A CROSS-COUNTRY REVIEW ON ENERGY EFFICIENCY DRIVERS

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ABSTRACT

Energy efficiency remains as the main mitigation factor to slow down the growth of energy consumption and related CO_2 emissions, undoubtedly the major responsible for climate change. Gaining insights into the driving forces that make efficiency change is a keystone to define energy policies and examine pathways to sustainable development. To this aim, this paper proposes a pyramidal approach for the analysis and decomposition of energy intensity, the main global efficiency indicator, using the LMDI method. First, the effects related to supply and demand sides of the energy system are separated in Primary Energy Factor and final energy intensity, respectively. Then, supply side is further decomposed to progressively reveal structural effects associated to transformation processes and fuel types. The approach is applied to the most emitting and consuming nations (China, United States, European Union, India, Russia, Japan) to provide a meaningful cross-country analysis over the period 1995-2017. Results show that energy intensity gains have been mainly driven by widespread demand side efficiency improvements from 25% to 61%. Regarding the supply side, unfavourable structural changes due to electrification, up to 12% in China, have only been offset by transformation efficiency gains about 6% in developed countries. Consequently, emerging economies have worsened their energy sector efficiency as they thrive. Changes in fuel mixes have generally contributed to energy intensity reductions (up to 4%) mainly due to shifts from coal and nuclear power towards gas and renewables plants. The proposed methodology could help stakeholders to effectively analyse the energy system and to develop policies to reduce its environmental impact.

Keywords
efficiency drivers, conversion efficiency, Primary Energy Factor, transformation sector, fuel mix, LMDI decomposition

World count
5063

1. INTRODUCTION

Climate change evidences [1] have led to over 1700 climate emergency declarations in 30 countries since 2016 [2], recognizing that urgent action is required to avoid potential irreversible environmental damage [3]. However, global CO_2 emissions keep on rising, despite researchers have placed them as the major responsible for this alarming situation [4], mainly driven by the energy-related and industrial flux during the last decade [5].

Effective mitigation measures will not be possible without gaining deep insights into emissions changes, in order to define future pathways to sustainable development and improve governance in this field [6,7]. In this respect, in 1990, as an application of the previous IPAT equation [8], Kaya [9] identified four underlying factors for CO_2 emissions (*F*): population (*P*), wealth (*g*), energy intensity (*e*) and carbon intensity (*f*):

$$F = P \cdot g \cdot e \cdot f = P \cdot \frac{G}{P} \cdot \frac{E}{G} \cdot \frac{F}{E} \qquad (1)$$

where *G* is Gross Domestic Product, an activity indicator used as a surrogate for the provision of final services, and *E* is primary energy consumption.

In the Kaya Identity (*fig. 1*), population and wealth are activity drivers which aim to measure the demand of energy services. Energy intensity indicates efficiency, which could counteract increments in activity by reducing the energy needed to provide the unit of service. Finally, carbon intensity sets a relation between emissions and energy to assess the effect of energy sources. A decrease in the use of emissive fuels to satisfy a given energy demand would reduce related emissions by decreasing the carbon intensity. Thus, the reduction of any of the Kaya indicators could have served to curb emissions growth.

However, historical trends have pointed out energy intensity as the main mitigating factor for decarbonisation within the former identity [10,11], for being the only decreasing driver for global past emissions. During the period 1995-2017, drops in energy intensity (31%) have been insufficient to offset the effects of population (32%) and wealth (121%) growths, with a roughly constant carbon intensity (1%), leading to a 54% increase in CO_2 emissions. In the future, slow but favourable improvements on carbon intensity are projected in addition to the decreasing energy intensity, thanks to the shift from emissive fossil fuels to cleaner energy sources. Nevertheless, they will not be sufficient to achieve emissions reductions, which will still increase by 14% until 2040 according to New Policies Scenario in IEA World Energy Outlook [12]. Consequently, efficiency improvement must remain as a key climate target until desirable carbon intensity reductions become significant, feasible and widespread.

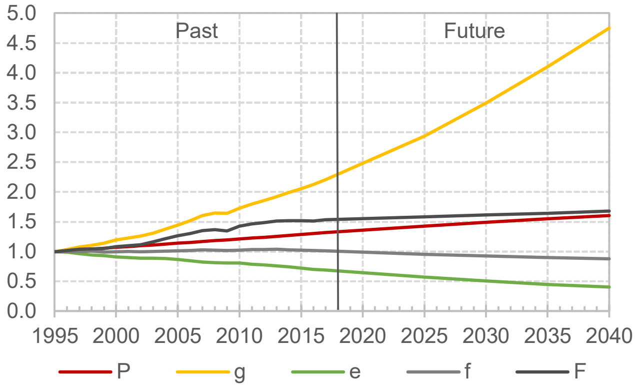

Fig. 1: Decomposition of global CO_2 emissions according to Kaya Identity. Reference year: 1995. Time period: 1995-2017-2040. Source: IEA [13,14]*, World Bank* [15] *(past) and IEA* [12] *(future).*

Energy intensity is an efficiency indicator that measures the impact of technology on the energy system (*fig. 2*), which aims to provide final services for satisfying human needs by the use of energy resources [16]. On the left side, the *energy sector* or *supply side,* involves the extraction of primary resources (Primary Energy, *PE*) to be transformed into energy products, either through conversion plants or directly carried over (*DCO*), and subsequently distributed to final users (Final Energy, *FE*). Within the supply side, energy can be lost as it is own used by the energy sector (*OU*) for heating, pumping, traction and other purposes, or degraded in conversion plants and distribution lines as transformation (*TL*) and distribution losses (*DL*), respectively. On the right, *demand side* concerns the consumption of final energy in end-use technologies where it is degraded for the provision of final services. Thus, energy intensity clusters the performances of supply and demand sides of the whole energy system.

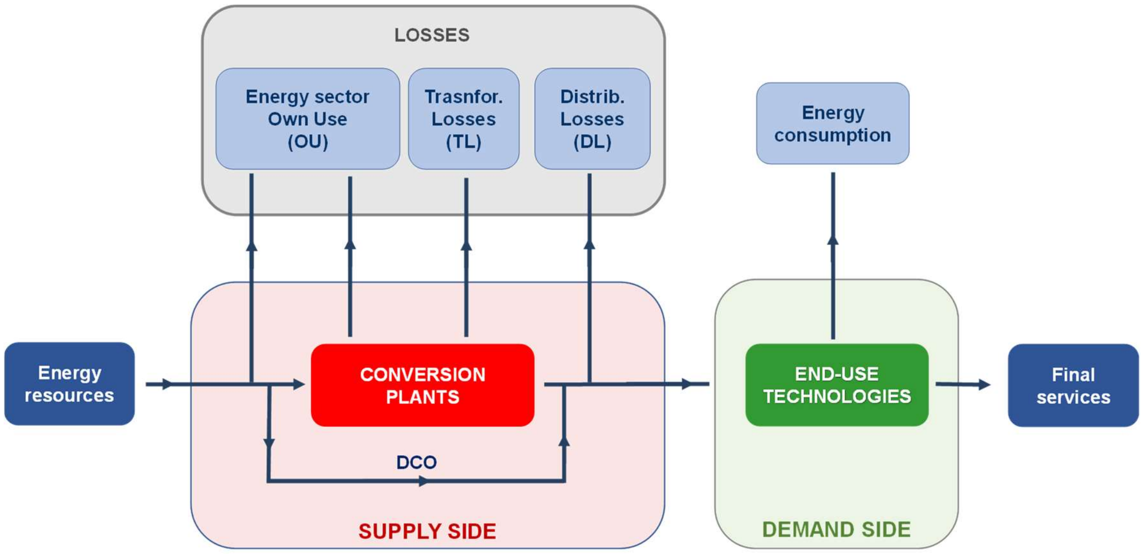

Fig. 2: Simplified scheme of the energy system.

In the literature, energy intensity has been widely decomposed into drivers, either as a factor within more extensive decompositions or independently. Some authors have disaggregated energy intensity to analyse the performances of the demand and supply sides of the energy system, by the introduction of two additional efficiency indicators:

final energy intensity (e_F = *FE/G*) and Primary Energy Factor (*PEF* = *PE/FE*), respectively. They assessed transformation and end-use efficiencies contributions to CO_2 emissions [17], energy supply [18], carbon intensity [19] and energy intensity trends [20] and inequalities [21]. Moreover, demand and supply side activities and actors have been considered when trying to model detailed and complete representations of the power system [22]. However, none of these studies aimed to deeper analyse the energy system structure.

Further decompositions are worthy as e_F and *PEF* are subjected to underlying structural effects that difficult the isolation of the impact of technical efficiency on intensity changes [23]. The demand side structure is shaped by the economic sectors in the production mix, while the supply side structure mainly depends on transformation processes and fuel types. Structural effects in an aggregate can be analysed as additional driving forces.

In this line, the demand side structure has been widely analysed by expressing final energy intensity as a weighted average of economic sector intensities. Liu and Ang [24] illustrated the different robust methods for decomposing the sectoral energy intensities. Ang and Zhang [25] presented an extensive review of papers in this field in 2000. Some recent studies have also analysed Chinese [26,27], Iranian [28] and Spanish [29] economic structures, as part of emissions decompositions.

As for the supply side structure, there are a few contributions in the literature. Landwehr et al. [30] identified the following contributions to *PEF*, in addition to technical efficiency of conversion plants: (a) trade of secondary energy carriers, which raises exporter and lessens importer *PEF,* since transformation losses due to the energy consumed by the latter are assigned to the former; (b) share of primary energy carriers in end-use (also referred to as Direct Carry Over); (c) multiple conversion stages, when secondary products are used as transformation inputs; (d) distribution losses and energy sector own use; and (e) demand and supply fuel mixes, requiring transformation processes adjustments. To assess these contributions, they broke *PEF* down according to the following categories: imported secondary energy, exported secondary energy, primary energy carriers in end-use and transformation output, which was further disaggregated in electricity and heat, oil products and coal products. Other authors [31,32] have decomposed *PEF* according to the economic sector structure and fuel mixes to analyse consumption and emissions changes. Therefore, they actually disaggregate *PEF* according to the demand's rather than supply's structure.

However, consensus on a methodology for energy intensity analysis is lacking to untangle its structural effects and make them meaningful and easier to understand. Despite efficiency has been disaggregated into drivers to different extents, there is not any comprehensive description of the energy system and its hierarchical decomposition. The impact on the energy sector efficiency of converted or directly carried over energy commodities is disguised, and so are the effects of different transformation types and energy losses. Additionally, there is no exhaustive comparative analysis of changes in efficiency for the main consuming nations in the literature.

Consequently, this paper proposes a methodological framework based on an energy intensity pyramid for its decomposition in structural and efficiency indicators. Setting the focus on the supply side of the energy system, which has been barely explored in the literature, the Primary Energy Factor is progressively broken down by transformation and fuel type. The pyramidal analysis will be applied to the six most consuming [13] and emitting [14] nations in the world (United States (US), European Union (EU), China, India, Japan and Russia), to provide relevant insights of their energy systems through the discussion of past trends and changes in intensity drivers, using the LMDI method. The paper starts with methodological issues such as the decomposition approach and the data sources and elaboration. Then, results are discussed in a sequence that follows the pyramidal hierarchy from upper to lower stages. Lastly, main conclusions are highlighted.

2. METHODS AND MATERIALS

2.1. Pyramidal approach

The pyramidal approach (*fig. 3*) consists in a progressive decomposition of energy intensity into drivers. For each stage, changes in energy intensity will be disaggregated to analyse the effect of different drivers, through the application of the logarithmic mean Divisia index (LMDI I) approach [33].

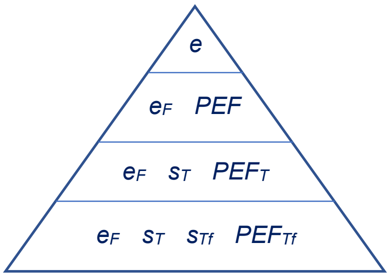

Fig. 3: Pyramidal approach for energy intensity decomposition.

On the top of the pyramid, energy intensity is used to evaluate the performance of the whole energy system as a ratio of primary energy to *GDP*:

$$e = \frac{PE}{G} \tag{2}$$

In the first stage, effects related to demand and supply sides of the energy system are assessed by the introduction of final energy intensity and Primary Energy Factor:

$$e = e_F \cdot PEF = \frac{FE}{G} \cdot \frac{PE}{FE} \tag{3}$$

where e_F is the final energy consumed in end-use technologies to provide the unit of service and *PEF* relates energy input and output of the energy sector. Changes in energy intensity (Δe) for a period from *0* to *t* can be decomposed as follows:

$$\Delta e = e^t - e^0 = \Delta e_{e_F} + \Delta e_{PEF} \tag{4}$$

$$\Delta e_{e_F} = L(e^t,\, e^0) \cdot ln\left[\frac{e_F^t}{e_F^0}\right] \tag{5}$$

$$\Delta e_{PEF} = L(e^t,\, e^0) \cdot ln\left[\frac{PEF^t}{PEF^0}\right] \tag{6}$$

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

$$L(a,\ b) = \frac{a-b}{ln(a/b)} \tag{7}$$

In the second stage, the focus is set on the supply side. *PEF* is broken down into the impacts of the transformation sector structure and the efficiency of each process:

$$e = \sum_T e_T = \sum_T \frac{PE_T}{G} = \sum_T \frac{FE}{G} \cdot \frac{FE_T}{FE} \cdot \frac{PE_T}{FE_T} = \sum_T e_F \cdot s_T \cdot PEF_T \tag{8}$$

where s_T is the structure of final energy by transformation type (T) and PEF_T is the inverse of the efficiency in each transformation. Transformation types are grouped as follows: Electricity, Heat and combined heat and power Plants (*EHP*); Oil refineries (*REF*); Other transformations (*OT*), including gas works, coal transformations, liquefication plants and others; and Direct Carry Over (*DCO*), which refers to energy that suffers no conversion.

The decomposition of energy intensity changes at this stage according to LMDI results in:

$$\Delta e = \Delta e_{e_F} + \Delta e_{s_T} + \Delta e_{PEF_T} \tag{9}$$

$$\Delta e_{e_F} = \sum_T L(e_T^t,\ e_T^0) \cdot ln\left[\frac{e_F^t}{e_F^0}\right] \tag{10}$$

$$\Delta e_{s_T} = \sum_T L(e_T^t,\ e_T^0) \cdot ln\left[\frac{s_T^t}{s_T^0}\right] \tag{11}$$

$$\Delta e_{PEF_T} = \sum_T L(e_T^t,\ e_T^0) \cdot ln\left[\frac{PEF_T^t}{PEF_T^0}\right] \tag{12}$$

where e_T is the ratio of primary energy into transformation T to *GDP*.

In the third stage, the efficiency of each transformation process is further disaggregated to uncouple the effects of the structure and efficiency by fuel:

$$e = \sum_{T,f} e_{Tf} = \sum_{T,f} \frac{PE_{Tf}}{G} = \sum_{T,f} \frac{FE}{G} \cdot \frac{FE_T}{FE} \cdot \frac{FE_{Tf}}{FE_T} \cdot \frac{PE_{Tf}}{FE_{Tf}} = \sum_{T,f} e_F \cdot s_T \cdot s_{Tf} \cdot PEF_{Tf} \tag{13}$$

where s_{Tf} is the structure of final energy by fuel type f in transformation T and PEF_{Tf} is the ratio of the primary energy to final energy for each fuel and transformation. Fuel types are grouped in six categories: coal, oil (both crude and oil products), natural gas, nuclear, biofuels and waste, and renewables (hydro, wind, solar, geothermal, etc.).

At this stage, LMDI method decomposes energy intensity changes as follows:

$$\Delta e = \Delta e_{e_F} + \Delta e_{s_T} + \Delta e_{s_{Tf}} + \Delta e_{PEF_{Tf}} \tag{14}$$

$$\Delta e_{e_F} = \sum_{T,f} L(e_{Tf}^t,\ e_{Tf}^0) \cdot ln\left[\frac{e_F^t}{e_F^0}\right] \tag{15}$$

$$\Delta e_{s_T} = \sum_{T,f} L(e_{Tf}^t,\ e_{Tf}^0) \cdot ln\left[\frac{s_T^t}{s_T^0}\right] \tag{16}$$

$$\Delta e_{s_{Tf}} = \sum_{T,f} L(e_{Tf}^t,\ e_{Tf}^0) \cdot ln\left[\frac{s_{Tf}^t}{s_{Tf}^0}\right] \tag{17}$$

$$\Delta e_{PEF_{Tf}} = \sum_{T,f} L(e_{Tf}^t,\ e_{Tf}^0) \cdot ln\left[\frac{PEF_{Tf}^t}{PEF_{Tf}^0}\right] \tag{18}$$

where e_{Tf} is the ratio of primary energy of fuel f into transformation T to GDP.

2.2. Data

Energy data are either directly reported or elaborated from International Energy Agency's (IEA) databases. First, Primary Energy (*PE*) and Final Energy (*FE*) are taken from *Total Primary Energy Supply* and *Total Final Consumption* in IEA *World Energy Balances 2019* (*EB*) [13]. For stages 2 and 3, primary and final energy must be allocated to the different transformation and fuel types to obtain PE_T, FE_T, PE_{Tf} and FE_{Tf}. The path from primary to final energy is revised in *fig. 4* to explain the elaboration of these data.

Once Statistical Differences (*SD*) and Transfers (*TR*) have been discounted from *PE*, Transformation Input (*TI*) can be directly carried over (I_{DCO}) or transformed through different conversion plants (I_{EHP}, I_{REF}, I_{OT}) with their corresponding Transformation Losses (TL_{EHP}, TL_{REF}, TL_{OT}). Then, conversion Outputs (O_{EHP}, O_{REF}, O_{OT}) can go upstream (backward flow, *BF*) or downstream to join *DCO* (O_{DCO}) as Transformation Output (*TO*), which can be own used by the energy sector (*OU*), lost in distribution lines (*DL*) or finally available for consumption (*FE*).

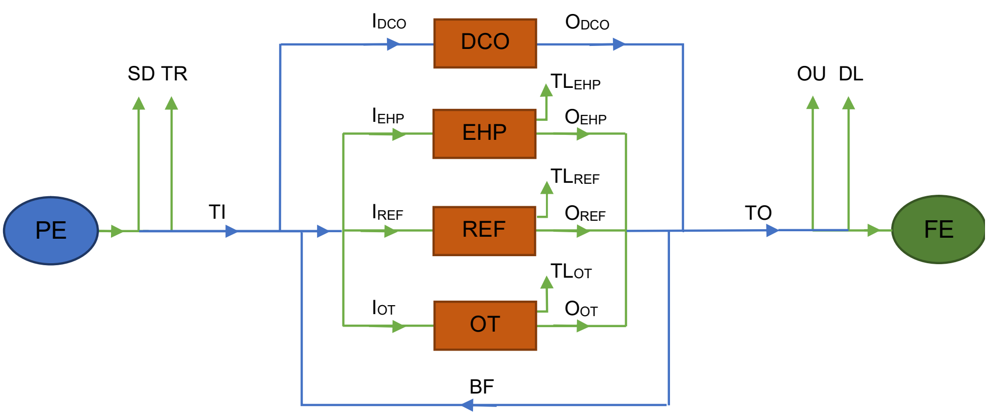

Fig. 4: Energy flow from Total Primary Energy Supply to Total Final Consumption for fuel f. Flows in green are directly obtained from IEA EB, while those in blue are elaborated.

PE_{Tf} is computed by moving the structure of transformation input by fuel, upstream to primary energy. Inputs to conversion plants are taken from the *EB*, while *DCO* and *BF*, are calculated assuming that they are positive and mutually exclusive:

$$\begin{cases} If\ \beta > 0 \Rightarrow DCO = \beta \ \ and \ \ BF = 0 \\ If\ \beta < 0 \Rightarrow \ DCO = 0 \ \ and \ \ BF = -\beta \end{cases} \tag{19}$$

where $\beta = PE_f - SD_f - TR_f - \sum_{T \neq DCO} I_{Tf}$

Then, PE_{Tf} is obtained assuming that SD_f, TR_f and BF_f can be allocated to transformation types proportionally to their respective share in transformation input:

$$PE_{Tf} = I_{Tf} + (TR_f + SD_f - BF_f) \cdot \frac{I_{Tf}}{\sum_T I_{Tf}} \tag{20}$$

Analogously, FE_{Tf} can be computed by moving the structure of transformation output by fuel downstream to final energy. Outputs from conversion plants are given in the *EB* and *DCO* output equals its input. Then, FE_{Tf} is obtained assuming that OU_f, DL_f and BF_f can be assigned to transformation types proportionally to their respective share in transformation output:

$$FE_{Tf} = O_{Tf} - (OU_f + DL_f + BF_f) \cdot \frac{O_{Tf}}{\sum_T O_{Tf}} \tag{21}$$

In this paper every electricity and heat flow in the IEA energy balances is allocated to the fuels from which they derive, according to IEA electricity and heat generation by source data [34]. Finally, PE_T and FE_T can be computed as the sum of primary and final energy by transformation and fuel over all fuels.

As for economic data, they are reported from the World Bank [15], expressed in *constant 2011$* and in *Purchasing Power Parities* to allow fair comparisons between economies and to eliminate the impact of the currency inflation.

3. RESULTS AND DISCUSSION

In this section, an energy intensity analysis is presented for the six most emitting and consuming nations during the period 1995-2017. Results aim to illustrate the application of the pyramidal approach to analyse their energy systems. Energy intensity is progressively disaggregated into its drivers, describing their trends and contribution to changes.

3.1. Efficiency and emissions' link

As a starting point, the link between energy intensity and CO_2 emissions is revised for the top emitting nations (*fig. 5*). Though decreases in energy intensity have been widespread, developing nations could not translate these significant efficiency gains into emissions' drops. Population growth and economic take-off have been the major responsible for alarming emissions rises in China and India, the former becoming the most emissive nation in 2006. Moreover, the energy consumption associated with these activity increases has been mainly supplied by emissive fuels, worsening their carbon intensity. In contrast, efficiency gains have been combined with decreasing carbon intensity in the US and EU to achieve noticeable emissions falls over the last years, being roughly constant in Japan and Russia. Note that large efficiency improvements do not necessarily lead to controlled emissions due to the effect of other Kaya drivers and/or highly inefficient starting points.

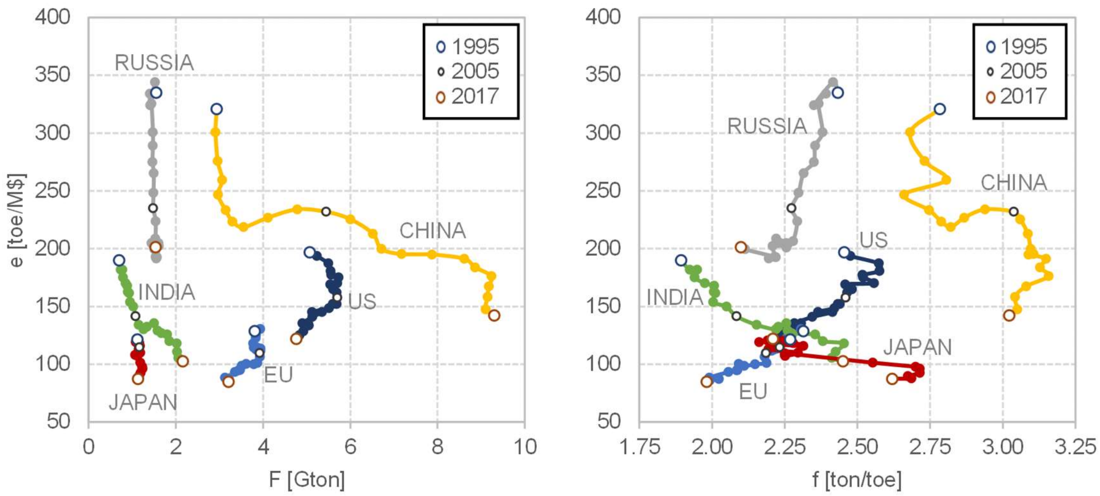

Fig. 5: Energy intensity (e) versus CO_2 emissions (F) (left) and versus carbon intensity (f) (right) by nation. Time period: 1995-2017. Source: IEA.

3.2. First stage

Differences between demand and supply sides in the energy system can be shown through a revision of final energy intensity and primary energy factor trends (*fig. 6*). Regarding the demand side, final efficiency improvements clearly show a decreasing energy demand to generate wealth. However, the lowest final energy intensities correspond to the lowest decreasing ratios, showing technical efficiency limits and leading to a potential convergence between nations, except for Russia. On the other hand, supply side efficiency has evolved less homogeneously. High *PEF* values in Japan, US and EU have been exceeded by increasing ones in Russia, China and India. Nevertheless, generalised downward trends in the last years have brought them closer. A deeper explanation of *PEF* trends requires descending to next stages in the pyramidal approach.

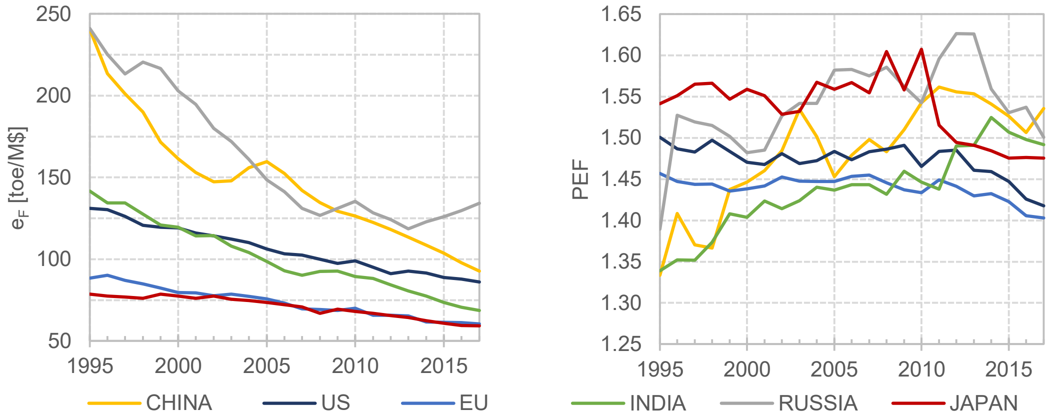

Fig. 6: Final Energy Intensity (e_F) and Primary Energy Factor (PEF) trends. Time period: 1995-2017. Source: IEA.

Energy intensity changes at this stage can be disaggregated according to *eq. 4* (*fig. 7*). The main responsible for efficiency improvement has been final intensity, with higher contributions than *PEF* in every case. Changes in *PEF* have only reduced energy intensity in developed nations, raising concerns about the difficulties of an economy to thrive without worsening the efficiency of its energy sector. Despite upward *PEF* effects, China, India and Russia have achieved the largest efficiency improvements, thanks to impressive final intensity drops.

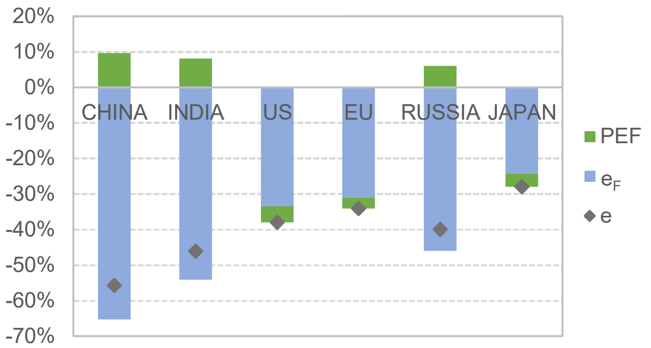

Fig. 7: Decomposition of changes in energy intensity (e) into final energy intensity (e_F) and Primary Energy Factor (PEF). Time period: 1995-2017.

3.3. Second stage

The structure of the energy sector by transformation type (s_T) is separated from the efficiency of transformation processes (PEF_T) in the second stage.

Trends for national transformation structures are shown in *fig. 8*. Most of primary resources are not converted in China and India, so being directly carried over to final consumption. Despite *DCO* shares are decreasing, with the expansion of *REF* and *EHP*, India still shows the structure of a non-developed nation, about 50% *DCO* (of which a 56% corresponds to biomass) and below 20% *EHP*. In contrast, refineries are the main transformation process in the developed countries, though their shares have decreased over the last years owing to the promotion of cleaner energy sources. In US and EU, refineries represent the major share (40-50%), despite being slightly substituted by *EHP* (over 20%), with a roughly constant *DCO* about 30%. Similarly, Japan relies on refineries for its energy supply, reduced from 60% to a steady 50% in the last decade due to a lower oil demand for heating, electricity and transportation [35]. This drop in Japanese *REF*'s share came with increases in *EHP* (30%) and *DCO* (10%). Finally, the Russian structure differs from the others since it is dominated by *EHP* (35%) due to large heat shares (22%), despite its low electrification (13%). Falls in *EHP* came along with progressive increases in refineries and *DCO* in the last years.

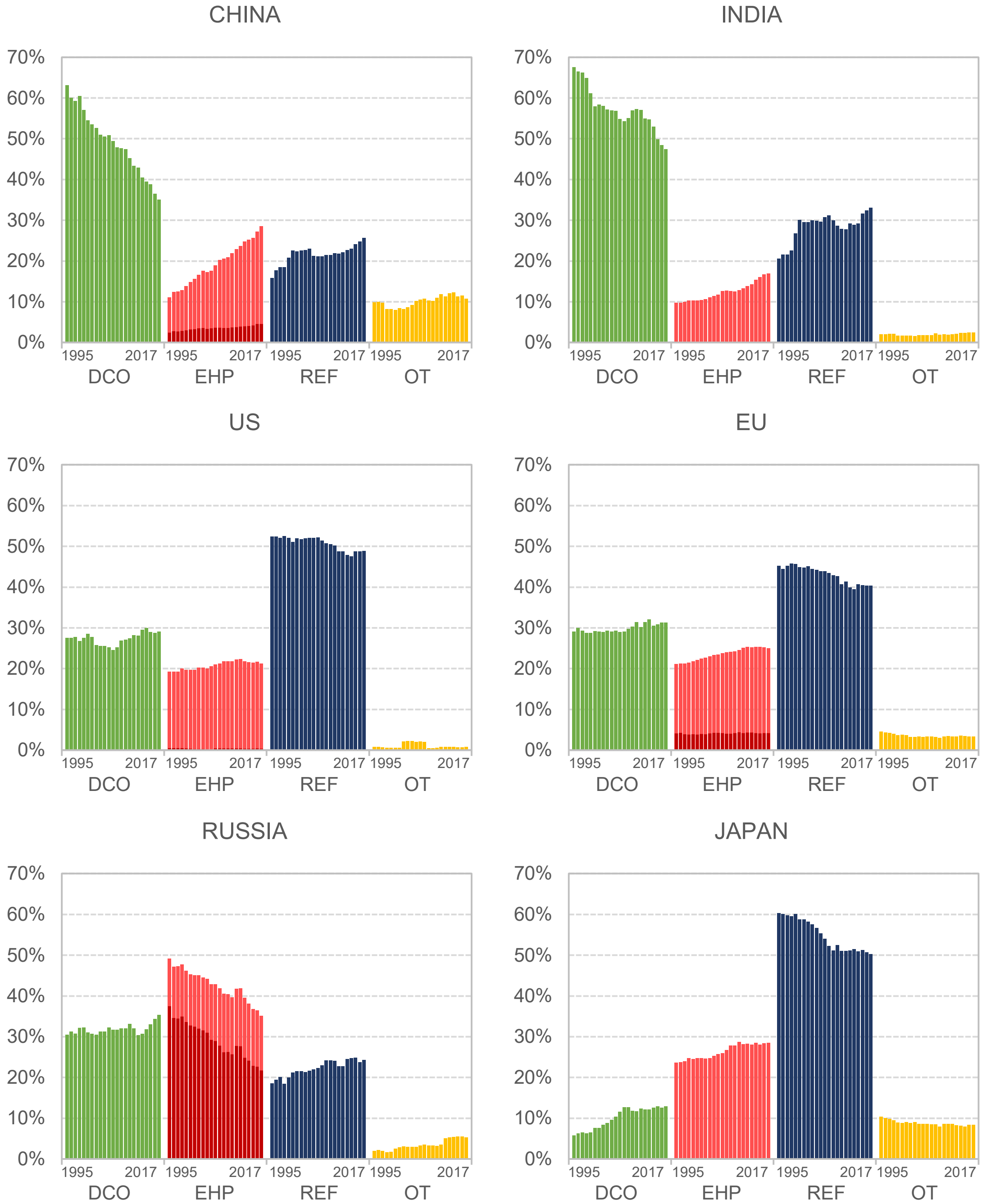

Fig. 8: Structure by transformation type (s_T). Time period: 1995-2017. DCO: Direct Carry over, EHP: Electricity and Heat Plants, REF: Refineries, OT: Other Transformations. Bottom dark red in EHP bars indicates heat share.

Next, trends in PEF_T (*fig. 9*) are discussed for the main transformation types:

- Despite this paper analyses *DCO* as a transformation type, energy that is directly carried over suffers no conversion. Consequently, PEF_{DCO} should be one, except for slight effects of *SD*, *TR*, *OU* and *DL*. Results show that the high own use of the energy sector in US and Russia, together with significant distribution losses in the latter, raised their PEF_{DCO} up to some 1.1. Values below 1 in Japanese trend are due to negative statistical differences.
- Oil transformation in refineries is a very efficient process [36], leading to PEF_{REF} values around 1.1. The high Russian figure (≈1.3) contrasts with average values. On the one hand, it is raised by high oil products exports since losses associated with their conversion impair exporter and benefit importer. Moreover, a large share of the refineries' output is recirculated in the energy sector to serve as input to *EHP*. Consequently, significant differences between *PE* and *FE* were introduced for this transformation type, also penalising its PEF_{REF}.
- Electricity and heat generation involves different fuels and conversion plants with PEF_{EHP} ranging between 1.5 and 3.7 in 1995. However, they are converging to some 2.5. While high PEF_{EHP} values are decreasing due to the globalization of efficient electricity generation, low Russian figure has significantly increased with the reduction of its heat share. Note that PEF_{EHP} is computed as a weighted average of electricity and heat transformation efficiencies. Hence, the larger heat share, the better PEF_{EHP}, since it is more efficiently generated than electricity. Moreover, Russia benefits from cogeneration plants which generated a 68% of the electricity production in 2017, in contrast to other nations where they present minor contributions. On the contrary, India has the worst PEF_{EHP} due to its reliance on inefficient coal plants and a neglectable heat production. Thus, energy conversion in *EHP* always penalise energy intensity due to its low conversion efficiency.
- Other transformations *PEF* are high and difficult to analyse since they concentrate processes of different natures, such as gas works, coal transformations or liquefication plants.

The structure and efficiency of the transformation sector can explain *PEF* trends in previous *fig. 6*. In China and India, *PEF* evolved from the lowest values, due to high *DCO* shares, to be among the biggest, because of high electrification in China (25%) and inefficient power plants in India ($PEF_{EHP} = 3.5$). US and EU have experienced downward *PEF* trends in the last 5 years due to a decreasing *EHP* share in favour of refineries and *DCO* due to gasification. Japanese *PEF* has been historically high due to large electricity and *OT* shares. However, it has abruptly dropped after 2010 thanks to noticeable PEF_{EHP} decreases and steady electricity figures. Finally, Russian *PEF* increases until 2012 as PEF_{EHP} grows to converge with figures in other countries due to the decreasing heat generation. Over the last years, its heat share stabilisation and drops in PEF_{EHP} have led to *PEF* reductions.

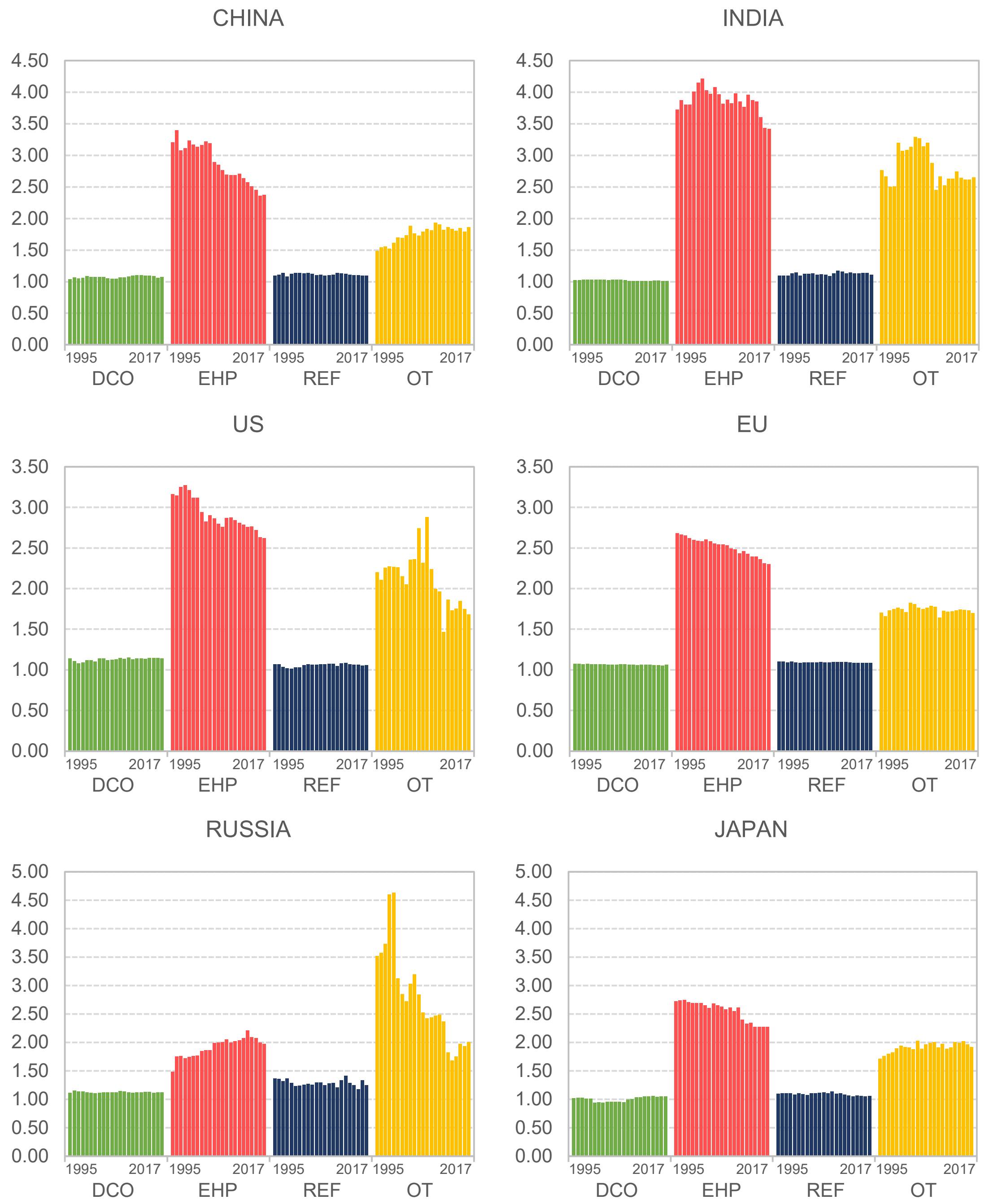

Fig. 9: Primary Energy Factor by transformation type (PEF_T). Time period: 1995-2017. DCO: Direct Carry over, EHP: Electricity and Heat Plants, REF: Refineries, OT: Other Transformations.

At this stage energy intensity changes are disaggregated according to *eq. 9* (*fig. 10*). Structural changes in China and India have been unfavourable (*DCO* to *EHP*) over efficiency improvements. In US, EU and Japan, structural changes (*REF* to *EHP*) have worsened energy intensity, though they have been cancelled by transformation efficiency gains. On the contrary, in Russia, structure has slightly contributed to intensity reductions (*EHP* to *DCO* and *REF*), but the worse efficiency due to the heat share's drop has offset the structure improvement. Hence, structural effects have always worsened energy intensity, either by shifts in transformation types or changes in electricity and heat shares within *EHP*.

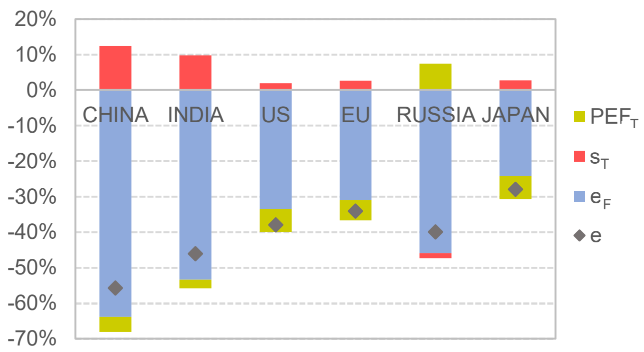

Fig. 10: Decomposition of changes in energy intensity (e) into final energy intensity (e_F), transformation structure (s_T) and PEF by transformation (PEF_T). Time period: 1995-2017.

3.4. Third stage

Supply side efficiency not only depends on transformation type, but also on the fuel being transformed (PEF_{Tf}). Thus, the analysis of fuel structure for each transformation (s_{Tf}) is also meaningful. Although energy intensity decomposition approach in this paper covers fuel structural effects for every transformation type, only *EHP* structure by fuel will be further explained, since *DCO* efficiencies are nearly one for every fuel, refineries only involve oil transformation and *OT* have a complex and heterogenous mix and a negligible share in most economies.

Fuel structures in *EHP* are shown in *fig. 11*. A persistent reliance on coal is observed, not only in China and India (≈70%), but also in present figures for developed countries (above 20%). Natural gas has replaced coal and oil, the latter becoming a minor source, only significant in Japan (7%). Nuclear shares are noticeable in developed countries (≈20%), though environmental concerns and nuclear accidents have lately cut these figures in EU and Japan, respectively. Biofuels and renewables have grown in every country but India, where energy consumption growth has been mostly supplied by coal. The promotion of these non-emissive sources in EU has achieved a hopeful share of some 30% in 2017.

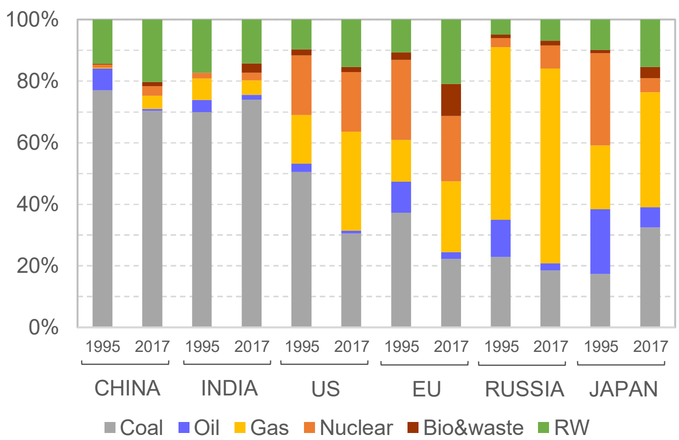

Fig. 11: Fuel structure in electricity and heat plants (s_{EHPf}). Years: 1995 and 2017.

Highlights on past and present *PEF* values in *EHP* by fuel type follow (*Table 1*):

- The average low *PEF* of non-combustible renewables (1.3), as the IEA primary energy accounting method assumes a direct equivalent approach (100% conversion efficiency) for hydro, wind and solar PV [37]. Thus, figures above 1 for these fuels cannot be related to technical conversion issues. For instance, the highest 2017 $PEF_{EHP,RW}$ occurs in Russia, where distribution losses (17%) and *EHP* own use (11%) were higher than in other nations.

- The average high nuclear *PEF* (3.6), due to the low efficiency of nuclear plants (≈ 33%) [38] and the adverse effects of distribution losses and energy sector own use. Highest and lowest values are found in Russia and Japan. On the one hand, losses in the Japanese power sector due to *DL* and *OU* (9%) are one third of those in Russia. Additionally, stringent policies promoting high-level nuclear technology after Fukushima accident [39] resulted in the especially high conversion efficiency (42%) of the remaining plants.
- The average fossil *PEF* about 2.4 is significantly better for Gas (2.2) and Oil (2.3) than for Coal (2.8), owing to the efficient combined cycle turbine plants and heat plants [36].
- The average biofuels and waste *PEF* (3.9) point them out as the least efficient process for electricity and heat generation. In contrast to high figures in China, India and US, Russia achieves low figures as they only use these fuels for heat production. In EU, competitive conversion efficiencies have been reached, even exceeding those in coal plants. This achievement is related to the higher use of gases and liquids for bioelectricity generation (40%) compared to less efficient biosolids plants in the rest of the nations, and to stimulation policies and recommendations [40].
- Decreasing PEF_{EHP} for every fuel reflect conversion technology enhancement over the period 1995-2017. The exception is Russia, where values increased due to drops in the heat share (from 78 to 63%) together with higher distribution losses and *EHP* own use (from 18 to 28%). Thus, higher PEF_{EHPf} figures do not necessarily mean a reversal of the advances in conversion technologies, as they may be due to other reasons in the energy sector.

	CHINA		INDIA		US		EU		RUSSIA		JAPAN	
Fuel	1995	2017	1995	2017	1995	2017	1995	2017	1995	2017	1995	2017
Coal	3.6	2.68	4.17	3.6	3.19	3.09	2.83	2.66	1.52	2.1	2.83	2.73
Oil	2.71	1.69	4.96	4.14	2.11	2.21	1.96	1.99	0.88	0.96	2.79	2.56
Gas	3.21	1.69	3.62	3.07	3.09	2.25	2.14	1.87	1.47	1.93	2.55	2.34
Nuclear	3.94	3.62	4.09	3.99	3.61	3.5	3.69	3.57	4.08	4.28	3.44	2.31
Bio&waste	4.35	4.42	-	8.65	8.11	4.01	2.14	2.16	1.48	1.72	2.88	2.88
Renewables	1.3	1.17	1.35	1.32	1.56	1.28	1.26	1.26	1.39	1.43	1.31	1.16

Table 1: Primary Energy Factor in Electricity and Heat Plants by fuel (PEF_{EHPf}). Years: 1995 and 2017.

In summary, shifting from Nuclear or Coal towards RW, Oil or Gas would normally result in a reduction of PEF_{EHP}. Additionally, fuel structure analysis can explain particular features in the previous stage. For instance, Japanese PEF_{EHP} drop in 2011 (*fig. 9*) induced by the shift from nuclear to fossil plants after Fuckushima accident [41], or PEF_T improvements in China and India (*fig. 10*) insufficient to offset unfavourable structural changes due to a better but still inefficient coal based electrification.

Finally, the complete energy intensity decomposition for every nation, including structures (s_{Tf}) and efficiencies (PEF_{Tf}) by transformation and fuel type, is shown in *fig. 12*. Both factors contribute to intensity reductions with the Russian exception, so that there have been positive structural changes in the fuel mixes together with improvements in the transformation efficiency. PEF_{Tf} impact is greater than s_{Tf}, especially in developing countries, with the exception of the EU, where the promotion of renewable plants has induced a positive change in the intensity to some 5%. Both China and Japan have experienced significant favourable changes in PEF_{Tf} (5%), mainly due to efficiency improvements of coal plants in the former and of nuclear plants in the latter. By contrast, both factors had a negative effect in Russia, since fuel structure worsened due to a rising nuclear share, and switching from heat to electricity plants led to an efficiency drop.

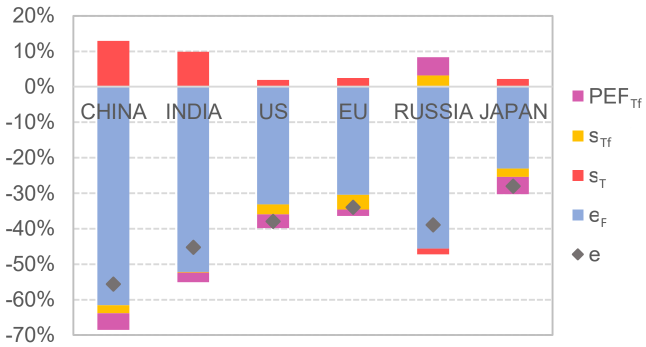

Fig. 12: Decomposition of changes in energy intensity (e) into final energy intensity (e_F), transformation sector structure (s_T), fuel structure by transformation type (s_{Tf}) and PEF by transformation and fuel type (PEF_{Tf}). Time period: 1995-2017.

4. CONCLUSIONS

Despite energy policies rely on carbon intensity as the main mitigating factor for climate change, historical trends have clearly placed energy efficiency as the unique driver curbing global CO_2 emissions growth. During the last decades, energy efficiency measures have been proved as feasible and effective worldwide, so they should remain as a keystone in the definition of future pathways to sustainable development.

To assess the impact of environmental policies on the efficiency of the energy system, this paper proposes a pyramidal approach to analyse and decompose energy intensity into its underlying factors. The main advantages of the new methodology should be remarked: it could serve as guidance for future analyses and for procedures standardization; it could help energy statisticians in their efficiency analysis and reporting duties; it defines structure indicators crucial to explain overall efficiency changes; and the results of its application could provide insights on energy sectors for the adjustment of national energy and climate policies.

Final energy intensity is shown as the major driver for efficiency improvement, though lower decreasing ratios in less intensive countries indicate technical efficiency limits, which could lead to a future convergence. During the period under study (1995-2017), developing nations such as China and India have achieved the largest efficiency improvements (56% and 46%, respectively), thanks to impressive final intensity drops (61% and 52%, respectively), which almost doubled those in developed nations. However, supply side efficiency changes have not been so significant (about one sixth of demand side change) and not always favourable. They have only contributed to efficiency gains in developed nations, raising concerns about the difficulties of an economy to thrive without worsening its energy sector efficiency due to a fossil fuel-based electrification.

A deeper analysis of supply side efficiency requires further decomposition into transformation types. Developing countries structures are dominated by directly carried over energy forms, unlike those in developed nations dominated by refineries. Structural changes have worsened energy intensity in every country due to shifts from highly efficient transformations such as Direct Carry Over (China and India), refineries (US, EU and Japan) and heat plants (Russia), with an average Primary Energy Factor (*PEF*) about 1.1, towards electrification, with an average *PEF* about 2.5. The improvement of transformation efficiency in developed countries has been high enough to cancel unfavourable structural changes, leading to slight but worthy energy sector efficiency gains (about 5%). On the contrary, for developing nations, lower transformation efficiencies and more adverse structural changes are responsible for significant losses in their energy sector efficiency (between 15 and 8%).

Over other transformations, the effects of fuel shifts in electricity and heat plants are highlighted. A hopeful structural change of some 5% is found in the EU, as electricity generation moves from coal and nuclear to efficient combined cycle gas plants and renewables, which are favoured by the 100% conversion efficiency assumption for non-thermal sources within the direct equivalent approach. Thus, the promotion of renewable electrification is twice convenient: it uses a non-emissive fuel to reduce carbon intensity and induces gains in energy sector efficiency to reduce energy intensity. Additionally, the improvement of power plants efficiencies for almost every fuel has caused non-negligible efficiency gains (up to 5% in China or Japan) in every country but Russia.

Unfortunately, emissions peak has not been already reached despite significant efficiency improvements worldwide. Great additional decarbonisation efforts to reduce carbon intensity are mandatory. The acceleration of renewable electrification, efficient power plants and coal phase out are the fundamentals of a near sustainable future.

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