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Unhiding the role of CHP in power & heat sector decomposition analyses

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A B S T R A C T

In many countries the role of combined heat & power (CHP) generation in the power & heat sector is significant. However, in decomposition analyses of the power & heat sector the contribution of CHP to observed changes in primary energy use or CO_2 emissions is generally not made explicit. In this paper, the contribution of CHP is shown for eight countries (China, Denmark, France, Germany, Italy, the Netherlands, Poland and the USA) in the period 2005–2016. In addition, an alternative method is proposed for power & heat sector decomposition analysis with five driving factors: volume effect, subsector effect, heat effect, fuel mix effect and efficiency effect. This method combines indicators from existing decomposition methods and complements them with a CHP specific heat effect. The proposed method provides improved insight in the factors driving change in primary energy use or CO_2 emissions in the power and heat sector, especially in case changes take place regarding either 1) the power-to-heat ratio, 2) the share of CHP electricity in total electricity production, 3) the CHP fuel mix, and/or 4) the efficiency of individual CHP fuels.

1. Introduction

In 2016 global energy-related CO_2 emissions amounted to 32.4 Gtonne (IEA, 2018a). The power & heat sector, including CHP and district heat boilers, was responsible for 41%, of these emissions (IEA, 2018a). As a major contributor to global CO_2 emissions, the power & heat sector is under a lot of pressure to become less carbon intensive. Mainly under influence of the implementation of renewable energy the average global carbon intensity has decreased by 20% between 1990 and 2017 (IEA, 2018a). Total CO_2 emissions in the power & heat sector, however, have increased in the same period by 46%, mainly explained by a strong increase in electricity consumption with 66%. A further increase of electricity use by 50–60% is expected by 2040 in comparison to 2017 levels (IEA, 2018a).

Besides using low carbon fuels and improving the efficiency of electricity generation, the CO_2 intensity of the power sector can also be reduced by applying cogeneration, also known as combined heat and power (CHP). By jointly producing electricity and useful heat, less primary energy is consumed compared to their separate production (Martens, 1998). Globally, 16% of electricity generation is produced in CHP plants with a total useful heat output of 11 EJ in 2016 (based on IEA, 2018b). Most CHP heat is generated in coal and natural gas-fired power plants, accounting for 52% and 39% of total useful heat output, with the remaining coming from biofuels, waste, oil and other fuels (based on IEA, 2018b). There is a wide country spread in CHP use, with many countries having - according to IEA statistics - no CHP capacity, whereas for a number of other countries CHP plants account for more than 55% of electricity generation (e.g. Mongolia, Kazakhstan, Poland, Russia, Belarus, Latvia, Denmark, Lithuania). In absolute sense the biggest amount of CHP heat is generated in China (37% of total global production), Russia (29%), United States (5%), Kazakhstan (4%) and Germany (3%).

As CHP plants generally have lower electric efficiencies compared to power-only plants, a growing share of co-generated electricity leads to more primary energy use in the power & heat sector. However, CHP heat typically replaces useful heat production elsewhere in the energy system, e.g. the heat produced by domestic or industrial boilers. Although it is generally acknowledged that good-performing CHP saves primary energy, these primary energy savings are realized at the overall energy system level and not in the power & heat sector. Therefore, if one wants to explain observed changes in primary energy use in the power & heat sector, it becomes important to explicitly take the useful heat generation from CHP plants into account.

Graus and Worrell (2011) have analysed *trends* in the performance of the power & heat sector, explicitly accounting for CHP. They applied different methods (e.g. power-loss, power & heat or power-only method) in order to calculate the change in energy-efficiency and CO_2 emission intensity of the power & heat sector. To not only gain insight in the

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trends driving the development of the power & heat sector, but also to be able to *quantify* the contribution of each of the drivers, decomposition analysis can be used. Decomposition analysis is a mathematical tool which has been applied in a variety of studies in energy-related environmental analyses (Ang and Zhang, 2000; Ang, 2004; Xu and Ang, 2013; Goh et al., 2018). Decomposition analysis can be used to decompose an aggregated indicator (e.g. the change in primary energy use or CO_2 emissions between a base year and a target year) into its driving forces, e.g. in a volume effect, a structure effect and an intensity effect. Decomposition analysis has also specifically been used by scholars for analysing the development of energy use and CO_2 emissions in the power generation sector, see Table 1 for an overview.

The way CHP is dealt with in the studies differs a lot. Some studies do not mention CHP at all, whereas Malla (2009) explicitly excludes CHP plants from the analysis. Karmellos et al. (2016) and Ang and Su (2016) recognized the role of CHP heat and included it in their analyses. However, they do not make the contribution of CHP to observed changes in the power & heat sector explicit.

In this study an attempt is made to fill the gap in literature with the following three objectives: 1) *explicitly* taking into account CHP in power & heat sector analysis using commonly applied decomposition methods, 2) proposing an alternative decomposition method for dealing with CHP, and 3) testing the added value of the alternative method to explain observed changes in primary energy used in the power & heat sector for policy makers.

2. Methods

2.1. Unhiding CHP in power sector decomposition analysis

Although some of the studies listed in Table 1 use different *volume indicators* in their decomposition identity such as GDP (Xie et al., 2019; Karmellos et al., 2016), electricity consumption (Liao et al., 2019) or fossil electricity only (Malla, 2009), the core of each of the decomposition identities used can be defined as:

$$\mathbf{CO_2 = \sum_i G \cdot \frac{G_{th,i}}{G} \cdot \frac{E_i}{G_{th,i}} \cdot \frac{CO_{2i}}{E_i}} \tag{1}$$

For explaining the observed change in *primary energy use* the basic decomposition identity would be the same as for CO_2 (equation (1)) but excluding the carbon emission factor and including all primary energy sources, rather than fossil energy alone:

$$\mathbf{E = \sum_i G \cdot \frac{G_i}{G} \cdot \frac{E_i}{G_i}} \tag{2}$$

Where:

E = Total primary energy input for power and heat generation
G = Total electricity generation in both CHP and power-only plants
i = Primary energy source

The analysis in this paper is focused on the decomposition of primary energy use. As any decomposition identity based on primary energy can be easily extended to include CO_2 - by applying the emissions factors of the fuels – the findings are relevant for emission-based decomposition analyses as well.

Equation (2) does not explicitly account for CHP heat. Phylipsen et al. (1998) were the first to coin a list of methods for allocating the primary energy input of CHP plants to its outputs. Two of them are widely applied: one based on the energy content of the output (generally referred to as the Power & Heat method), and one on the exergy content of the output (generally referred to as the Power-loss method). A third well-known method, the Power-only method, neglects the useful heat from CHP (Graus and Worrell, 2011). A decomposition analysis based on the Power-only method would use equation (2). Karmellos et al. (2016) used the Power & Heat method,[1] whereas Ang and Su (2016) used the Power-loss method in their analysis. In the Power & Heat method, electricity and heat are summed up, neglecting the quality (exergy) difference between the two outputs. For this method the following three-factor decomposition identity can be set up:

$$E = \sum_i (G + H) \cdot \frac{G_i + H_i}{G + H} \cdot \frac{E_i}{G_i + H_i} \tag{3}$$

Where:

H = Total heat generation in CHP plants (see equation (2) for the other symbols)

The Power-loss method, used by Ang and Su (2016), builds upon the fact that in certain types of power plants the production of useful heat is at the expense of power production, i.e. if no heat is produced in such plants, the power output is higher. How much higher is determined by the so-called power-loss factor. A power-loss factor of e.g. 0.2 means that for every unit of useful heat production, 0.2 units of power production is "lost" compared to the situation of power-only production. A three-factor decomposition identity based on this method looks like this:

$$E = \sum_i (G + \alpha \cdot H) \cdot \frac{G_i + \alpha \cdot H_i}{G + \alpha \cdot H} \cdot \frac{E_i}{G_i + \alpha \cdot H_i} \tag{4}$$

Where:

α = Power-loss factor (see equations (2) and (3) for other symbols)

Unhiding CHP in the Power-only method (equation (2)), the Power & Heat method (equation (3)) and the Power-loss method (equation (4)) leads to the following four-factor decomposition identities:

$$\text{Power-only:} \quad E = \sum_{j,i} (G) \cdot \frac{G_j}{G} \cdot \frac{G_{j,i}}{G_j} \cdot \frac{E_{j,i}}{G_{j,i}} \tag{5}$$

$$\text{Power \& Heat:} \quad E = \sum_{j,i} (G + H) \cdot \frac{G_j + H_j}{G + H} \cdot \frac{G_{j,i} + H_{j,i}}{G_j + H_j} \cdot \frac{E_{j,i}}{G_{j,i} + H_{j,i}} \tag{6}$$

$$\text{Power-loss:} \quad E = \sum_{j,i} (G + \alpha \cdot H) \cdot \frac{G_j + \alpha \cdot H_j}{G + \alpha \cdot H} \cdot \frac{G_{j,i} + \alpha \cdot H_{j,i}}{G_j + \alpha \cdot H_j} \cdot \frac{E_{j,i}}{G_{j,i} + \alpha \cdot H_{j,i}} \tag{7}$$

Where:

j = subsector (Power-only or CHP) (see equations (2)–(4) for other symbols)

These decomposition identities include an additional structure effect, showing a shift of (electricity) production between the subsector "Power-only" and the sub-sector "CHP".

2.2. Alternative method for power generation sector decomposition analysis

The methods given by equations (5)–(7), which are previously used, but without the subsector distinction, have their pros and cons. It might e.g. be questioned whether the recalculation of useful heat into electricity by the Power-loss method (α·H) and the summing of electricity and heat in the Power & Heat method (G + H) provides the best insight

[1] Although Karmellos et al. (2016) used this principle in their analysis, they did not include the heat in the calculation but subtracted the fuel amount assigned to the produced heat from the total fuel input based on the power-to-heat ratio: $E^* = E - E \cdot \frac{H}{H+G}$, where E* is the corrected primary energy use.

Table 1
Literature review of power generation sector decomposition analysis.

Studies	Decomposition identity used*	Countries analysed	How dealt with CHP?
Malla (2009)	$CO_2 = \sum_i G_{th} \cdot \frac{G_{th,i}}{G_{th}} \cdot \frac{E_i}{G_{th,i}} \cdot \frac{CO_{2i}}{E_i}$	Seven Asian Pacific and Northern American countries	CHP explicitly excluded
Zhang et al. (2013)	$CO_2 = \sum_i Y \cdot \frac{G}{Y} \cdot \frac{G_{th}}{G} \cdot \frac{G_{th,i}}{G_{th}} \cdot \frac{E_i}{G_{th,i}} \cdot \frac{CO_{2i}}{E_i}$	China	CHP not mentioned
Gu et al. (2015)	$CO_2 = \sum_i G \cdot \frac{G_{th}}{G} \cdot \frac{G_{th,i}}{G_{th}} \cdot \frac{E_i}{G_{th,i}} \cdot \frac{CO_{2i}}{E_i}$	China	CHP not mentioned
Karmellos et al. (2016)	$CO_2 = \sum_i Y \cdot \frac{G_c}{Y} \cdot \frac{G}{G_c} \cdot \frac{E_i}{G} \cdot \frac{CO_{2i}}{E_i}$	EU countries	CO_2 emissions corrected for CHP heat (power & heat method)
Ang and Su (2016)	$CO_2 = \sum_i G \cdot \frac{G_{th}}{G} \cdot \frac{G_{th,i}}{G_{th}} \cdot \frac{E_i}{G_{th,i}} \cdot \frac{CO_{2i}}{E_i}$	124 countries	CO_2 emissions corrected for CHP heat (power loss method)
Jiang and Li (2017)	$CO_2 = \sum_i G \cdot \frac{G_{th}}{G} \cdot \frac{E}{G_{th}} \cdot \frac{E_i}{E} \cdot \frac{CO_{2i}}{E_i}$	USA	CHP not mentioned
Wang et al. (2018)	$CO_2\ intensity = \frac{CO_2}{G} = \sum_i \frac{G_{th}}{G} \cdot \frac{E}{G_{th}} \cdot \frac{E_i}{E} \cdot \frac{CO_{2i}}{E_i}$	China	CHP not mentioned
Xie et al. (2019)	$CO_2 = \sum_i Y \cdot \frac{FE}{Y} \cdot \frac{G_c}{FE} \cdot \frac{G}{G_c} \cdot \frac{G_i}{G} \cdot \frac{E_i}{G_i} \cdot \frac{CO_{2i}}{E_i}$	China	CHP not mentioned
Liao et al. (2019)	$CO_2 = \sum_i G_c \cdot \frac{G}{G_c} \cdot \frac{G_{th}}{G} \cdot \frac{E}{G_{th}} \cdot \frac{CO_{2i}}{E}$	China	CHP not mentioned
De Oliveira-De Jesus (2019)	$CO_2\ intensity = \frac{CO_2}{G} = \sum_i \frac{8760 \cdot K}{G} \cdot \frac{K_{th}}{K} \cdot \frac{G_{th}}{8760 \cdot K_{th}} \cdot \frac{G_{th,i}}{G_{th}} \cdot \frac{E_i}{G_{th,\,i}} \cdot \frac{CO_{2i}}{E_i}$	Latin America & Caribbean	CHP not mentioned

Where:
E = Primary energy input (fossil)
FE = Final energy consumption
G = Electricity generation
G_{th} = Thermal electricity generation (fossil)
G_c = Electricity consumption
Y = GDP
K = Installed capacity
K_{th} = Installed thermal capacity (fossil) i = Primary energy source

* symbols used in the earlier studies have been unified to allow easier comparison.

in the factors that drive change in the power & heat sector:

- The most meaningful volume indicator is electricity, not useful heat, because changes in useful heat production are not necessarily a volume effect: a change in heat volume may be solely due to a shift between CHP and heat boiler-only production, i.e. total heat production at the overall energy system level might remain constant. Only the Power-only method uses electricity alone as volume indicator (see equation (5)).
- When analyzing a shift between the subsectors "Power-only" and "CHP", electricity is the only commodity that actually *can* be shifted between the two subsectors since useful heat is only produced in the CHP subsector. The Power-only method is the only method using electricity alone for analyzing shifts between the sub-sectors (see equation (5)).
- By neglecting the useful heat, however, the Power-only method does not provide good insight in fuel mix changes in the power & heat sector since part of the fuel consumption in the power & heat sector is used for producing useful heat. Efficiency changes in the power generation sector are also not well addressed by the Power-only method since the production of CHP heat contributes to the overall performance of the power & heat sector. For analyzing fuel mix and efficiency effects, the Power & Heat method and Power-loss method are therefore better methods than the Power-only method as they include the useful heat (see equations (6) and (7)).

Based on this, an alternative decomposition method is proposed combining the preferred indicators of the existing methods. This alternative method has two variants, one based on a combination of the Power-only and Power-loss method and one based on a combination of the Power-only method and Power & Heat method:

$$E = \sum_{j,i} G \cdot \frac{G_j}{G} \cdot \frac{G_j + \alpha \cdot H_j}{G_j} \cdot \frac{G_{j,i} + \alpha \cdot H_{j,i}}{G_j + \alpha \cdot H_j} \cdot \frac{E_{j,i}}{G_{j,i} + \alpha \cdot H_{j,i}} \quad (8)$$

$$E = \sum_{j,i} G \cdot \frac{G_j}{G} \cdot \frac{G_j + H_j}{G_j} \cdot \frac{G_{j,i} + H_{j,i}}{G_j + H_j} \cdot \frac{E_{j,i}}{G_{j,i} + H_{j,i}} \quad (9)$$

Compared to equations (5)–(7), a fifth driving factor is added to the decomposition identities: the *heat effect* (highlighted in yellow) For the subsector "Power-only" this heat effect is zero by definition in absence of useful heat production. In the remainder of this paper the alternative method is referred to as the *Power & CHP method* (with subscript "1" for the variant based on the Power-loss method, and with subscript "2" for the variant based on the Power & Heat method).

2.3. Data sources, data limitations, selection of countries

The primary data source used in this paper was the IEA Energy Balance (IEA, 2018b). The Energy Balance distinguishes four subsectors: main activity producer electricity plants, autoproducer electricity plants, main activity producer CHP plants and autoproducer CHP plants. In the analysis the four subsectors were merged into two: "Power-only" and "CHP". This was done to simplify the analysis since four subsectors would have required an additional driving factor in equations (5)–(9).

A limitation in the data is the way autoproducer CHP is dealt with in the IEA Energy Balance: since only sold heat is reported, the heat directly consumed on (industrial) sites and the fuel needed for producing that heat is not included in the figures for autoproducer CHP (IEA/Eurostat, 2005). This leads to an underestimation of the actual contribution of autoproducer CHP to total heat production, and has impact on the absolute decomposition results found for the power & heat sector of a country in case significant shifts between onsite heat consumption and sold heat take place. Such shifts can take place in reality (for example because of changed ownership of a CHP plant) or just in the energy statistics (for example by improved country reporting to the IEA). It was beyond the scope of this study to explore this further in-depth. The effect, if any, is deemed small, however, and does not alter the conclusions of this paper.

In the analysis the following eight IEA fuel categories were used: coal/coal products, oil products, natural gas, nuclear, biofuels/waste, solar/wind/other, hydro and geothermal.

In order to test the alternative method and determine its added value, the period 2005–2016 was chosen for decomposing primary energy use trends in the power & heat sector. This e.g. allowed to include China in the analysis, which is - in absolute sense - the biggest CHP country globally (IEA provides CHP statistics for China since 2005 only). To allow for a rich variety of data, countries with different CHP characteristics were included in the analysis, see Table 2. The eight selected countries account for more than 50% of global heat production from CHP in 2016 (based on IEA, 2018b).

2.4. Quantifying the driving factors for each decomposition method

For the decomposition analysis of the power & heat sector of the eight countries using equations (5)–(9), the Log Mean Divisia (LMD) approach was used. Advantages of the LMD approach are the lack of a residual for multi-factor decomposition analysis and the ease of applying multi-dimensional decomposition analysis (Ang and Wang, 2015). The LMD equations are provided in Table 3. The coloured cells indicate that the methods share the same factors for analysis. Note however that all factors become the same in absence of CHP heat, i.e. for the subsector "Power-only", independent from the choice of decomposition method.

3. Results & discussion

3.1. Overview

Fig. 1 shows for the eight countries the results based on the five different decomposition methods. For each country the observed change in primary energy use between 2005 and 2016 is provided (red dotted line). In addition, the primary energy use in 2016 is given as well to put the change in context. It shows for example that the primary energy use in the Chinese power & heat sector more than doubled; that for Germany, France, Italy and the USA the primary energy use declined by 9–13%; that Denmark experienced a more significant decrease of the energy use in the sector (−25%); and that Poland (−2%) and the Netherlands (+3%) only saw a small decrease/increase. Especially for the Netherlands (and to a smaller extent also for Poland) the upper and lower range of the driving factors) are relatively big compared to the other countries (for the Netherlands they range from about +300 to −300 PJ whereas the difference in primary energy is only +25.9 PJ between 2005 and 2016).

Table 2
Selected countries with their CHP characteristics in the period 2005–2016*.

	Power-to-heat ratio power & heat sector		Power-to-heat ratio CHP subsector		CHP electricity as share of total electricity		ΔCHP electricity 2005-2016	ΔCHP heat 2005-2016	CHP Fuel dominance (>50% share)	Major shifts between CHP fuels	Δ overall CHP efficiency
	2005	2016	2005	2016	2005	2016	TWh (% change)	PJ (% change)	Share (%) 2005→2016	Share (%) 2005→2016	% 2005→2016
CHI	4.3	5.9	1.6	1.7	36.8%	28.3%	+831.9 (+90.4%)	+1674.6 (+80.2%)	Coal: 99→97%	-	45.9→50.8%
DEN	1.2	1.2	1.0	0.7	81.6%	55.6%	-12.6 (-42.7%)	-14.8 (-14.0%)	-	Bio: 19→44% NG: 28→11%	71.2→78.5%
FRA	12.2	21.4	0.5	0.7	4.3%	3.4%	-6.0 (-24.4%)	-76.4 (-45.2%)	NG: 62→42% Bio: 15→52%	Bio: 15→52% NG 62→42% Oil 15→5%	77.9→71.7%
GER	6.1	6.8	0.9	1.3	14.5%	19.3%	+34.9 (+39%)	-24.8 (-6.8%)	-	Bio: 12→31% Coal 35→24%	74.5→68.6%
ITA	5.5	4.7	1.8	1.7	31.8%	36.5%	+10.7 (+11.3%)	+26.7 (+13.8%)	NG: 65→66%	Bio: 5→14% Oil: 25→16%	58.3→60.9%
NLD	2.8	4.0	1.6	1.4	57.5%	36.2%	-15.7 (-27.4%)	-25.2 (-19.5%)	NG: 70→59%	Bio: 6→24% NG: 70→59%	68.4→68.9%
POL	2.5	3.1	2.3	2.8	92.1%	88.6%	+4.1 (+2.8%)	-30.3 (-13.8%)	Coal: 94→90%	-	48.6→48.3%
USA	61.5	30.5	4.8	2.2	7.8%	7.4%	-14.8 (-4.5%)	+25.8 (+103.4%)	NG: 59→72%	NG: 59→72% Coal 20→12%	43.9→70.1%

* Colors indicate the direction of change, where (light) green is a positive change for CHP, and red and orange a negative change. Light green and red are used for relatively big changes, orange and dark green for smaller changes; CHI = China, DEN = Denmark, FRA = France, GER = Germany, ITA = Italy, NLD = Netherlands, POL = Poland, USA = United States.

Table 3
LMD equations used per method for each of the five effects.

Driving factors	Decomposition methods				
	Power-only	Power-loss	Power & CHP_1	Power & CHP_2	Power & Heat
Volume effect (VE)	$LM \times \ln \frac{G_t}{G_0}$	$LM \times \ln \frac{(G + \alpha \cdot H)_t}{(G + \alpha \cdot H)_0}$	$LM \times \ln \frac{G_t}{G_0}$		$LM \times \ln \frac{(G + H)_t}{(G + H)_0}$
Subsector effect (SE)	$LM \times \ln \frac{\left(\frac{G_j}{G}\right)_t}{\left(\frac{G_j}{G}\right)_0}$	$LM \times \ln \frac{\left(\frac{G_j + \alpha \cdot H_j}{G + \alpha \cdot H}\right)_t}{\left(\frac{G_j + \alpha \cdot H_j}{G + \alpha \cdot H}\right)_0}$	$LM \times \ln \frac{\left(\frac{G_j}{G}\right)_t}{\left(\frac{G_j}{G}\right)_0}$		$LM \times \ln \frac{\left(\frac{G_j + H_j}{G + H}\right)_t}{\left(\frac{G_j + H_j}{G + H}\right)_0}$
Heat effect (HE)	-	-	$LM \times \ln \frac{\left(\frac{G_j + \alpha \cdot H_j}{G_j}\right)_t}{\left(\frac{G_j + \alpha \cdot H_j}{G_j}\right)_0}$	$LM \times \ln \frac{\left(\frac{G_j + H_j}{G_j}\right)_t}{\left(\frac{G_j + H_j}{G_j}\right)_0}$	-
Fuel mix effect (FME)	$LM \times \ln \frac{\left(\frac{G_{j,i}}{G_j}\right)_t}{\left(\frac{G_{j,i}}{G_j}\right)_0}$	$LM \times \ln \frac{\left(\frac{G_{j,i} + \alpha \cdot H_{j,i}}{G_j + \alpha \cdot H_j}\right)_t}{\left(\frac{G_{j,i} + \alpha \cdot H_{j,i}}{G_j + \alpha \cdot H_j}\right)_0}$		$LM \times \ln \frac{\left(\frac{G_{j,i} + H_{j,i}}{G_j + H_j}\right)_t}{\left(\frac{G_{j,i} + H_{j,i}}{G_j + H_j}\right)_0}$	
Efficiency effect (EE)	$LM \times \ln \frac{\left(\frac{E_{j,i}}{G_{j,i}}\right)_t}{\left(\frac{E_{j,i}}{G_{j,i}}\right)_0}$	$LM \times \ln \frac{\left(\frac{E_{j,i}}{G_{j,i} + \alpha \cdot H_{j,i}}\right)_t}{\left(\frac{E_{j,i}}{G_{j,i} + \alpha \cdot H_{j,i}}\right)_0}$		$LM \times \ln \frac{\left(\frac{E_{j,i}}{G_{j,i} + H_{j,i}}\right)_t}{\left(\frac{E_{j,i}}{G_{j,i} + H_{j,i}}\right)_0}$	

with: $LM = \log mean = \frac{E_{0,i,j} - E_{t,i,j}}{\ln \frac{E_{0,i,j}}{E_{t,i,j}}}$

If one looks at China's results, it is clear that the volume effect is the dominant driver. It is actually so dominant, that the decomposition results seem similar for the five methods. For the other countries differences between all, or at least some, of the methods are visible. An important finding is that a relatively small role of CHP in the power & heat sector of a country does not lead to decomposition results that are independent from the method chosen and dominated by the subsector "Power-only". In France and the USA, for example, CHP only plays a marginal role in the power & heat sector (see Table 2). Still the results for both counties in Fig. 1 show diversity between the five methods which is explained by differences in the driving factors of the subsector "CHP". At the same time, in Italy and the Netherlands, countries in which the role of CHP in the power & heat sector is significant, the difference between the five methods is less pronounced. These results may not seem intuitive at first glance, but they show the merits of unhiding the contribution of CHP in power & heat sector decomposition. In the next sections, explanations are given for the observed effects by discussing each driving factor in more detail. The reader is also referred to the Supplementary Material in which an overview of the results for all eight countries is given.

3.2. Volume effect (VE)

The volume effect found in the Power & Heat method is different from the other methods except for Denmark, see Fig. 1. This is because the volume indicator used by the Power & Heat method is the total electricity production plus the useful heat output (see Table 3), which is impacted by a (substantial) change in the power-to-heat ratio of the power & heat sector as a whole. The latter is the case in the all countries except Denmark (see Table 2).

The contribution of useful heat to the volume effect is by definition bigger for the Power & Heat method than for the Power-loss method as in the latter the useful heat is multiplied with a power-loss factor of 0.2. As discussed in section 2.2, the possible impact of useful heat on the volume effect of the Power & Heat method (and, thus, to a lesser extent the Power-loss method) makes that these decomposition methods may not offer the true volume effect one is looking for when analyzing the power & heat sector.

Only for China and France the volume effect in Fig. 1 is split between the two subsectors (VE-PP and VE-CHP). The explanation is that the direction of change for both subsectors is the same in these countries. In China both the subsector "Power-only" and the subsector "CHP" is growing in volume, whereas in France both subsectors show a decreasing volume. For the six other countries the direction of change is opposite. i.e. either the one subsector is increasing in volume and the other decreasing, or the other way around. In that case it is not meaningful to allocate the volume effect to the two subsectors, as this would lead to a positive (or a negative) volume effect for both subsectors, whereas intuitively the volume effect of one of the subsectors should point in a diffferent direction. This can be illustrated with the data from the Netherlands. In the period 2005–2016 the Dutch subsector "CHP" shrank whereas the subsector "Power-only" grew. In Table 4 the volume effect is shown for two different calculations: 1) one in which the power & heat sector as whole is decomposed with two subsectors, and 2) one in

Fig. 1. Driving factors in the power & heat sector (red-dotted line provides the change in primary energy use in the power & heat sector between 2005 and 2016)VE = volume effect, SE = subsector effect, HE = heat effect, FME = fuel mix effect, EE = efficiency effect, PP = subsector "Power-only", CHP = subsector "CHP". (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Case Netherlands 2005–2016: volume effect CHP subsector can either be negative or positive (illustration for Power-only method).

	Decomposition of the power & heat sector		Decomposition of the subsectors separately	
PJ	Power Plants	CHP	Power Plants	CHP
Volume effect	62	59	241	-133
Subsector effect	179	-192	NA	NA
Total of the two effects	241	-133	241	-133

which the two subsectors are decomposed separately. In the first case the volume effect of the CHP subsector is positive (which is counterintuitive), in the second negative. Note that in the first case the sum of volume effect and subsector effect is the same as the volume effect in the second case. This means that in the second case the shift from CHP to power-only plants is included in the volume effect, withouta subsector effect (NA). The explanation is found in the LMD equation which is used for calculating the volume effect (see also Table 3 in section 2.4):

$$VE_{CHP} = \frac{E_{2005,CHP} - E_{2016,CHP}}{\ln \frac{E_{2005,\ CHP}}{E_{2016,\ CHP}}} \cdot \ln \frac{V_{2016}}{V_{2005}} \tag{10}$$

Whereas the log mean (left side of the equation) is CHP specific, and by definition a positive number, the natural log at the right side of the equation is only looking at the volume of the power & heat sector as a whole (which is also a positive number), and not at the volume of the subsector "CHP" (a negative number). An important lesson, therefore, for multi-dimensional decomposition analysis is to only disaggregate the volume effect if the direction of change in all subsectors is the same.

3.3. Subsector effect (SE)

The subsector effect is a driving factor that explains how much of the observed change in primary energy use can be allocated to volume shifts between the subsectors. A net positive subsector effect (SE-PP + SE-CHP) means that the volume is shifted to the less efficient subsector (i.e. the subsector that needs more fuel input for producing the same output/volume), whereas a net negative subsector effect means the opposite. In Fig. 1 the subsector effects are shown per subsector, but in Table 5 they are summed. For Denmark and Poland the net subsector effect is always negative (i.e. a shift takes place to the more efficient subsector). For the other countries the net subsector effect is either positive or negative, depending on the decomposition method. Often the Power & Heat method and in some cases the Power-loss method gives a different outcome which is explained by the inclusion of useful heat in the calculation of the subsector effect in these methods.

For the USA the net subsector effect is close to zero for all methods except the Power & Heat method. This is explained by the small change in the share of CHP electricity in total electricity production from 7.8% in 2005 and 7.4% in 2016, see Table 2 (section 2.4). For the Power-only method and the Power & CHP methods it is always true that the subsector effect is zero in case of a constant share of CHP electricity in total electricity production as these methods do not include the useful heat production in the calculation of the subsector effect. Like for the volume effect, the possible impact of useful heat on the subsector effect of the Power & Heat method (and to a lesser extent the Power-loss method)

Table 5
Net subsector effect for each decomposition method.

PJ	Power-only	Power-loss	Power & CHP_1	Power & CHP_2	Power & Heat
China	-1256	-896	-1256	-1256	385
Denmark	-59	-41	-59	-59	-10
France	-12	7	-12	-12	120
Germany	35	-9	35	35	-76
Italy	30	18	30	30	-24
Netherlands	-14	9	-14	-14	74
Poland	-33	-30	-33	-33	-19
USA	3	3	3	3	-106

makes that these decomposition methods may not offer the true subsector effect one is looking for when analyzing the power & heat sector.

3.4. Heat effect

The heat effect is only used in the Power & CHP method and the effect is only found and meaningful for the subsector "CHP". It is therefore zero, by definition, for the subsector "Power-only" and should not be applied in decomposition analyses where no distinction is made between CHP and power-only production to avoid flawed calculation results. The heat effect can be considered a *relative* volume effect. The more heat produced (relative to the electricity production by CHP plants), the more primary energy consumed (all other factors constant). It is a relative effect, which means that it is not affected by an absolute reduction of the useful heat output in a country (such as in Denmark and the Netherlands, see Table 2). Table 6 shows that if the power-to-heat ratio in the subsector "CHP" is decreasing (more useful heat output per unit of electricity output), the heat effect is positive and contributes to an increase of the primary energy use in the power & heat sector. If the power-to-heat ratio is increasing the heat effect is negative. The heat effect is zero in case the CHP power-to-heat ratio does not change in a country. This explains the small contribution of the heat effect to the observed change in primary energy use in China, Italy and, to a lesser extent, the Netherlands. See also the HE-effect in Fig. 1 which is not or hardly visible for these countries.

3.5. Fuel mix effect (FME)

The fuel mix effect provides the contribution to the observed change in primary energy use because of fuel mix changes *in* a subsector. This means that the fuel mix effect does not account for interactions *between* the two subsectors. The latter interactions are dealt with in section 3.3 (subsector effect).

In Fig. 1 the fuel mix effect for each country is the *net* fuel mix effect and does not provide details how individual fuels contributed to the effect. A fuel that has a positive fuel mix effect is increasingly used (and therefore leads to an increase of primary energy use), whereas a fuel with a negative fuel mix effect is used less. If a switch takes place from a more efficient fuel to a less efficient fuel the net effect is a higher primary energy use. Denmark is an interesting country for discussing the effects per fuel in more detail since the Power & CHP_2 method and the Power & Heat method show a positive net fuel mix effect for the subsector "CHP" whereas the other decomposition methods show a negative net fuel mix effect. In Fig. 2 the results are shown.

The fuel category biofuels and waste (futher referred to as "biomass") has a positive fuel mix effect which means its use increased between 2005 and 2016, whereas the use of the other fuel categories decreased. This is also confirmed by the change in fuel shares as presented in Fig. 3. The net negative fuel mix effect found for the Power & Heat method and the Power & CHP_2 method implies that in these methods biomass conversion is more efficient than the weigthed average conversion of coal, oil and natural gas. The opposite is true for the other methods and is explained by the inclusion of useful heat production in the calculation of the fuel mix effect in the Power & Heat method and the Power & CHP_2 method.

Fig. 3 also explains why the fuel mix effect for the Danish subsector "Power-only" is virtually absent in Fig. 2: the majority of the "fuel" used in this subsector is wind energy (part of the IEA fuel category Solar/wind/other) which hardly changes between 2005 and 2016.

If the fuel mix changes in the subsector "CHP" and subsector "Power-only" are mainly shifts between fuels with similar efficiencies, the fuel mix effect results of the five methods are very close. This is for example the case for the CHP subsector in Poland (see Fig. 1). It is important to not confuse the fuel mix effect with the efficiency effect. If the efficiency of a fuel category improves between 2005 and 2016, the efficiency effect leads to *less* primary energy use, independent from the decomposition method chosen. This is shown in section 3.6.

As argued in section 2.2, the useful heat production plays a role in observed fuel mix changes since fuel is needed to produce the useful heat. Therefore, decomposition methods that include useful heat

Table 6
Heat effect versus change in CHP power-to-heat ratio.

	Decomposition methods		Change CHP power-to-heat ratio
	Power & CHP_1 [PJ]	Power & CHP_2 [PJ]	2005 -> 2016
China	-93	-324	1.6 -> 1.7
Denmark	19	52	1.0 -> 0.7
France	-20	-51	0.5 -> 0.7
Germany	-63	-194	0.9 -> 1.3
Italy	2	8	1.8 -> 1.7
Netherlands	5	17	1.6 -> 1.4
Poland	-19	-74	2.3 -> 2.8
USA	123	495	4.8 -> 2.2

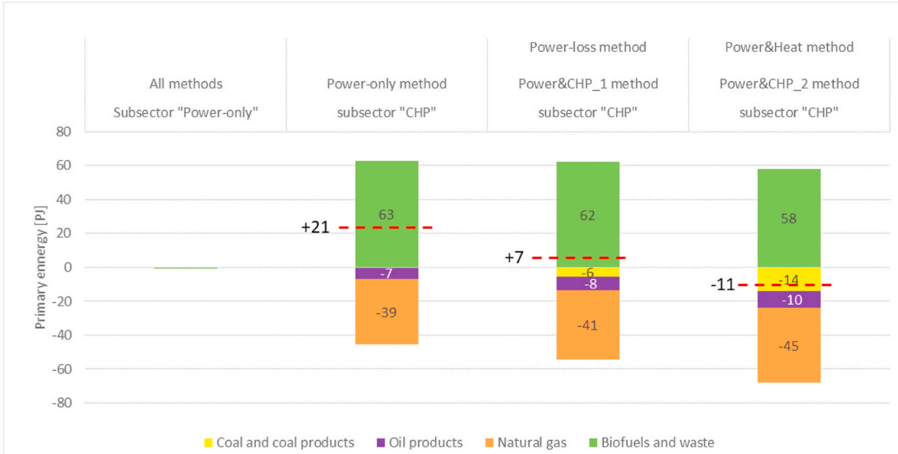

Fig. 2. Fuel mix effect power & heat sector Denmark 2005–2016 (net fuel mix effect indicated with the red-dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. Fuel share in 2005 and 2016 as a percentage of total primary energy use in Denmark in the subsector "CHP" and the subsector "Power-only".

production in the calculation of the fuel mix effect (all methods except for the Power-only method) lead to more meaningful insights in the contribution of the fuel mix effect to the oberved change in primary energy use in the power & heat sector.

3.6. *Efficiency effect (EE)*

The efficiency effect provides the contribution to the observed change in primary energy use because of changes in the conversion efficiency of an *individual* fuel. This means that the efficiency effect does not account for changes in primary energy use because of fuel mix changes between fuels with different conversion efficiencies. The latter was dealt with in the previous section. The efficiency effect for the Power-only subsector is the same for all methods (explained by the use of the same efficiency indicator, see Table 3), whereas for the CHP subsector the efficiency effect calculated with the Power-loss method is the same for the Power & CHP method_1, and the efficiency effect calculated with the Power & Heat method is the same for the Power & CHP method_2 (see also Table 3).

Except for Denmark, Germany and Poland, a negative net efficiency effect of the CHP subsector was found for all five decomposition methods. This means that because of efficiency improvement less primary energy was used in 2016 compared to 2005. For Denmark, Germany and Poland a positive efficiency effect of the CHP subsector was found for the Power & CHP_2 method and the Power & Heat method. Germany was chosen to illustrate the efficiency effect in more detail, see Fig. 4.

Fig. 4 only shows four fuel categories: coal/coal products, natural gas, oil products, and biofuels/waste. The fuel categories solar/wind/other, hydro and nuclear are not present in the figure since the IEA Energy Statistics use default efficiencies for these fuels (IEA/Eurostat, 2005). These default efficiencies do not change between 2005 and 2016 (e.g. for nuclear the electric efficiency is 33% in 2005 and in 2016, whereas for solar PV, wind and hydro it is 100%) which makes that the

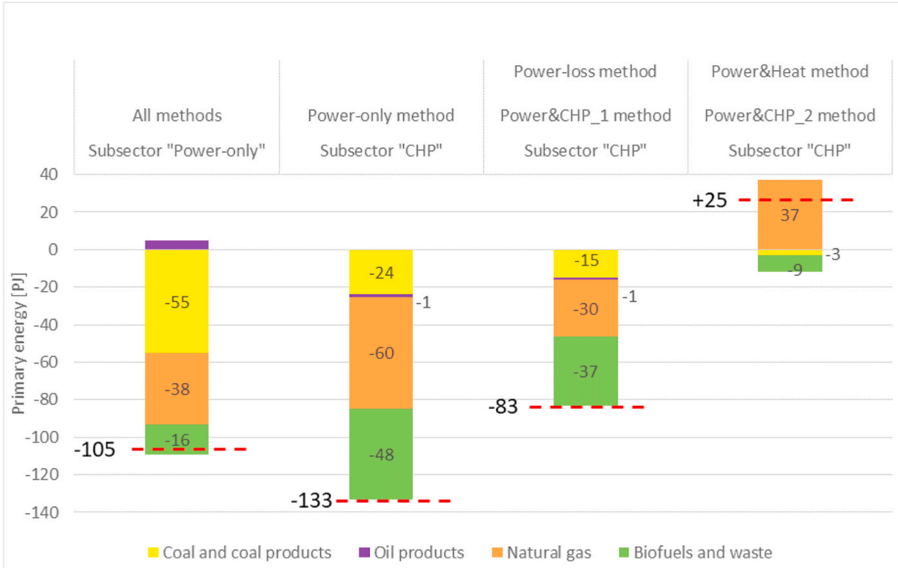

Fig. 4. Efficiency effect power & heat sector Germany 2005–2016 (net efficiency effect indicated with the red-dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

efficiency effect is zero (e.g. for nuclear: $\ln \frac{33\%}{33\%} = 0$).

In Table 7 various efficiencies, including the efficiency indicators used in the five methods, are shown for 2005 and 2016 for Germany. It is indicated (with red and green) which of the 2016 efficiencies increased or decreased since 2005. The figures in the table can be used to explain what happens in Fig. 4. For the subsector "Power-only" oil-based power

Table 7

Change in conversion efficiencies in the German power & heat sector between 2005 and 2016.

2005	Coal	Oil	Natural gas	Biomass
thermal efficiency CHP	49.4%	9.2%	37.9%	24.1%
electric efficiency CHP (power-only method)	26.6%	48.4%	39.6%	29.1%
overall efficiency CHP (power & heat method)	76.1%	57.6%	77.6%	53.3%
Electric effiency CHP (based on power-loss method)	36.5%	50.2%	47.2%	34.0%
electric efficiency power-only plants	38.9%	39.1%	42.0%	30.3%
electric efficiency power & heat sector	37.6%	41.9%	40.3%	29.7%
overall efficiency power & heat sector	43.1%	44.8%	66.9%	42.0%
2016*				
thermal efficiency CHP	47.9%	5.9%	27.0%	18.9%
electric efficiency CHP (power-only method)	28.9%	51.4%	44.8%	36.8%
overall efficiency CHP (power & heat method)	76.8%	57.3%	71.9%	55.7%
electric efficiency CHP (based on power-loss method)	38.5%	52.6%	50.2%	40.6%
electric efficiency power-only plants	39.8%	35.6%	53.1%	33.4%
electric efficiency power& heat sector	38.7%	41.2%	46.5%	35.4%
overall efficiency power & heat sector	43.8%	43.4%	68.0%	46.7%

* red colours indicate that efficiencies decreased between 2005 and 2016, green colours point at an increase.

Grey coloured cells indicate fuels for which the *efficiency effect* for a decomposition method is positive, i.e. leading to an increase in primary energy use.

production shows a positive efficiency effect for all five decomposition methods which is explained by a decreasing electric conversion efficiency between 2005 and 2016 (from 39.1% to 35.6%). For the subsector "CHP" natural gas-based CHP plants show a positive efficiency effect for the Power & CHP_2 method and the Power & Heat method which is explained by a decrease of the overall CHP efficiency (thermal efficiency + electric efficiency) between 2005 and 2016 (from 77.6% to 71.9%). The data in the table reveals that the thermal efficiency of natural gas-based CHP declined whereas the electric efficiency increased, but to a lesser extent.

As the Power-only method is possibly under or overestimating the performance of the power & heat sector, since the impact of efficiency changes in useful heat production are neglected,[2] the two variants of the Power & CHP method (and thus the Power-loss method and the Power & Heat method as well) offer the better efficiency indicators. Whether the Power & CHP_1 method should be preferred over the Power & CHP_2 method depends on the type of CHP plants in a country. For the Netherlands, for example, about 50% of the electricity produced by CHP plants in 2016 came from plants that do not experience power loss (derived from CBS, 2019), which means that for the Netherlands an average of the results of the Power & CHP method_1 (using the Power-loss indicator) and Power & CHP method_2 (using the Power & Heat indicator) may offer the most accurate efficiency effect. Adding this detail to the analysis is only possible in case disaggregated technology specific data is available. Such detail is not available in the IEA data, which were used in this paper.

4. Conclusion & policy implications

The first objective of this paper was to *explicitly* take into account CHP in power & heat sector analyses. This was done for existing decomposition methods (Power-only, Power & Heat, Power-loss) and for a proposed Power & CHP method. The results show that, independent from the method chosen, even for countries with low shares of CHP in the power generation sector such as France and the USA, CHP can have a significant contribution to the observed change in primary energy use. This provides a justification to analyse CHP as a separate subsector. An additional argument for unhiding the CHP contribution is the different dynamics the subsector "CHP" experiences compared to the subsector "Power-only", since the latter is showing a strong shift towards variable renewable energy sources such as 100% efficient wind and solar in many countries, whereas the subsector "CHP" is showing a shift toward biomass, being typically less efficient than e.g. natural gas.

The second objective of this paper was to propose an alternative decomposition method for dealing with CHP: The Power & CHP method. Two variants were proposed: one being a combination of the Power-only and the Power-loss method, and one being a combination of the Power-only and the Power & Heat method. The Power-only method offers the best volume indicator to calculate the volume effect and the subsector effect. A volume indicator based on electricity and heat (such as used in the Power-loss and Power & Heat method) is less appropriate for analysing the volume and subsector effect of the power & heat sector since 1) useful heat is also generated outside the power & heat sector (e.g. by domestic boilers) which means that an increase of heat production in the power & heat sector is not necessarily showing a volume growth but rather a structure change (an increase of heat production in the power & heat sector at the expense of useful heat generation elsewhere in the energy system); and 2) electricity is the only commodity that can be shifted between the subsectors "Power-only" and "CHP", since the subsector "Power-only" does not produce heat. The Power-loss method and Power & Heat method offer the best indicators for the fuel mix effect and the efficiency effect. Since both effects provide insight in the *performance* of the power generation sector, neglecting the heat which the Power-only method does masks the true effects. Whether the Power-loss indicators (Power & CHP method_1) or the Power & Heat indicators (Power & CHP method_2) should be chosen depends on which type of CHP plants are used in a country. The Power-loss indicator will lead to the most meaningful results for countries for which the CHP production is dominated by CHP plants that experience power-loss (i.e. condensing steam turbines). The Power & Heat indicator will lead to the most meaningful results in countries where the majority of CHP plants does not experience power-loss (examples are internal combustion engines, gas turbines and back-pressure steam turbines).

The third objective of this paper was to test the added value of the proposed Power & CHP method for explaining observed changes in primary energy use in the power & heat sector. Apart from the merits of unhiding the contribution of CHP in the power & heat sector, which is true for all methods (see above), the question is to what extent the proposed method offers added value for policy makers compared to the other methods. It is recalled that all five decomposition methods provide the *same* results for the subsector "Power-only" and that they *only* provide differences for the subsector "CHP" in case there are changes in: 1) the sector-wide power-to-heat ratio, 2) the share of CHP electricity in total electricity production, 3) the CHP fuel mix, or 4) the efficiency of individual CHP fuels.

For future policy analyses of the power & heat sector that aims to explain an observed changed in primary energy use or CO_2 emission in its driving factors, it is recommended to not use the Power & Heat method and the Power-loss method because of the way these methods calculate the volume effect and the subsector effect. Whether a researcher can choose for the simple Power-only method (in which the CHP heat is neglected) depends on whether one of the four changes mentioned above takes place in the subsector "CHP". If none of these changes takes place, one can choose the Power-only method even in countries with a significant share of CHP production. It is however recommended to apply the proposed Power & CHP method as it is a "no-regret" choice: in case the subsector "CHP" does not experience any of the above four changes, it provides the same result as the Power-only method, but in case one of these changes does take place, the method is able to explain in detail how the subsector "CHP" has contributed to observed changes in the power & heat sector.

[2] In case the efficiency of heat production in CHP does not change, the Power-only method gives the same results as the other methods.

CRediT authorship contribution statement

Robert Harmsen: Conceptualization, Methodology, data analysis, Visualization, writing. **Wina Crijns-Graus:** data preparation, output checks, writing, reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112208.

References

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Pol. 32, 1131–1139.
Ang, B.W., Su, B., 2016. Carbon emission intensity in electricity production: a global analysis. Energy Pol. 94, 56–63.
Ang, B.W., Wang, H., 2015. Index decomposition analysis with multidimensional and multilevel energy data. Energy Econ. 51, 67–76.
Ang, B.W, Zhang, F.Q., 2000. A survey of index decomposition analysis in energy and environmental studies. Energy 25 (12), 1149–1176.

CBS (Statistics Netherlands), 2019. Electricity: Production and Means of Production. https://opendata.cbs.nl/statline/#/CBS/en/. (Accessed 6 January 2020).
De Oliveira-De Jesus, S., 2019. Effect of generation capacity factors on carbon emission intensity of electricity of Latin America & the Caribbean, a temporal IDA-LMDI analysis. Renew. Sustain. Energy Rev. 101, 516–526.
Goh, T., Ang, B.W., Xu, X.Y., 2018. Quantifying drivers of CO_2 emissions from electricity generation–Current practices and future extensions. Appl. Energy 231, 1191–1204.
Graus, W.H.J., Worrell, E., 2011. Methods for calculating CO_2 intensity of power generation and consumption: a global perspective. Energy Pol. 39, 613–627.
Gu, B., Tan, X., Zeng, Y., Mu, Z., 2015. CO_2 emission reduction potential in China's electricity sector: scenario analysis based on LMDI decomposition. Energy Procedia 75, 2436–2447.
IEA, 2018a. World Energy Outlook 2018 Edition. International Energy Agency (IEA), Paris, France.
IEA, 2018b. World Energy Balances Database, 2018 edition. International Energy Agency (IEA), Paris, France.
IEA/Eurostat, 2005. Energy Statistics Manual. International Energy Agency (IEA), Paris, France. https://www.iea.org/training/toolsandresources/energystatisticsmanual/.
Jiang, X-T, Li, R., 2017. Decoupling and decomposition analysis of carbon emissions from electric output in the United States. Sustainability 9 (6), 886.
Karmellos, M., Kopidou, D., Diakoulaki, D., 2016. A decomposition analysis of the driving factors of CO_2 (Carbon dioxide) emissions from the power sector in the European Union countries. Energy 94, 680–692.
Liao, C., Wang, S., Zhang, Y., Song, D., Zhang, C., 2019. Driving forces and clustering analysis of provincial-level CO_2 emissions from the power sector in China from 2005 to 2015. J. Clean. Prod. 240 (10), 118026.
Malla, S., 2009. CO_2 emissions from electricity generation in seven Asia-Pacific and North American countries: a decomposition analysis. Energy Pol. 37, 1–9.
Martens, A., 1998. The energetic feasibility of CHP compared to the separate production of heat and power. Appl. Therm. Eng. 18, 935–946.
Phylipsen, G.J.M., Blok, K., Worrell, E., 1998. Handbook on International Comparisons of Energy Efficiency in the Manufacturing Industry. Department of Science, Technology and Society, Utrecht University.
Wang, J., He, S., Qiu, Y., Liu, N., Li, Y., Dong, Z., 2018. Investigating driving forces of aggregate carbon intensity of electricity generation in China. Energy Pol. 113, 249–257.
Xie, P., Gao, S., Sun, F., 2019. An analysis of the decoupling relationship between CO_2 emission in power industry and GDP in China based on LMDI method. J. Clean. Prod. 211, 598–606.
Xu, X.Y., Ang, B.W., 2013. Index decomposition analysis applied to CO_2 emission studies. Ecol. Econ. 93, 313–329.
Zhang, M., Liu, X., Wang, W., Zhou, M., 2013. Decomposition analysis of CO_2 emissions from electricity generation in China. Energy Pol. 52, 159–165.