PAPER IV

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CO_2 emissions attributed to annual average electricity consumption in OECD (the Organisation for Economic Co-operation and Development) countries

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ABSTRACT

When regulating GHG emissions at the country or product level, it is critical to determine the GHG emissions from electricity consumption. In this study, we calculated production-based and consumption-based CO_2 emission intensities of electricity for the OECD (the Organisation for Economic Co-operation and Development) countries during 1990–2008. We examined the impact of annual development, allocation procedure in combined heat and power production, and electricity trade on CO_2 emissions. The studied factors significantly, yet highly variably, influenced the results for many countries. The consumption-based CO_2 emission intensity of electricity differed significantly from the production-based intensity for some European OECD countries such as Switzerland, Norway, Slovakia, and Austria. As the use of the production-based method in assessing, verifying, and monitoring the GHG performance of specific products can be highly misleading, the use of consumption-based methods are preferable. The absolute value of CO_2 emissions embodied in electricity net imports accounted for more than 5% of the overall national CO_2 emissions in at least some of the years studied for 13 European countries. The electricity trade and the related GHG emission leakage may increase in the future if effective emission reduction and regulation measures are not more widely implemented.

1. Introduction

Ambitious climate change mitigation requires significant changes in many economic sectors, in particular in the production and consumption of energy [1]. As an energy carrier, electricity plays a fundamental role in modern society and is a mainstay of the worldwide manufacturing industry. While the consumption of primary energy has doubled since the early 1970s, electricity consumption has increased almost fourfold [2,3]. In 2005, CO_2 emissions from fuel combustion in power generation constituted approximately one quarter of all anthropogenic GHG (greenhouse gas) emissions globally [4]. According to many scenarios (e.g.[5]), the electrification of society is set to continue.

Power has been increasingly traded between nations [6,7]. The transfer of electricity between utilities in neighbouring regions has been common practice for many years due to its economic efficiency, which derives from reduced overall requirement for reserve margins and balanced load fluctuations within the market area [6]. In 2008, OECD countries consumed 9244 TWh electricity, imported 372 TWh and exported 360 TWh [6]. Electricity trading between distant locations is limited due to transmission losses. For many countries, however, imported electricity accounts for a significant proportion of total electricity consumption. OECD countries for which imports accounted for more than 30% of total electricity consumption in 2008 were Luxembourg, Switzerland, Denmark, Hungary, Slovenia, Slovakia, and Austria [6]. Furthermore, new transmission system operator investments are underway, with those of European significance corresponding to more than 12% of the existing network until 2020 [8]. In addition, a unified electricity grid for Europe and North Africa by 2050 has been envisioned [9]. Electricity trading is, consequently, likely to increase.

Analysis of the development of GHG emissions of nations and product systems can be carried out by using both prospective (scenario) and retrospective perspectives. In order to understand the feasibility of certain GHG emission development paths, the potential impacts of various technologies and structural changes in the energy system need to be assessed. In this kind of prospective assessment procedure, methods such as consequential life cycle assessment [10,11] and system-level modelling of energy systems [11–13], land use [14], and economies [15], can be used. The assessment of historic GHG emissions by means of retrospective analysis is also important, both to obtain information on trends and for regulation at the country and product level.

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The Kyoto Protocol sets binding GHG emission targets for the period 2008–2012 for those industrialised countries which have ratified the Protocol [16]. The GHG emission reduction targets set under the Kyoto Protocol and the further targets that are currently being negotiated are based on annual production-based GHG emissions within nations [16,17]. The trade of goods, however, may have a significant influence on the development of country-specific GHG emissions associated with the consumption of goods and services [18–20]. Peters et al. [20] estimated that, in 2008, approximately 7.8 Gt of embodied CO_2 emissions were shifted around the globe due to international trade. This is 26% of global CO_2 emissions. Net fossil CO_2 emission transfers from developing to developed countries increased from 0.4 to 1.6 Gt CO_2 during 1990–2008 [20]. GHG emission leakage occurs when the consumption of goods and related production are geographically separated. The risk of significant emission leakage between countries exists at least as long as a comprehensive and effective climate convention is lacking.

One solution to reduce significant emission leakage could be the introduction of consumption-based emission targets for countries or products. This would require the determination of emissions over the life cycle of products. Different types of voluntary standards and criteria-based GHG emission performance rules covering the life cycle of various products have been developed and implemented in recent years [21–24]. In 2009, the EU (European Union) introduced the first ever mandatory criteria for product-based life cycle GHG emissions performance: for transportation biofuels and other bioliquids [25]. Similar binding criteria may also be applied to other products in the future.

Regarding electricity consumption within the monitored product systems, the determination of related GHG emissions is a key issue. The GHG emissions associated with electricity consumption may vary significantly depending on the way the electricity is produced and how the related GHG emissions are determined. Typically, electricity is purchased from the electricity grid, which is formed between a number of power plants and consumption points with various transmission, distribution, and transformation connections. The GHG emissions from final electricity consumption result from fuel combustion and provision; the production and construction of power plants, other capital goods and infrastructure; and from electricity transmission and distribution losses. The relative contribution of these sources varies significantly depending on the form of electricity production [26,27]. However, with respect to GHG emissions from the current electricity production mix, CO_2 emissions from fuel combustion contribute most significantly to the life cycle GHG emissions of electricity production and are the most reliably evaluated [27,28]. Besides the production mix, the choice of allocation method for CHP (combined heat and power production) is essential when assessing the CO_2 emissions of power production from CHP [4]. Furthermore, the consideration of electricity trading is of significant importance, yet it is often ignored.

Emissions embodied in trade have been studied by means of global environmentally extended input–output analyses, including electricity among other goods and services [18–20]. These analyses derive data on trade, economic input–output by sectors, energy consumption, and CO_2 emissions by region and sectors from the GTAP (Global Trade Analysis Project), which compiles primary data from voluntary contributions by each region [29]. Thus, trade is determined based on monetary exchanges. Although the GTAP is widely used in economic analyses, it includes significant uncertainties, such as the currency and quality of primary data, and the unknown magnitude of adjustments made by the GTAP [18,19]. Consequently, such analyses cannot provide accurate data for CO_2 emissions associated with the electricity trade between nations.

Previous studies have examined the GHG emissions of single electricity production technologies [27], the impact of allocation method on CO_2 emissions from CHP (e.g. [4,30]), and the uncertainty of CO_2 emission intensities at various geographic levels in the continental US [31]. Also, the role of international trade on GHG emissions in general has been studied (e.g.[18]). However, according to the knowledge of the authors, the above-mentioned issues have not been studied comprehensively and transparently together in a wider extent for a range of countries. In this paper, we study the role of CO_2 emissions embodied in the electricity trade between nations with respect to annual national CO_2 emissions of electricity consumption. The aim of the paper is to provide information on country-specific electricity emissions for use in a) assessing, verifying, and monitoring the GHG performance of specific products, and b) international climate policy making regarding emission leakage between countries. Data on the production and fuel mix and associated CO_2 emissions, own energy consumption of power plants, distribution and transformation losses, as well as imports and exports of electricity are readily available for various countries. However, detailed data on electricity trading between countries of origin and destination exist only for the OECD countries. Here, we present the estimates for CO_2 emissions from fossil fuel combustion embodied in electricity trade for the 30 OECD countries in 1990, 1995, and 2000–2008. Chile, Estonia, Israel, and Slovenia, which have since been accepted as OECD members in 2010, are not considered in this paper.

2. Material and methods

We examined the CO_2 emission intensity of electricity consumption in the studied countries by both ignoring and considering the CO_2 emissions embodied in the electricity trade; i.e. we estimated the production-based and consumption-based CO_2 emissions of countries. In both cases, the final consumption of electricity was determined by subtracting own use of electricity by power plants, electricity used for heat pumps, electric boilers, and pumped storage, as well as transmission and distribution losses and energy industry consumption of electricity from the net production. First, we calculated the annual production-based CO_2 emission intensity of electricity (g CO_2/kWh_e) by determining the total CO_2 emissions from fuel combustion in power production and dividing this by the total amount of electricity produced and transferred to consumption points within a country. In this approach, it was assumed that electricity imports to a country have the same CO_2 emission intensity as the electricity produced within the particular country. Secondly, we calculated the CO_2 emissions embodied in electricity trade and estimated the consumption-based CO_2 emission intensity of electricity (g CO_2/kWh_e).

The annual national production-based and consumption-based CO_2 emission intensity of electricity were calculated using equations (1)–(6). In the calculations, we used the latest available data from the IEA (International Energy Agency). The CO_2 emissions from fuel combustion, categorised as electricity output from main electricity producers, autoproducers, and combined heat and power producers, as well as own use of electricity, were taken from the IEA database 'CO_2 emissions from fuel combustion' [3]. The data for electricity production, distribution and transformation losses, imports, exports, and final consumption, as well as electricity and heat production in CHP plants were taken from the IEA database 'Energy Balances' [6]. The data for bilateral electricity trade of the OECD countries were taken from the IEA publication 'Electricity Information' [7], in which electricity is considered to be imported or exported when it has crossed the national territorial boundaries of the country (if electricity is transited through a country, the amount is shown as both an import and an export). The overall national CO_2 emission data were taken from the UNFCCC (United Nations

Framework Convention on Climate Change) [32]. We present the results for eleven years: 1990, 1995, and 2000–2008. National consumption-based CO_2 emission intensities of electricity were calculated only for those OECD countries that trade electricity. Isolated regions do not trade electricity, as they are currently constrained by thermodynamics and the economy of transmission. Thus, for the island nations of Iceland, Japan, Australia, and New Zealand, and also for Korea, production-based emission intensities correspond to consumption-based emission intensities. As some OECD countries import electricity from non-OECD countries, we calculated the production-based CO_2 emission intensity of electricity supply for the non-OECD countries in question using the IEA databases mentioned above. In cases where the origin of electricity import was not known, we applied the production-based CO_2 emission intensity of OECD average. The particular emission intensity was also applied for electricity imports from Luxembourg to Germany between 1990 and 2001 due to lack of reliable data.

The CO_2 emission intensity of electricity production varies throughout the year. Thus, in practice, the emissions embodied in the electricity trade are influenced by the moment of trade. However, data on electricity trade with countries of origin and destination are only available at the annual level. Consequently, we assumed that the production of electricity consumed within and exported from a particular country have the same CO_2 emission intensity. However, quarterly data are available on national electricity production and related combustible fuel utilisation, imports, exports, and final consumption [33]. By using this data for one studied year, 2008, the magnitude of the uncertainties due to the above-mentioned simplification was analysed. The potential error in the annual consumption-based CO_2 emission intensity of electricity due to imports and related quarterly variation in the use of combustible fuels were calculated using equations (7) and (8).

In LCA (life cycle assessment), there are several ways of allocating emissions for various products in multi-product processes [34,35]. In determining GHG emissions of electricity in combined heat and power production, the allocation issue arises. CHP plants are built to jointly produce electricity and heat, which renders them economically competitive [30]. In general, the allocation of emissions can be based on a physical relationship, such as the energy or exergy content of the products, or on some other relationship, such as the price of the products [21]. Additionally, for CHP production, allocation methods based on fuel use in hypothetical alternative stand-alone production of heat, power, or both heat and power have been introduced (e.g.[36,37]). The method selected for the allocation procedure has a significant impact on the results. Frischknecht [30] used energy content, exergy content, price, 'motivation heat' and 'motivation electricity' as examples of parameters for determining the allocation factors for power and heat. As regards the emissions allocated to power, 'motivation heat' and 'motivation power' reflect the lower and upper limits, respectively, allocating 0% and 100% to the power. Both of these options can be reasonably used for allocation when either heat or power can be clearly assumed to be the main product. However, this is not usually the case, as both products typically have economic value. As power has higher exergy content and, normally, a significantly higher price level per energy unit produced compared to heat [30], the allocation of all emissions to heat can generally be considered misleading. Graus and Worrell [4] employed five different methods for calculating the CO_2 intensity of power generation. The lowest intensity was calculated by allocating emissions according to the energy output of heat and power in enthalpic terms, the highest by employing a 'motivation power' method in which all emissions are allocated to electricity. The results based on many other allocation factors, such as exergy content and product price, typically fall within this range [4,30]. Thus, we selected the allocation factor based on the energy content of heat and power outputs from CHP for the lowest limit. In this method, emissions are allocated on an equal basis to electricity and heat output in enthalpic terms (weighting factor $A = 0.5$ in equation (1)). For the upper limit of power-related CO_2 emissions from CHP we selected the 'motivation electricity' method (weighting factor $A = 1.0$ in equation (1)).

The annual national CO_2 emissions allocated to electricity production for each country were calculated using equation (1):

$$E_{\mathrm{el\,prod}} = E_{\mathrm{ep}} + E_{\mathrm{CHP}} * \left(\frac{A * \mathrm{el}_{\mathrm{CHP}}}{A * \mathrm{el}_{\mathrm{CHP}} + (1-A) * h_{\mathrm{CHP}}} \right) + E_{\mathrm{own}} * \frac{\mathrm{el}_{\mathrm{tot}}}{\mathrm{el}_{\mathrm{tot}} + h_{\mathrm{tot}}} + E_{\mathrm{autoel}} + E_{\mathrm{auto\,CHP}} * \frac{A * \mathrm{el}_{\mathrm{auto\,CHP}}}{A * \mathrm{el}_{\mathrm{auto\,CHP}} + (1-A) * h_{\mathrm{auto\,CHP}}} \quad (1)$$

in which

$E_{\mathrm{el\ prod}}$ = annual CO_2 emissions allocated to total electricity production

E_{ep} = annual CO_2 emissions from main activity electricity plants (excluding CHP plants and own use)

E_{CHP} = annual CO_2 emissions from main activity CHP plants

A = weighting factor for allocating CO_2 emissions between electricity and heat

$\mathrm{el}_{\mathrm{CHP}}$ = annual electricity output from main activity CHP plants

h_{CHP} = annual heat output from main activity CHP plants

E_{own} = annual CO_2 emissions from own use of electricity, CHP, and heat plants

$\mathrm{el}_{\mathrm{tot}}$ = annual total electricity output from electricity, CHP, and heat plants

h_{tot} = annual total heat output from electricity, CHP, and heat plants

$E_{\mathrm{auto\ el}}$ = annual CO_2 emissions from autoproducer electricity plants (excluding CHP plants and own use)

$E_{\mathrm{auto\ CHP}}$ = annual CO_2 emissions from autoproducer CHP plants

$\mathrm{el}_{\mathrm{auto\ CHP}}$ = annual electricity output from autoproducer CHP plants

$h_{\mathrm{auto\ CHP}}$ = annual heat output from autoproducer CHP plants

The annual electrical energy produced and transferred to final consumption points[1] within a country was calculated using equation (2):

$$\mathrm{el}_{\mathrm{pat}} = \mathrm{el}_{\mathrm{cons}} - \mathrm{el}_{\mathrm{imp}} + \mathrm{el}_{\mathrm{exp}} \quad (2)$$

in which

$\mathrm{el}_{\mathrm{pat}}$ = annual electrical energy produced and transferred to final consumption points within a country

$\mathrm{el}_{\mathrm{cons}}$ = annual total final electricity consumption [refers to electricity production plus imports minus exports minus electricity used at power stations (own use) minus electricity used for pumped storage, heat pumps, and electric boilers minus transmission and distribution losses minus energy industry consumption]

$\mathrm{el}_{\mathrm{imp}}$ = annual electricity imports (absolute value)

$\mathrm{el}_{\mathrm{exp}}$ = annual electricity exports (absolute value)

The annual national production-based CO_2 emission intensity of electricity (g CO_2/kWh$_e$) was calculated using equation (3):

$$I_{\mathrm{pb}} = \frac{E_{\mathrm{el\ prod}}}{\mathrm{el}_{\mathrm{pat}}} \quad (3)$$

The annual national CO_2 emissions embodied in electricity imports to a country were calculated using equation (4):

[1] Electricity exports from a producing country are considered as final consumption points of the particular country.

$$E_{\text{emb imp}} = \sum_{j=1}^{J} \text{el}_{\text{imp},j} * I_{\text{pb},j} \quad (4)$$

in which

$E_{\text{emb imp}}$ = annual CO_2 emissions embodied in electricity imports to a given country

j = index of country from which electricity is imported

J = number of countries from which electricity is imported

$\text{el}_{\text{imp},j}$ = annual electricity imports from country j

$I_{\text{pb},j}$ = annual production-based CO_2 emission intensity of electricity in country j

The annual national CO_2 emissions from electricity production consumed domestically were calculated using equation (5):

$$E_{\text{dom}} = I_{\text{pb}} * (\text{el}_{\text{pat}} - \text{el}_{\text{exp}}) \quad (5)$$

The annual national consumption-based CO_2 emission intensity of electricity (g CO_2/kWh$_e$) was calculated using equation (6):

$$I_{\text{cb}} = \frac{E_{\text{dom}} + E_{\text{emb imp}}}{\text{el}_{\text{cons}}} \quad (6)$$

The potential error (%) in the annual national production-based CO_2 emission intensity of electricity (g CO_2/kWh$_e$) due to quarterly differences in the use of combustible fuels was calculated using equation (7):

$$\Delta I_{\text{pb}} = \frac{\text{el}_{\text{CF},k}}{\text{el}_{\text{PROD},k}} * \frac{\text{el}_{\text{PROD},y}}{\text{el}_{\text{CF},y}} - 1 \quad (7)$$

in which

ΔI_{pb} = potential error (%) in the annual national production-based CO_2 emission intensity of electricity

$\text{el}_{\text{CF},k}$ = electricity output from combustible fuels in quarter k in year y

$\text{el}_{\text{PROD},k}$ = domestic production of electricity in quarter k in year y

$\text{el}_{\text{CF},y}$ = electricity output from combustible fuels in year y

$\text{el}_{\text{PROD},y}$ = domestic production of electricity in year y

The potential error (%) in the annual national consumption-based CO_2 emission intensity of electricity (g CO_2/kWh$_e$) due to quarterly differences in the use of combustible fuels was calculated using equation (8):

$$\Delta I_{\text{cb}} = \frac{\sum_{j=1}^{J} \left(\text{el}_{\text{imp},j} * I_{\text{pb},j} * \Delta I_{\text{pb},j} \right)}{\text{el}_{\text{cons}} * I_{\text{cb}}} \quad (8)$$

in which

ΔI_{cb} = the potential error (%) in the annual national consumption-based CO_2 emission intensity of electricity

j = index of country from which electricity is imported

J = number of countries from which electricity is imported

3. Results

The calculated CO_2 emissions from electricity production for the OECD countries combined were approximately 3.7–3.9 Gt in 1990 and 4.7–5.0 Gt in 2008. The annual production-based CO_2 emission intensity of electricity decreased steadily by approximately 10% between 1990 and 2008, from 579 to 612 g CO_2/kWh$_e$ in 1990 to 507–536 g CO_2/kWh$_e$ in 2008. The given ranges derive from the selected allocation method for CHP, with the lower end corresponding to the energy-based allocation and the higher end to the 'motivation electricity' method. The impact of the choice of allocation method was not very significant at the overall OECD level, as only around 10% of electricity was produced by CHP (Table S1 in the supplementary data). However, the impact was highly significant at the country level, for some countries, as later discussed.

The variation in annual production-based CO_2 emission intensities of electricity in the studied countries, was significantly high, ranging from almost zero in Norway during all the studied years to over 1800 g CO_2/kWh$_e$ in Poland in 1990 (Tables S2 and S3 in the supplementary data). However, high values of over 1000 g CO_2/kWh$_e$ occurred only in three countries, Poland, the Czech Republic and Greece, during the studied period. In these countries, the use of fossil fuels, in particular coal, constituted a significant proportion of electricity production. The high values may also indicate poor quality of the original data. Besides Norway, other examples of countries with low production-based CO_2 emission intensities were Sweden and Switzerland. The higher the fossil fuel-based electricity production was in a given country, the higher was the CO_2 emission intensity of energy production. The share of fossil fuels of the electricity production mix varied significantly between countries [6].

The annual variation in production-based CO_2 emission intensity of electricity was moderate at the average OECD level, but considerable for many individual countries due to changes in the fuel mix and in production technologies. Examples of such countries are Luxembourg, Norway, Finland, Sweden, Denmark, and France. For the Nordic countries, in particular, annual fluctuations in hydropower and nuclear power production significantly affected the respective amount of fuel used in electricity production.

The allocation procedure for CHP increased the variability of the results when the amount of electricity produced with CHP was high. Examples of countries with a relatively high share of CHP of electricity production are Poland, Denmark, Finland, and Sweden (Table S1 in the supplementary data). Relatively, the largest range in estimated production-based CO_2 emission intensity of electricity due to the allocation procedure for CHP was in Sweden, where the lower end (energy-based allocation) CO_2 emissions totalled only 30% of the CO_2 emissions in the higher end (all for electricity) on average between 2000 and 2008. Other countries where the respective ratio due to variation was significant were Switzerland (54%), Denmark (55%), Norway (57%), and Finland (65%). According to the statistics, CHP production plays a role in some countries without any heat output. A case example is Italy, where CHP production increased significantly during the 1990s, but its first year of heat output was 2004. Thus, the choice of allocation method does not affect the results prior to that year.

The difference between national production-based and consumption-based CO_2 emission intensity of electricity was highly significant for Switzerland, Norway, Slovakia, Austria, and Sweden, and fairly significant for Denmark, Finland, Hungary, and Italy (Fig. 1). Of these countries, only Denmark was a net exporter of CO_2 emissions embodied in electricity trade. This means that Denmark sold electricity with a lower CO_2 emission intensity than it purchased from other countries. For the other above-mentioned countries the opposite was true. For the rest of the studied countries, the difference was typically less than 10% within the studied years. The Netherlands, for example, imports a significant share of its final electricity consumption, but mainly from Germany, in which the CO_2 emission intensity of electricity production is relatively close to that of the Netherlands.

For a few European countries with a high share of electricity trade compared to final electricity consumption, the CO_2 emissions embodied in electricity trade were significant compared to overall national CO_2 emissions. Such countries include Switzerland, Slovakia, Luxembourg, Austria, and Finland (Fig. 2). Here again, the impact of the allocation procedure was considerable in cases where a significant amount of the electricity production of the country

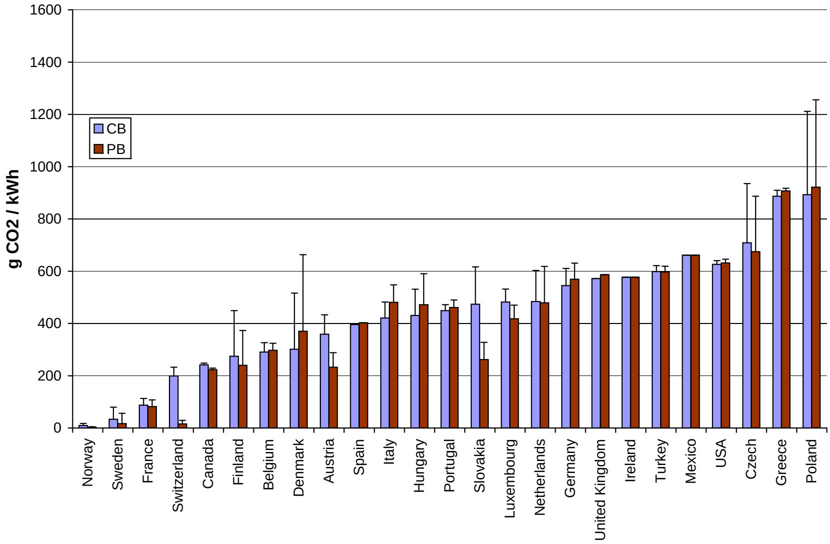

Fig. 1. Production-based (PB) and consumption-based (CB) CO_2 emission intensities of electricity (g CO_2/kWh$_e$) in OECD countries with electricity trade averaged between 2006 and 2008. The error bars illustrate the impact of the selected method to allocate CO_2 emissions between electricity and heat in combined heat and power production (CHP). The coloured columns correspond to the energy-based allocation and the upper limit of the error bars correspond to the 'motivation electricity' method.

from which the electricity was imported to the studied country was based on CHP production. However, for the majority of OECD countries, the electricity trade had an insignificant impact on overall CO_2 emissions. This is mainly due to the low amount of electricity traded compared to final electricity consumption.

The potential impact of averaging trade over a year instead of a shorter time period did not have a significant impact on the annual consumption-based CO_2 emission intensity of electricity. The difference between using annual data and quarterly data was estimated to be less than ±10% for each of the OECD countries in 2008 (Table S8 in the supplementary data). The impact was the higher the more a country imported electricity from a country in which the variation in the use of combustible fuels in electricity production was relatively high. The highest difference was found

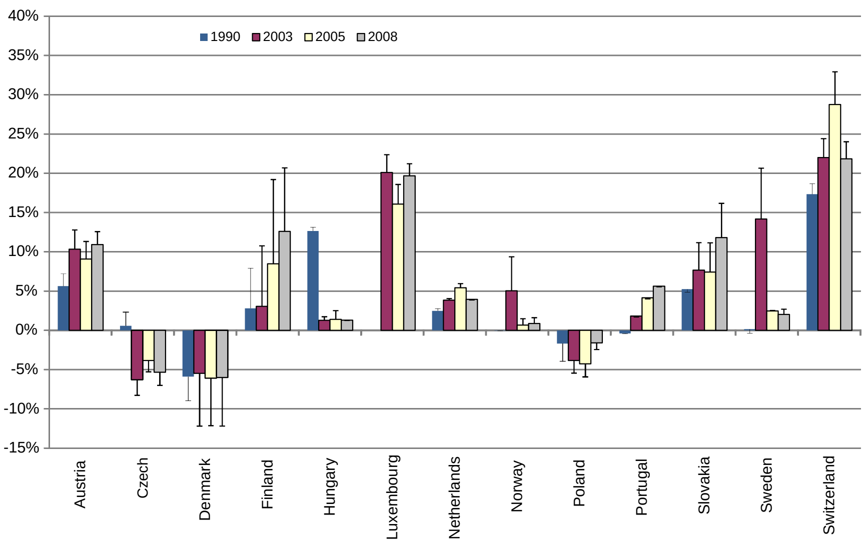

Fig. 2. CO_2 emissions embodied in net imports of electricity compared to total national CO_2 emissions (excl. LULUCF) for countries in which the share exceeds 5% for any studied year (negative values refer to export of embodied CO_2 emissions). The error bars illustrate the impact of the selected method to allocate CO_2 emissions between electricity and heat in combined heat and power production (CHP). The coloured columns correspond to the energy-based allocation and the ends of the error bars correspond to the 'motivation electricity' method.

for Hungary (9%), Greece (8%), and Finland (7%). Most of the uncertainty resulted from imports from Ukraine, Bulgaria, and Russia. For these origins, the quarterly variation in CO_2 emission intensity of electricity was not known.

4. Discussion and conclusions

4.1. Differences in production-based and consumption-based CO_2 emission intensities of electricity

For several OECD countries, the production-based and consumption-based CO_2 emissions of final electricity consumption deviated significantly. This is true when there is a difference in the CO_2 emission intensities of produced and transferred electricity between the country considered and the countries from which the electricity is imported to the country considered. Thus, a country may have significant amount of CO_2 emissions embodied in its imports or exports even if the net electricity trading of the country is at a low level. Switzerland, Luxembourg, Norway, and Sweden had the highest CO_2 emissions embodied in imports in relative terms. In Switzerland, the production-based CO_2 emissions of electricity were low, as nearly all electricity was produced with hydro and nuclear power. Switzerland's imports constituted more than half of its consumption; however, its exports were of the same order of magnitude as its imports. The electricity imported from France and, in particular, from Germany had much higher intensity than the Swiss exports. Luxembourg imported nearly as much as it consumed. Luxembourg is a small country with primarily natural gas-based domestic production, and its CO_2 emission intensity was relatively low. In Norway and Sweden the CO_2 emission intensity of electricity production was low due to significant use of hydropower in both countries and also nuclear power in Sweden.

Denmark, the Czech Republic, and Poland had more CO_2 emissions embodied in electricity exports than in their imports. Thus, their production-based CO_2 emissions were greater than those of their own consumption. In Denmark, 80% of total production in 2008 was produced with fuels, mainly hard coal and natural gas. Even though Denmark imported slightly more electricity than it exported in 2008, it had more CO_2 emissions embodied in exports than imports. Denmark imported low CO_2 emission intensive electricity from Sweden and Norway. The Czech Republic had relatively high production-based CO_2 emissions due to significant coal use. Exports from the Czech Republic were more than twice as large as imports to the country, and around one fourth of the annual production in 2008 was exported. Poland had very high CO_2 emissions embodied in exports, as its production-based CO_2 emissions were the highest in the OECD due to significant use of coal. Poland's trade in 2008 was at a low level relative to total consumption, although its exports were slightly higher than imports.

4.2. Uncertainties

Our quantitative uncertainty analysis showed that ignoring the exact moment of the electricity trade, by considering only annual averaged data, probably does not have a significant impact on the consumption-based CO_2 emission intensity of electricity in various countries. Naturally, the calculated impact could have been somewhat higher if monthly or weekly data would have been applied. One clear limitation in our approach to determining the CO_2 emissions of electricity trade is the assumption that the production mix of the electricity traded from a country corresponds to the average production mix of the electricity produced within the country. This is not necessarily the case in practice. The average electricity production mix of a country consists of a number of production mixes of smaller regions. Thus, the electricity that is traded from a region of a country to another country should correspond to the production mix of that particular region, taking into account inland transfers. However, how to determine the appropriate size of region in this context is not clear. In addition, comparable public statistics for electricity production, consumption, and transfers are not available for a regional analysis. More research and agreements of various stakeholders are likely required in order to determine more specific data on the GHG emissions embodied in electricity trade.

Uncertainty in this study is also due to the data used. There is some uncertainty related to the accounting of CO_2 emissions from fossil fuel combustion due to problems in determination of fuel-specific characteristics such as moisture, lower heating value, and carbon content (e.g.[38]). In addition, the figures related to CHP should be interpreted with caution. The dividing line between main producers and autoproducers and between inputs and outputs of the CHP plants is unclear, and not always consistent. It is likely that the impact of these uncertainties on our results is not significant, but we could not analyse the magnitude quantitatively in this paper.

For six countries, namely Germany, Poland, the Czech Republic, Slovakia, Spain, and Turkey, some electricity imports from non-specified origins were identified. For Poland and Slovakia 100% of the electricity imported in 1990 was from non-specified origins. The respective figures for the other four countries were: Germany 21% (1990), Czech Republic 6–20% (2003–2008), Spain 1% (2005), and Turkey 1–8% (2000–2002, 2008). The share of imports of final electricity consumption in 1990 was 10% and 30% for Poland and Slovakia, respectively. For the other four countries the corresponding share was insignificant. Consequently, the consumption-based CO_2 emission intensity of electricity was highly uncertain due to imports from non-specified origins only for Slovakia in 1990. CO_2 emission intensity of electricity was not available for Luxembourg between 1990 and 2001. However, this had no impact on any other countries' consumption-based CO_2 emission intensity of electricity, as the electricity was only exported to Germany, corresponding less than 0.2% of the final electricity consumption of Germany.

4.3. GHG emission leakage

Most OECD countries involved in electricity trading are a part of the European Union. The majority of CO_2 emissions from fuel combustion are regulated and monitored at the EU level under the EU Emission Trading Scheme (ETS) from 2005 onwards [39]. Of the non-EU countries studied here, Norway is included in the system. Electricity trading between the countries included in the EU ETS often induces some GHG emission leakage, but within the EU ETS, the overall emissions are limited by an annual cap. The CO_2 emissions from electricity production may induce leakage out of the EU ETS if electricity imports to the EU from the countries outside the EU ETS increase. Total emissions might also potentially increase due to more ineffective production in the countries to which emissions are shifted compared to the EU ETS region.

In total, imports from outside the EU ETS accounted for 2–3% of the final electricity consumption between 2000 and 2008 in the countries inside the EU ETS included in the study. Countries with significant imports from outside the EU ETS include Finland with 16%, Hungary with 13%, Greece with 10%, and Italy with 9% imports of the total final electricity consumption in 2008. The share of the imports of final electricity consumption slightly increased only in Finland since the introduction of the EU ETS in 2005.

Although electricity trade seems to constitute a relatively minor part in the overall CO_2 emissions embodied in trade, it is a factor to be considered. In addition, electricity trading is likely becoming an increasingly important factor in the future [8,9]. Therefore, the extension of the EU ETS to countries with significant electricity exports to the EU ETS region could offer a means of avoiding the unintended leakage effect. Another option could be the introduction of consumption-based method to determine the emissions for the electricity imported to the EU ETS region. An emission regulation system similar to the EU ETS effectively avoiding significant emission leakage could work also for other electricity market areas with significant electricity trade between nations.

4.4. Consumption-based GHG performance rules for products

The annual average production-based CO_2 emission intensity of electricity (Tables S2 and S3 in the supplementary data) is often used in basic life cycle assessment. This may be highly misleading with respect to certain countries. The consumption-based estimates presented in this paper with respect to the CO_2 emissions embodied in the electricity trade provide a more reliable picture of the GHG emission intensity of the electricity consumed (Tables S4 and S5 in the supplementary data). Consequently, we advocate the use of the consumption-based method in preference to the production-based method for LCA purposes.

Allocation of the emissions for power and heat in CHP can have significant impacts on the national GHG emission intensities of electricity consumption, as shown in this paper. Allocation is one of the most problematic methodological issues in LCA, and the allocation procedure is always a subjective choice. This problem needs to be addressed when introducing GHG performance rules for products. We selected allocation methods that gave a reasonable range for the purposes of this study. We are unable, however, to suggest any allocation method as being superior to others based on the results of this study.

Our figures do not include upstream GHG emissions. These, however, typically constitute a relatively low share of GHG emissions of the overall electricity production mix (e.g.[40,41,42]), although for certain power production technologies they may be significant [26,27]. However, an extensive shift in energy production systems may occur within the next few decades with the large-scale introduction of low GHG emission intensive power production technologies as a result of ambitious climate change mitigation targets [1]. Consequently, in the overall life cycle of electricity consumption, the contribution of GHG emissions not related to direct fuel combustion might increase significantly and would therefore need to be considered more carefully. In particular, GHG emissions related to the cultivation and harvesting of bioenergy has already been widely discussed (e.g.[43,44]).

Other critical methodological issues related to GHG emissions from electricity consumption also need to be considered. Various geographical choices including regional, country, and market area levels as well as temporal choices including instant, monthly, annual, and perennial considerations, can be rationalised. Soimakallio et al. [37] concluded that national or regional production mix figures should only be used for analyses concerning electricity consumption at the national or regional level, respectively. They also concluded that a solution for avoiding arbitrary selection of electricity market area could be the introduction of figures based on the contract between the electricity seller and the customer with real-time accounting. Currently, such data and respective reporting practices do not generally exist. One important research question is the definition of appropriately short time periods for the determination of GHG emission intensity figures.

4.5. Concluding remarks

The CO_2 emissions attributable to electricity consumption vary country-specifically and annually. They also vary depending on the method of analysis, such as the emissions allocation method used for combined heat and power production, and the consideration of electricity trading. Use of the production-based method for determining the emissions of electricity consumption within countries for purposes of assessing, verifying, and monitoring the GHG performance of specific products may be highly misleading. The consumption-based method should therefore be preferred. Uncertainties can be reduced by improving the quality of the data. Regarding GHG performance rules for products, especially mandatory, open methodological issues, such as allocation procedure, need to be solved keeping in mind that any single solution is always subjective. According to our results, the absolute value of CO_2 emissions embodied in electricity net imports may be relatively significant for some countries. Regarding the overall CO_2 emissions embodied in trade, electricity plays a relatively minor role. However, unless effective emission reduction and regulation measures are implemented more intensively, this role may increase in the future.

Climate policy instruments, such as national GHG emission reduction targets and product GHG performance rules, may act as required incentives in climate change mitigation. However, if implemented as incomplete and applied inappropriately, such instruments entail serious risks with respect to GHG emission leakage. Effective emission regulation should result in the intended emission reductions. The emission accounting methods used in regulation should, therefore, be fit for task. It should be noted that assessment of the environmental impacts of various decisions, such as climate policies and measures, based on retrospective approaches should be carefully assessed using prospective consequential assessment methods. Changes in electricity consumption have short- and long-term impacts which may vary significantly from those assessed using retrospective average figures, such as the ones presented in this paper [37]. The obvious advantage of the retrospective approach is the ability to reliably verify and monitor GHG performance, which is crucial for effective emission regulation.

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Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.energy.2011.12.048.

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