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RESEARCH ARTICLE

How production-based and consumption-based emissions accounting systems change climate policy analysis: the case of CO_2 convergence

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Abstract

Much of the existing research analyses on emissions and climate policy are dominantly based on emissions data provided by production-based accounting (PBA) system. However, PBA provides an incomplete picture of driving forces behind these emission changes and impact of global trade on emissions, simply by neglecting the environmental impacts of consumption. To remedy this problem, several studies propose to consider national emissions calculated by consumption-based accounting (CBA) systems in greenhouse gas (GHG) assessments for progress and comparisons among the countries. In this article, we question the relevance of PBA's dominance. To this end, we, firstly, try to assess and compare PBA with CBA adopted in greenhouse gas emissions accounting systems in climate change debates on several issues and to discuss the policy implications of the choice of approach. Secondly, we investigate the convergence patterns in production-based and consumption-based emissions in 35 Annex B countries for the period between 1990 and 2015. This study, for the first time, puts all these arguments together and discusses possible outcomes of convergence analysis by employing both the production- and consumption-based CO_2 per capita emissions data. The empirical results found some important conclusions which challenge most of the existing CO_2 convergence studies.

Keywords Consumption-based accounting · CO_2 convergence · Climate policy · CO_2 and trade · Annex B countries

Introduction

After two decades of contentious and exhaustive debates, the parties finally have reached a climate deal at the 21st of Climate Summit in 2015, which marks a major step forward to averting climate catastrophe. In order to achieve the long-term climate goal, the Paris Agreement emphasize that it is necessary to peak global greenhouse gas (GHG) emissions in early 2020s and global economy becomes carbon neutral by the end of the century (IEA 2017). With the Paris Agreement, all countries participated in efforts to reduce GHG emissions under the principles of common but differentiated responsibilities. Based on these principles, while most of the developed countries have taken absolute reduction targets, other countries have had commitments based on intensity and deviations from business as usual targets. Some countries' proposed objectives are generally on track to achieve their targets that they have pledged at the Paris Agreement, yet it is not sufficient to meet 2^c target objective.

Among the GHGs, carbon dioxide (CO_2) has the largest share and due to its relevance to climate policy and growing concerns about carbon leakage and competitiveness, monitoring CO_2 emission developments both in total and per capita emissions are one of the most important objectives at a global scale. However, it is equally important to notice how emissions are calculated as different accounting approaches could usually provide different outcomes.

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There are mainly two different approaches in measuring human-induced GHG emissions: production-based accounting (PBA) and consumption-based accounting (CBA). PBA (territorial) calculates emissions that are generated from the domestic production of goods and services irrespective of whether they are consumed domestically or are exported. Since the Kyoto Protocol and its follow up agreements, including the recent Paris Agreement, countries are required to prepare their national GHG emission inventories based on the PBA (Afionis et al. 2017). This approach, however, have been criticized as it does not take into account the international emission flows in the form of goods and services that have been produced in one country and consumed in another.[1] To overcome this issue, several studies propose to consider national emissions calculated by CBA systems in GHG assessments for progress and comparisons among the countries. These studies suggest that to better understand environmental footprints, CBA approach should be applied in emission calculations as it attributes all emissions, directly and indirectly, occurring along the production chain to the final consumer of the products (Peters and Hertwich 2008; Tukker and Dietzenbacher 2013; Steininger et al. 2014; Afionis et al. 2017; Grasso 2017; Peters et al. 2016).

Main difference between the PBA and CBA is the distribution of the CO_2 trade balance between two trading partners. The PBA generally provides significant advantages to the countries, who have outsourced their emissions to some developing countries. This outcome particularly raises some objections from countries hosting emission intensive exporting industries, who argue that the importers of emission-intensive goods should bear the responsibility (Dobson and Fellows 2017).[2] For instance, if a country experiences a huge trade deficit, where imports exceed their exports, it is more likely that this country will have a higher consumption-based emissions (CBE) than the production-based emissions (PBE). If, on the other hand, the country dominantly exports energy-intensive products and imports less energy intensive products in their trade, it is possible to see that this country's CBE are lower than the PBE. Consequently, while some countries benefit from this outcome, the others might be disadvantageous.

Much of the existing research analyses on emissions and climate policy are still dominantly based on emissions data provided by production-based accounting system as national GHG emission inventories take a production perspective. This study argues that many of such analysis could be misleading or incomplete only relying on data provided by the PBA as it ignores trade perspective and environmental impacts of consumption.

The objectives of this study are twofold. First, the study tries to assess and compare consumption-based (CB) perspective with current PB perspective adopted in GHG emission accounting system in climate change debates on several issues such as distributional issues in GHG emission reduction, commitments in international climate negotiations, carbon leakage issues and decoupling as well as effectiveness of climate mitigation policies and to discuss the policy implications of the choice of approach. Secondly, a recent strand in the literature dealing with emissions seeks to identify how CO_2 emissions per capita is evolving, specifically whether they are empirically converging or diverging. Within this context, the second aim of the study is to test and compare unconditional and conditional β convergence by separately estimating the familiar cross-sectional regression with per capita CO_2 emissions data calculated with the CB and PB accounting systems. This study particularly discusses and analyses the convergence in CO2 emissions with a focus on how the outcome differs when consumption-based emissions are taken into consideration. As almost all literature on CO_2 emissions convergence employs data based on standard production perspective, it can be argued that such assessments could be incomplete and need further insight with the CBE. Assessing the existence of convergence with the CBA data could identify unintended outcomes of PBA approach and helps to develop new policies according to these needs. To the best of our knowledge, this paper is the first to empirically consider both the CBE and PBE in emission convergence literature.

The organization of this paper is as follows. After the "Introduction" section, the "Role and impacts of the PBA and the CBA on climate policy analysis" section will discuss how adopting different emissions accounting systems changes the understanding of emissions and how these two approaches might have an influence on climate policy discussions. The "Convergence studies on CO_2 emissions" section will provide a brief literature review on convergence debates. The "Methodology, data, and findings" section empirically applies and compares the results of both the consumption- and production-based CO_2 emissions per capita on convergence analysis for the Annex B countries. The "Conclusion" section discusses policy considerations and ends with conclusion.

Role and impacts of the PBA and the CBA on climate policy analysis

As the global trade volume and international integration of supply chains have been growing significantly in past decades, it is fair to expect the emissions calculated by different approaches will also differ. Abovementioned differences in

[1] Emissions embodied in trade are significant part of the global emissions as recent studies estimated that up to 25–30% of global emissions are generated from such operations (Zhang et al. 2017; Wang et al. 2015; Davis and Caldiera, 2010; Peters and Hertwich 2008).

[2] The gap between embodied emissions in imports and exports might be due to the increasing gap between the trade volume of import and export as well as changing the trade patterns.

CO_2 emissions calculated by both the PBA and the CBA clearly illustrates that international trade and emissions embodied in trade cannot be ignored while determining the underlying driving forces behind global, regional, and national emissions (Liddle 2018; Mir and Storm 2016). In this regard, alongside the PBA, considering the CBA will provide several useful insights into the GHG emission analysis. Besides, making a distinction between the CBE and PBE will have several implications and address some important policy considerations (Sato 2012). In this section, we will briefly discuss how economics and political perspective may diverge and develop on current analysis on GHG emissions when recognizing the role of consumption in global emissions by adopting CB perspective.

Impacts on climate negotiations

As mentioned earlier, national GHG emission inventories are officially calculated with the PBA system since the Rio Convention and the PBA generally provides significant advantages to some countries. Hence, selecting different GHG accounting systems may have an important impact in defining binding commitments across countries during climate negotiations (Boitier 2012). It is argued that the eventual realization of CBA will more likely have the ability to resolve some of the sensitive issues encountered in global climate debate. If adopted by the UNFCCC, the CBA particularly provides a flexible approach to the parties and shed lights on trade-related emissions as well as the design of alternative mitigation policies (Amador et al. 2017). In fact, it is argued that the adoption of the CBA as a target base in international negotiations may have several potential advantages as this accounting system can transform the issue of the distribution of responsibility for emissions across countries into a self-enforcing situation of fair and cost-efficient global coordination, which would eventually improve the overall effectiveness in terms of GHG emission reductions (Dobson and Fellows 2017; Grasso 2016).

It is also argued that if the objectives of environmental goals are clear and the concerned pollutants are global, measuring emissions through the CBA system is analytically the most appropriate tool to monitor and assess the impacts and policy responses (OECD 2011; Peters et al. 2016). This clearly matches with the objectives of climate mitigation as GHG emissions are global pollutants and there are certain and clear targets in recent Paris Climate Agreement such as reducing emissions to be neutral after 2050.

It is important to note that post-Paris negotiations cannot be successful to secure more ambitious reductions without an equitable distribution of responsibility. As set out in the Paris Agreement text, this will be achieved by periodic review, known as “global stocktake.” The Paris Agreement mandates that the global stocktake should be undertaken in a comprehensive and facilitative manner, in light of equity and the best available science.[3] During these global stocktakes, in order to improve the transparency and clarity of information to facilitate the assessment of collective progress, the CBA could be considered one of the main accounting systems to better track the emissions and its sources (Grasso 2017). If post-Paris Agreement negotiations adopt the CBA as a supporting system, then, new considerations and adjustments are needed following these changes. As a result, studies focusing on emissions allocation, burden sharing, and equity issues have to reconsider their assessments on entirely new data sets, such as emissions both total, sectoral, and per capita emissions, calculated by the CBA.

The impacts on decoupling, leakage, and EKC analyses

Global energy-related CO_2 emissions from fossil fuels and industry were flat for the third consecutive year in 2016 even as the global economy grew (IEA; 2017). This minimal increase of 0.2% in global emissions illustrates a divergence of the trend of 2.2% average growth during the previous decade, signaling a continuing decoupling of emissions and economic activity. According to some studies, recent trends in carbon reduction illustrate the success of developed countries efforts in terms of decarbonisation and decoupling. Achievements in recent GHG emission reductions were considered mainly due to the growing deployment of renewable energy and improvements in energy efficiency as well as structural changes in the global economy (IEA 2017). This success story should be questioned as current PBA system does not account for exported emissions in their CO_2 data. Therefore, even if decoupling is observed for some of the developed countries, the result should be approached cautiously as this outcome might also be due to the leakages (Davis and Caldeira 2010; Wiebe and Yamano 2016; Chen et al. 2017). That is, energy-intensive manufacturing production from developed countries might have shifted to developing countries. In a fragmented climate policy regime, as we have seen in the cases of the Rio Convention and the Kyoto Protocol, it is highly likely that pollution-intensive industries will contract in countries with relatively strong environmental regulation and expand in those where there is none or relatively weak environmental regulations (Copeland and Taylor 2013). This outcome will result in carbon leakage. Some studies, for instance, estimate that binding commitments under the Kyoto Protocol have increased committed Annex B countries’ embodied carbon imports from non-Annex B countries by almost 8% (Peters et al.

[3] For the Stocktaking process and long-term objectives of the Paris Agreement, see http://www.wri.org/blog/2017/05/insider-designing-global-stocktake-under-paris-agreement-catalyst-climate-action

2016). Ignoring the leakage issue will create a false sense of achievement and misinformation for the public and policymakers. By using PB approach, it is not possible to detect the carbon leakage occurring from developed countries to developing countries. This emphasizes the importance of considering alternative emission calculations and new policies and perspectives based on the CBA as this approach can help to identify cases of carbon leakage and policy efforts for prevention (Peters et al. 2016; SEI 2017).

Related to decoupling and carbon leakage issues, a similar line of studies focus on emissions and economic growth relation through so-called environmental Kuznets curve (EKC) hypothesis, which implies that economic development in the early stages leads to a deterioration in the environment, but after a certain level of economic growth such deterioration slows and decreases further. Even though empirical evidence on growth and carbon emissions show mixed results, numerous studies found that the inverted U shape EKC is particularly valid for many developed countries (Mir and Storm 2016). Major drawbacks of these studies, however, are to use PBE data in their analysis (Aşıcı and Acar 2016; Mir and Storm 2016). It is argued that many of developed countries have reduced their emissions thanks to partially outsourcing these emissions to developing countries. As a result, the EKC analysis could illustrate the GHG emissions are reduced as the countries become richer without changing their unsustainable consumption patterns (Aşıcı and Acar 2016). Therefore, the EKC analysis by using the PBA data may not be reliable and requires such analysis to be tested also with emissions data calculated by the CBA. Recent studies considering CBE when testing the EKC hypothesis found that reaching the turning point in the relationship between income and emissions requires very high income per capita and take decades to arrive that point, which will overshoot the critical 2^{c} level (Mir and Storm 2016). This illustrates that the issue of delinking of economic growth with emissions should be reconsidered carefully by adopting the CBA data, otherwise such arguments could be misleading as cleaning environment at home does not guarantee an overall reduction at the global level. In the case of a complete global agreement on GHG emissions, however, this issue could be relatively irrelevant as one expects there will be no room for carbon leakage.

Impacts on climate mitigation policies

Designing effective and appropriate policies and measures to reduce GHG emissions are at the core of climate and environment policy. Most of the current climate mitigation policies adopt territorial-based regulations which eventually takes the PBA perspective (Peters et al. 2016). To ensure a more equitable, fair, and swifter transition to a low-carbon future, current PB policies alone are not adequate to limit global emissions (Scott et al. 2016). Identifying emissions based on the CBA and distinguishing the embodied emissions in trade will provide clear and fair information whether designed policies and measures lead to real reductions in GHG emissions or relocation of industry and emissions to countries with no regulation. If CB perspective considered in policymaking as a main accounting system, then the policy should specifically focus on household consumption patterns and international trade (Hubacek 2016). Accordingly, this will require relevant knowledge, infrastructure, and resources to change household behavior towards low-carbon society (Brizga et al. 2017). As a result, the CBA provides new perspectives on existing mitigation policies and presents an opportunity to address emissions embodied in trade. When consumption- and trade-related emissions are targeted, policymakers become more likely to adopt more comprehensive policies, as it becomes more essential to accompany a set of policy mechanisms addressing demand, trade, and business supply chains (Scott 2016). In this respect, in addition to current PB perspectives, new policies such as eco-labelling and consumption tax on carbon contents will become increasingly important when attention is given to domestic consumption.

Energy- and emission-related indicators can be used to measure and evaluate environmental impacts as well as the effectiveness of policy measures to tackle these impacts. Setting up sustainability targets and monitoring their progress through indicators are particularly important with respect to policy response. In this regards, emission indicators calculated with production perspective is insufficient and needs CB approach alongside for environmental performance analysis as it is a more convenient way of measuring sustainability by taking into account both the direct and indirect impacts of consumption. Therefore, another argument to support for adopting CB perspective in emission accounting as a complementary to the PBA is to set up more specific and focused emission indicators for a better understanding of the dynamic changes of CO_2 emissions and to provide necessary information for policy making (Scott and Barrett 2015).

Convergence studies on CO_2 emissions

After discussing possible outcomes of choosing different approaches in the calculation of emissions on several issues such as decoupling, EKC, leakage, and climate mitigation policies, we now turn our attention to adjusting these arguments to another line of research dealing with income-emissions relationship to identify how CO_2 emissions per capita is evolving, specifically whether they are empirically converging or diverging. In this section, while we provide some literature review on CO_2 emission convergence, the main focus will be given on how finding convergence or divergence might be relevant from climate policy perspective in parallel with abovementioned CBA-PBA discussions.

The idea of convergence studies on CO_2 emissions is based on the EKC hypothesis and income convergence. The convergence hypothesis suggests that pollution falls faster in countries with high levels of pollution than in countries with low levels of pollution. This outcome resembles the EKC hypothesis. Under the convergence hypothesis, however, change in pollution is not necessarily dependent on economic growth as in the case of the EKC (Brock and Taylor 2003; Stern 2017). From income convergence perspective, environmental—and thus CO_2 emissions—convergence has been inspired by the earlier economic convergence literature. CO_2 emissions convergence can, as in the case of income convergence, be roughly divided into three different concepts: (i) β convergence; (ii) σ convergence, and (iii) stochastic convergence. As shown by Sala-i-Martin (1996), β convergence relates to the mobility of different individual economies within the given distribution of world income. From CO_2 emissions convergence perspective, β convergence occurs when the emissions of a poorer country, with lower initial levels of emission per capita, tend to grow faster than the ones from a rich country and there is a catching-up effect with the more polluting countries. While σ convergence relates to whether or not the cross-country distribution of the world income shrinks over time, stochastic convergence relies on the time series properties of income series.[4]

By highlighting two research lines, that investigate per capita income convergence among countries on the one hand, and the relationship between the wealth and environmental degradation, so-called EKC on the other hand, Strazicich and List (2003) presented the first study on convergence on CO_2 per capita, arguing that there is a potential gap in the literature and needs to be investigated whether spatial emissions among countries have converged. By doing so, it is believed to provide a link between the empirical literature that correlates pollution and incomes and the literature that finds spatial incomes have converged through time (Karakaya et al. 2017). Following Strazicich and List, further studies argued that investigating per capita emission convergence among countries are important for globally, both for developed and developing countries. The fast-growing literature analyzed many different aspects of CO_2 per capita convergence ranging from different policy perspectives for a different group of countries and different time periods.[5]

There have been many studies in the literature that evaluate the gaps in per capita emissions between countries and consider distributional issues related to CO_2 emissions. For this purpose, convergence in emission per capita received greater attention by many of those studies (Yavuz and Yilanci 2013; Barassi et al. 2017; Kıran Baygın 2017). Examining convergence patterns in cross-country emissions, it may be possible to receive some important information, which will provide some useful insights for climate policy. The main motivation for studying emission convergence is that convergence in per capita terms could influence the political economy of negotiations in international climate regime (Aldy 2006; Bilgili and Ulucak 2018).

In terms of equity issues, many effort sharing approaches consider emission per capita as a principal basis. That is, by giving equal emission rights to pollute, each individual eventually converges their emissions amount over the time. This assumes that developed countries per capita emissions stabilize or decrease, while emissions per capita in developing countries gradually increases (Criado and Grether 2010). If per capita emissions among countries diverge, allocating emissions through on per capita basis would be more costly as it would result in substantial amount of international transfer rents through carbon allowance trading. Developing countries will be less likely to agree on emissions reduction obligations if there is no convergence in per capita emissions. In the case of emission convergence globally, however, the magnitude of rent transfers would be reduced, and accordingly, adoption of international agreement could be more acceptable by all parties (Aldy 2007; Brannlund et al. 2015).

Development in CO_2 per capita emissions also provides significant information on the performance of policies and measures applied by individual countries. In this respect, convergence in emission per capita is a key concern for policymakers as it provides knowledge of what can be expected concerning future convergence at the global scale (Sato 2012). Relevant to effectiveness of mitigation policies, many climate change models projecting future emission scenarios assume that the emissions are converging over time (Zhou and Wang 2016). Therefore, investigating convergence patterns in CO_2 emissions becomes essential as it is important to see whether these assumptions are accurate or, at least, whether there is a trend in GHG emissions in this direction (Barassi et al. 2011).

Empirical studies on CO_2 emission convergence find mixed results and the results largely depend on the sample taken into account and the technique used. Recent reviews on CO_2 emission convergence literature indicate that while many of global scale studies show divergence in emissions per capita, there is usually convergence in per capita emissions among majority of developed countries (Pettersson et al. 2014).

As mentioned above, convergence analysis on per capita emissions could reveal many important insights regarding climate policies. A major limitation of available convergence studies is that they all focus on the PBA perspective and fail to consider the role of consumption perspective, where it is one of the main driving forces that effects changes in emissions.

[4] These various concepts can in turn be divided into absolute and conditional convergence. In contrast with absolute convergence, conditional convergence assumes the possible differences among countries.

[5] For a detailed literature review of convergence studies on environment, please refer to Pettersson et al. 2014; Bilgili and Ulucak 2018; Acar et al. 2018.

This study objects some of the arguments with respect to interpretation of the convergence results such as mentioned in the above literature. Convergence studies on CO_2 emissions usually suggest that, if there is convergence observed among countries, it is plausible as countries equity issues are minimized (Barassi et al. 2017). This study argues that even though a convergence pattern is empirically found in CO_2 emissions across countries with the PBA data, policymakers should be cautious with such outcome as the result may well mean that emission reduction burden is outsourced by developed countries to developing countries. As discussed in the "Role and impacts of the PBA and the CBA on climate policy analysis" section, the PBA system does not account for the occurrence of relocation of emission intensive and trade-exposed industries from developed to developing countries. In this regard, we claim that emission convergence analysis should also be reconsidered by using new dataset calculated by the CBA.[6] By doing so, new insights could emerge and some ignored aspects of emissions and economic growth could be more strongly highlighted. In parallel to the abovementioned arguments regarding impacts of adopted emissions accounting on several climate policy issues, we believe that convergence analysis studied with the PBE and CBE could be discussed with similar arguments. The following section will discuss these issues within the convergence perspective and tries to argue how adopting CBE will offer new insights into the climate policy debates.

With regard to equity and fair share, using CB perspective is believed to be more advantages than the PB perspective in climate negotiations for two reasons. First, in terms of a fair share, per capita emissions are best characterized with the CBA as whoever consume goods should also share the responsibility. As an end user, the consumer should be held responsible for the goods that he/she consumes whether produced domestically or imported. However, if a product produced within the territory yet exported abroad, in this case, the emissions associated with this product should be under foreign consumers' responsibility rather than the exporting countries'. This fact however is not fully reflected in current climate discussions as all studies analyzing convergence in production-based CO_2 emissions per capita. The producing and consuming countries responsibilities should be differentiated and this can be properly measured by CO_2 per capita based on CBA (Liu et al. 2015). Secondly, any convergence studies using per capita emissions based on PBA could be misleading if there are leakage issues. If the leakage is taking place, for instance, it is not unreasonable to expect a regional or global convergence as developed countries per capita emissions will be lower and unmitigated developing countries emissions will be higher. One needs to see CO_2 per capita emissions calculated by CBA are also converging. Otherwise, it is possible that the emissions are outsourced and carbon footprints for developed countries have not improved.

Once again, by giving reference to the leakage issues, it is possible to have some understanding of the emissions convergence and decoupling relationship. It can be argued that any assessment in convergence analysis cannot provide significant information with respect to decoupling discussions when analysis is made only by using PB emission data. If we find convergence by using both data sets, then, it is possible to claim that decoupling is truly taking place as CBA proves that the leakage issue is minimized. Using both PB and CB accounting data also helps to identify whether improvements in emissions and in decoupling are due to the designed mitigation policies or to the outsourcing of production (Chen et al. 2017; Wiebe and Yamano 2016).

Even though the EKC and emissions convergence have been analyzed separately for a long time, it is argued that they are closely related (Martino and Nguyen-Van 2016; Stern 2017). If the argument of the EKC holds true, this will consequently result in a convergence in emissions between the developed and developing countries since we will see a decrease in emissions while developed countries continue to grow and developing countries emissions will increase as they experience economic growth (Stern 2017; Martino and Nguyen-Van 2016). On the other hand, if there is no proof of EKC, the emissions may or may not converge by depending on the other factors. Some studies found that the existence of EKC for some of the countries could occur simply due to the existence of pollution heavens (Kearsley and Riddel 2010). Cole (2004), for instance, found that the existence of EKC for the North and South regions of the world is due to the outsourcing of the emissions by the North towards the South regions. Therefore, it can be argued that if the empirical study finds the EKC by using the PBE data, the convergence may not be found if the analysis used the CBE data for the same group of countries. Both the EKC and convergence analysis should also be tested with the CBE data in order to reach a robust conclusion. This highlights the importance of using CBE data as reliable analysis on the EKC dependent on the correct using of the data sets.

Methodology, data, and findings

(i) Methodology

[6] A number of recent studies acknowledges ecological footprint in convergence analysis. Yet, these studies do not solely rely on CO_2 emissions per capita, instead use ecological footprint as an indicator, which includes six environment-related components (Ulucak and Apergis 2018; Bilgili and Ulucak 2018; Solarin 2019; Özcan et al., 2019). Our study differs from these studies both in terms of scope, database, and methodology as their analysis cover much broader context while we directly focus on CO_2 emissions calculated by PBA and CBA.

In order to estimate absolute and conditional convergence in CO_2 emissions measures, we use the familiar cross-sectional regression tests in the tradition of Mankiw et al. (1992) and Strazicich and List (2003). A generic representation of this regression used by Mankiw et al. (1992) to estimate income convergence is as follows:

$$\gamma_i = \alpha + \beta \ln y_{i,0} + \varphi Z_i + \varepsilon_i \tag{1}$$

where γ_i denotes the growth rate of income between 0 and t, $\ln y_{i,\,0}$ is the initial value of income, α is a constant term, β is convergence parameter, Z_i denotes the control variables, and ε_i is an error term. Equation (1) is transformed to the following specification by Strazicich and List (2003) to test CO_2 emissions convergence

$$\gamma_i = \alpha + \beta lnCO_{2i,0} + \varphi Z_i + \varepsilon_i \tag{2}$$

where α, β, Z_i, and ε_i are the same as in Eq. (1). In Eq. (2), dependent variable is the annual growth rate of per capita CO_2 emissions and $\ln CO_{2i,\,0}$ denotes the initial level of per capita CO_2 emissions. Equation (2) tests the following hypotheses: while $\varphi = 0$ and $\beta < 0$ implies absolute convergence, $\varphi \neq 0$, and $\beta < 0$ suggests conditional convergence. Thus, when no control variables are included, the absolute β convergence is tested, simply by regressing the average annual growth rate of per capita CO_2 emissions on the initial level of per capita emissions for a cross-section of countries (Pettersson et al. 2014). On the other hand, when the control variables are included, the conditional β convergence is tested.

If β is found negative and statistically significant, it is interpreted as the existence of β convergence (being absolute or conditional depends upon the existence of control variables in the regression) in per capita CO_2 emissions, meaning the CO_2 emissions per capita of different countries converge to the same steady state level regardless of the differences in the development gap among countries. Moreover, smaller β implies higher convergence rate (Hao et al. 2015).

Legitimate concerns can be raised about the validity of cross-sectional β convergence approach when we review the recent developments in econometric methods such as new estimation techniques (system or difference GMM) for panel data approach, newly developed unit root tests (RALS-LM), or club convergence approach. This is because all these econometric methods can be considered an alternative to cross-sectional β convergence analysis and give more robust empirical results. Even though we are in complete agreement with these concerns, our main aim in this study is to bring how changes in emission accounting system influences empirical results and policy implications up for discussion. Hence, we decided to build our empirical analysis (as a case study) on the pioneering research by Strazicich and List (2003) which is the first study analyzing conditional convergence in CO_2 emissions and suggest other approaches for future studies.

(ii) Data

The variable selection is one of the most important parts of this study. As discussed in the previous section, the empirical literature testing CO_2 emissions convergence so far has commonly employed PBE of CO_2 (Strazicich and List 2003; Aldy 2006; Panopoulou and Pantelidis 2009; Barassi et al. 2011; Yavuz and Yilanci 2013). This is mainly because it is the officially accepted emissions measurement by the UNFCCC and the data for multiple countries and years are easily available in most datasets. We argue that from a policy perspective, isolating emissions policies from the dynamics of consumption-based emissions or ignoring consumption-based emissions while making policy implications may lead to failure of these policies. In this respect, we first distinguish between two sides of CO_2 emissions and utilize two primary data: (i) annual PBE of CO_2 measured in tonnes per capita (*pba*) and (ii) annual CBE of CO_2 measured in tonnes per capita (*cba*). The data for *pba* and *cba* are taken from Global Carbon Atlas Database (2018).[7] While *pba* calculates emissions that are generated from the domestic production of goods and services irrespective of whether they are consumed domestically or are exported, *cba* attributes emissions to the final consumers of goods and services. As discussed above, the difference between two accounting system indicates the net effect of emissions embodied in trade. While positive value of difference indicates net export of emissions, negative value shows net import of emissions.

Secondly, we include a vector of control variables (Z_i) that may be hypothesized to affect long-run emissions rates. They are real GDP per capita (constant 2010 US$) (*gdpper*), real GDP per capita squared (constant 2010 US$) (*sqgdpper*), population density (people per square km of land area) (*pd*), and trade volume per capita (constant 2010 US$) (*xmper*)[8]. The data for *gdpper*, *sqgdpper*, *pd*, and *xmper* are extracted from World Bank (2017). While *gdpper*, *sqgdpper*, and *pd* are commonly used control variables to test CO_2 emissions convergence in the literature, *xmper* can be regarded as our contribution to the literature to show the difference between *pba* and *cba*.

We follow the suggestion of the EKC literature and include real GDP per capita and real GDP per capita squared as the control variables. GDP per capita has a positive relationship with both the *pba* and *cba* through different mechanisms. *pba* emissions increase as GDP per capita increases simply due to every additional production uses more fossil fuels. Therefore, the fossil fuel content of a country's energy mix becomes more important in the case of *pba*. In the case of *cba*, the mechanism

[7] The Global Carbon Atlas Database (2018) can be viewed from http://www.globalcarbonatlas.org/en/CO2-emissions

[8] (*xmper*) data is calculated by dividing exports plus imports of goods and services by total population.

works through the income and consumption relation, such a way that as countries become richer, the households spend more of the production, which results in more in emissions. Hence, the sign of the *gdpper* is expected to be positive in terms of both CO_2 emissions measures. Next, we include population density. As expressed by Strazicich and List (2003), countries with greater population density will tend to make more efforts to reduce emissions and thus converge to lower emissions rates. Our expectation for population density, therefore, is negative. However, it is important to emphasize that while the effect of population density on emissions rates may be statistically significant and greater (the absolute value) in magnitude in terms of *pba*, this may not be necessarily true for *cba*. This is because the emissions policies to reduce GHGs directly target the reduction of *pba* rather than *cba*. In addition to standard variables, this study also considers a newly identified control variable in order to examine for the effects on conditional convergence: trade volume per capita. This variable is considered to be more closely related with *cba* emissions rather than *pba*. Both the trade volume and patterns of trade are expected to have a significant impact on *cba* (Liddle 2018). The gap between embodied emissions in imports and exports might be due to the increasing gap between the trade volume of imports and exports as well as changing trade patterns. If a country experiences a huge trade deficit, where imports exceed their exports, it is more likely that this country will have a higher CBE than PBE. If, on the other hand, this country dominantly exports energy intensive products and imports less energy intensive products in their trade, it is possible to see that the country's CBE are lower than its PBE. According to "Pollution Heaven Hypothesis," for instance, pollution intensive industries will contract in countries with relatively strong environmental regulation and expand in those where there is no or relatively weak environmental regulations (Copeland and Taylor 2013). Such environmental policy differences may serve as an important source of comparative advantages for the latter group of countries. As earlier global climate agreements, particularly the Rio Convention and the Kyoto Protocol, did not include all countries in terms of GHG reduction pledges, the issue of carbon leakage has been seen a serious challenge to international climate mitigation programs. We, therefore, believe that including *xmper* as a control variable will provide us some useful insights to analyze the result of the findings.

This study covers 35 Annex B countries for the period between 1990 and 2015. The countries are listed in Table 1.[9] In all estimations, all series are in natural logarithm and 2003 is chosen to serve as midpoint in our sample for all control variables.

[9] Due to the issues on completeness of data on *CBA*, we excluded Iceland, Liechtenstein, Luxemburg, Malta, and Monaco from the original Annex B list.

Table 1 Country list

Australia	Estonia	Latvia	Slovak Republic
Austria	Finland	Lithuania	Slovenia
Belgium	France	Netherlands	Spain
Bulgaria	Germany	New Zealand	Sweden
Canada	Greece	Norway	Switzerland
Croatia	Hungary	Poland	Ukraine
Cyprus	Ireland	Portugal	UK
Czech Republic	Italy	Romania	USA
Denmark	Japan	Russian Federation	

Before proceeding to the empirical results, a simple approach to detect convergence or divergence in our sample in terms of both CO_2 emissions measures can be useful. Figures 1 and 2 present a scatter plot of each 35 countries' average CO_2 emissions per capita growth between the period of 1990–2015 against their initial value (1990). Both figures reveal a negative relationship between average growth rates and initial values, suggesting CO_2 emissions convergence. However, it is obviously seen that the slope of *pba* is steeper than the slope of *cba* indicating the speed of absolute convergence is greater in magnitude for *pba*. Not surprisingly, this may be a consequence of solely taking into account production side of CO_2 emissions while making policy implications. Of course, these figures can be regarded only as a preliminary analysis and do not give any information about the magnitude and statistically significance of the convergence parameter or the effect of control variables on convergence. We now turn to examine the statistical significance of convergence parameter and the effects of control variables on convergence.

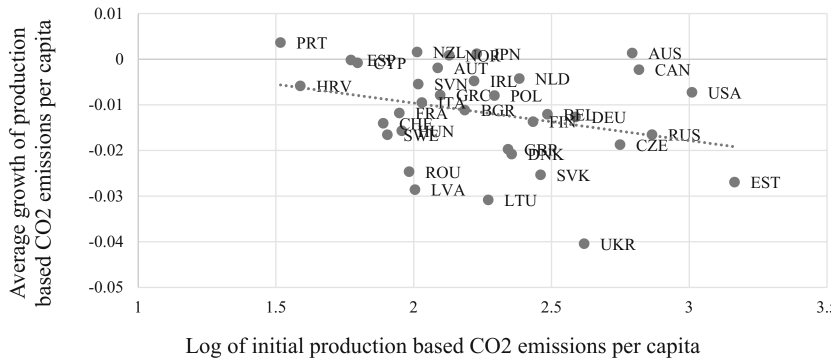
(iii) Findings

This study first tests the absolute β convergence, yet we also include a number of control variables into the empirical test to analyze conditional convergence. While doing this, we also try to see the impacts of different combinations of control variables in order to test the robustness of the empirical analysis.

Cross-sectional regression test results for 35 Annex B countries for the period 1990–2015 are summarized in Table 2. While dependent variable is the average growth rate of *pba* for the upper panel of Table 2, it is the growth rate of *cba* for the lower panel of Table 2.

The second and third columns give the constant term and the coefficient of convergence parameter (β), respectively. Equations (2.1) and (2.7) show the absolute convergence results, while Eqs. (2.2) to (2.6) and (2.8) to (2.12) present conditional convergence results using different control variables. As indicated before, β is expected to be between 0 and -1 as an indication of convergence and the higher absolute value of β, the stronger convergence.

Fig. 1 Production-based CO_2 emissions convergence



The third column of Eqs. (2.1) and (2.7) shows the results for absolute convergence. While statistically significant β coefficient (-0.008) between 0 and -1 indicates absolute convergence in *pba*, it is clearly seen that the absolute convergence parameter (-0.007) is negative but statistically insignificant for *cba*. In addition to this, in accordance with Figures 1 and 2, the speed of convergence in *pba* is greater than *cba* (in spite of statistically insignificance of this coefficient). It means that the slope of convergence in *pba* is getting stepper than *cba*.

When *gdpper* is used as a control variable, both convergence parameters reported in the third column in Eqs. (2.2) and (2.8) (-0.007 and -0.011) are statistically significant at 10% and 1% levels and the sign of *gdpper* provides a strong support for our position on our expectations. The fact that *gdpper* has a positive relationship with both the *pba* and *cba* through different mechanisms can be clearly seen in these empirical results. Moreover, while the absolute value of conditional *cba* convergence parameter increases (from 0.007 to 0.011), the absolute value of conditional *pba* convergence parameter decreases (from 0.008 to 0.007). Same conclusion appears when *sqgdpper* is used as a control variable (from 0.007 to 0.011 vs. from 0.008 to 0.007).

Eqs. (2.4) and (2.10) suggest that *pd* is negative (this is also consistent with our expectations) and but statistically insignificant at conventional levels. The fact that the emissions policies to reduce air pollutants directly target the reduction of *pba* rather than *cba* is obvious in the estimate results of Eqs. (2.4) and (2.10). This is because while the absolute value of convergence parameter increases the highest point (0.010) for *pba*, it almost remains same (0.008) (the lowest point) for *cba*.

When we consider our newly identified control variable (*xmper*) shown in Eqs. (2.5) and (2.11), we can suggest that *xmper* is statistically significant in both cases (0.005 vs. 0.006), indicating it has a significant effect on convergence in terms of *pba* and *cba*. However, in accordance with our expectations, this so-called effect is greater for *cba*. Moreover, while the convergence parameter for *cba* (-0.010) is highly significant at 1% level, it is statistically insignificant for *pba* (-0.007).

(iv) Discussion of the results

The CO_2 convergence per capita results are compared and assessed accordingly, for the Annex B countries with *pba* and *cba*.

On absolute convergence, our model finds a different pattern, such that while per capita emissions calculated by the PBA shows convergence at 10% significance level, the per capita emissions calculated by the CBA indicates divergence among the Annex B countries for the period of 1990–2015. This raises the issue of fairness in the allocation of responsibility between producers and consumers. As argued earlier, an international emissions allocation that is assigned based only on PB principles ignores the fact that those emissions are actually consumed somewhere else through trade. Therefore,

Fig. 2 Consumption-based CO_2 emissions convergence

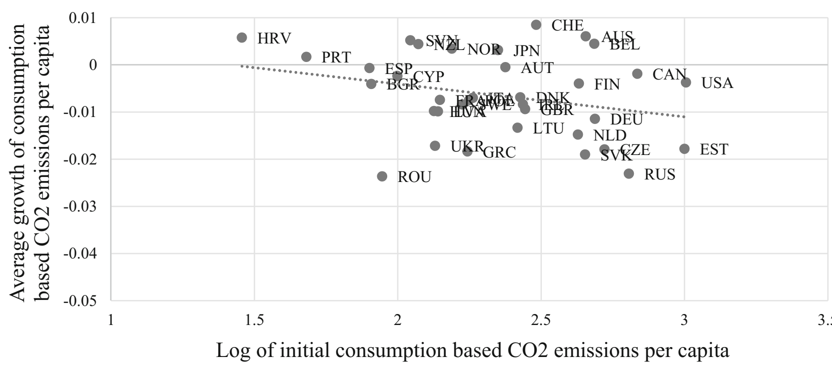


Table 2 Cross-section tests for conditional convergence in per capita production-based and consumption-based CO_2 emissions among 35 Annex B countries from 1990 to 2015

Eq.	α	β	*gdpper*	*sqgdpper*	*pd*	*xmper*
Dependent variable: average growth rate of production-based CO_2 emissions per capita						
2.1	0.007 (0.66)	−0.008 (−1.82)*				
	$\overline{R}^2$ = 0.064		F = 3.31*		n = 35	
2.2	−0.070 (−3.67)***	−0.007 (−2.03)*	0.007 (4.46)***			
	$\overline{R}^2$ = 0.404		F = 12.53***		n = 35	
2.3	−0.033 (−2.69)**	−0.007 (−2.05)**		0.0004 (4.35)***		
	$\overline{R}^2$ = 0.393		F = 12.02***		n = 35	
2.4	0.020 (1.45)	−0.010 (−2.20)**			−0.002 (−1.39)	
	$\overline{R}^2$ = 0.089		F = 2.67*		n = 35	
2.5	−0.040 (−1.84)	−0.007 (−1.68)				0.005 (2.40)**
	$\overline{R}^2$ = 0.182		F = 4.78**		n = 35	
2.6	−0.263 (−1.60)	−0.009 (−2.49)**	0.056 (1.66)	−0.002 (−1.28)	−0.001 (−1.26)	−0.006 (−1.80)*
	$\overline{R}^2$ = 0.487		F = 7.46***		n = 35	
Dependent variable: average growth rate of consumption-based CO_2 emissions per capita						
2.7	0.010 (1.01)	−0.007 (−1.68)				
	$\overline{R}^2$ = 0.051		F = 2.82*		n = 35	
2.8	−0.049 (−3.44)***	−0.011 (−3.45)***	0.007 (4.88)***			
	$\overline{R}^2$ = 0.439		F = 14.31		n = 35	
2.9	−0.016 (−1.72)*	−0.011 (−3.47)***		0.0004 (4.93)***		
	$\overline{R}^2$ = 0.443		F = 14.54***		n = 35	
2.10	0.016 (1.35)	−0.008 (−1.82)*			−0.001 (−0.91)	
	$\overline{R}^2$ = 0.046		F = 1.81		n = 35	
2.11	−0.036 (−2.44)**	−0.010 (−2.82)***				0.006 (3.73)***
	$\overline{R}^2$ = 0.318		F = 8.92***		n = 35	
2.12	0.022 (0.16)	−0.012 (−3.59)***	−0.007 (−0.23)	0.0007 (0.45)	−0.001 (−1.23)	0.0003 (0.12)
	$\overline{R}^2$ = 0.420		F = 5.92***		n= 35	

Dependent variable is the average annual growth rate of CO2 emissions in country *i*. *t* statistics are shown in parentheses. *, **, and *** denotes significance at 10%, 5%, and 1%, respectively

finding convergence in per capita emissions among the sample countries based on the PBA does not necessarily refer to a fair distribution of emission allocation in global climate agreements. Since our results indicate divergence in per capita consumption emissions, developing countries will be less likely to agree on burden sharing allocation of emission distribution adopted by the Annex B countries. This will put forward a strong case for developing countries asking for incorporating consumption-based principles into climate negotiation talks.

Likewise, by comparing the convergence results, it is possible to have, at least, some idea on the relationship between income and environmental pressure, specifically on decoupling issues. As our CBE analysis does not find absolute convergence among the Annex B countries, similar to Mir and Storm (2016) argument, this result might support the claim that there is no convincing decoupling taking place between the income and emissions for the sample period. While acknowledging the recent improvements in emissions reduction in the developed regions, the observed PBE reductions achieved by the Annex B countries could, therefore, partially be due to outsourcing these emissions to non-binding developing countries.

Model results with control variables provide some important implications on conditional convergence, which also support for the arguments of the need for separation of the convergence data based on the PBA and the CBA.

gdpper has positively correlated and statistically significant for both *pba* and *cba*. It is reasonable to expect such outcome for both cases. Moreover, similar to Fan et al. (2016) findings, the impact of *gdpper* on convergence in *cba* has been more stronger. This is also what one would expect as CBA data includes both domestically consumed and imported emissions. Since economic theory suggests that imports are positively and closely correlated with the level of domestic income, when countries get richer, this will lead to increases in imports and consequently increases in imported emissions. PBE, however, include exported emissions alongside domestically consumed and as economic theory suggests that exports are dependent on the partner countries income rather than the domestic income. As a result, impacts of *gdpper* will be limited on the *pba* only through domestic consumption.

In the case of *pd*, we have seen a reverse outcome compared with *gdpper*, such that including the *pd* had more influence on conditional beta convergence for the *pba* compared with *cba*. As discussed above, *pd* is more influenced with PB policies and therefore it would have more impact on *pba* and less on *cba*.

The control variable of *xmper* is particularly introduced to see the role of the foreign trade in CO_2 emissions growth. When the *xmper* is included in model, we see that it has no significant impact on *pba* as the beta sign is statistically insignificant even at the 10% level. The result with the *cba*, however, finds that the *xmper* has significant impact on consumption per capita emissions growth and beta is statistically significant even at the 1% level. Besides, the magnitude of the beta coefficient becomes much stronger. Similar to Liddle (2018) findings, this outcome supports our argument that foreign trade is an important factor in affecting the growth of CO_2 emissions and therefore comprehensive trade-related policies should be designed to tackle to curb the emissions.

Finally, when the model includes all control variables, both data sets result in improving the beta convergence, however, the impact on *cba* is even stronger. Another important finding is that the PBE data provides some support for the existence of the EKC hypothesis, yet the CBE data does not support the EKC as the signs of *gdpper* and *sqgdpper* are opposite the expectations and statistically insignificant.

Conclusion

Emission and economic growth relationship has been analyzed extensively by many studies. Several empirical analyses are applied on these issues and it is important to notice that the analyses are based on emissions data provided by the PBA. This study argues that many of these analyses could be misleading or incomplete only relying on data provided by the PBA as it ignores trade perspective.

Today, we live in a world in which economic production process and supply chains are international and global trade of goods and services from production sites in one country to final consumers in another is very common in this globalized network of production and consumption, who should be held accountable for reducing associated GHG emissions. Studies indicate that emission reductions achieved by the Annex B countries during First Kyoto Period were offset by net emission transfers from non-Annex B to Annex B countries. This emphasizes the importance of considering alternative emission calculations and new policy perspectives.

This study, therefore, suggests that the CBE accounting should be considered an important tool in CO_2 emission analysis. The CBE particularly address emissions embodied in trade, that is not included in traditional production-based national emissions inventories. The CBE, as an alternative to the PBE, could provide significant advantages to policymakers both in terms of presenting valuable tools for understanding CO_2 emission patterns in detail and to develop target-based policies and measures to address emissions originating from outside country (Afionis et al. 2017).

This study particularly discusses and analyses the convergence in CO_2 emissions with a focus on how the outcome differs when the CBE accounting taken into consideration. As almost all literature on environmental convergence employs data based on standard production-based perspective, it can be argued that such assessment could be incomplete and needs further insight with the CBE. Convergence analysis using per capita CBE will provide better information and make more sense in terms of analyzing climate change and economic growth relationship issues, such as decoupling and the EKC by linking emission leakage concerns.

The empirical part of this study tests beta convergence of CO_2 per capita measured both by PB and CB accounting system. It is argued that convergence results may be the same or considerably differ when the accounting system is distinguished. By doing so, a number of conclusions and policy implications can be drawn depending on the results obtained from different accounting systems.

PBE model results show the existence of a negative and statistically significant relationship between initial levels of CO_2 emissions per capita and subsequent growth rates. When convergence in per capita consumption emissions is tested, we find no absolute convergence for the Annex B countries. Inclusion of some of the control variables, however, makes the convergence results more robust for the CBE analysis as the beta becomes more significant and stronger.

Since our results indicate divergence in per capita consumption emissions, in contrary to convergence findings for the production-based CO_2 per capita, this would imply that developing countries will be less likely to agree on burden sharing allocation of emission distribution adopted by the Annex B countries. The PBE results indicate that there is existence of EKC relationship as emissions per capita increase with the GDP per capita but decrease with the *sqgdpper*. Yet, we see no evidence of EKC when we run the model with consumption-based emissions per capita as the signs are in opposite direction and statistically insignificant. From our convergence analysis and EKC assumptions, it is fair to argue that policymakers should not confidently assume that economic growth will also bring environmental improvement in the coming years. Even though we might see some improvements in energy efficiency and deployment of renewable energy, it is important to develop further mitigation policies and measures to tackle CO_2 emissions. These policies should particularly focus on consumption as it is an important driver of emissions that needs to be more specifically targeted. The findings of the study also suggests that at least some part of the observed decoupling of economic growth and production-based CO_2 emissions among the Annex B countries are indeed due to the leakages. Without policy attention to this sort of interregional carbon *leakage*, developing countries will struggle to meet their emissions targets that are committed at the Paris Agreement.

In order to reduce consumption-based emissions, countries should adopt new and innovative tools to target how to change consumer behavior, by providing knowledge and incentives to switch to smoother low-carbon society. New policies and measures should also address to decrease embodied emissions in traded products originating from other countries. Recent studies discuss a number of CB policy instruments that may help improve the economic well-being and environmental effectiveness of unilateral climate policies (Peters et al. 2016).

Finally, it is also important to notice that the CBA should not be considered a substitute instead, it should be considered a complementary to the PBA system. With the CBA, it is possible to identify new policy interventions and increase the potential to break down barriers that exist between developed and developing countries in international climate policy (Scott and Barrett 2015).

Since this study argues that many existing studies on convergence analysis are misleading as they use only the PBE data and challenges the results as they partially capture the whole picture of the theoretical framework of the CO_2 emissions and economic growth nexus, there are many dimensions of future studies on convergence, which needs to be explored. In this regard, we suggest future studies analyzing environmental convergence by using different MRIO databases (both the PBA and CBA data) with more heterogeneous country groupings and also at sectoral level within the country, with different convergence indicators (such as emissions per gdp, energy per GDP) and certainly with different convergence techniques (such as conditional convergence, sigma convergence, and club convergence).

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