Revisiting Kaya Identity to Define an Emissions Indicators Pyramid

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Abstract

The impact of energy use on the planet due to related CO_2 emissions is continuously increasing, despite the adoption of efficiency and decarbonisation policies and widespread environmental awareness. Climate change mitigation will only succeed if the driving forces of consumption and emissions are deeply analysed, and effective means are provided to reverse their trends. To this aim, the Kaya Identity framework is revisited to classify indicators and decomposition studies in the literature. A comprehensive pyramid approach is proposed for the progressive disaggregation and discussion of energy and emissions changes. The approach is applied to the OECD and non-OECD to provide meaningful regional analysis of past trends and future projections according to stated policy intentions. Results show that a hopeful change has already begun in the developed region due to a sustained decrease of the energy intensity and a promising reduction of the carbon intensity. Emerging economies follow the performance of developed nations since 2013, held back by later economic development. Activity slowdown, energy conservation, renewable electrification, efficient power plants and coal phase out appear as the keystones for decarbonisation. As a result, emissions stabilisation could have already been achieved as rises in emerging countries are offset by drops in developed nations. However, more stringent climate policies, especially targeting carbon drivers, are urgently needed to enable emissions reductions compatible with a global temperature increase of *1.5ºC.*

Highlights

- Classification of indicators and studies in the framework of Kaya Identity.
- Definition of an Emissions Indicators Pyramid for analyses standardisation.
- Activity slowdown and cleaner electricity drive emissions drop in the OECD since 2007.
- Hopeful efficiency and carbon intensity changes in developing nations since 2013.
- Energy intensity must be halved and carbon intensity quartered in 2040.

Keywords

Emissions drivers, Kaya Identity, energy drivers, energy efficiency, decomposition method

Word count

8102

Nomenclature

Carbon Capture and Storage	CCS
Carbon intensity	f
Carbon intensity of *GDP*	h
CO_2 emissions	F
Conversion efficiency	η
Energy degradation	L
Energy intensity	e
Energy use	E
Final Energy Factor	FEF
Gross Domestic Product	G
Kaya Identity	KI
Nuclear	Nuc
Per capita income or wealth	g
Population	P
Primary Energy Factor	PEF
Renewables	Ren

Subscripts

Conversion devices	CD
Conversion input	CI
Conversion output	CO
Conversion plants	CP
Distribution	D
Extraction and treatment	ET
Final	F
Fossil fuels	fos
Passive systems	PS
Primary	P
Useful	U

1. Introduction

Global concern about climate change and environmental sustainability has become widespread, together with the awareness of holding the world temperature increase below *1.5ºC* (Edo et al., 2019). However, the continuous growth of the energy use and energy-related CO_2 emissions remains an unsolved problem, despite the implementation of efficiency and decarbonisation policies worldwide (Jackson et al., 2018). It seems clear that humanity is conscious of the serious environmental problem but is not providing the necessary means for its mitigation. Actions must be taken before the problem becomes an emergency, so urgent treatment is required to avoid irreversible damage (Huaman and Xiu Jun, 2014).

The impact of energy use on the environment can be illustrated through the global energy chain (*fig. 1*), which shows the map of the whole energy system (IPCC, 2007). Energy resources, also referred to as primary energy products (E_P), are extracted from nature and treated to be directly distributed to final sectors (*direct carry over, DCO*) or transformed in *conversion plants*. After the distribution, the so-called final energy products (E_F) turn into different useful energy forms (E_U), mainly heat and motion, through *conversion devices*. Finally, useful energy is converted into final services within passive systems (Cullen and Allwood, 2010; Pérez-Lombard et al., 2011). So, the demand for energy services is met through a process that must be continuously adjusted to avoid supply difficulties, geopolitical stress and economic harms. Additionally, the energy chain has a threefold impact on the environment: the depletion of natural resources at the beginning of the sequence (*source exhaustion*), the energy degradation (L) throughout the chain (*thermal pollution*) and gas emissions (mainly CO_2, F) derived from the extraction, conversion and transportation of energy (*greenhouse effect*). The last two effects contribute to the world energy imbalance and are raising the temperature at local or global level (Covey et al., 2005).

For the mitigation of these impacts, it is essential to identify and quantify the *driving forces* that make consumption and emissions change. However, the complex link between human activities and energy use (Schipper et al., 1992) hinders the isolation of cause-effect relationships. Therefore, drivers should be considered as a proxy to provide insights on what induces overall changes, rather than to represent an exact causality (Nakicenovic et al., 2000). With the help of the global energy chain, in an upward direction, drivers may be grouped in three categories: activity, efficiency and carbon drivers.

First, activity drivers aim to measure the demand for energy services. In this sense, they comprise the phenomena that generate or change the quantity or quality of services to satisfy human needs (Pérez-Lombard et al., 2013), such as population, welfare, living standards, economy, etc. Secondly, efficiency drivers address the direct impact of technology on the global energy chain. Efficiency improvements counteract increments in activity by reducing the amount of energy needed to provide the unit of service. Finally, carbon drivers set a relation between emissions and energy, and they are currently placed at the forefront of climate policies. Their reduction would allow energy consumption levels to be maintained with a minor environmental impact.

Over the last decades, decomposition analyses of the environmental impact of the energy system have been developed in the literature. The IPAT identity (Ehrlich and Holdren, 1972) was pioneering in disaggregating the Impact on sustainability into three drivers: Population, Affluence and Technology. As an application of the former, the Kaya Identity (*KI*) (IPCC, 2014) expressed CO_2 emissions as the product of demographic (population, P), economic (per capita income, g), efficiency (energy intensity, e) and emissive (carbon intensity, f) factors.

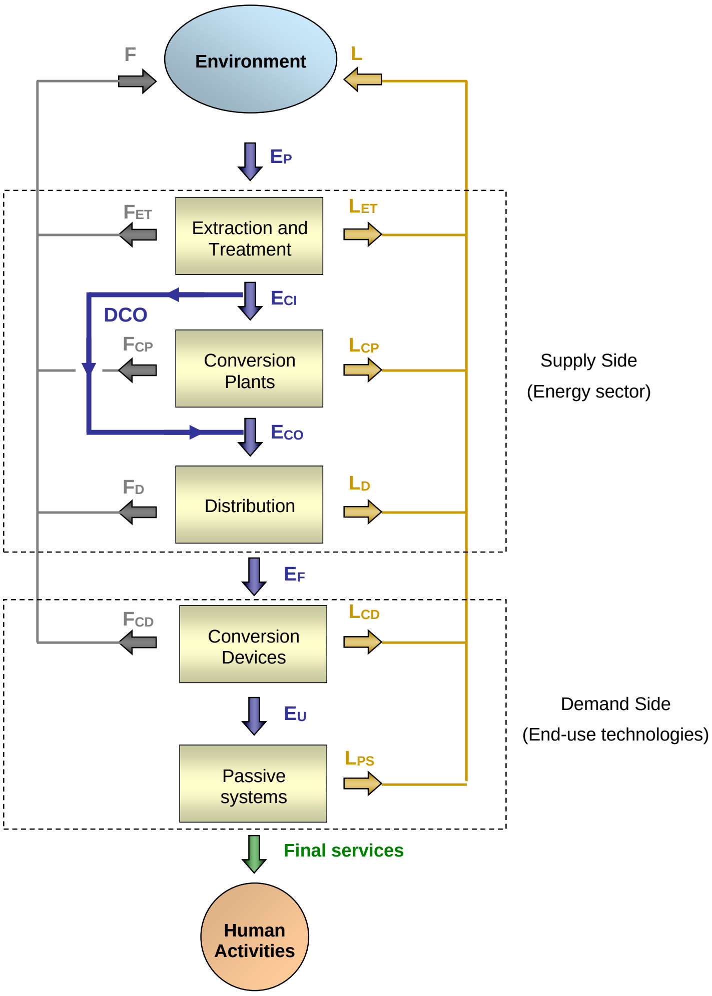

Fig. 1. Schematic of the global energy system. Emissions (F), energy products (E) and energy losses (L) are shown for each stage: extraction and treatment (ET), conversion plants (CP), distribution (D), conversion devices (CD) and passive systems (PS).

Kaya Identity has become a standard in the research field as climate change has turned into a critical problem for the international community (Niu et al., 2011) due to the close relation between CO_2 emissions and the global temperature rise (Allen et al., 2009). Nevertheless, this decomposition is not unique, as factors in the *KI* may be also decomposed or combined to define additional indicators. The decomposition of factors would provide further insights by exploring hidden aspects in the original identity. However, disaggregation is not always possible or convenient due to data unavailability and harder collection requirements. In contrast, simplified versions of the *KI* combine factors and allow a basic assessment of the emissions drivers. Thus, the choice of the aggregation level and corresponding indicators depends on the purpose of the study. Additionally, there is a lack of homogeneity and consistency among the different versions of the *KI*. The absence of a standard nomenclature for indicators leads to ambiguity and confusion. Setting a hierarchy of disaggregation levels is necessary to reach consensus and identify the key indicators for climate change mitigation.

Consequently, this paper aims to revisit energy and emissions drivers to explain how demand and supply sides of the energy system impact on the environment. Indicators and studies within the framework of the *KI* are classified to standardise the terminology in this field. A pyramid approach is proposed to set a hierarchy that allows stepwise analyses, rather than single decompositions. A novel extension of the Kaya Identity is defined at the base of the pyramid, to discuss hitherto hidden links of the energy chain. The proposed indicators are used to disentangle existing emissions scenarios and criticise stated policies. Note that underlying structural changes of subcategories in the aggregate, such as transformation types and consuming sectors, are out of this paper's scope.

To reach these goals, the paper starts with a revision of the *KI* framework by proposing a classification of indicators and sorting out previous decomposition studies. Secondly, the methodological section presents the *Emissions Indicators Pyramid* and describes the decomposition method and the data sources. The proposed approach is applied to past (1990-2018) and future (2019-2040) trends for the developed (OECD) and developing (non-OECD) regions, for which no comparison has been found in the literature. Then, the gap between stated policies and sustainable scenarios is shown in terms of the proposed emissions drivers to discuss future directions and policy implications. Lastly, the main conclusions are highlighted.

2. A revision of Kaya Identity framework

The Kaya Identity decomposes CO_2 emissions (F) in four drivers: population (P), wealth (g), energy intensity (e) and carbon intensity (f)

$$F = P \cdot \frac{G}{P} \cdot \frac{E}{G} \cdot \frac{F}{E} = P \cdot g \cdot e \cdot f \tag{1}$$

where G is Gross Domestic Product (GDP) and E is energy consumption.

Besides those in the original identity, additional indicators can be defined from their combination and disaggregation. *Table 1* classifies *KI* related indicators to establish a standard nomenclature and an algebra of indicators.

Concerning activity indicators, many factors are used to measure the demand for energy services. Regarding specific consuming sectors, physical magnitudes such as floor area in buildings, tons of product in industry and km-person in passenger transport are commonly used. On a broader scale, only population and per capita income are worldwide available. To comprise demographic (P) and wealth (g) effects, a single economic magnitude often serves as a proxy of the demand for energy services: the Gross Domestic Product (G).

Efficiency indicators are grouped in energy intensity within the original *KI*. They aim to measure the direct impact of technology on the energy chain in two ways. On one side, they indicate the energy needed for the provision of services. If main energy flows in *fig. 1* are normalised to an activity measure, primary (e), final (e_F) and useful (e_U) energy intensities are obtained. Primary energy intensity (or simply energy intensity) evaluates the performance of the whole energy system; final energy intensity indicates the efficiency on the demand side; and useful energy intensity only addresses passive systems. On the other hand, the ratios of energy outputs to energy inputs in the energy sector (E_F/E_P) and in the conversion devices (E_U/E_F) result in primary (η_P) and final (η_F) conversion efficiencies, respectively. They assess efficiency from a thermodynamic perspective, in contrast to the service-oriented definition of the energy intensity. The inverse of the efficiency in the transformation of primary to final energy is referred as *Primary Energy Factor* (*PEF*), while the inverse of the conversion efficiency of final to useful energy could be denoted as *Final Energy Factor* (*FEF*). Thus, conversion efficiencies can be used to relate energy intensities ($e = PEF \cdot e_F = PEF \cdot FEF \cdot e_U$). The absence of data regarding useful energy prevents the assessment of related indicators despite their interest.

Table 1. Classification of indicators in the framework of Kaya Identity.

Group	**Type**	**Name**	**Symbol**	**Unit**	**Equations**
Activity	Demographic	Population	P	*Million*	$G = P \cdot g$
	Economic	Gross Domestic Product	G	*M$*	
Efficiency	Energy Intensity	Primary energy intensity	e	*toe/M$*	$e = E_P/G = PEF \cdot e_F$
		Final energy intensity	e_F		$e_F = E_F/G = FEF \cdot e_U$
		Useful energy intensity	e_U		$e_U = E_U/G$
	Conversion efficiency	Primary conversion efficiency	η_P	*non-dim*	$\eta_P = E_F/E_P$
		Final conversion efficiency	η_F		$\eta_F = E_U/E_F$
		Primary energy factor	PEF		$PEF = 1/\eta_P$
		Final energy factor	FEF		$FEF = 1/\eta_F$
Carbon	Carbon intensity	Primary carbon intensity	f	*ton/toe*	$f = F/E_P = s_{fos} \cdot f_{fos} = f_F \cdot \eta_P$
		Fossil carbon intensity	f_{fos}	*ton/toe*	$f_{fos} = F/E_{P,fos}$
		Final carbon intensity	f_F	*ton/toe*	$f_F = F/E_F = s_{F,fos} \cdot f_{F,fos}$
		Fossil final carbon intensity	$f_{F,fos}$	*ton/toe*	$f_{F,fos} = F/E_{F,fos}$
		Carbon intensity of GDP	h	*ton/M$*	$h = F/G = e \cdot f$
	Fuel share	Fossil fuel share in primary energy	s_{fos}	*non-dim*	$s_{fos} = E_{P,fos} / E_P$
		Fossil fuel share in final energy	$s_{F,fos}$		$s_{F,fos} = E_{F,fos} / E_F$
Equity	Wealth	Per capita income	g	*k$/cap*	$g = G/P$
	Energy per capita	Per capita primary consumption	E_P/P	*toe/cap*	$E_P/P = g \cdot e$
		Per capita final consumption	E_F/P	*toe/cap*	$E_F/P = g \cdot e_F$
	Emissions per capita	Per capita CO_2 emissions	F/P	*ton/cap*	$F/P = g \cdot h$

As for carbon indicators, both fuel use and fuel type should be addressed, though they are clustered as carbon intensity in the original *KI*. The ratios of emissions to main energy flows are referred to as carbon intensities, either primary (f) or final (f_F). Final carbon intensity is commonly used in sectoral analyses, despite being strongly dependent on the efficiency of the energy sector ($f_F = f \cdot PEF$). Regarding fuel types, the fossil share, either in primary (s_{fos}) or in final energy ($s_{F,fos}$), can be introduced to fairly assign emissions to fossil fuels, resulting in fossil carbon intensities (f_{fos} and $f_{F,fos}$). Lastly, the ratio of emissions to activity, denoted as the carbon intensity of *GDP*, comprises efficiency and emissive factors ($h = e \cdot f$).

Finally, equity indicators can be used to assess the impact of economic, energy and emissive inequality at international (developed vs. developing countries (Duro and Padilla, 2006)) and national (urban vs. rural areas (Liu et al., 2011)) levels. Per capita income, final and primary per capita consumption and per capita emissions can be used as equity indicators in the framework of *KI*.

The classification of indicators also facilitates the understanding of previous research on the subject, as the lack of homogeneity in terms and definitions of different decomposition approaches is noticeable in the literature. *Table 2* classifies main studies in this field in original, simplified and extended versions of the *KI*. It also renames their indicators according to the nomenclature set in *table 1*.

Concerning the original *KI*, researchers such as Raupach et al. (2007) or Muradov (2013) applied it to past global trends to explain the soaring emissions since 2000. In addition to continued increases in population and wealth, they identified the cessation of declining trends in energy and carbon intensities as the major drivers for emissions growth. Muradov proposed means to their reduction and Raupach et al. expanded the scope to regional behaviours to assess the implications for global equity, with a focus on the most emitting nations. Similarly, Tavakoli (2018) decomposed past emissions of the top ten emitting countries to identify the most critical drivers: *P* in Russia, Japan and Iran, *g* for the US, Canada and India, *e* for Korea and Brazil and *f* for China. Su et al. (2019) used *KI* to draw some light on decarbonisation pathways in some developing (BRICS) and developed (G7) countries. Energy intensity appeared as the main reduction factor in the G7, while it had been offset by the affluence growth in the BRICS. Finally, Ayompe et al. (2020) analysed emissions in Africa due to the lack of studies in low-income countries, and highlighted the need to start curbing the carbon intensity by supplying non-emitting energy for their development.

Additionally, *KI* has been used to explain future trends and to develop emission scenarios and climate models. For instance, Nakićenović et al. (1998) discussed more than *400* scenarios of global and regional emissions by decomposing them in terms of the *KI*, while Schandl et al. (2016) assessed the potential for decoupling emissions and economic growth, according to different scenarios. The original *KI* is also used by many international organisations (Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA), etc.) to report their results.

Simplified versions of the *KI* have been applied to outline the global context or to highlight some effects. They are used as an introduction to more detailed analyses or as a proxy in the absence of necessary data. Some authors combined population and wealth into *G*, such as Nakićenović et al. (1998), due to lack of information, and Jackson et al. (2019), who focused on energy and carbon factors and their structures. In contrast, others clustered efficiency and carbon drivers into carbon intensity of *GDP*. Raupach et al. (2007) used *h* to summarise the joint effects of *e* and *f* throughout its analysis of the original Kaya Identity. Canadell et al. (2008) and Muradov (2013) used it to compare the carbon footprint of different economies. Ouahrani et al. (2011) highlighted main emissions drivers of Mediterranean countries to suggest policy recommendations. Raftery et al. (2017) developed CO_2 emissions projections to conclude that limiting global warming in *1.5ºC* would require *h* to decline much faster than in the past. Finally, most simplified versions implemented both combinations simultaneously, so they used *G* as a unique activity driver and the carbon intensity of *GDP* for efficiency and carbon factors. Friedlingstein et al. (2014) used it as an effective way to understand short-term trends, since the expansion of *G* and the fall of *h* tend to drive changes at this time scale. Similarly, Akimoto et al. (2014) applied such simplification to explain the trade-off needed for halving CO_2 emissions by 2050.

On the other hand, extended versions have been also developed by disaggregating factors to assess hidden effects. In this respect, industrialisation has been assessed as an additional factor in *KI* to examine the contribution of industrial activities to CO_2 emissions by introducing the share of industrial *GDP* (s_{IND}) (Yao et al., 2015). However, this approach is insufficient as buildings and transport already contributed by *26%* and *25%* to global emissions in 2018 (IEA, 2020a), so their impact should not be neglected. Regarding efficiency factors, Kawase et al. (2006) broke energy intensity down into primary energy factor and final energy intensity to analyse past and future trends for UK, Japan, France and Germany. However, they did not discuss the reasons driving efficiency changes in the energy sector based on *PEF* results, so their sound decomposition was not fully exploited. They also tried to isolate the effect of Carbon Capture and Storage (*CCS*) by adding the ratio of emissions including and excluding these techniques (s_{CCS}). As for carbon drivers, Peters et al. (2017) separated the impacts of the fossil fuel share and their carbon intensity. They disaggregated past carbon drivers for the world and the four most emissive nations. However, the contributions of these factors to emissions changes were not assessed. Finally, Le Quéré et al., (2019) expanded both efficiency and carbon factors. They evaluated the impact of extraction, conversion and transmission of fossil fuels ($PEF_{fos} = E_{P,fos} / E_{F,fos}$) on CO_2 emissions, and thus missed the global supply side efficiency and the impact of renewable and nuclear electrification. They also used final fossil share and fossil carbon intensity to explain the pathways of *18* developed countries to decarbonisation.

In summary, global and regional emissions have only been analysed by means of original or simplified Kaya identities, whereas extended studies have only been applied at national level. Therefore, meaningful indicators have not been assessed for broad geographical areas, leaving the performance of certain links in the global energy chain unevaluated. In addition, analyses rarely compare drivers' contributions to past and future trends, making it difficult to track mitigation measures. In this respect, the gap between existing policies and sustainable scenarios needs to be discussed.

To fill these gaps, this paper proposes an extension of the *KI* to further decompose energy and emissions. It assesses hidden effects by separating efficiency of the energy sector (*PEF*) from that of the end-use technologies (e_F), and fossil carbon intensity (f_{fos}) from fossil share (s_{fos}). The novel pyramid approach is applied to the developed and developing regions, due to the lack of detailed decompositions at this level. Trends are analysed through equity factors in addition to the more common activity, efficiency and carbon factors. Past (1990-2018) and future (2019-2040) trajectories are combined to assess the feasibility of climate targets. The comparison of stated policies and IPCC mitigation pathways is presented in terms of the proposed indicators to show how far the current intentions are from a sustainable future.

Table 2. Classification of Kaya Identity studies.

Kaya Identity	Equation	Study	Year of publication	Scope			Time		Decomposition method		Absolute value											
				World	Regional	National	Past	Future	Mult.	Addit.	F	E_P	P	G	g	e	e_F	PEF	f	s_{fos}	f_{fos}	h
Original	$F = P \cdot g \cdot e \cdot f$	Nakićenović et al.	1998	X			X	X			X	X	X	X		X			X			
		Raupach et al.	2007	X	X	X	X		X		X	X	X	X	X	X			X			X
		Muradov	2013	X			X		X										X			
		Schandl et al.	2016	X		X		X	X		X	X										
		Tavakoli	2018	X		X	X		X						X	X						X
		Su et al.	2019		X	X	X			X	X	X	X	X	X	X			X			
		Ayompe et al.	2020		X	X	X			X					X							
Simplified	$F = G \cdot e \cdot f$	Nakićenović et al.	1998	X			X	X	X	X	X	X	X	X		X			X			
		Jackson et al.	2019	X			X		X		X			X								
	$F = P \cdot g \cdot h$	Raupach et al.	2007	X	X	X	X		X		X	X	X	X	X	X			X			X
		Canadell et al.	2008	X	X	X	X		X		X											X
		Ouahrani et al.	2011	X	X	X	X			X	X		X									X
		Muradov	2013	X			X	X	X										X			
		Raftery et al.	2017	X			X	X	X		X											
	$F = G \cdot h$	Friedlingstein et al.	2014	X		X	X	X	X		X			X								X
		Akimoto et al.	2014	X			X	X		X	X			X	X							
Extended	$F = G \cdot e_F \cdot PEF \cdot s_{CCS} \cdot f_{CCS}$	Kawase et al.	2006			X	X	X		X												
	$F = P \cdot g \cdot s_{IND} \cdot e_{IND} \cdot f$	Yao et al.	2015		X	X	X		X	X												
	$F = G \cdot e \cdot s_{fos} \cdot f_{fos}$	Peters et al.	2017	X		X	X	X		X						X			X	X		
	$F = G \cdot e_F \cdot s_{F,fos} \cdot PEF_{fos} \cdot f_{fos}$	Le Quéré et al.	2019		X	X	X	X		X	X											

3. Methodology and data

The paper focuses on CO_2 emissions from fossil fuel combustion as they are the dominant flow ($\approx$ *80%*) within the CO_2 emissions from human activities (Friedlingstein et al., 2020) and the major source of anthropogenic global warming (Canadell et al., 2007).

For their analysis, the Emissions Indicators Pyramid (*fig. 2*) consists in the progressive decomposition of emissions (F) into drivers to set a hierarchy of indicators and disaggregation levels.

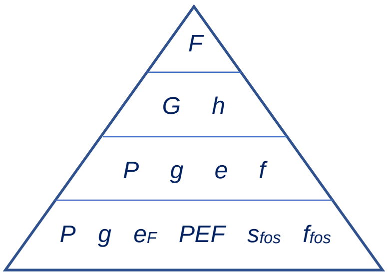

Fig. 2. Pyramid approach for emissions decomposition.

At the first stage, the demand for services (G) and the emissions needed for their provision (h) constitute the simplest decomposition level. Secondly, demographic (P) and economic (g) factors disaggregate G, while energy (e) and carbon (f) intensities break h down to result in the original Kaya Identity. Finally, at the base of the pyramid, a novel extension of the *KI* is proposed to express emissions as the product of six factors:

$$F = P \cdot \frac{G}{P} \cdot \frac{E_F}{G} \cdot \frac{E_P}{E_F} \cdot \frac{E_{P,fos}}{E_P} \cdot \frac{F}{E_{P,fos}} = P \cdot g \cdot e_F \cdot PEF \cdot s_{fos} \cdot f_{fos} \qquad (2)$$

where E_F is final energy consumption, E_P is primary energy consumption, $E_{P,fos}$ is the primary consumption of fossil fuels, e_F is the final energy intensity, PEF is the primary energy factor, s_{fos} is the share of fossil fuels in primary consumption and f_{fos} is the carbon intensity of fossil fuels.

Removing carbon indicators in *eq. 2*, primary energy can be written as the product of four factors:

$$E_P = P \cdot \frac{G}{P} \cdot \frac{E_F}{G} \cdot \frac{E_P}{E_F} = P \cdot g \cdot e_F \cdot PEF \qquad (3)$$

This extension of the *KI* allows a deeper analysis of efficiency and carbon drivers. Regarding energy intensity, e_F addresses the final use of energy in conversion devices and passive systems (*demand side*) while *PEF* assesses the efficiency of the energy sector (*supply side*). Both indicators are subject to underlying structural effects. On one hand, e_F improves with shifts toward less intensive economic sectors (from industry to services) and more efficient conversion devices (e.g., from combustion engines to electric motors) and passive systems (e.g., from SUVs to sedan cars). On the other hand, *PEF* benefits from shifts towards transformation processes with minor conversion losses (from power plants to refineries or *DCO*). *PEF* also improves with changes in the electricity mix towards more efficient power generation, mainly due to coal plants phase out in favour of gas combined cycles. Moreover, it benefits from renewable promotion, since a *100%* conversion efficiency is commonly assumed for hydro, wind and photovoltaic primary energy accounting (Macknick, 2011). The analysis of these indicators separately allows isolating the efficiency trends of different sides of the energy system, whose improvements require independent and specific measures. They must be treated alone for the definition of sound policies on each side.

As for carbon intensity, the disaggregation into s_{fos} and f_{fos} allows the direct allocation of carbon intensity to fossil fuels. The analysis of s_{fos} explains defossilisation pathways due to shifts towards non-emissive fuels. It also reflects renewable penetration, once the nuclear share is discounted. Then, climate policies can be monitored as they often include fossil or renewable targets. The examination of f_{fos} assesses shifts towards fuels with lower C/H ratios (better-quality fuels or from coal and oil to gas) and the introduction of *CCS* which will reduce emissions for a given fossil energy consumption.

The contribution of each factor to changes in CO$_2$ emissions (ΔF) in the period from *0* to *t* can be computed by applying the logarithmic mean Divisia index (*LMDI I*) approach in additive form (Ang, 2005):

$$\Delta F = F^t - F^0 = \Delta F_P + \Delta F_g + \Delta F_{e_F} + \Delta F_{PEF} + \Delta F_{s_{fos}} + \Delta F_{f_{fos}} \tag{4}$$

where the contribution of each driving factor (ΔF_X) is calculated as:

$$\Delta F_X = L(F^t, F^0) \cdot ln\left[\frac{X^t}{X^0}\right] \tag{5}$$

and $L(a,b)$ is the log mean difference between *a* and *b*:

$$L(a, b) = \frac{a-b}{ln(a/b)} \tag{6}$$

Analogously, the contribution of factors to changes in energy consumption (ΔE) can be written as:

$$\Delta E = \Delta E_P + \Delta E_g + \Delta E_{e_F} + \Delta E_{PEF} \tag{7}$$

where the contributions of energy driving factors (ΔE_X) is calculated as:

$$\Delta E_X = L(E^t, E^0) \cdot ln\left[\frac{X^t}{X^0}\right] \tag{8}$$

For the selection of the historical data sources (1990-2018), several datasets from different organisations have been compared. Discrepancies do not affect the results qualitatively, adding robustness to the results. The explanation of different energy accounting methods responsible for the main differences can be found in Grubler et al. (2012). Past series have been assembled from the International Energy Agency for CO$_2$ emissions (IEA, 2020a), primary and final energy consumption (IEA, 2020b), and from the World Bank (World Bank, 2020) for population and *GDP*. Monetary data are expressed in purchasing power parities (*PPP*) at constant 2017 prices.

For future series (2019-2040), the dispersion in the results from different sources and scenarios reflects huge uncertainty due to environmental policies, technology development, demographic and economic growth, fuel prices, etc. This paper uses future trends to illustrate the proposed approach and to allow temporal continuity, rather than to select the most likely scenario. To this aim, *IEA Stated Policies Scenario* (IEA, 2020c) is chosen, as it projects the impact of existing targets and announced policy intentions. So, it could serve to discuss how far they will place us from reaching sustainable development if political actions do not become more stringent. To this respect, they are compared with climate change mitigation pathways underpinning the *Special Report on Global Warming of 1.5°C* by the IPCC (Huppman et al., 2019) as well as with earlier emissions scenarios targeting *2ºC* temperature increase (IAMC, 2014).

Note that in order to harmonize data and reduce discrepancies in definitions between historical and future databases, past emission series have been modified to exclude those derived from industrial and non-renewable municipal waste. IPCC data are also modified to discount emissions from industrial processes and to be coherent with IEA's primary energy accounting method (physical energy content), when possible. Note also that projections miss the short-term (2020-2024) effect of COVID-19, since future data are not available on an annual basis.

4. Discussion and results

In this section, the proposed approach is discussed by its application to past and future changes in energy and emissions for the developed (OECD) and developing (non-OECD) regions. Results are presented in a sequence that follows the Emissions Indicators Pyramid from upper to lower stages. Finally, equity indicators are analysed as additional drivers to explain the different trajectories towards economic growth, efficiency gains and decarbonisation.

4.1. Regional application of the pyramid approach

First, at the vertex of the pyramid, past and future trends of energy and emissions are compared (*fig. 3*). Primary energy use in developed nations has experienced a *23%* growth up to 2007, has fallen by *5.2*% since then, and is expected to drop in the future (*9%*). Meanwhile, consumption in developing nations has more than doubled since 1990, surpassed developed nations in 2005 and will keep on growing in the future. Consequently, global consumption will increase at the pace imposed by emerging nations, slightly offset by the downward trend in the OECD.

Analogously, developed nations have already inverted their emissions upward trend after 2007 and could further decrease in the future (*30%*) due to faster decarbonisation and efficiency improvements. However, stated climate policies will not be sufficient to stop emissions growth in developing nations (*14%*). As a result, global emissions could only stabilise as drops in developed nations cancel out increases in developing countries.

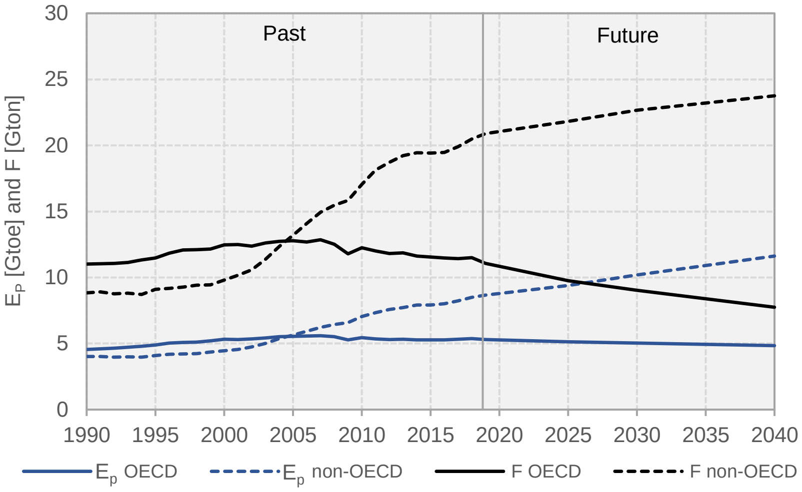

Fig. 3. Primary energy consumption (E_P) and CO_2 emissions (F) by region. Sources: IEA, 2020a, 2020b, 2020c.

Therefore, emerging economies could be blamed for future climate change if issues such as equity and production are neglected. On the one hand, developing nations could claim their right to approach the living standards of developed nations, which have supported their development with cheaply available fossil fuels for centuries (Steckel et al., 2011). On the other hand, trade is boosting emissions in the developing region, due to the displacement of heavy industries from developed countries. So, much of the production of developing countries is consumed in developed regions, suggesting the interest in accounting for both consumption and production-based emissions (Davis and Caldeira, 2010). For instance, in 2018, territorial emissions in developed nations, such as the EU (*3 Gton*) and the US (*5.4 Gton*), would increase due to emissions embodied in trade by *17%* and *7%*, respectively. In contrast, in developing countries, such as China, territorial emissions (*10 Gton*) were above consumption-based figures (*9 Gton*). Thus, trade raised China's emissions by *1 Gton*, while discounting *0.9 Gton* from joint EU - US emissions (Friedlingstein et al., 2020).

Decomposing emissions according to the first stage in the pyramid allows the initial assessment of the main causes of their change (*fig. 4*). Activity has doubled in the developed region and quadrupled in the developing countries. Consequently, it has contributed to rising emissions in both regions. In contrast, the decarbonisation of the economy has only offset activity growth in the OECD. As governments will not intentionally renounce economic growth, policies point to the carbon intensity of *GDP* as the only instrument for limiting CO_2 emissions. In fact, some national reduction goals were announced in terms of this indicator, especially in developing countries, such as India and China. Nevertheless, they will only be effective if they are enough to cancel out the activity growth. Otherwise, the emissions upward trend will not be reversed. How to act on each driver will be clarified by descending the pyramid.

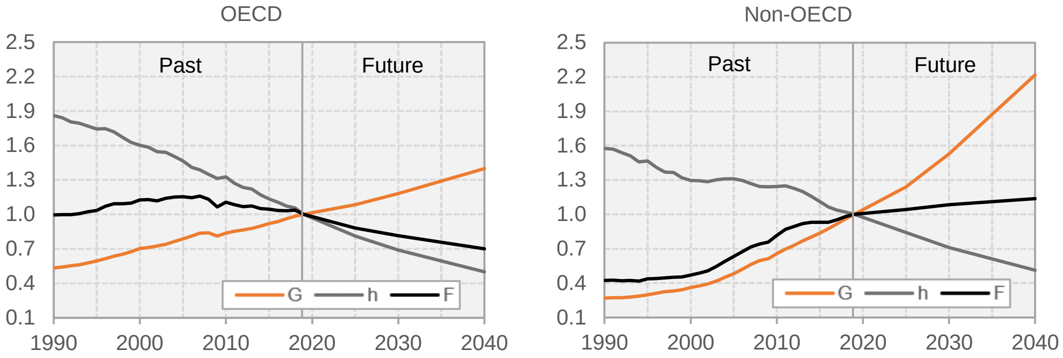

Fig. 4. Trends for indicators in the simplified Kaya Identity by region. CO_2 emissions (F), Gross Domestic Product (G) and carbon intensity of GDP (h). Reference year 2019. Sources: IEA, 2020a, 2020b, 2020c; World Bank, 2020.

In the second stage of the pyramid, the original Kaya Identity allows a deeper comparison of the factors causing emissions and energy changes (*fig. 5*). For developed nations, the driving factors will maintain the trends of the last decade into the future. Slower economic and demographic growth, together with constant efficiency gains and effective decarbonisation policies, will likely lead to a slight reduction in consumption and a significant drop in emissions. Hence, developed nations would experience a hopeful change as they could combine activity growth with a decrease in their environmental impact. Meanwhile, large changes will take place in developing regions to almost double their wealth and significantly raise their population by 2040. In this respect, their great efforts upon efficiency and carbon intensity reduction will not be enough to cancel out future increases in energy and emissions.

Note that crises have affected both regions differently. In 2008, the economic crisis was not so global. It caused a sharp fall in wealth, consumption and emissions in developed countries, but did not change upward trends in emerging nations, which considerably aided the rapid financial recovery in 2010 (Peters et al., 2012). Similarly, the COVID crisis seems to seriously damage OECD short-term trends, and consequently favours energy and emissions dips to 2025, while little impacts will be noticed in the non-OECD.

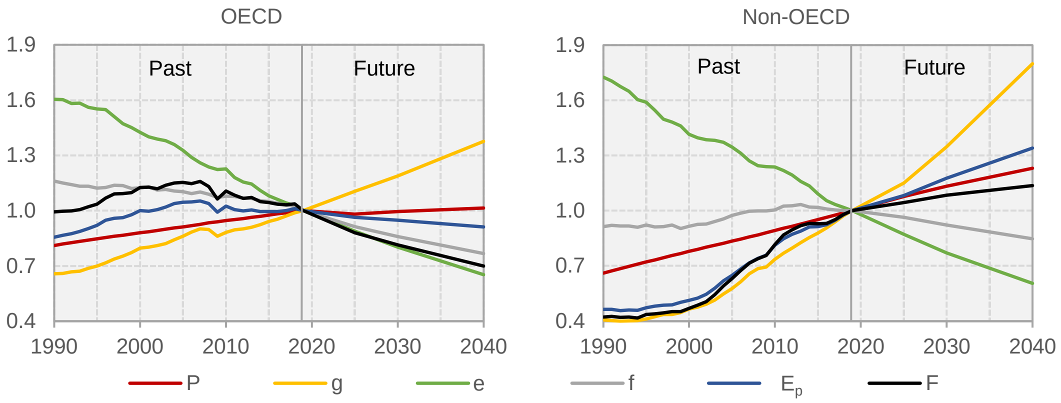

Fig. 5. Trends for driving factors in the Kaya Identity by region. CO_2 emissions (F), primary energy supply (E_P), population (P), wealth (g), energy intensity (e), carbon intensity (f). Reference year 2019. Sources: IEA, 2020a, 2020b, 2020c; World Bank, 2020.

Meaningful conclusions may also be extracted from the indicators introduced in the third stage of the pyramid. *Figure 6* shows the decomposition of primary energy intensity into *PEF* and e_F. Significant final efficiency improvements indicate a decreasing energy demand to generate wealth in both regions and a more efficient or conservative use of the energy by final users. However, the lowest final energy intensities correspond to the lowest decreasing ratios, showing technical efficiency limits. Despite the gap is narrowing, the non-OECD (*84 toe/M$*) still has room for improvement to reach values of the OECD (*62 toe/M$*). In the future, their trends could converge as globalisation allows the spread of efficient conversion devices and passive systems across borders.

Efficiency in the energy sector is strongly shaped by electrification[1] (*fig. 7*), since conversion losses introduced by power plants raise *PEF* compared to more direct energy forms or more efficient transformation processes. In this respect, past values of *PEF* in developing countries were especially low as most of the energy used was not transformed (mainly traditional biomass). However, *PEF* has grown up to *1.48*, and surpassed that of the developed countries as the *DCO* is replaced by electricity. Electrification levels are getting closer in both regions (*23%* OECD vs. *19%* non-OECD) and they are likely to converge to some *25%* in 2040, according to stated policies.

However, electrification can be achieved with no detriment of *PEF* if renewable promotion and shifts towards more efficient power generation are sufficient to counteract the losses introduced in the energy sector. For this reason, *PEF* in developed countries started to improve in 2008, when electricity reached a standstill, and will continue improving despite future electrification. In fact, the EU plans to meet half the energy demand with electricity without increasing *PEF*, thanks to *80%* of renewable power generation in 2050 (European Commission, 2019). Similarly, the US aims to produce carbon pollution-free electricity by 2035 (USA, 2021), mostly generated by renewable sources as the capacity of some nuclear reactors is gradually retired and derated (EIA, 2021). In developing countries, *PEF* is also projected to improve, although rapid coal-based electrification raised it in the past. Nevertheless, slower changes to more efficient electricity generation and their coal dependence will still place *PEF* above that of developed countries in 2040. For instance, India recognised the future coal dominance in power generation in its Nationally Determined Contributions (*NDC*), though they expect to limit *PEF* through highly efficient supercritical technology (GoI, 2016).

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[1] In this paper, electrification is defined as the share of electricity in final energy consumption.

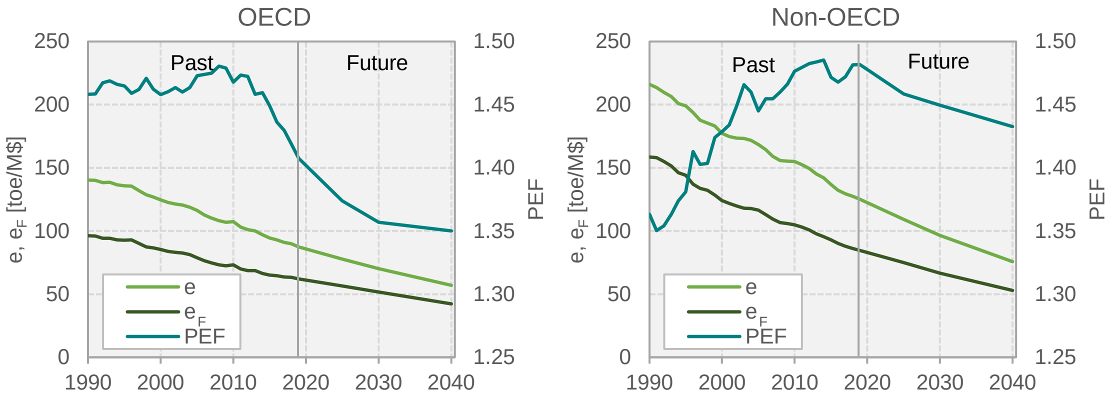

Fig. 6. Trends for efficiency indicators, i.e., primary (e) and final (e_F) energy intensities and Primary Energy Factor (PEF) by region. Sources: IEA, 2020b, 2020c; World Bank, 2020.

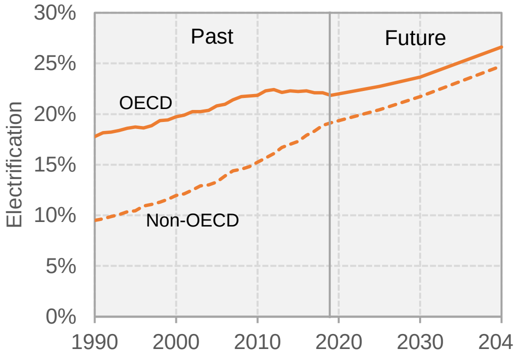

Fig. 7. Trends for electrification by region. Sources: IEA, 2020b, 2020c.

The evolution of carbon drivers (*fig. 8*) can be explained by regional energy mixes (*fig. 9*). In the OECD, the fossil share has decreased to *79%* since 1990, as the renewable share in energy supply has doubled from *6%* to *12%*, despite a roughly constant nuclear share. Moreover, there have been shifts among fossil fuels towards gas, aided by the boom in liquefied natural gas (Jackson et al., 2020). Consequently, the fossil carbon intensity has dropped to *2.7 ton/toe*, due to the gas carbon content (*2.2 ton/toe*) below that of oil (*2.5 ton/toe*) and coal (*3.9 ton/toe*). In contrast, defossilisation did not begin in developing countries until 2015, which have supported their past development on coal and worsened their fossil share (*81%*) and fossil carbon intensity (*3 ton/toe*).

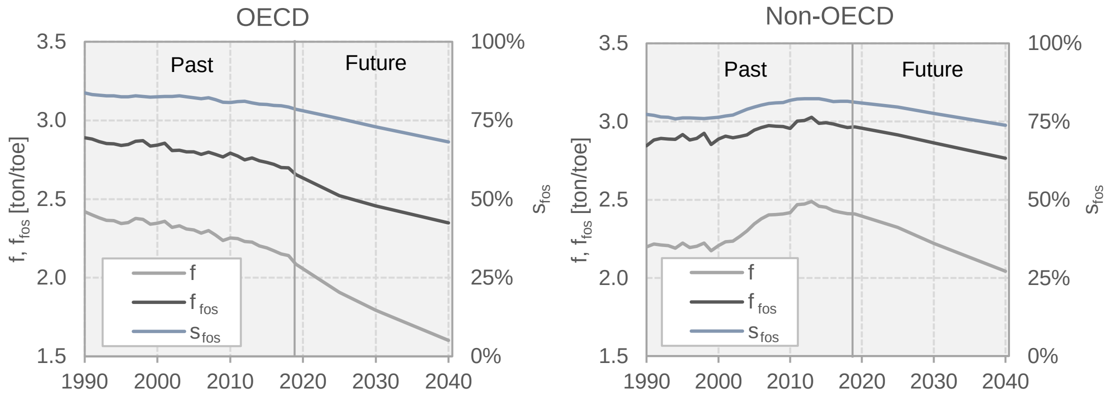

Fig. 8. Trends for carbon indicators, i.e., carbon intensity (f), fossil share (s_{fos}) and fossil carbon intensity (f_{fos}). Sources: IEA, 2020a, 2020b, 2020c.

In the future, both regions will continue shifting from coal towards gas and renewables. Thus, coal phase out will allow simultaneous benefits in the fossil share and the fossil carbon intensity.

The OECD will achieve lower fossil shares, despite similar renewable shares (*22%*) due to higher nuclear supply. Moreover, the OECD will reduce the coal share to a *6%*, while it will remain the main energy source in developing countries (*26%*), resulting in lower fossil carbon intensity (*2.35* vs. *2.77 ton/toe*).

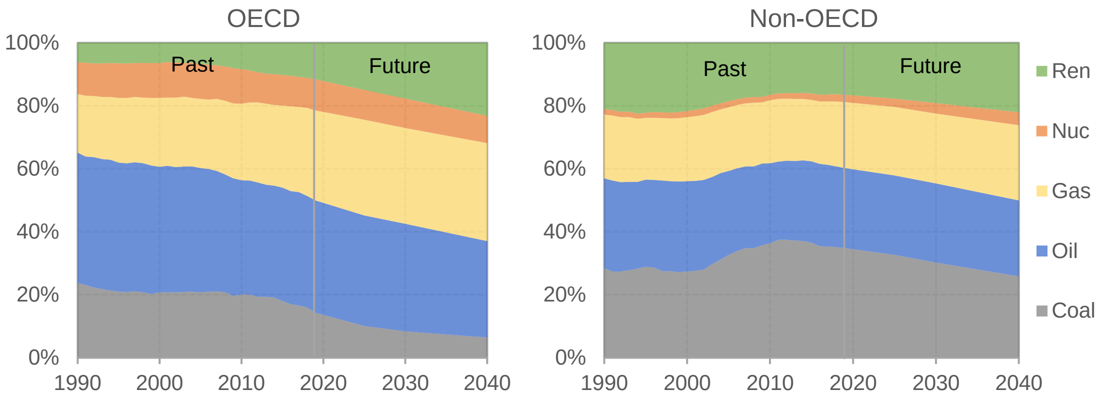

Fig. 9. Trends for primary energy mix by fuel and by region. Sources: IEA, 2020b, 2020c.

The contribution of factors to changes in energy (*fig. 10, left*) and emissions (*fig. 10, right*) allows summarising the results. Developed countries will reverse the upward energy trend (*0.7 Gtoe* rise vs. *0.5 Gtoe* drop) since population stabilisation and improvements in demand and supply sides efficiency will counteract minor increases in wealth. Moreover, the abatement of the carbon intensity will join energy drivers to reduce emissions by *3.3 Gton*. The contribution of s_{fos} above that of f_{fos} to future OECD emission reductions shows the greater impact of switching from coal to renewables than to gas.

For developing nations, major improvements in e_F along with the reversal of *PEF*, s_{fos} and f_{fos} trends will partially outbalance the constant activity growth and cut energy consumption and emissions growths by two thirds and a quarter, respectively. Therefore, developing nations have supported their recent economic growth in emissive fuels, whereas they are moving towards defossilisation and decarbonisation.

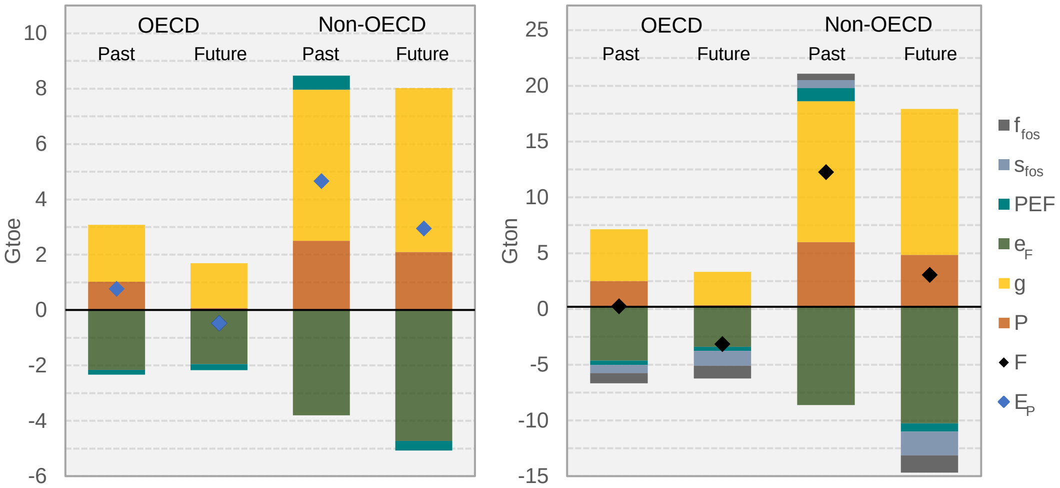

Fig. 10. Energy (left) and emissions (right) changes decomposition by region according to the extended Kaya Identity. CO$_2$ emissions (F), primary energy supply (E$_P$), population (P), wealth (g), final energy intensity (e$_F$), Primary Energy Factor (PEF), fossil share (s$_{fos}$) and fossil carbon intensity (f$_{fos}$). Past (1990-2019) and future (2019-2040). Sources: IEA, 2020a, 2020b, 2020c; World Bank, 2020.

4.2. Reducing inequality: the main underlying driver

Equity indicators can be used to explain inequality between regions and to assess the extent to which their residents are responsible for environmental impacts (*table 3*). The uneven distribution of population and wealth leads to huge differences between absolute and per capita figures. Developed nations have only one fifth of non-OECD population, but their per capita figures are about *4* times higher in wealth and roughly *3* times in consumption and emissions. Therefore, although the developing region has been the most consumer and emitter since 2005 in absolute terms, their inhabitants should not be held responsible for the planet's environmental crisis. In this sense, inequality should be seen as an additional factor, driving the development of emerging nations as they improve living standards. However, they should not forget about climate objectives on their path to development. Although restrictions for the lower and middle classes are undesirable, reduction measures could target higher-income citizens. Also, they could combine economic growth and increased energy use with emissions drops, by basing their progress on clean resources. To this aim support, investment and assistance from developed countries are essential.

Table 3. Equity indicators by region. Sources: IEA, 2020a, 2020b, 2020c; World Bank, 2020.

Indicator	***Unit***	***Year***	***OECD***	***Non-OECD***	***Ratio***
P	*Million*	1990	1104	4176	0.26
		2019	1360	6314	0.22
		2040	1380	7775	0.18
g	*k$/cap*	1990	29.4	4.5	6.60
		2019	44.7	11.0	4.07
		2040	61.5	19.8	3.11
E/P	*toe/cap*	1990	4.1	1.0	4.28
		2019	3.9	1.4	2.84
		2040	3.5	1.5	2.34
F/P	*ton/cap*	1990	10.0	2.1	4.72
		2019	8.1	3.3	2.46
		2040	5.6	3.1	1.84

The evolution of wealth, efficiency and consumption can also be analysed by plotting primary energy intensity versus per capita income over the period 1990-2040 (*fig. 11, left*). Different trajectories explain the path to economic development and efficiency improvement. Both regions work to be richer and to enjoy better technology. However, convergence is still far from being achieved, especially for wealth, due to large differences in starting points. In 2040, developed countries will remain *40 k$/cap* richer, while the gap in energy intensity will narrow to *19 toe/M$*. Lastly, note that developing nations trajectories show per capita consumption increases, while those of developed nations decrease. Nevertheless, there will be no convergence on this indicator even in 2040.

The comparison of energy and carbon intensities in absolute terms is also illustrative (*fig. 11, right*). The OECD evolves in the right direction, being more efficient and less emissive. In contrast, developing nations did not translate their efficiency gains into carbon intensity improvements until 2013, and remain *28%* more emissive (*2.04 ton/toe*) than developed nations in 2040.

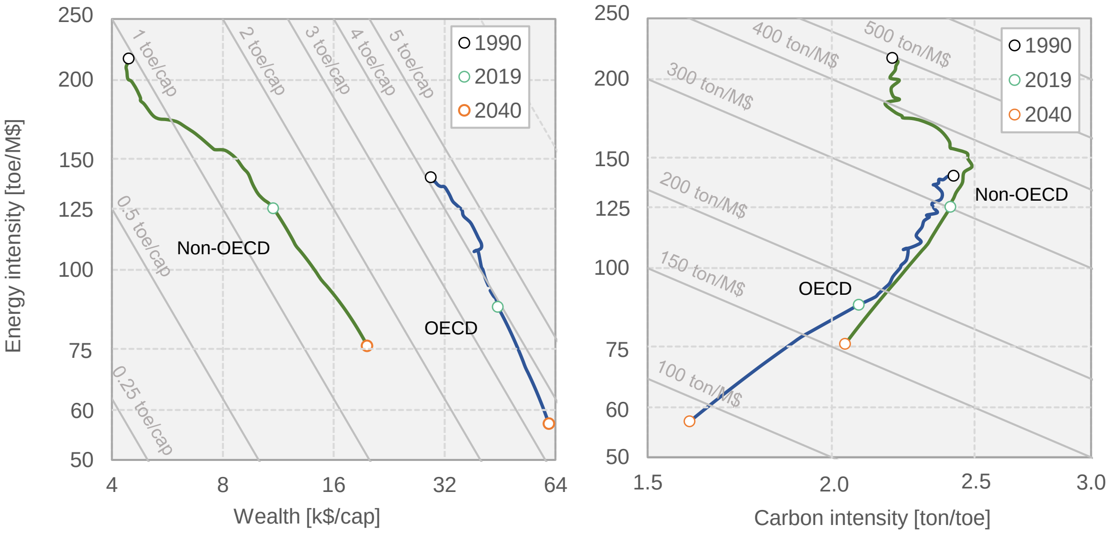

Fig. 11. Primary energy intensity (e) vs. per capita income (g) (left) and vs. carbon intensity (f) (right) by region. Sources: IEA, 2020a, 2020b, 2020c; World Bank, 2020.

5. Policy implications and future direction

In order to reveal policy implications at a global scale, *fig. 12* compares emissions for IEA Stated Policies Scenario (*SPS*) with the IPCC mitigation pathways compatible with temperature increases up to *1.5ºC* (green envelope). Sustainable scenarios show that a sharp drop in emissions is needed in contrast to the stabilisation of *SPS*. Every pathway within the envelope peaks before 2030 and net zero emissions become feasible from 2040 onwards. The later they peak, the more steeply they should decline, because cumulative emissions to be compensated reduce the time to achieve net zero emissions. In brief, the shorter the time left, the more pronounced the change will have to be.

Nevertheless, these IPCC scenarios could be considered utopian if previous experience in this field serves as reference. The median of earlier mitigation scenarios (blue envelope) projected a lower growth rate in the past decade to limit global warming to *2ºC.* Climate pledges of the Copenhagen accord were not only insufficient, but they have also been unfulfilled (Höhne et al., 2020). Moreover, a lower temperature rise is now targeted in order to avoid irreversible environmental damage (IPCC, 2018). Consequently, the gap between current emissions and those needed to meet temperature goals has widened over the last decade.

Unexpectedly, COVID crisis has reversed the path and could place emissions back on the sustainable track. Pandemic lockdowns and restrictions have led to an unprecedented *7%* emissions drop in 2020 (Le Quéré et al., 2021). However, a further decline in emissions of around *3.5%/yr* are required over the next decade, so urgent actions should be taken to impede a rebound to pre-COVID levels.

Therefore, major investments in economic recovery should be properly directed to provide the means to achieve fossil-free economies (IEA, 2020d) and national pledges should be revised and strengthened. In 2020, *75* Parties to the Paris agreement updated their *NDC*, although they only accounted for about *30%* of global GHG emissions (UNFCCC., 2021). Additionally, many countries committed to net-zero emissions by 2050, covering around *70%* of global CO_2 emissions (IEA, 2021). However, the involvement of every country by submitting new commitments will be necessary. Emissions targets will not succeed unless specific actions for their achievement are defined. Pledges are likely to be empty promises if they are not adequately monitored to ensure that they are met.

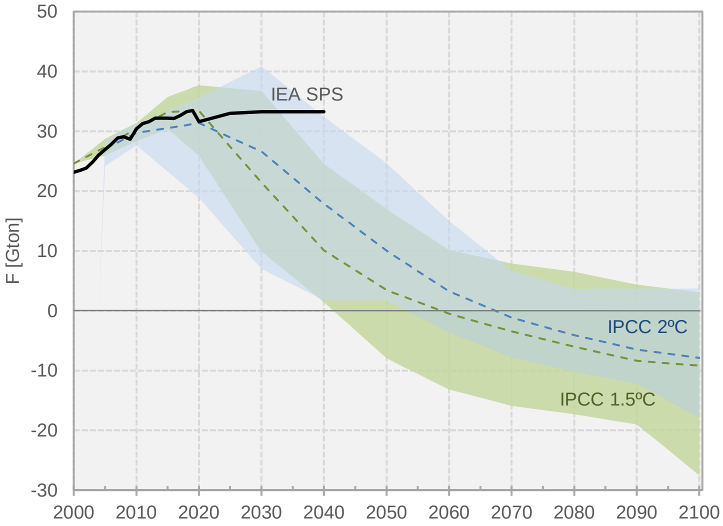

Fig. 12. Global CO_2 emissions scenarios: IEA Stated Policies Scenario (SPS) and IPCC scenarios compatible with 1.5ºC (green envelope) and 2ºC (blue envelope) temperature increase. Dashed lines indicate median scenarios. Sources: Huppman et al., 2019; IAMC, 2014; IEA, 2020a, 2020c.

In order to design and monitor future actions, the gap between stated policies and *1.5ºC* sustainable pathways in 2040 (*table 4, fig. 13*) is shown in terms of the proposed Emissions Indicators Pyramid:

- Population and wealth are expected to grow in every scenario, as their control conflicts with development goals (Karstensen et al., 2020). However, stated policies project increases in population (*20%*) and wealth (*56%*) above the IPCC median scenario, suggesting that their rational growth would be convenient for sustainability.
- Final energy intensity is projected to drop by *34%* according to *SPS*, since energy efficiency policies are well established and have been proved effective worldwide. However, the IPCC median (*40%*) suggests that additional efforts for efficiency improvement are required. In this line, policy makers should encourage the retrofit and purchase of efficient technologies by setting stringent minimum efficiency standards and incentives in every economic sector. In parallel, final users should change their behaviour to adopt energy conservative patterns.
- The Primary Energy Factor will slightly increase or decrease depending on whether shifts to more efficient or renewable power plants will be rapid enough to counteract losses from electrification (González-Torres et al., 2021). Despite the current urgency to electrify the energy system, its pace will be constrained by battery's limitations, the grid capacity and solutions for certain transport modes, such as aviation. Consequently, large changes in the efficiency of the energy sector are neither expected nor necessary (constant median IPCC scenario and *3%* drop for *SPS*).
- The fossil share drop from stated policies (*10%*) falls well short of what is required by sustainable scenarios (*44%* mean reduction). Defossilisation is a powerful factor as non-combustible sources will lead to zero emissions, even if other drivers are not addressed. For this reason, some countries recognise the nuclear role to complement renewables as a baseload energy source (UK Gov, 2021) despite the security concerns and the low efficiency of nuclear plants. Renewable energy must surge, as solar and wind plants become more competitive (IRENA, 2020). Also, new sources will appear in the energy mix, such as hydrogen, whose production must be carbon-free. Additionally, fossil fuel subsidies need to be eliminated (Lazarus and Van Asselt, 2018) to encourage the energy mix transformation,

while investment should be especially directed to reduce the fossil share in emerging countries.

- Fossil carbon intensity shows a high dispersion, with results ranging from *2%* rise to *56%* drop. Sustainable scenarios projecting the lowest improvements for this indicator are those which aim for the lowest fossil shares to offset total carbon intensity. Thus, stated policies will not be enough, as they will only achieve a slight fall in the fossil carbon intensity (*7%*), together with insufficient fossil share reductions. To improve this indicator, gas share could keep on rising in the short-term, to replace oil and coal. Nevertheless, it could never be used to meet new energy demand as it would result in the undesirable increase of the fossil share. Gas can only serve as a “bridge fuel” to ensure energy security during the energy transition (Jackson et al., 2020). In the long-term, gas consumption will need to be also replaced by clean energy sources or offset by *CCS* techniques.

In summary, stated policies will not succeed in declining emissions, as a result of insufficient improvements in every indicator. In contrast, the median of sustainable scenarios shows an impressive *70%* drop by 2040, which requires roughly halving the final energy intensity, the fossil share and the fossil carbon intensity. Special attention should be paid to carbon factors, which present the highest gaps and therefore require the most urgent and stringent actions.

Table 4. Emissions drivers. Current (2019) and target figures (2040) compatible with a 1.5ºC global warming. Sources: Huppman et al., 2019; IEA, 2020a, 2020b; World Bank, 2020.

Year	***P*** [*billion*]	***g*** [*k$/cap*]	e_F [*toe/M$*]	***PEF*** [-]	s_{fos} [%]	f_{fos} [*ton/toe*]	***F*** [*Gton*]
2019	7.67	15	87	1.43	81	2.9	33.5
2040 Median (25th / 75th)	8.81 (8.79 / 8.83)	23 (22 / 24)	52 (42 / 57)	1.43 (1.34 / 1.51)	45 (38 / 53)	1.8 (1.3 / 2.1)	10.7 (7.8 / 16.6)
Change [%/yr] Median (25th / 75th)	0.7 (0.6 / 0.7)	2 (1.7 / 2.1)	-2.4 (-3.4 / -2)	0 (-0.3 / 0.2)	-2.7 (-3.5 / -2)	-2.2 (-3.8 / -1.5)	-5.3 (-6.7 / -3.3)

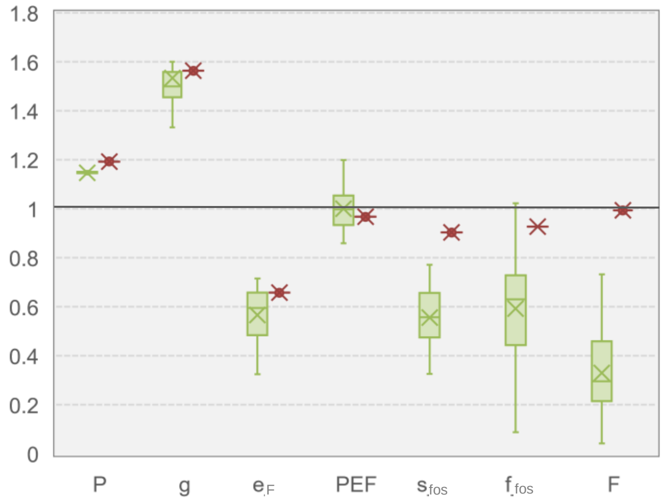

Fig. 13. Changes over the period 2019-2040 in population (P), wealth (g), final energy intensity (e_F), Primary Energy Factor (PEF), fossil share (s_{fos}), fossil carbon intensity (f_{fos}) and CO_2 emissions (F) according to IEA Stated Policies Scenario (red) and IPCC 1.5ºC scenarios (green). Sources: Huppman et al., 2019; IEA, 2020a, 2020b, 2020c; World Bank, 2020.

6. Conclusions

Palliative measures such as international agreements and efficiency and decarbonisation policies have been clearly insufficient to curb energy use and CO_2 emissions. Climate change could only be halted if every stage of the energy chain is addressed, and the drivers of consumption and emissions are controlled. To this aim, meaningful indicators are defined and classified to enable the development and monitoring of robust and homogeneous policies. A pyramid approach is proposed to set a hierarchy of drivers, which could serve as guidance for future analyses and for procedures standardisation. The disaggregation levels in the *Emissions Indicators Pyramid* allow tiered conclusions to be drawn about the trajectories of developed (OECD) and developing (non-OECD) nations and their implications in terms of policies and duties.

An encouraging change has begun, as the developed region has been able to decouple activity and emissions growths since 2007. However, recent efforts upon efficiency and decarbonisation in the developing region remain insufficient to offset their economic and demographic growth. Regarding efficiency drivers, the improvement in final energy intensity worldwide allows reducing the gap between regions, thanks to the spread of enhanced end-use technology. On the supply side, available technologies have made electrification compatible with efficiency gains in the energy sector only in the OECD. As for carbon drivers, the increasing gas share in developed countries has induced a decrease in fossil carbon intensity, while the promotion of renewables has pushed down the fossil share. In contrast, carbon indicators in the non-OECD have only improved since 2013, as their economic boom mainly relied on coal. Thus, it seems the developing region follows the favourable performance of the developed nations, delayed by later economic development.

Current political intentions will only allow for emissions stabilisation as decreases in developed nations counteract increases in emerging countries. However, keeping global temperature rise below *1.5°C* requires a *70%* drop in emissions by 2040. Thus, more stringent policies must be urgently adopted to narrow the gap between stated policies and sustainable pathways. Carbon drivers should be especially addressed as they deviate significantly from their sustainable targets. In the short term, policies should encompass fossil share reductions and gas surge, while research and investment make the transition to full defossilisation feasible. In addition, globalisation should be seen as an opportunity to reduce regional inequality, as it enables the diffusion of advanced technology, knowledge and expertise. Developed nations must intensify efforts to accelerate their emissions drop and to support the reversal of emerging nations trends to succeed in climate change mitigation.

Despite expecting a radical change after decades of unfulfilled commitments may seem utopian, the COVID crisis unexpectedly brought emissions back on track. Keeping emissions on the sustainable path requires the greening of economic recovery, as well as citizens and governments moving from words to deeds.

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