPES on 2010[55]. Moreover, the modern biomass was the commodity that has mainly increased, reaching the 71.4 % of total renewable commodity used by Gabon on 2015[56]. Considering Singapore, its $CO2_{int}$ reduction could be linked to adopted transition energy policy toward a mix of cleaner energy commodity for electricity production, principally from the use of oil fuel to the use of natural gas, in fact, the last-mentioned represents recently about 95% of the total energy commodity employed on electricity production by Singapore[57]. Consequentially, the behaviour of these countries is considered an exceptional one, and they will be kept out from the following analyses, in order not to influence the studying of the average behaviour of countries.

The longitudinal analysis shown in Figure 8 confirms the qualitatively observation of a bell shape, in fact Low-HDI and Medium-HDI countries have increased their $CO2_{int}$, while the High-HDI countries show an intermediate trend, as some of them have increased their $CO2_{int}$ and others have decreased it or kept it constant, and on the other hand, the Very-High-HDI countries have generally decreased their $CO2_{int}$. Therefore, from this observation, we can infer a strong relation between $CO2_{int}$ of a country and its development level.

In order to analyse the average behaviour of the countries at different development levels, we elaborated Figure 9 to immediately identify the average $CO2_{int}$ and HDI variation during the period of interest. Therefore, the broken lines showed Figure 8 are substituted in Figure 9 by straight lines connecting the coordinate of each country in 1990 and 2014. Each straight line of Figure 9, so the average trajectory of each country is represented by Equation 2, whose slope is specified by Equation 3.

Considering a margin of confidence of the 30%, 84 countries (namely 87.5%) on 96 analysed countries (considering also Gabon, Kuwait and Singapore) lie within these confidence criteria. In order to highlight the variation of $CO2_{int}$ in the different stages of development of the analysed countries, Figure 9 shows the change of $CO2_{int}$ ($\Delta CO2_{int}$) in the time span from 1990 to 2014 for the Low-HDI (b), Medium-HDI (c), High-HDI (d) and Very-High-HDI (e) countries. It is possible to appreciate qualitatively that Low-HDI and Medium -HDI countries show a trajectory with an accentuate positive $\Delta CO2_{int}$, while High-HDI countries show trajectories with both negative and positive $\Delta CO2_{int}$, and Very-High-HDI countries show trajectories mostly with negative $\Delta CO2_{int}$.

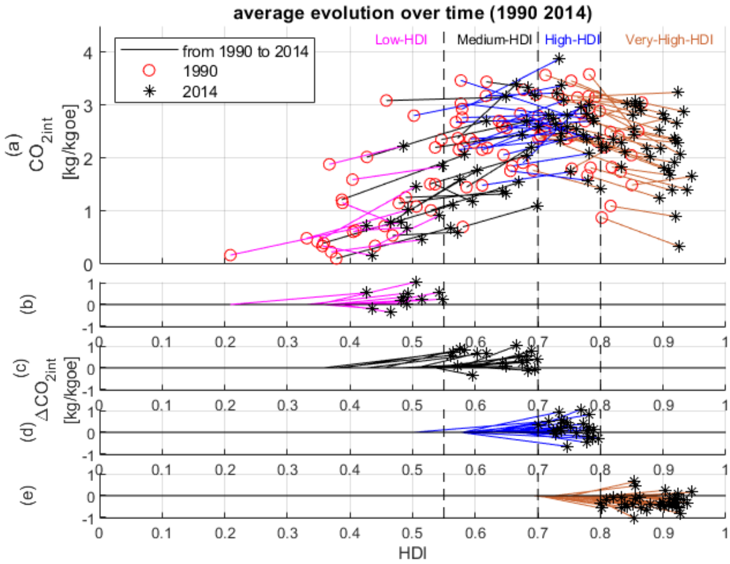

Figure 9. Figure 9(a). Average evolution over time of the correlation between $CO2_{int}$ and HDI for the analysed countries (excluding Gabon, Kuwait and Singapore) from 1990 to 2014. Figure 9(b)(c)(d)(e). the relation between $CO2_{int}$ changing ($\Delta CO2_{int}$) at 2014 respect to 1990 with HDI for the analysed countries for the different development level (in (b) the Low-HDI, in (c) Medium-HDI, in (d) the High-HDI countries and in (e) the Very-High-HDI countries. In all figures, the x-axis reports the HDI values of each country. In (a) the y-axis reports the $CO2_{int}$ values (in kg/kgoe) of each country. In (b), (c), (d) and in (e) the y-axis reports the change of $CO2_{int}$ ($\Delta CO2_{int}$) (in kg/kgoe). Each straight line connects the coordinates of 1990 with the ones of 2014 for each country of the sample. The three black dotted lines delimit the four development levels (introduced by Table 8), which are specified on the top of the figure, and the trajectories of the countries belonging to different development levels are highlighted by distinct colour in order to help their individuation according to their belonging level to the year 2014

What showed qualitatively in the previous figure is studied quantitatively by means of the frequency analysis of the slope, namely $\Delta CO2_{int}/\Delta HDI$, as shown by Figure 10. The frequency distribution, shown in Figure 10, has been computed considering ten bin of 2.6 kg/kgoe/HDI, considering that the whole range of distribution goes from -14.4 to 11.5. Thus, the values of mode, reported in Table 10, depends on the chosen bin. Table 10 reports the descriptive variables of the distributions. Figure 10 shows the whole sample distribution as yellow bars, the one for the Low-HDI countries (pink line), Medium-HDI (black line), High-HDI (blue) and Very-High-HDI (brown). Recalling that all the analysed countries have increased their HDI over the considered timespan, it follows that when a country has a negative slope means that it has decreased its $CO2_{int}$.

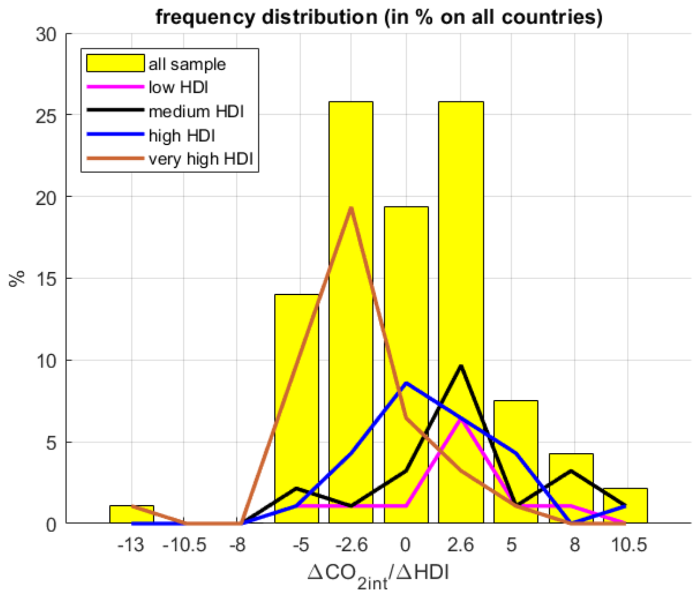

Figure 10 frequency distribution in % of the total population (excluding Gabon, Kuwait and Singapore). In the x-axis, the range of slope values are reported, in the y-axis, the frequencies (in % of the analysed sample) of the slopes are reported. The figure reports 5 distributions simultaneously, The yellow bars represent the whole sample, and the broken lines the countries of the different development levels which are reported with different colours, depending on their level as specified by the legend in the figure.

The distribution of the whole countries (red bars, in Figure 10) shows that the majority of the countries has a slope between -5 and 2.6 kg/kgoe per point of HDI, with two peaks at -2.6 and 2.6. The distributions relative to the Low-HDI and Medium-HDI countries (the purple and blank line respectively, in Figure 10) confirm their general positive trajectory, as the increased their $CO2_{int}$ in the 24 years analysed with a rate of about 2.6 kg/kgoe/HDI. The High-HDI countries (the blue line, in Figure 10) show the wider distribution with a maximum at zero and a mean value at 1.5 kg/kgoe per point of HDI (see Table 10). The distribution relative to the Very-High-HDI countries shows that these countries have a negative slope, reporting a sharp peak around -2.6 kg/kgoe per point of HDI.

Development level	***N° countries***	***Min***	***Max***	***Median***	***Mean (m_{ave})***	***Mode (m_{freq})***	***Standard deviation***
LOW-HDI	11	-4.7	6.7	2.4	1.9	2.6	3.21
MEDIUM-HDI	20	-5.8	10.9	3.3	2.6	2.6	4.06
HIGH-HDI	24	-4.5	11.5	1.0	1.5	0	3.43
VERY-HIGH-HDI	38	-14.4	6.5	-2.9	-2.6	-2.6	3.29
ALL Countries	93	-14.4	11.5		0.1	-	4.13

Table 10. Descriptive variables of the frequency distribution of the rate $\Delta CO2_{int}/\Delta HDI$ (kg/kgoe per point of HDI) for the whole countries sample (escluding Gabon, Kuwait and Singapore) distinguished for their development level. The mean values are specified with the sign m_{ave} (average slope), the mode values are specified with the sign m_{freq} (most frequent slope).

With the results drawn from the distribution frequency, it is possible to compute the variation on time of the average value of HDI and $CO2_{int}$ typically for each development level (see Table 11). The HDI changing is obtained using the mean value relative to 1990 and relative to 2014. The $CO2_{int}$ changing of each development level is computed using Equation 2 according to the mean value of the slope reported by Table 10. Table 11 shows the same information reported by the mean value of the slope of each development level shown in Table 10.

Development level	$\frac{\Delta HDI_{mean}}{\Delta t}$	$\frac{\Delta CO_{2int\ mean}}{\Delta t}$
Low-HDI	0.0052	0.010
Medium-HDI	0.0055	0.014
High-HDI	0.0058	0.009
Very-High-HDI	0.0047	-0.012

Table 11. variation over time of the mean value of HDI and of the mean value of $CO2_{int}$ typically of each level of development.

5.2 Sustainability of CO_2 scenarios and countries development

The results shown in the previous paragraph link the evolution of the $CO2_{int}$ of a country to its development level (HDI). Therefore we want to use this observation to depict a possible scenario of country development in the future and their impact on the environment. In this paragraph, we reconstruct the evolution of $CO2_{int}$ and HDI of the four cluster of countries according to their level in 2014. Prior to the formulation of future scenarios, it is necessary to define our assumptions within the "hypothesis of continuity".

5.2.1 Hypothesis of continuity

The hypothesis of continuity assumes that the use of the energy (behaviours), namely $CO2_{int}$, changes as a country change its HDI level and that it corresponds to the typical behaviour of the development group it belongs.

Therefore, we define the continuity hypothesis as the following:

- When a nation progresses from one stage of development to the other, it will experience the typical behaviour of the new belonging level.
- The individuated slope are the only ones existing and that they remain unchanged over time.
- It is assumed that there is no transitions phase from one development stage to the other. The $\Delta CO2_{int}/\Delta HDI$ slope of each development level does not change over time.

This hypothesis could not be observed in the data because the available time span (1990-2014) is not enough to observe the behaviour transition of a specific country thorough all the development level.

Assuming the validity of the continuity hypothesis is verified, it follows that each a nation increases its development level passing from a Low-HDI value toward the theoretical maximum HDI value of 1 following the most frequent trajectory on the bell curve in Figure 11. Figure 11 shows the most frequent behaviour (blue curve) and the mean behaviour (black curve) of all nations for each level of development separately. The path described by the blue curve is useful to guess the probable trajectory of a single nation. Instead, the path described by the black curve is useful to predict the trajectory of each development group. Each path described in Figure 11 is constructed, for the blue curve, with the values most frequent slope, observed in the previous paragraph (m_{freq}), while for the black curve by using average slope (m_{ave}), both reported in Table 10.

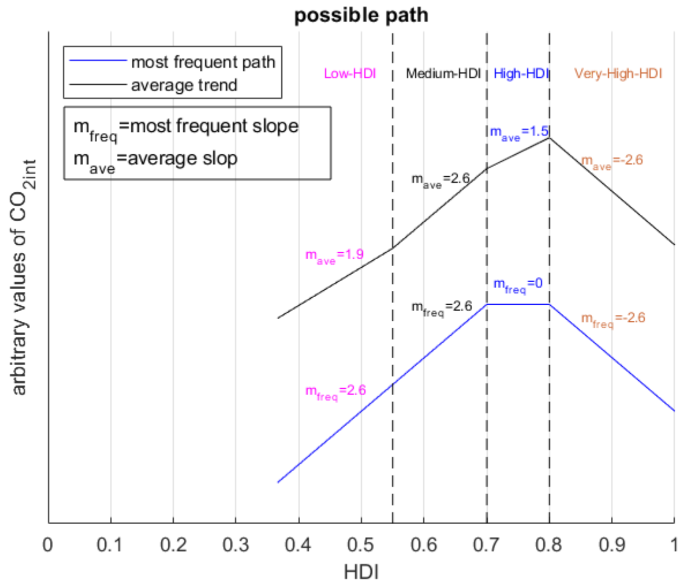

Figure 11. Possible trajectory of a nation that goes from a low value of HDI to the value of HDI equal to 1. The x-axis reports the HDI values, the y-axis reports the $CO2_{int}$ values. The $CO2_{int}$ values of the trajectories are generic values, with the unique object to show the difference between the two paths. The trajectory described by the blue curve is constructed with the most frequent slope values, in other words, with the mode values of the frequency distribution of the slope in each development level (see Table 10). The trajectory described by the black curve is constructed with the values of the average slope, that is the values of the average of the frequency distribution of the slope in each development level (see Table 10). The black dotted lines delimit the HDI ranges where there is the typical behaviour of the development level, which level is specified at the top of the figure with a different colour of the others. The various slope values shown at the top of each curve are highlighted with the identifying colours of the development level where they occur.

An attempt to verify the continuity hypothesis could be made by using unofficial data of HDI, which would allow analysing a more extended period. In this regard, we use the indicator developed by Leandro prados de la Escosura, called Historical Index of Human Development (HIHD)[58]. This index reconstructs a value of HDI for a large number of countries from 1870 to 2015, using data related to LEB, literacy rate, gross total enrolment rate at school and GDP[59].
In Figure 12 is showed the evolution of the HIHD and $CO2_{int}$ for Turkey from 1960 to 2014. Turkey shows a change in behaviour over time, as it initially shows a typical behaviour of the Medium-HDI level, increasing its $CO2_{int}$ from 1.57 kg/kgoe in 1960 to 2.71 kg/kgoe in 1985, instead, from 1985 to 2014, it shows a typical behaviour of the High-HDI level, where its $CO2_{int}$ is approximately constant until to reach 2.85 kg/kgoe in 2014.
This analysis does not allow to validate the hypothesis because Turkey does not go through all the development levels, but indicates that a certain consistency with the available data. Moreover, it is noteworthy to underlying that reconstructed HIHD by "de la Escosura" does not

coincide with the official values of HDI, for this reason, the value of HIHD for Turkey reports in Figure 12 are lower than the UNDP dataset[37].

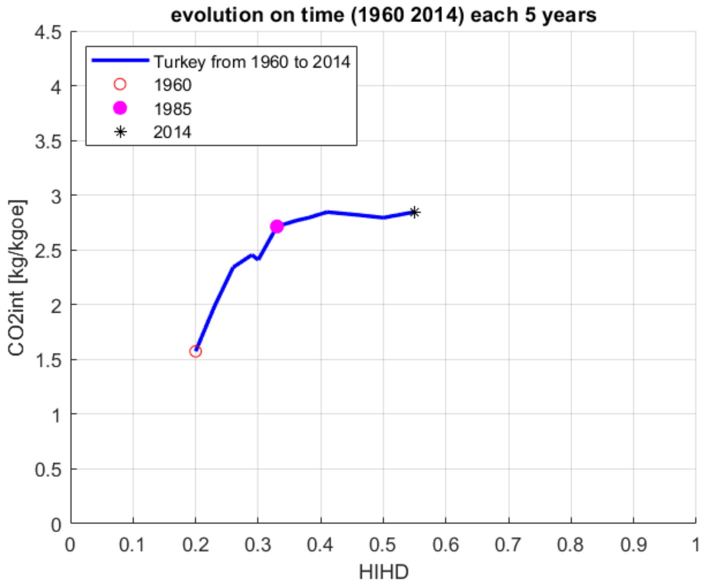

Figure 12. Correlation between $CO2_{int}$ and HIHD in Longitudinal analysis from 1960 to 2014, for Turkey. The x-axis reports the HIHD values of the Turkey over time, and y-axis reports $CO2_{int}$ values (in kg/kgoe) of Turkey over time. The broken line represents the evolution over time of the coordinates of Turkey with a time interval of 5 years. The years of beginning and end of analysis and the year of change of the slope (1985) are highlighted by using different marker signs, as shown in the legend.

5.2.2 The world of the 2050

The paragraph aims at modelling future scenarios until the year 2050, according to different energy use scenarios, in order to evaluate the cumulative CO_2 emissions. It is possible to compute the cumulative CO_2 emissions between 2000 and 2050, by using the analysis of the previous paragraph and by considering the increasing trend of population and of TPESpc. The cumulative emissions will be compared with a budget of 1000 Gt, which is considered as the limit to respect in order to keep the global warming below 2°C with a probability of 75%[17].

Four scenarios will be modelled: Business As Usual (BAU), Energy Bound (EB), Energy and $CO2_{int}$ Bound (ECB) and Extreme (EX). BAU scenario supposes a no trend variation for $CO2_{int}$ and for TPESpc up to 2050. EB scenario imposes a maximum limit of energy consumption per capita. ECB imposes the same target of EB and in addition it is imposed a maximum limit of $CO2_{int}$. EX supposes that the targets of ECB will be reached already by 2021.

As before, the countries are grouped based on their development level of 2014, and for clearness, the groups will be referred with the acronym of Table 8. Hence, the construction of the scenarios is computed by using the estimation of mean value of HDI, of $CO2_{int}$ and of TPESpc of each group.

According to the prediction of United Nation Population Division, the population of 188 considered countries will increase from 7.23 billion (2014) to 9.67 billion (2050). L and M groups will have the most significant increase concerning the other groups who will maintain the population almost constant (see Figure 13).

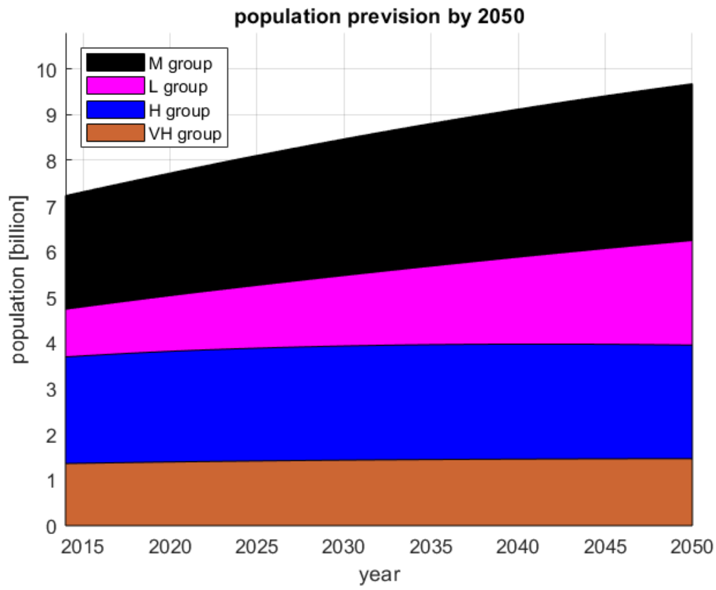

Figure 13. Future prevision of the global population by 2050, by highlighting the contribution of each group of countries. The x-axis reports the years from 2014 to 2050, the y-axis reports the value of population (in billion). The contribution of each group are distinguished by different colours as shown by the legend in figure

According to the evolution of the mean HDI of each group, L group will pass from Low-HDI level to Medium-HDI by 2026, M group will pass from Medium-HDI level to High-HDI by 2026, and from High-HDI to Very-High-HDI by 2043. H group will pass from High-HDI level to Very-High-HDI by 2021. The evolution over time of the mean HDI is shown in Figure 14.

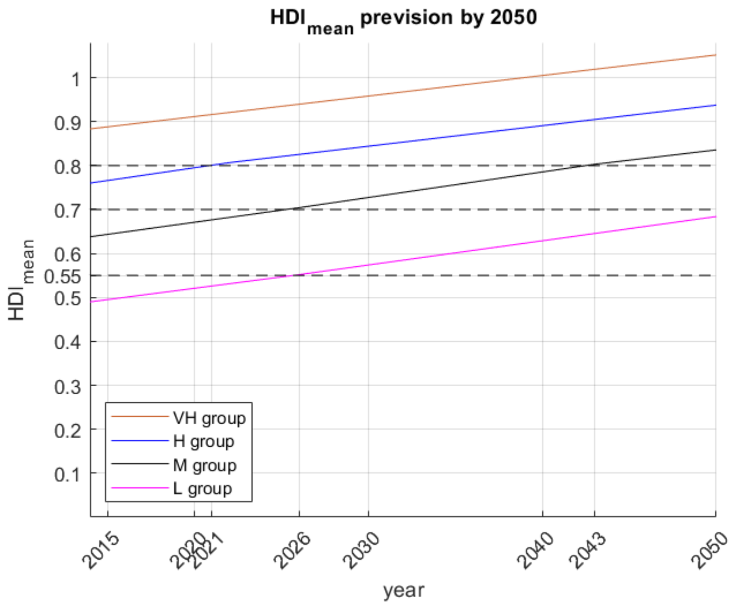

Figure 14. Estimation of mean HDI of each group by 2050. The x-axis reports the year from 2014 to 2050, the y-axis reports the mean HDI of each group. Each curve represents the evolution over time of the mean HDI of each group, and the groups are distinguished by using different colours as shown by the legend in the figure. The three horizontal black dot-line delimit the four levels of development.

5.2.2.1 Scenario Business As Usual (BAU)

The Business As Usual scenario assumes that the historical trend of mean $CO2_{int}$ and of mean TPESpc of each group continue to remain constant until the year 2050. The evolution over time of $CO2_{int}$ and of TPESpc depend on estimations of HDI, reported by Figure 14.

Figure 15 shows the estimation of mean HDI and of mean $CO2_{int}$ of each group. The trajectory of each group changes slope reaching the next development level. In according to the criteria of estimation of HDI and of $CO2_{int}$, the slopes of the trajectories are coincident with the mean value of slope reported in Table 10. Thus, according to this estimation, the L group will increase its $CO2_{int}$ throughout timespan, but with higher slope from the year 2026; the M group will increase its $CO2_{int}$ until the year 2043, and with lower slope from the year 2026, and from the year 2043 to 2050 the M group will decrease its $CO2_{int}$; the H group will increase its $CO2_{int}$ until the year 2021 and after that its $CO2_{int}$ will decreases; while the VH group will always decrease its $CO2_{int}$ (see Figure 15).

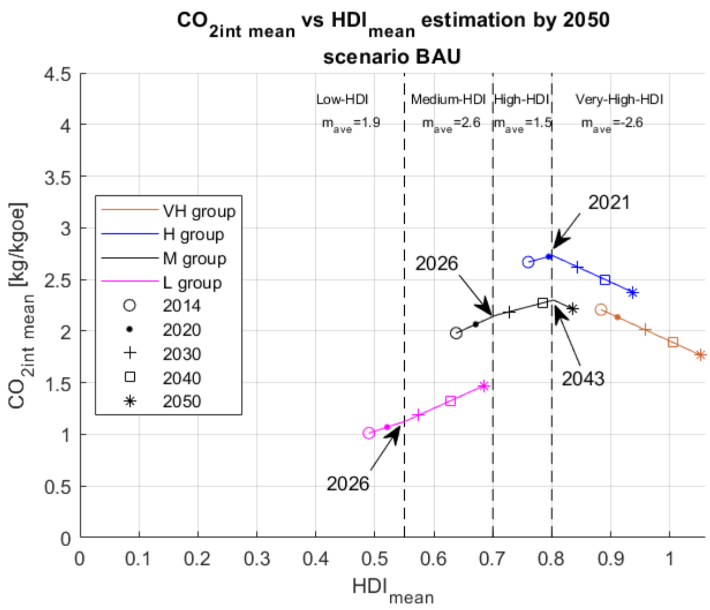

Figure 15. Estimation of the evolution over time of the relation between mean $CO2_{int}$ and mean HDI of each group by 2050, according to Business As Usual scenario. In the x-axis the mean HDI of each group are reported, in the y-axis the mean $CO2_{int}$ (in kg/kgoe) of each group are reported. Each broken line shows the evolutions of the coordinates of mean HDI and of mean $CO2_{int}$ of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure. In each broken line is highlighted the value of coordinates at each decade and by 2014. The year of transition from one development level to others is annotated for each group. The three vertical dot-lines delimit the four development levels which are specified in the top of the figure. Below each name of the level of development has reported the slope (m_{ave}) that characterises each level.

Figure 16 shows in a time-scale the same evolution of mean $CO2_{int}$ reported by Figure 15. According to BAU scenario, H group will reach the peak of $CO2_{int}$ (2.73 kg/kgoe) by 2021, and on 2050 it will still have the highest $CO2_{int}$ (2.38 kg/kgoe), followed by M group (2.21 kg/kgoe), by VH group (1.77 kg/kgoe) and by L group (1.47 kg/kgoe). Thus with these trends, the L group still will have a lower $CO2_{int}$ than VH group, even if the first will have an increasing trend and the other a decreasing trend.

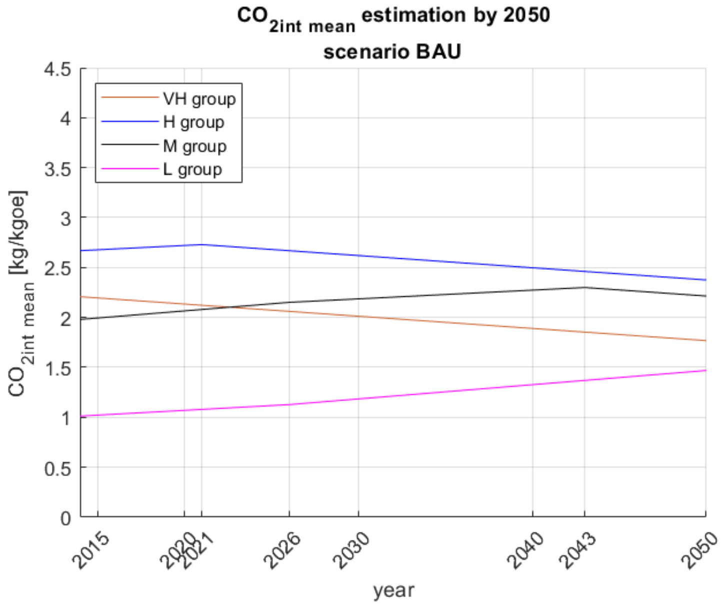

Figure 16. Estimation of the evolution over time of the mean $CO2_{int}$ of each group by 2050, according to Business As Usual scenario. In the x-axis the years from 2014 to 2050 are reported, in the y-axis the mean CO_{2int} (in kg/kgoe) of each group are reported. Each broken line shows the evolutions of the mean $CO2_{int}$ of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

Figure 17 shows the estimation of the evolution of mean TPESpc of each group. The mean TPESpc of VH group will remain constant throughout the timespan. Because it is supposed that these countries have reached the saturation point of the relation between HDI and TPESpc. The saturation point coincides with an HDI equal to 0.88. The mean TPESpc of the other groups will increase with an exponential trend, according to the relation between HDI and TPESpc and because it is supposed that they will increase their HDI. The mean TPESpc of H group will increase until the year 2038, when it reaches the saturation point, while the L and M groups will never reach it (see Figure 17).

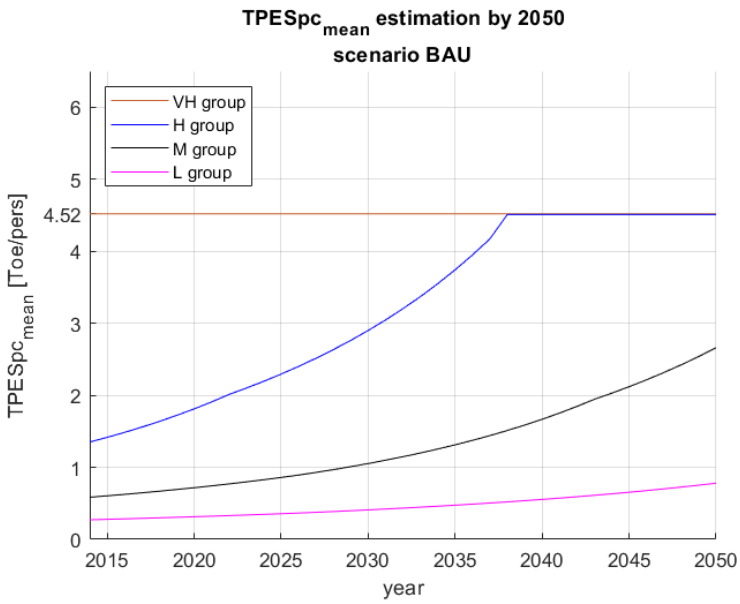

Figure 17. Estimation of the evolution over time of the mean TPESpc of each group by 2050, according to Business As Usual scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axis, the mean TPESpc (in Toe/pers) of each group are reported. Each broken line shows the evolutions of the mean TPESpc of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

Figure 18 shows the estimation of global TPES. According to BAU scenario, the global TPES will be 28.8 GToe by 2050, namely 150% higher than 2014 level. L and M group will account for higher TPES than VH group, and M group probably will keep increasing its consumption after the year 2050, while L group will keep consuming a low amount of energy (see Figure 18).

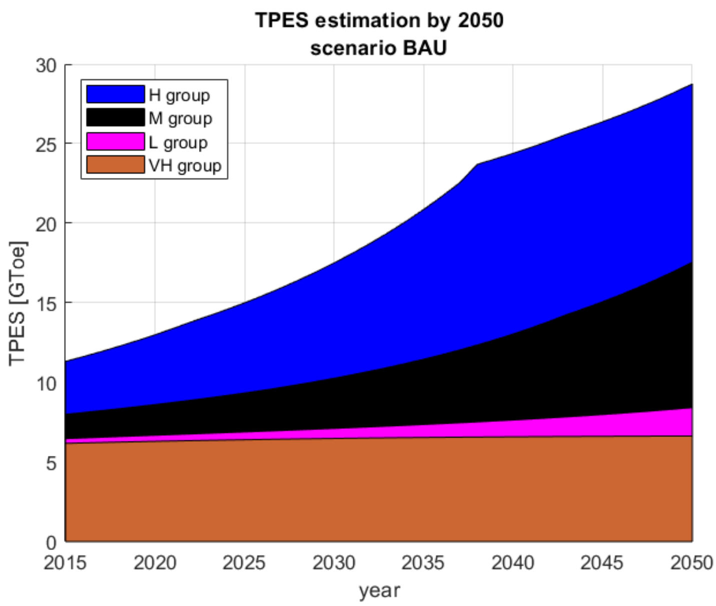

Figure 18. Estimation of the evolution over time of the global TPES by 2050, according to Business As Usual scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axis, the global TPES values (in GToe) are reported. In the figure are highlighted the different contributions of each group, distinguished by different colours depending on the representative group, as specified by the legend in the figure.

Therefore, the BAU scenario will generate cumulative CO_2 emissions between 2000 and 2050 of 2039 Gt, and these cumulative emissions will exceed the budget of 1000 Gt already by 2031 (see black curve of Figure 25).

5.2.2.2 Scenario Energy Bound (EB)

The Energy Bound scenario is computed until the year 2020 with the same estimations of BAU scenario, and after this year it is imposed a maximum limit to the TPESpc. Therefore, the estimation of the mean $CO2_{int}$ of each group is the same of the one of BAU scenario, shown in Figure 16.

A maximum limit of TPESpc of 1.97 Toe/pers is imposed. For the countries of VH group, which have a TPESpc higher than the limit, a constant decreasing rate is imposed until they reach the target. The value of the target (1.97 Toe/pers) is the TPESpc of Hong Kong, which is individuated as a virtuous country, because it is the countries among the top-10 for HDI with lowest TPESpc on 2014. The decreasing rate is chosen by referring to the European Union target of 2030. The 2030 target of the European Union sets out as the objects an energy efficiency of 32.5%, which means that the comprehensive TPES of all 28 countries of UE should be equal to 1273 Mtoe by 2030[60]. It means that the European Union countries should have a TPESpc equal to 2.48 Toe/pers, by considering that their population will be 512 million on 2030[49].

Therefore, according to this estimation, from 2021, the VH countries should decrease their annual energy consumption of 5.81% until to reach a 2.48 Toe/pers by 2030. After that, these countries will keep decreasing their TPESpc with the same rate until to reach the value of 1.97 Toe/pers by 2034 (see Figure 19). Figure 19 shows, that the H group will reach the limit of energy consumption by 2022; M group will reach the limit on 2044; while L group will always have a mean TPESpc below the limit (0.78 Toe/pers in 2050).

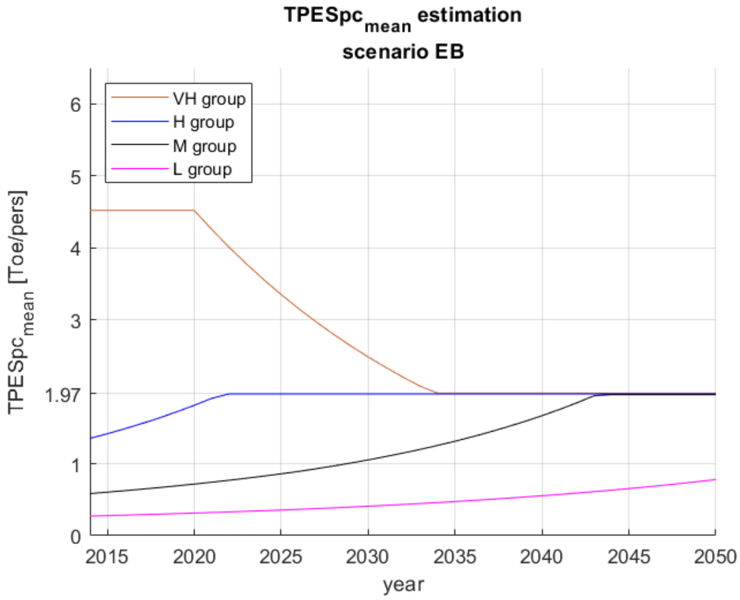

Figure 19. Estimation of the evolution over time of the mean TPESpc of each group by 2050, according to Energy Bound scenario. In the x-axis the years from 2014 to 2050 are reported, in the y-axis, the mean TPESpc (in Toe/pers) of each group are reported.. Each broken line shows the evolutions of the mean TPESpc of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

According to this scenario, the global TPES will be 16 GToe by 2050, namely 43.2% lower than the consumption estimated in BAU scenario.

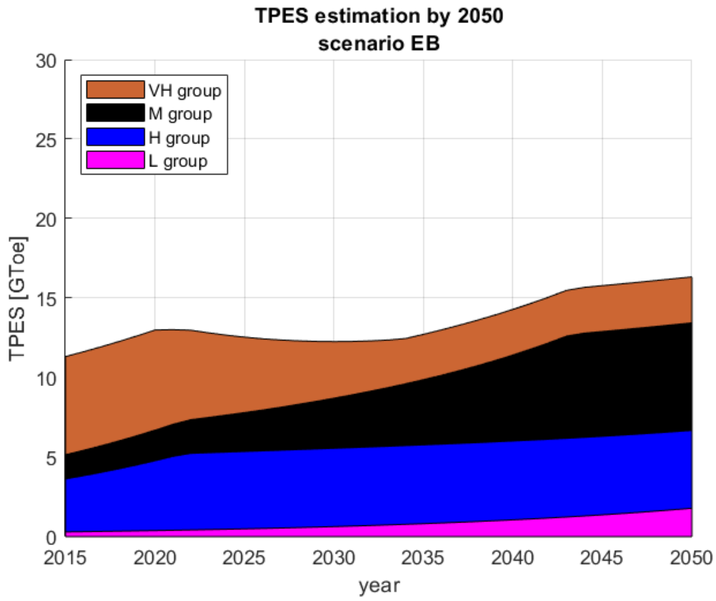

Figure 20. Estimation of the evolution over time of the global TPES by 2050, according to the Energy Bound scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axi,s the global TPES values (in GToe) are reported. In figure are highlighted the different contributions of each group, distinguished by different colours depending on the representative group, as specified by the legend in the figure.

According to these criteria, the cumulative CO_2 emissions between 2000 and 2050 of scenario EB will be 1547 Gt, which will exceed the budget of 1000 Gt already by 2034 (see blue curve of Figure 25).

5.2.2.3 Scenario Energy and $CO2_{int}$ Bound (ECB)

The Energy and $CO2_{int}$ Bound scenario is constructed considering an evolution of TPESpc and of TPES equal to the scenario EB (see Figure 19 and Figure 20 respectively), and in addition, a maximum limit of $CO2_{int}$ is imposed. In other words, from 2021, a value of 0.9 kg/kgoe is imposed as the maximum limit for $CO2_{int}$. Since all groups have a value of CO_{2int} higher than this limit, a constant annual decreasing rate is imposed until to reach this target. The value of 0.9 kg/kgoe coincides with the value of $CO2_{int}$ of Sweden in 2014. Sweden is identified as a virtuous nation for two main reasons: the low value of its $CO2_{int}$ combined with a high value of its HDI, as well as it has reduced CO2 emissions significantly from 1970 to 2011[46].

The decreasing rate imposed to reach the value of 0.9 kg/kgoe was calculated considering the 2030 target of European Union about greenhouse gases emissions reduction. This target aims at cutting emissions by at least 40% below 1990 levels by 2030. It means the CO_2 emissions of the European Union countries should be 2416.2 Mt by 2030[61]. For initial analysis, it is supposed that a reduction of 40% of the greenhouse gases corresponds with a reduction of 40% of the $CO2_{int}$. It means that the scenario considers a more ambitious target than the one of European Union, but it is consistent with the fact that the European Parliament supported updating the target to 55% below 1990 levels by 2030[62]. Therefore, considering that the European Union countries will have likely a CO_2 emissions of 3221.6 Mt by 2020[63], the European Union countries should reduce their CO_2 emissions with a constant decreasing rate of 2.84% in order to reach the target (CO_2<2416.2 Mt) by 2030. As a consequence, the ECB scenario imposes that the mean $CO2_{int}$ of each group decreases from 2021 with an annual decreasing rate of 2.84%, until to reach the value of 0.9 kg/kgoe.

Figure 21 shows the estimation of the mean $CO2_{int}$ of each group according to ECB scenario. With these criteria of estimation, the L group will reach the target by 2027, M and VH group will reach it by 2049 and by 2050 respectively, while the H group will never reach the target within the considered time span, reaching a $CO2_{int}$ of 1.15 kg/kgoe by 2050 (see Figure 21). In this scenario, the annual $CO2_{int}$ decreasing of VH group is five times higher than BAU scenario.

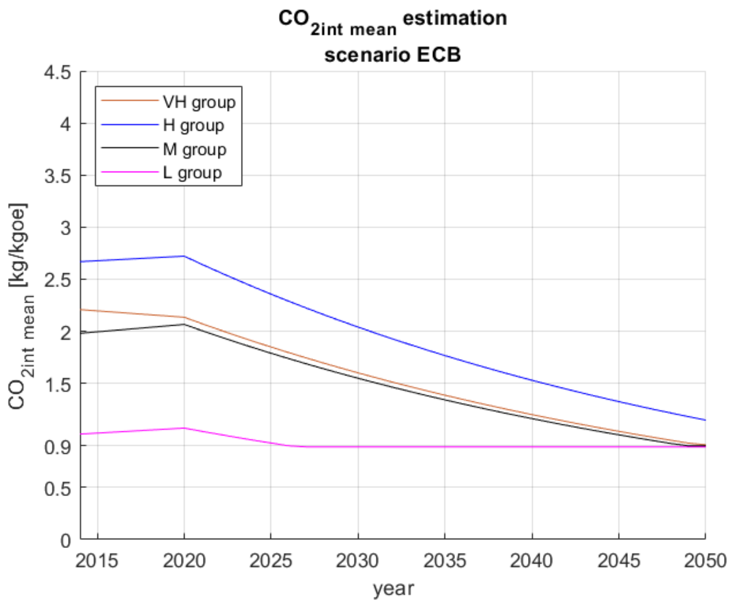

Figure 21. Estimation of the evolution over time of the mean $CO2_{int}$ of each group by 2050, according to Energy and $CO2_{int}$ Bound scenario. In the x-axis the years from 2014 to 2050 are reported, in the y-axis the mean CO_{2int} (in kg/kgoe) of each group are reported. Each broken line shows the evolutions of the mean $CO2_{int}$ of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

As a consequence of these estimations, the ECB scenario will generated a cumulative CO_2 emissions between 2000 and 2050 of 1239 Gt, and this cumulative emissions will exceed the budget of 1000 Gt by 2037 (see orange curve of Figure 25).

5.2.2.4 Scenario Extreme (EX)

The Extreme scenario is constructed with the same limit imposed by ECB scenario from 2020, but with the difference that the targets are reached already from 2021. In other words, from 2021 all groups will have a maximum TPESpc of 1.97 Toe/pers and a $CO2_{int}$ of 0.9 kg/kgoe. Therefore, Figure 22 and Figure 23 shows the evolution of mean CO2int and of mean TPESpc of each group respectively according to these construction criteria. The scenario EX differs from ECB scenario mainly for the estimation of $CO2_{int}$. In fact, in ECB scenario almost all countries reach the target of 0.9 kg/kgoe at the end of analysis' timespan, instead in scenario EX all the countries reach the target already on 2021 (see Figure 22). About the TPESpc, the two scenarios are different just for the estimation of the energy consumption of VH group. In fact, in ECB scenario, this group reaches the target by 2034 (see Figure 19), while in EX scenario, the target is reached by 2021 (see Figure 23). For that reason, the estimation of global TPES of these two scenarios are different just until the year 2034, indeed both estimate a global TPES of 16 GToe by 2050 (see Figure 20 for the estimation of ECB scenario, and Figure 24 for the estimation of EX scenario).

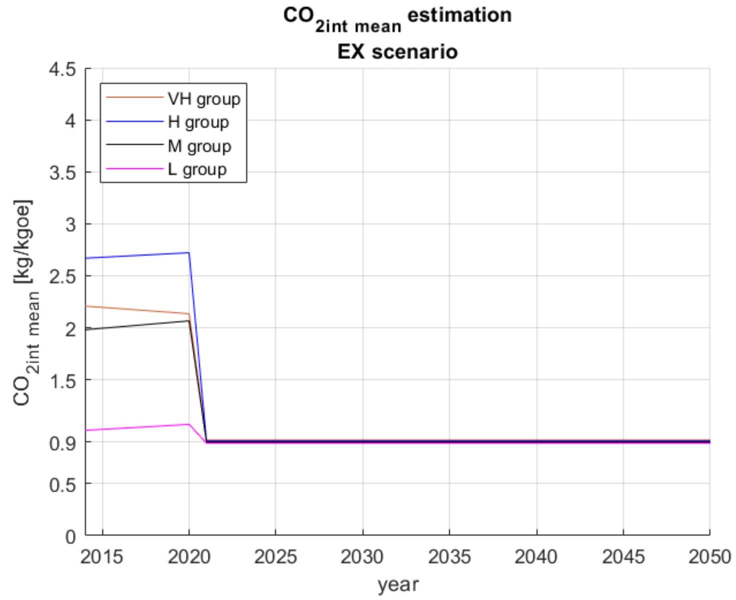

Figure 22. Estimation of the evolution over time of the mean $CO2_{int}$ of each group by 2050, according to Extreme scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axis, the mean CO_{2int} (in kg/kgoe) of each group are reported. Each broken line shows the evolutions of the mean $CO2_{int}$ of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

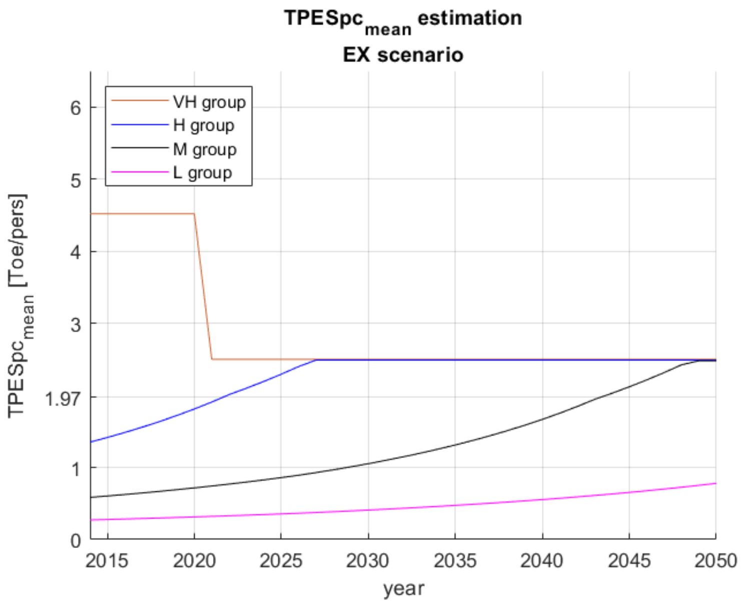

Figure 23. Estimation of the evolution over time of the mean TPESpc of each group by 2050, according to Extreme scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axis, the mean TPESpc (in Toe/pers) of each group are reported. Each broken line shows the evolutions of the mean TPESpc of each group, which are distinguished by a different colour depending on the representative group, as specified by the legend in the figure.

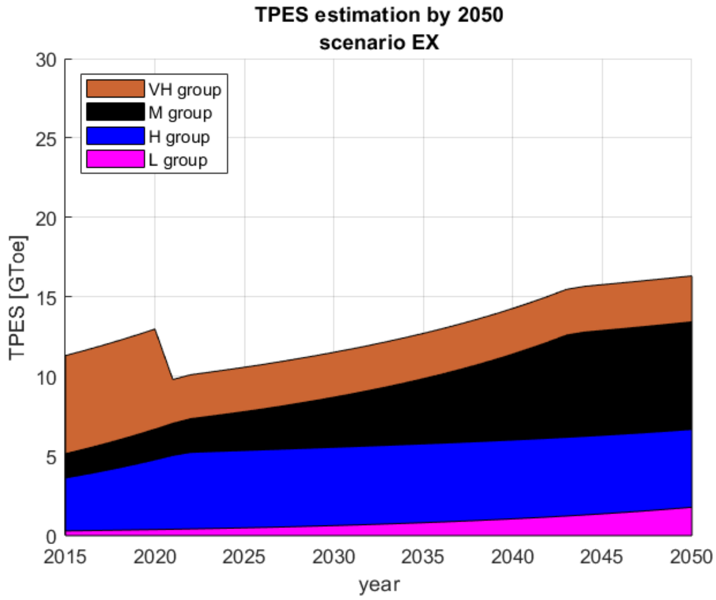

Figure 24. Estimation of the evolution over time of the global TPES by 2050, according to Extreme scenario. In the x-axis, the years from 2014 to 2050 are reported, in the y-axis, the global TPES values (in GToe) are reported. In the figure are highlighted the different contributions of each group, distinguished by different colours depending on the representative group, as specified by the legend in the figure.

Therefore, the scenario EX will produce cumulative CO_2 emissions between 2000 and 2050 of 982 Gt (see Figure 25). In other words, this scenario will create the condition to maintain global warming below 2°C with a probability of 75%.

5.2.2.5 Comparison of scenarios

As the scenarios have been constructed, both report the same cumulative CO_2 emissions by 2020 and a value on 2014 equal to the historical cumulative emissions between 2000 and 2014 (462 Gt). After that year, the EX cumulative emissions is immediately different from the baseline (the BAU cumulative emissions), and the one of EB and ECB scenario slightly change from the baseline (see Figure 25). The cumulative CO_2 emissions of BAU and EB have a super-linear growth since the annual emissions of CO_2 of these scenarios always increase from 2014 to 2050. The cumulative emissions of ECB have a sub-linear growth since the annual CO_2 emissions decrease from 2000 to 2050 until to reach a similar level of the EX scenario. Instead, the cumulative emissions of EX scenario change immediately slope on 2021, and after that, they have a super-linear increase, because the global annual CO_2 emissions increase from 2021 until reach a value of 14.7 GT on 2050.

Nevertheless, the scenarios that implement action to contain CO_2 emissions would produce cumulative emissions by 2050 that is significantly lower than the baseline. EB scenario will generate cumulative emissions 24.1% lower than the baseline. The ECB scenario will generate cumulative emissions 39.2% lower than the baseline. The EX scenario will produce cumulative emissions 51.8% lower than the baseline.

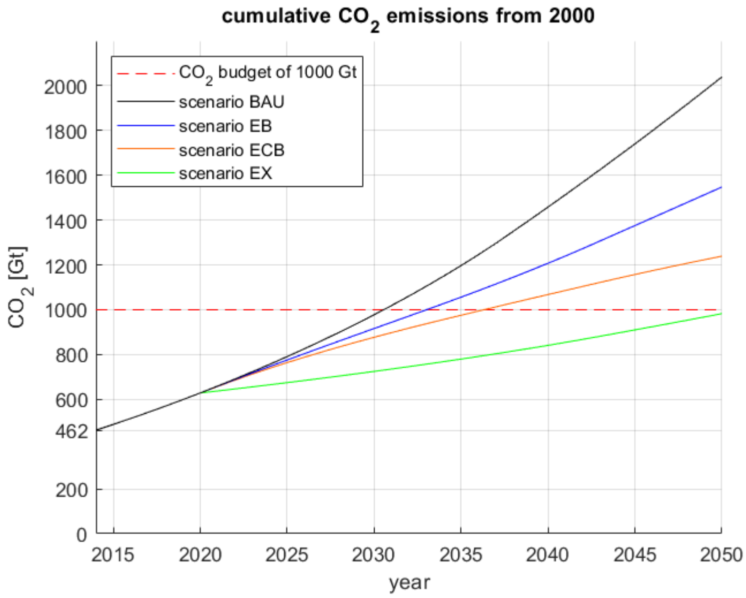

Figure 25. Evolution of the evolution over time of the cumulative CO_2 emissions between 2000 and 2050, according to the four scenarios. The x-axis reports the years from 2000 to 2050, the y-axis reports the values of cumulative emissions CO_2 since 2000. The red horizontal line represents the budget of 1000 Gt, the black curve represents the Business As Usual scenario (BAU), the blue curve the Energy Bound scenario (EB), the orange curve the Energy and $CO2_{int}$ Bound (ECB) scenario, and the green curve the Extreme (EX) scenario. The cumulative CO_2 emissions value of 2014 corresponds to the historical one from 2000 to 2014 equal to 462 Gt.

5.3 Discussion

The relationship between $CO2_{int}$ and HDI adds new perspective on the linkage between energy and wellbeing.

Cross-sectional (Figure 7) and by longitudinal analysis (Figure 8) showed that the quality of energy of a country, meaning the $CO2_{int}$, changes at the increasing of the country's HDI following a bell curve.

The results of Figure 10 show that each country group exhibit a different evolution $CO2_{int}$ depending on the level of development (HDI):

- Low-HDI countries increase their $CO2_{int}$ of 1.9 kg/kgoe per point of HDI
- Medium-HDI countries increase their $CO2_{int}$ of 2.6 kg/kgoe/HDI
- High-HDI countries have variegated behaviours, as:
  - 20.8% of these countries decrease their $CO2_{int}$ of more than 1.3 kg/kgoe/HDI
  - 33.3% of these countries maintain almost constant their $CO2_{int}$
  - 45.8% of these countries increase their $CO2_{int}$ of more than 1.3 kg/kgoe/HDI
- Very-High-HDI countries decrease their $CO2_{int}$ of 2.6 kg/kgoe/HDI

Considering that sustainable development is determined by a simultaneous improvement of the quality of life and a reduction of the impact on the environment, our analysis shows that only Very-High-HDI countries and partially for High-HDI countries have the capability of achieving this objective. On the contrary, all the other countries in development (HDI less than 0.7) did not show the capability of following a sustainable development path, that achieves a higher quality of life by using carbon-based energy technology.

These results are partially in line with the findings of Pîrlogea[47] and of Costa[18]. In fact, they affirm that countries with HDI higher than 0.8can improve their quality of life by reducing their carbon dioxide emissions[18], and in turn their $CO2_{int}$[47]. Nevertheless, they neglect that some High-HDI countries can also follow sustainable development. They do not individuate this detail, because the relation between HDI and $CO2_{int}$ has never been analysed in literature before.

However, Gabon, a country of Medium-HDI level, has experienced from 1990 to 2014 the highest $CO2_{int}$ decreasing of all analysed countries. This exceptional case demonstrates that even Medium-HDI countries can reduce their $CO2_{int}$ while increasing their wellbeing. At the same time, it is important to an underling that Gabon paid this sustainable development with an increase of its HDI 40% lower than the other countries trend. Furthermore, the high decreasing $CO2_{int}$ of Gabon testify that the trend imposed in Extreme scenario is improbable, as the decreasing rate imposed by Extreme scenario is about 150% higher than the one experienced by Gabon. In fact, if all the countries would have the Gabon trend they will reach the target of 0.9 kg/kgoe by 2037, instead of the year 2021 as assumed by the Extreme scenario.

On the other side, the decreasing of $CO2_{int}$ of Singapore could represent an example for all Very-High-HDI countries, as its annual $CO2_{int}$ decreasing is equal to trend imposed by ECB scenario in line with the 2030 European Union targets. Therefore, the huge $CO2_{int}$ decreasing of Singapore, caused by a transition from oil to natural gas[57], suggests that a transition toward renewable energy and compliance with IPCC[12] recommendation are achievable.

Further investigations about the linkage between development and quality of energy studied in this word for the first time are necessary. Three points of further improvements of this study are proposed:

- Overcome the simplification applied to the indicators' time evolution and elaborate a model that better fits the historical data.
- Analyse in more detail the behaviour of the High-HDI countries as they exhibited a variegated trend. It could be interesting to investigate the existence of subgroups with a specific and more coherent behaviour. A first guess, looking at Figure 9(d), can be to divide the High-HDI group into two subgroups: one below the value of 0.75 HDI and one above it.
- Analyse the causal relation between $CO2_{int}$ and HDI. in order to understand what factors determine the bell shape. A first hypothesis is a linkage to an economic indicator. For example, countries with HDI lower than 0.7, characterised by a low-income level[25], could not be able to invest economic resource on energy transition without compromise with the improvement of their wellbeing. In fact, it is well-known for low-income countries the positive correlation between increasing income and improving quality of life, which is connected to the improvement of health care, water and food quality and educational system [8]. Therefore, sacrifice economic resources for the implementation of renewable energy source could have a negative effect on all these important factors for human wellbeing.

6 Conclusion

This work investigates the relationship between energy consumption, environmental sustainability of energy technology and country development. These dimensions were analysed using a data-driven approach. The Human development index (HDI) has been chosen as a suitable proxy of wellbeing, and it reports info about the development of the countries too, while the $CO2_{int}$ index, which accounts for the quality of the energy supply of a country, has been chosen to synthesize together information about the energy consumption and the emissions of a country.

The relation between $CO2_{int}$ and HDI studied in longitudinal analysis exhibit an interesting bell curve shape: countries with HDI less than 0.7 have increased their $CO2_{int}$ at the increase of their HDI (in the time span from 1990 to 2014), while similarly, some countries with HDI between 0.7 and 0.8 have increased their $CO2_{int}$ and others have decreased it, and countries with HDI more than 0.8 have decreased their $CO2_{int}$.

Generalising this observation, we calculate four decarbonisation path of four groups of countries (Low-HDI, Medium-HDI, High-HDI and Very-High-HDI) that represent the 99% of the global population. The considered scenarios are *Business As Usual* (BAU), *Energy Bound* (EB) and *Energy and* $CO2_{int}$ *Bound* (ECB) and *Extreme* scenario (EX). These scenarios are investigated with the aim of understanding if the 2030 European Union targets are compliant with the IPCC recommendation of 1000 Gt budget of CO_2 emission to maintain the global warming below 2°C.

The Business As Usual (BAU) scenario results estimate a cumulative CO_2 emissions between 2000 and 2050 of 2039 Gt, in line with the findings of Costa[18] and of Pîrlogea[47] . This result confirms the unsustainability of the actual path of development which will bring the CO_2 concentration in the air at 560 ppm by 2050 [17], which will result in global warming higher than 2°C [64].

The Energy Bound (EB) scenario assumes a 5.81% yearly decrease of the TPESpc, from 2021 until a value of 1.97 Toe/pers is reached for each group of countries. In this case, the cumulative CO_2 emissions will be of 1547 Gt, that corresponds to a 50% probability global warming lower than 2°C, according to Meinshausen[17].

The Energy and $CO2_{int}$ Bound (ECB), consider a decreasing of TPESpc similar to the EB scenario and a decreasing of the $CO2_{int}$, with an annual rate of 2.84% until reaching a value of

0.9 kg/kgoe for all countries. The effect will be a cumulative CO_2 emission of 1239 Gt, compatible with a probability of 50-75% to maintain the global warming below 2°C [64].

The further assumption of the Extreme (EX) scenario is to achieve the target of CO2int and TPESpc by 2021. In this case the cumulative CO_2 emissions between 2000 and 2050 will be of 982 Gt, therefore it will be compliance with the budget of CO_2 emission of 1000 Gt that would guarantee to maintain the global warming below 2°C with a probability of 75% [17 64].

The ECB and EX scenarios suggest that to maintain the global warming below 2°C, it is necessary a further decrease the $CO2_{int}$ of all countries, until having a net-zero CO_2 emissions by 2050, as suggested by IPCC[12] and by the Paris Agreement.

The bell curve relation between $CO2_{int}$ and HDI, never reported in the literature before, offer another fundamental point of view on the linkage between energy and wellbeing. It shows how the development of countries is reflected by their energy-supply quality chain.

Moreover, it shows that sustainable paths of development are available but it requires low carbon energy technologies at all level of country development. Instead, the actual situation shows that only countries with HDI higher than 0.8 are capable of increasing their quality of energy supply by reducing their $CO2_{int}$, while countries with HDI less than 0.7 are not able to reduce their $CO2_{int}$ without compromise their wellbeing, most likely because they cannot afford a green energy transition economically without scarifying necessary resources for the improvement of their quality of life. This situation partially reflects what affirmed by Costa[18] and by Pîrlogea[47] stating that countries with lower HDI have to increase their emissions in order to increase their HDI. However, as shown by the investigated scenarios, it is necessary that also countries with a low development level participate in the limitation of CO_2 emissions to be compliant with the CO_2 budget of 1000 Gt.

An interesting development of this study is to investigate how these countries can trace a sustainable path improving their wellbeing while limiting their CO_2 emissions.

This objective could be reached if our society changes its prospects of how happiness can be reached. By adapting to a sustainable and less consumeristic lifestyle, as affirmed in the first edition of the World Happiness Report [8] and Zidanšek[9].

7 Appendix

7.1 Selected articles for the state of the art

Paper title	**Authors**	**Year**	**Source**	**Cited by**
Energy, EROI and quality of life	Lambert, J.G., Hall, C.A.S., Balogh, S., Gupta, A., Arnold, M.	2014	Energy Policy	90
Energy consumption, human well-being and economic development in central and eastern European nations: A cautionary tale of sustainability	Jorgenson, A.K., Alekseyko, A., Giedraitis, V.	2014	Energy Policy	40
Does increasing energy or electricity consumption improve quality of life in industrial nations?	Mazur, A.	2011	Energy Policy	34
Considerations concerning the energy demand and energy mix for global welfare and stable ecosystems	Jess, A., Kaiser, P., Kern, C., Unde, R., Von Olshausen, C.	2011	Chemie-Ingenieur-Technik	26
Energy and quality of life	Pasten, C., Santamarina, J.C.	2012	Energy Policy	24
What might be the energy demand and energy mix to reconcile the world's pursuit of welfare and happiness with the necessity to preserve the integrity of the biosphere?	Jess, A.	2010	Energy Policy	21
Dynamic linkages among energy consumption, environment, health and wealth in BRICS countries: Green growth key to sustainable development	Zaman, K., Abdullah, A.B., Khan, A., (...), Hamzah, T.A.A.T., Hussain, S.	2016	Renewable and Sustainable Energy Reviews	19
Energy consumption and Sustainable Economic Welfare in G7 countries; A comparison with the conventional nexus	Menegaki, A.N., Tugcu, C.T.	2017	Renewable and Sustainable Energy Reviews	9
Decoupling between human development and energy consumption within footprint accounts	Akizu-Gardoki, O., Bueno, G., Wiedmann, T., (...), Hernandez, P., Moran, D.	2018	Journal of Cleaner Production	4
Energy consumption inequality and human development	Wu, Q., Clulow, V., Maslyuk, S.	2010	2010 International Conference on Management Science and Engineering, ICMSE 2010	4
Exploring the bi-directional long run relationship between energy consumption and life quality	Al-Mulali, U.	2016	Renewable and Sustainable Energy Reviews	3
Modelling of quality of life in terms of energy and electricity consumption	Nadimi, R., Tokimatsu, K.	2018	Applied Energy	2
Energy use analysis in the presence of quality of life, poverty, health, and carbon dioxide emissions	Nadimi, R., Tokimatsu, K.	2018	Energy	1
Sustainable energy policy options in the presence of quality of life, poverty, and CO_2 emission	Nadimi, R., Tokimatsu, K., Yoshikawa, K.	2017	Energy Procedia	1

Table 12. *Selected articles for the literature review. For each article, the title, the authors, the year of publication, the source, the number of citation are reported*

7.2 Energy indexes

Index	Acronymus	Data Sources	Description	Characteristics	Ref,
Electricity level	EL	IEA	high level of development	% of the population with access to electricity (International Energy Agency, 2017)	[28]
Electricity Consumption (per capita)	ELC (pc)	World Bank and EIA	electricity consumption	Electricity consumption = (electricity generation) – (loses of transmission and distribution) – (energy consumed by the generating units) + (net electricity imports) [33]	[23,30]
Energy Return Of Investment	EROI	Elaboration data from World Bank and EIA	quality of energy	the energy gained (and useful for human wellbeing) from a unit of energy spent in the process of obtaining energy [27]	[27]
Lambert Energy Index	LEI	World Bank and EIA	combination of energy quality, energy consumption and the income distribution	Is a geometric mean of standard value of EROI, PEC and Gini-index of income [27]	[27]
Primary Energy Consumption	PEC (pc)	EIA	energy consumption	Primary Energy Consumption = (primary energy consumption for production) + (net imports) it does not count energy loses for transformation and distribution) (U.S. Energy Information Administration, s.d.)	[27–30]
Total Final Energy Consumption per capita	TFC pc	IEA and world Bank	energy consumption.	Total Final Energy Consumption = (primary energy consumption for production) + (net imports) + (net stock change) -(international transport) – (energy loses for transformation and distribution) [2].	[23,25,26,32]
Total Primary Energy Footprint (per capita)	TPEF pc	computed from data extracted from IEA	Energy consumption	Computed from TPES and using the Global Multi Regional Input-output methodology, which consider a consumption base account (CBA) in order to allocate the energy to the consumer and no to the producer [24]	[24]
Total Primary Energy Supply (per capita)	TPES (pc)	World Bank and IEA	energy consumption	Primary Energy Consumption = (primary energy consume for production of energy) + (net imports) + (net stock change) – (international transport). It does not count energy loses for transformation and distribution) [2]	[19,21,22,24,31]

7.3 Wellbeing indexes

Category	Index	Acronym	Data source	Definition	Ref
wealth	Gross Domestic Product per capita	GDP pc	World Bank	is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output. Then it is divided by the midyear population. It is counted in Purchasing Power Parity (PPP) [36].	19–23,27,30–32
wealth	Gross National Income (purchasing power parity) per capita	GNI (ppp) pc	World Bank	the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad. then it is divided by the midyear population. It is counted in Purchasing Power Parity (PPP) [36]	23,28,29,31,32
wealth	Gross National Product per capita	GNP (ppp) pc	World Bank	the total value of goods produced and services provided by a country during one year, equal to the gross domestic product plus the net income from other countries. It is counted in Purchasing Power Parity (PPP) [25].	25,26
wealth	Poverty Rate	PR	World bank	defined as decreasing the percentage of people living on less than $1.90 a day (2011 PPP prices) to no more than 3 percent of the global population (World Bank, s.d.).	31,32
Health	Children Underweight rate	CUR	World Bank	% of the children under age 5 below that two standard deviations from the median weight for international reference (The World Bank, s.d.).	27
Health	Environmental Diseases Disability-Adjusted Life Years	ED DALYs	World Health Organization (WHO)	The gap between the actual and the ideal health status. It accounts diseases as under nutrition, sexual and reproductive health, addictive substance, environmental risks, occupational risks, and etc. It is calculated as the sum of the years of life lost due to premature mortality and the years lost due to disability for people living with bad health condition [31].	32
Health	Fertility Rate	FERT		counted from the births per woman	20
Health	Health Expenditure per capita	HE pc	World Bank	is total health expenditure divided by population in U.S. dollars and in international dollars converted using purchasing power parity (PPP) rates from the World Bank's International Comparison Project [33].	27,21
Health	Infant Mortality Rate	IMR	United Nations Development Program and world bank	The number of infants that die before reaching one year of age, per 1000 live births in a given year [33].	20,23,28–32
Health	Improved Water Access	IWA	World Bank	refers to the % of people with access to at least 20 litres of water a person a day from an improved	23,28,29,31,32

				source, such as piped water into a dwelling, public tap, tube well protected dug well, and rainwater collection, within 1 kilometre of the dwelling [36].	
Health	Improved access water (rural)	IWA(R)	World Bank	refers to the % of rural population with access to at least 20 litres of water a person a day from an improved source, such as piped water into a dwelling, public tap, tube well, protected dug well, and rainwater collection, within 1 kilometre of the dwelling[36].	[27]
Health	Life Expectancy at birth	LEB	World Bank	is the number of years a new born infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life [33].	[21,23,25,28–32]
Health	Physician and Hospital Beds pc	PHB pc	world bank	Physicians include generalist and specialist medical practitioners, Hospital beds are inpatient beds for both acute and chronic care available in public, private, general, and specialized hospitals and rehabilitation centres [33].	[30]
Health	Proportion of under nourish in the total population[%]	PUN	FAO	% of people whose dietary energy consumption is continuously below a minimum dietary energy requirement for maintaining a healthy life and carrying out a light physical activity [65]	[25,26]
Education	Literacy Rate	LR	CIA	percent of population with 15 age and over able to write and read [25].	[25]
Education	Literacy Rate female	LRF	FAO	% of female age 15 and above able to write and read [65].	[27]
Education	Mean Years of schooling	MYS	World Bank	Average number of years of education received by people ages 25 and older, converted from education attainment levels using official durations of each level [37].	[23,28,31,32]
Education	School enrolment, tertiary	SET	World Bank	defined as the number of students enrolled in tertiary education (college), as a percentage of the age group that officially corresponds to tertiary education (in the U.S., ages 18–22)[30].	[30]
self-report	Subjective Well Being	SWB	Inglehart [38] and World Values Survey	Self-report about life satisfaction (score 1 to 10) [25].	[25,26,30]
health	Male Suicides per capita	MS pc	United Nations Demographic Yearbook		[30]
multiple index	Human Development Index	HDI	United Nation Development Program	is a composite index focusing on three basic dimensions of human development: the ability to lead a long and healthy life, measured by life expectancy at birth; the ability to acquire knowledge, measured by mean years of schooling and expected years of schooling; and the ability to achieve a decent standard of living, measured by gross national income per capita [37].	[22,24–27]

Multiple index	Index for Sustainable Economics Welfare	ISEW	combined data from world Bank, OECD dataset	account for different 6 element (the consumption, the public expenditure for defensive, capital growth, unpaid work, depletion of natural environmental, and cost of damage of pollution [19].	[19]
Equality	Gender Inequality Index	GII	FAO	The Gender Inequality Index is a composite measure reflecting inequality in achievements between women and men in three dimensions: reproductive health, empowerment and the labour market. It varies between zero (equality) and one (no equality) [65].	[27]
Multiple index	Quality of Life (of Pasten)	QL		combination of 4 variables, the IWA, LEB, IMR and the MYS [28].	[28]
Multiple index	Quality of Life (of Nadimi)	QoL		combination of 6 variables, the IWA, LEB, IMR, MYS, GDP and the GNI [23].	[23,31,32]

Table 13 List of all wellbeing indexes and their definition

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