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# Carbon dioxide emissions allocation: A review

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ABSTRACT

Carbon dioxide ($CO_2$) emissions allocation plays a fundamental role in determining reduction responsibility at economy level or emission permits at firm level. Past decades have seen the development and applications of various methods for $CO_2$ emissions allocation. This paper provides a literature review of $CO_2$ emissions allocation with emphasis on the evolution of allocation methods used. It begins with a summary of the most popular allocation principles and criteria that lay a foundation for the development of allocation methods. We then classify the existing allocation methods into four groups, namely indicator, optimization, game theoretic and hybrid approaches. The main features and findings of past studies are identified and summarized. While the fairness principle prevails in earlier studies, the efficiency principle has been found to receive increasing attention recently. We also present a comparison of the empirical results based on ten popular indicator methods to show how indicator choice affects the allocation results. Issues related to selecting appropriate methods in $CO_2$ emissions allocation are finally discussed. Further research may be carried out to strike a balance between fairness and efficiency so that the allocation results become more widely acceptable and economically feasible.


## 1. Introduction

Climate change, resulting from the growing concentrations of greenhouse gases (GHGs) in the atmosphere, has been regarded as one of the major challenges in the 21st century. Scientists have shown that it brings about environmental degradation and natural disasters threatening human safety and health (Walther et al., 2002). In order to avoid more dangerous long-term effects of climate change, the Intergovernmental Panel on Climate Change (IPCC) has emphasized the importance of limiting the increase of global average temperature not greater than 2 °C. The target requires a reduction of global GHGs emissions, mainly carbon dioxide ($CO_2$), by at least 50% until 2050, which implies that future emission space would become extremely stringent (Pan et al., 2014a). As a consequence, there is a strong political desire for the allocation of restricted emission space in order to achieve global GHGs emission reduction target.

A necessary but challengeable step is to reach a consensus on the responsibility sharing of $CO_2$ emission reductions between different countries. Although it has universally been agreed that all the countries need to take responsibilities in reducing global $CO_2$ emissions (Chakravarty et al., 2009), previous international climate change conferences have not reached an explicit agreement on the burden sharing after Kyoto Protocol. Within a country, debates also exist on the responsibility sharing of emission reductions between different regions/cities. At firm level, carbon emission trading (CET) has widely been regarded as a cost-effective tool for realizing $CO_2$ emission reduction (González-Eguino, 2011). In practice, the European Union Emission Trading Scheme (EU ETS) as the biggest emission trading market took effect in 2005.[1] As the largest $CO_2$ emitter, China launched its pilot ETS in seven provinces and cities in 2013/2014 and will establish its national ETS in 2017. In the existing CET systems, an open question always arises on how to allocate $CO_2$ emission permits among the participating firms at the beginning of each trading period (Cramton and Kerr, 2002; Böhringer and Lange, 2005; Zetterberg et al., 2012).

Undoubtedly, the allocation of $CO_2$ emissions may be performed at different levels, e.g. the burden sharing between countries, the decomposition of national emission reduction target into regional ones, and the distribution of tradable emission permits between firms in a CET system (Bohringer and Lange, 2005; Baer et al., 2008; Yi et al., 2011). Since earlier 1990s, there has been a continuous research interest in examining the issue of $CO_2$ emissions allocation that led to a great deal of publications in diverse international journals. The purpose of this study is to provide an up-to-date review of past studies on $CO_2$ emissions allocation, with particular emphasis on the classification and evolution of

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[1] In the first two phases (2005–2007 and 2008–2012), emission permits were allocated to the participating firms mainly by grandfathering. When allocating permits to new entrants, benchmarking would be adopted. In the third phase (2013–2020), full auctioning is applied to the electricity sector and a "transitional free allocation" based on benchmarking is used for other sectors (Zetterberg et al., 2012).

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allocation methods used. It is expected that this review study will be helpful to scholars for identifying the key features of past studies and understanding the similarities as well as the differences between different allocation methods.

The remainder of this study is organized as follows. Section 2 describes the main principles and criteria used for $CO_2$ emissions allocation. Section 3 classifies the main allocation methods into four groups, namely indicator, optimization, game theoretic and hybrid approaches, and describes the main developments of each group. In Section 4, the key features of past studies in methodological aspect and application scheme are discussed. We also conduct a comparison of the allocation results by several popular indicators to show how the results are affected by indicator choice. Section 5 concludes this study with brief discussions on method choice and potential future research topics.

## 2. Principles of Emissions Allocation

One primary issue in $CO_2$ emissions allocation is to determine the allocation principle to be followed. In literature, different allocation criteria have been advocated and applied, which may broadly be divided into two categories, namely fairness and efficiency principles. Fairness principle is often linked to more general concepts of distributive justice (Rose, 1990). Efficiency principle is mainly relevant to the economic efficiency of emission reduction, e.g. the minimization of total abatement cost. Although fairness and efficiency principles have their special focuses, several scholars such as Welsch (1993) and Zhou et al. (2014) argued that efficiency may also be treated as a type of fairness.

Table 1 summarizes some commonly used allocation criteria with their interpretations and operational rules, which are compiled from earlier studies such as Rose (1990, 1998), Rose and Stevens (1993), Ringius et al. (1998, 2002), Berk and den Elzen (2001), Rose and Zhang (2004), and Vaillancourt and Waaub (2004).[2] It can be observed from Table 1 that quite a few criteria have ever been employed for $CO_2$ emissions allocation. Most of them follow the fairness principle while taking different perspectives, e.g. sovereignty, egalitarianism, horizontal equity, vertical equity and polluter pays. An exception is the merit criterion following the efficiency principle, based on which emission permits are distributed in proportion to the reciprocal of emission intensity. In addition, most of the criteria are used for $CO_2$ emissions allocation at country level. While grandfathering is mainly used for the distribution of emission permits at firm level, in operation it is indifferent from the sovereignty criterion that is used at country level.

It should be pointed out that each criterion given in Table 1 can be implemented by using different indicators. On the other hand, an indicator may also be used for implementing different allocation criteria. For example, the sovereignty criterion can be implemented based on historical $CO_2$ emissions or energy consumption. The indicator of $CO_2$ emissions can also serve for more than one criterion, e.g. sovereignty and polluter pays. Different combinations of allocation criterion and reference indicator usually have different welfare implications, which explains the difficulty in reaching a consensus on the responsibility sharing between entities only by one indicator. As such, many emissions allocation methods have been proposed based upon one or more allocation criteria, which are schematically summarized in the next section.

## 3. Emissions Allocation Methods

Under the umbrella of fairness and efficiency principles, many different methods have been proposed for $CO_2$ emissions allocation. In this study, we classify the existing methods into four groups, namely indicator, optimization, game theoretic and hybrid approaches (see Fig. 1).[3]

### 3.1. Indicator Approach

Indicator approach, the most commonly used emissions allocation approach, means that emission permits or reduction targets are allocated based on certain indicator(s). It consists of single and composite indicator approaches. In the single indicator approach, an individual indicator is used to distribute emission permits or reduction targets among participating entities (Rose, 1990; Rose and Stevens, 1993; Rose et al., 1998). The composite indicator approach integrates multiple indicators representing different criteria into a composite indicator, based on which the aggregate emission permits or reduction targets are allocated to each participant (Ringius et al., 2002; Vaillancourt and Waaub, 2004).

#### 3.1.1. Single Indicator Approach

Owing to its simplicity and ease of use, the single indicator approach has been widely used to allocate $CO_2$ emission permits or reduction targets since the 1990s (Miketa and Schrattenholzer, 2006). In practice, the indicators selected for use are quite broad in scope. As shown in Table 2, an indicator may generate a few allocation methods or rules, which are dependent upon the allocation criteria followed. For example, in the case of GDP indicator, the amounts of emission permits allocated to participating entities are proportional to their GDP when the economic activity criterion is adopted. However, when the ability to pay criterion is used, the amounts of emission reductions allocated become proportional to GDP. In the followings, we shall summarize the main developments of some popular indicators.

*3.1.1.1. Population.* Population-based allocation rules have been widely advocated in $CO_2$ emissions allocation at country level. Grubb (1990) first developed an allocation method for tradable $CO_2$ emission permits on an adult per capita basis. Later, Agarwal and Narain (1991) highlighted the use of equal per capita allocation rule at country level, which was used by Bertram (1992) to allocate tradable $CO_2$ emission permits. Since then, many scholars have contributed to examine equal per capita allocation scheme in both methodological and application aspects. Examples of such studies are Larsen and Shah (1994), Edmonds et al. (1995), Rose et al. (1998), Azar (2000), Baer et al. (2000), Leimbach (2003), Rose and Zhang (2004), Böhringer and Welsch (2006), Sørensen (2008), Chakravarty et al. (2009) and Zhou et al. (2013).

Acknowledging the strengths of per capita allocation scheme, some scholars argued that $CO_2$ emissions allocation needs to take into account the fairness between different generations. For instance, Grübler and Fujii (1991) considered discounted historical responsibility and proposed equal future per capita emission permits allocation method. By contrast, den Elzen et al. (1992) developed equal per capita cumulative emission permits allocation rule, by which everyone is allowed to emit the same amount of $CO_2$ emissions annually, independent of time or place lived. Since equal per capita cumulative emissions allocation rule accounts for the historical responsibility of developed countries, several studies, e.g. Ding et al. (2009), Yu et al. (2011), Pan et al. (2014a) and Wei et al. (2014), advocated to use it in negotiating the emission reduction responsibility of different countries.

Considering the fact that per capita $CO_2$ emissions vary across different counties, Meyer (2000) proposed the contraction and convergence (C&C) approach for $CO_2$ emissions allocation. The rationale of the C&C approach is that global $CO_2$ emissions need to be cut down substantially

[2] It should be pointed out that the list of criteria given in Table 1 is definitely not complete. Other criteria, e.g. willingness to pay (Vaillancourt and Waaub, 2004), are not included since they were rarely implemented in earlier studies.

[3] While the classification is rather encompassing, it does not cover all the existing emissions allocation methods, e.g. the Boltzmann distribution method proposed by Park et al. (2012).

**Table 1**
Main allocation criteria with their interpretations and operational rules.

| Criterion | Interpretation | Operational rule |
|---|---|---|
| Sovereignty/ Grandfathering | All nations (firms) have equal right to pollute and to be protected from pollution | Distribute permits in proportion to historical emissions (energy) |
| Egalitarianism | All people have equal right to pollute and to be protected from pollution | Distribute permits in proportion to population |
| Ability to pay | Mitigation costs vary directly with national economic wellbeing | Distribute permits inversely to GDP or per capita GDP |
| Economic activity | All nations should be allowed to maintain their standard of living | Distribute permits in proportion to GDP |
| Horizontal equity | All countries should be treated equally in terms of changes in welfare | Distribute permits to equalize net welfare change (net loss as proportion of GDP equal for each nation) |
| Vertical equity | Welfare gains vary inversely with national economic wellbeing, and welfare losses vary directly with GDP | Progressively distribute permits (net gain/loss proportions inversely/directly correlated with per capita GDP) |
| Polluter pays/Historical responsibility | Nations with more historical emissions need to take more abatement burdens | Distribute reduction responsibility in proportion to cumulated emissions |
| Merit (efficiency) | Nations should be compensated for emission reduction efforts | Distribute permits inversely to emission intensity |

and per capita $CO_2$ emissions in different countries should gradually be equalized. This line of thought was followed by many subsequent studies, e.g. Berk and den Elzen (2001), den Elzen (2002), Böhringer and Welsch (2004, 2006) and Persson et al. (2006). As a major extension to the C&C approach, Höhne et al. (2006) introduced the common but differentiated convergence (CDC) approach. With the CDC approach, both Annex I and non-Annex I countries' per capita $CO_2$ emissions are required to converge to a certain level for a given period of time. The difference is that non-Annex countries are allowed to increase their per capita $CO_2$ emissions to a level higher than the world average by a certain rate before convergence. As discussed by Hof et al. (2010) and van Ruijven et al. (2012), the CDC approach considers Annex I countries' historical responsibility and non-Annex I countries' needs for development so that it is more favorable to developing countries.

*3.1.1.2. Emission (Energy).* Of the allocation schemes based on emission indicator, grandfathering represents the most popular one at firm level owning to its lower data requirement, wider acceptability and potential for reducing carbon leakage (Schmidt and Heitzig, 2014). It means that free emission permits are allocated in proportion to historical emissions of the entity (Bohringer and Lange, 2005). Some scholars ever compared grandfathering with benchmarking, an alternative popular allocation scheme based on emission intensity, for emission permits distribution among firms. See, for example, Jensen and Rasmussen (2000), Edwards and Hutton (2001), Demailly and Quirion (2006), Neuhoff et al. (2006), Zhao et al. (2010) and Zetterberg et al. (2012). It was found that grandfathering suffered from the limitations of rewarding carbon intensive firms, punishing carbon efficient firms, creating a hinder against new firms and giving windfall profits to certain sectors which pass through carbon cost to product price.[4]

Apart from grandfathering, several other allocation criteria based on emission indicator were also advocated, e.g. sovereignty, historical responsibility and polluter pays (Rose, 1990; UNFCCC, 1997; Rose et al., 1998; Ringius et al., 1998, 2002; Rose and Zhang, 2004; Vaillancourt and Waaub, 2004). The sovereignty criterion is analogous to grandfathering in operation while they respectively handle $CO_2$ emissions allocation at country and firm levels. The criterion of historical responsibility indicates that emission reductions are allocated according to a country's responsibility for temperature increase. Similar to historical responsibility, the polluter pays criterion says that emission reductions are shared based on historical emission levels. In comparison, historical responsibility and polluter pays put emphasis on past responsibility, while sovereignty and grandfathering highlight the needs for future development (van Ruijven et al., 2012).

As a complement to the simple indicators, more complicated emission indicators for accounting $CO_2$ emissions inventory, e.g. consumption-based emissions, have been advocated (Wiedmann, 2009). While production-based emission accounting method is straightforward, consumption-based emission accounting has been paid more attention in the past years, e.g. Munksgaard and Pedersen (2001), Peters and Hertwich (2008) and Peters (2008). Apart from production-based and consumption-based accounting rules, several scholars ever examined the criterion of shared responsibility between producers and consumers, e.g. Ferng (2003), Bastianoni et al. (2004) and Lenzen et al. (2007). Such indicators offer new perspectives in determining a country's emission reduction responsibility, while suffers the uncertainty in choosing a suitable model for calculation.

Additionally, several scholars argued the use of energy indicators (e.g. energy consumption or production) for $CO_2$ emissions allocation because a majority of $CO_2$ emissions come from burning fossil fuel (Rose and Zhang, 2004; Zhou et al., 2013). In operation, the use of energy indicators is often linked to the criterion of grandfathering, while it is possible to implement it under the historical responsibility and polluter pays criteria.

*3.1.1.3. GDP/Per Capita GDP.* The three allocation criteria, i.e. horizontal equity, ability to pay and economic activity, are built upon the GDP indicator (Rose, 1990; Rose et al., 1998; Rose and Zhang, 2004). The horizontal equity criterion aims to allocate $CO_2$ emission permits to equalize the net welfare change, which requires estimating carbon abatement cost functions (Welsch, 1993). The ability to pay criterion assumes that richer countries need to take more responsibility in reducing $CO_2$ emissions than poorer countries, which implies that emission reductions are allocated in proportion to GDP. The economic activity criterion says that $CO_2$ emission permits are allocated in proportion to GDP, which implicitly indicates that all countries have equal rights to maintain their living standard. In contrast, the use of horizontal equity and economic activity criteria may aggravate the imbalance in economic development between developed and developing countries.

The applicability of per capita GDP in $CO_2$ emissions allocation has also been examined extensively, which is usually linked to the criteria of vertical equity and ability to pay. For example, Rose (1990) proposed the vertical equity criterion to allocate $CO_2$ emissions, which means that the participating entity with higher capacity to pay (per capita GDP) should take more economic burden. Winkler et al. (2002) suggested the use of per capita GDP for $CO_2$ emissions allocation based on the ability to pay criterion. Compared to horizontal equity and economic activity criteria, both vertical equity and ability to pay criteria tend to assign more emission reductions to developed countries, which relatively mitigate the burden of developing countries in cutting $CO_2$ emissions.

*3.1.1.4. Emission Intensity.* Emission intensity often refers to $CO_2$ emissions per unit of GDP or physical product, and its use for $CO_2$ emissions allocation emphasizes the efficiency of carbon mitigation. Some scholars argued that $CO_2$ emission reductions should be allocated in proportion to emissions per unit of GDP, which is built upon the assumption that more carbon efficient participants should be compensated or rewarded for previous reduction efforts (Rowlands, 1997; Winkler et al., 2002). To

[4] In the third phase of EU ETS, the share of $CO_2$ emission permits allocated by auctioning is gradually increasing. The transition from grandfathering to auctioning is mainly to avoid the problems arising from grandfathering and ensure efficiency and transparency of the system (Zetterberg et al., 2012).

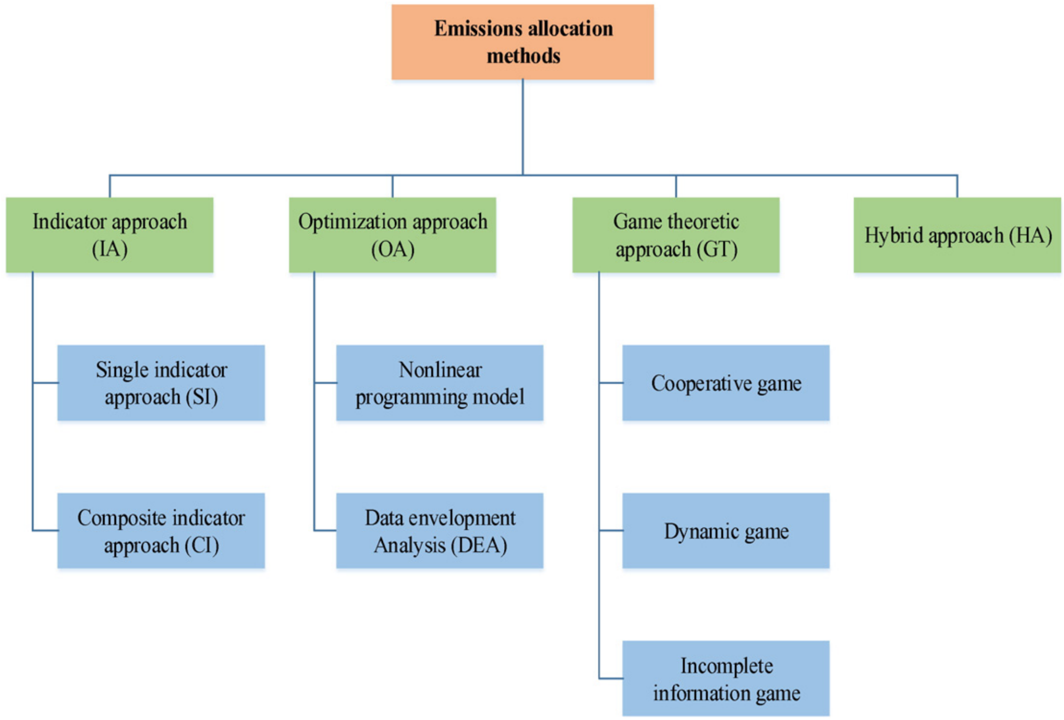


**Fig. 1.** Classification of emissions allocation methods.

smooth the transition of a country's burden shares in global emissions from the beginning year to the ending year, Miketa and Schrattenholzer (2006) further extended the approach under the contraction and convergence framework.

**Table 2**
Main indicators for $CO_2$ emissions allocation.

| Indicator | Allocation criterion | Allocation rule |
|---|---|---|
| Population | Egalitarianism | Equal adult per capita permits<br>Equal per capita permits<br>Equal future per capita permits with discounted historical responsibility<br>Equal past and future per capita permits<br>Equal per capita permits by C&C<br>Equal per capita permits by CDC |
| Emission | Sovereignty/grandfathering | Proportional permits to historical emissions (country/firm) |
| | Polluter pays | Proportional reductions to a historical level |
| | Historical responsibility | Proportional reductions to cumulative emissions |
| Energy | Sovereignty/grandfathering | Proportional permits to energy consumption<br>Proportional permits to energy production |
| GDP | Economic activity<br>Ability to pay<br>Horizontal equity | Proportional permits to GDP<br>Proportional reductions to GDP<br>Equal net abatement cost to GDP |
| Per capita GDP | Ability to pay | Proportional reduction to per capita GDP |
| | Vertical equity | Equal net abatement cost to per capita GDP |
| Emission intensity | Merit (efficiency) | Proportional reductions to emissions per unit of GDP<br>Proportional reductions to emissions per unit of GDP by C&C<br>Proportional permits to emissions per unit of production outputs (*also called benchmarking*) |

Note: C&C = contraction & convergence; CDC = common but differentiated convergence.

The indicator of $CO_2$ emissions per unit of product is often used to allocate $CO_2$ emission permits at firm level, which is also termed as benchmarking or output-based allocation (Groenenberg and Blok, 2002). Compared to grandfathering, benchmarking avoids rewarding carbon inefficient firms and punishing rapidly growing firms, which encourage firms to improve their carbon efficiency. Nevertheless, the implementation of benchmarking requires more detailed data and thus bears more efforts/costs in data collection and consolidation.

The single indicator approach covers a variety of indicators which usually reflect different fairness perspectives. A major strength of the single indicator approach is that it is easy for policy makers to understand the implication of an indicator and to use it in practice, e.g. allocating free emission permits between firms in ETS. However, the indicator used may not be accepted by all since it is usually more favorable to one group of entities.

*3.1.2. Composite Indicator Approach*

Composite indicator approach, which was widely used in assessing environmental or sustainability performance (Zhou et al., 2006, 2007; Böhringer and Jochem, 2007; Hatefi and Torabi, 2010; Floridi et al., 2011; Luzzati and Gucciardi, 2015), has also received increasing attention in $CO_2$ emissions allocation owing to its strength in integrating different fairness criteria.

The Triptych method, initially proposed by Phylipsen et al. (1998) for the allocation of emission reductions among EU member countries, may be regarded as a naïve composite indicator approach. As a bottom-up method, it distinguishes among three groups of sectors, i.e. power sector, energy-intensive industry and domestic sector. For the power sector, the maximum requirement for fossil fuel consumption and the minimum requirement for renewable energy use are set to determine its emission permit. For the energy-intensive industry, its emission permit is estimated by assigning a minimum level of emission efficiency improvement. The emission permit for the domestic sector is estimated by setting per capita $CO_2$ emissions at a certain level. A country's emission permit can be derived by adding the three sectoral emission permits together. Several scholars later extended the Triptych method to study the global burden sharing of GHGs reduction, e.g. Groenenberg et al. (2001, 2004) and den

Elzen et al. (2008b). The Triptych method has several strengths such as distinction between sectoral circumstances and consideration of emission reduction potentials among different countries (Ekholm et al., 2010; Hof and den Elzen, 2010). However, a large volume of data is needed for setting the targeting efficiency indicators and determining the benchmarks for all sub-sectors in using the Triptych method.

Multi-criteria decision analysis (MCDA) as a popular decision aiding tool plays a major role in constructing composite indicators. Ringius et al. (1998) used the weighted sum method to aggregate a group of indicators based on different weight settings for the allocation of GHG emission reductions among OECD countries. Yi et al. (2011) developed a composite indicator for determining the emission intensity reduction targets of different provinces in China by using the weighted sum method. In spite of the popularity of the weighted sum method in constructing various types of composite indicators, researchers have shown that the weighted product method hold several desirable properties, e.g. theoretical meaningfulness (Ebert and Welsch, 2004) and less information loss (Zhou et al., 2006; Zhou and Ang, 2009). In $CO_2$ emissions allocation, Beckerman and Pasek (1995) suggested that emission permits are allocated in proportion to the product of population and emission intensity. Baer et al. (2008) developed a Greenhouse Development Rights (GDRs) framework on the basis of the weighted product of capacity (wealth) and responsibility (contribution to climate change).

In addition to the simple MCDA methods, the applicability of more advanced MCDA techniques in $CO_2$ emissions allocation have also been examined. An example is Vaillancourt and Waaub (2004, 2006) who introduced a dynamical multicriterion method by considering different fairness and efficiency criteria to find a compromise solution in international climate change negotiations.

Compared to the single indicator approach, the composite indicator approach can easily integrates different fairness and efficiency criteria so that the allocation results might be more easily accepted by different entities. However, the determination of the weights for different indicators as well as the selection of an appropriate MCDA method for constructing composite indicators pose challenge for the use of composite indicator approach in $CO_2$ emissions allocation.

### 3.2. Optimization Approach

Previous studies have also explored the use of optimization approach, either linear or nonlinear programming models, for $CO_2$ emissions allocation from an efficiency perspective. A typical example of linear programming model is data envelopment analysis (DEA), which has been used to allocate $CO_2$ emissions at different levels.[5] At country level, Gomes and Lins (2008) proposed a zero sum gains DEA (ZSG-DEA) model to reallocate $CO_2$ emission permits among the Annex I and Non-Annex I countries. The ZSG-DEA model was recently employed by Chiu et al. (2015) and Pang et al. (2015) to allocate emission permits among sample countries. Färe et al. (2012) proposed a DEA model to examine the magnitude and timing of $CO_2$ emission reductions in 28 OECD countries during 1992–2006. At region level, DEA models have been used to examine the optimal $CO_2$ emissions allocation between different provinces in China (e.g. Wei et al., 2012; Wang et al., 2013; Zhou et al., 2014). The study by Zhou et al. (2014) found that the spatial–temporal allocation strategy seems to be more economically attractive in controlling the increase of $CO_2$ emissions in China. Applications of DEA to $CO_2$ emissions allocation at firm level can be found in Lozano et al. (2009) and Sun et al. (2014).

In addition to DEA models, more complicated nonlinear programming models have also been employed to examine $CO_2$ emissions allocation. For example, Filar and Gaertner (1997) investigated the allocation of world GHGs emission reductions by using nonlinear programming. The Regional Integrated model of Climate and the Economy (RICE model), initially developed by Nordhaus and Yang (1996), was also used to examine the optimal emission paths of GHGs in different regions (Cantore and Padilla, 2010). The strength of the RICE model lies in its capability in integrating climate and economy models. However, it was questioned by Skott and Davis (2013) for having an intrinsic distributional bias in favor of rich countries.

### 3.3. Game Theoretic Approach

The allocation of $CO_2$ emissions often requires the negotiations among different participants, which may be treated as a game in which each player strives for more permits for its benefit. The allocation results can then be regarded as an equilibrium solution to the game. As such, game theoretic approach has been advocated and used to search for the optimal allocation of emission permits or reductions.

At country level, Filar and Gaertner (1997) investigated the allocation of world GHGs emission reductions among countries by using the Shapley value method in cooperative game theory. Eyckmans and Tulkens (2003) introduced a cooperative game method to deal with the global burden sharing of emission reductions in climate negotiations. Germain and Steenberghe (2003) applied a dynamic game method to address the allocation of $CO_2$ emission permits among countries. Viguier et al. (2006) developed a two-level game model for assessing the strategic allocation of $CO_2$ emissions among different countries in the European Union.

Scholars have shown that emissions allocation at firm level can also be performed by using game theoretic models. For example, Mackenzie et al. (2008) suggested using rank-order contests in the initial allocation of permits among firms. The study by Mackenzie et al. (2009) further discussed the benefits of the incomplete information game method in emission permits allocation. Liao et al. (2015) examined the initial distribution of $CO_2$ emission permits among three power plants in Shanghai by using the Shapley value approach. Ren et al. (2015) proposed a Stackelberg game model to examine the allocation of $CO_2$ emission reduction targets in a decentralized make-to-order supply chain.

Compared to the indicator approach, the game theoretic approach is much more complicated and lack of transparency. However, it owns the merit of incorporating the negotiations between different entities in $CO_2$ emissions allocation.

### 3.4. Hybrid Approach

The hybrid approach refers to a mixture of various methods that cannot be attributed to the first three groups. In the hybrid approach, one practice is to use multiple indicators without constructing a composite indicator, e.g. the multi-stage regime proposed by Berk and den Elzen (2001). The multi-stage regime allows gradual increase in the number of countries covered and the level of reductions based on the participation threshold and allocation rules. While the multi-stage regime is flexible in allocating emission reductions, the actual emissions for a country often deviate from the emission permits allocated and the determination of the targets for the subsequent commitment periods is rather challengeable (den Elzen, 2002; den Elzen et al., 2005a, 2008a; den Elzen and Meinshausen, 2006; Ekholm et al., 2010). Gupta and Bhandari (1999) followed the idea of 'common but differentiated' responsibility and proposed a hybrid method, in which percentage emission reductions adjusted by an efficiency index and equal per capita emissions are respectively used for the $CO_2$ emissions allocation of Annex I and non-Annex I countries. Sijm et al. (2001) presented a multi-sector convergence approach for emissions allocation by

[5] DEA as a nonparametric performance evaluation methodology has been widely used to assess $CO_2$ emission performance and evaluate alternative abatement strategies (Lozano and Gutierrez, 2008; Bosetti and Buchner, 2009; Lozano et al., 2009; Kuosmanen et al., 2009; Zhou et al., 2010; Picazo-Tadeo et al., 2014).

combining the Triptych method, per capita convergence scheme and the multi-stage regime.

Another practice of the hybrid approach is to incorporate two or more groups of emission allocation approaches. For example, Ridgley (1996) proposed an integrated model to distribute GHGs emission reduction burdens among countries by combining the composite indicator and optimization approaches. Yu et al. (2014) proposed a hybrid approach to allocate regional $CO_2$ emission reductions in China by 2020 based on the particle swarm optimization algorithm, fuzzy c-means clustering algorithm, and Shapley decomposition. Zhang et al. (2014) studied $CO_2$ emission permits allocation at region level in China by integrating information entropy, gravity model and the Shapley value, which aims to consider vertical equity, historical responsibility, merit and economic connection between regions simultaneously.

Compared to other approaches, the hybrid approach is usually more complicated so that the allocation results are lack of transparency. Nevertheless, it has a theoretical merit of considering different fairness and efficiency criteria simultaneously.

## 4. Main Features and Findings of Past Studies

Over 100 studies have been collected from major environmental and climate economics journals such as *Ecological Economics*, *Energy Policy*, *Climate Policy* and *Climatic change*. Table A.1. in the Appendix A provides a classification of the studies collected by allocation principle, allocation method, application level, and the targeting indicator for allocation. To study possible trends over time, we divide the time frame into five equal spans of time, i.e. 1990–1994, 1995–1999, 2000–2004, 2005–2009 and 2010–2015. As shown in Fig. 2, the number of studies keeps increasing in the first four periods of time, which shows researchers' growing interest in this field.

### *4.1. Application Scheme*

Application scheme refers to the application level and the targeting indicator used for a study, which are provided in the last two columns of Table A.1. Application level represents the level at which $CO_2$ emissions are allocated, including country, region and firm. In this study, the allocation of $CO_2$ emissions among different countries or above is classified as country level, while the allocation among different states/provinces or cities is treated as regional level. Targeting indicator refers to the indicator used for emissions allocation, which is composed of emission permits, emission reductions and emission intensity reductions. Theoretically, the three types of indicators can be converted to each other in some way. Considering the fact that many studies do not distinguish between $CO_2$ emission permits/reductions and GHG emission permits/reductions intentionally, we treat them equally and use the term “emission permits/reductions” in Table A.1.

Fig. 3 shows the changes that have taken place over time by application level. It is found that most of the studies (77%) deal with emissions allocation at country level. In particular, all the studies before 2000 focus on the allocation of emission reductions or permits among different countries. A total of 14% of the studies examine emission permits allocation at firm level. Since CET systems have gradually been established after 2000, it is not surprising that the studies on $CO_2$ emission permits distribution among firms did not appear in the first two time frames. Since grandfathering and benchmarking are widely used in the initial allocation of carbon allowances in existing CET systems, scholars have shown great interest in comparing their effectiveness. See, for example, Jensen and Rasmussen (2000), Edwards and Hutton (2001), Bohringer and Lange (2005), Demailly and Quirion (2006), Neuhoff et al. (2006) and Zetterberg et al. (2012). Finally, it is worth pointing out that about 9% of studies deal with $CO_2$ emissions allocation among provinces in China, which should be attributed to the growing concern on energy conservation and emission reduction by Chinese central government and the target-oriented regulation on energy consumption and $CO_2$ emissions at province level in recent years.

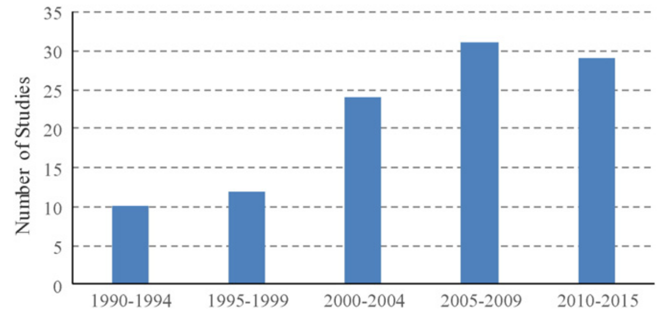


**Fig. 2.** Trend in the number of studies over time.

Fig. 4 shows that that almost all the studies take emission permits/reductions as the targeting indicator for allocation. Nevertheless, three recent studies, Yi et al. (2011), Yu et al. (2014) and Zhang and Hao (2015), chose emission intensity reductions as the targeting indicator, which can be explained by the fact that China mainly implemented intensity-based emission regulation and performance evaluation policies at province level in the past decade. In 1990–1999, scholars were mainly devoted to examine emission reduction burden sharing among countries to cater for the requirements by international climate change negotiations, e.g. Rose (1990), Smith (1991), Bohm and Larsen (1994), Phylipsen et al. (1998) and Ringius et al. (1998). With the development of CET systems in different countries, studies on investigating the initial allocation of emission permits between firms have also appeared. Examples of such studies are MacKenzie et al. (2008, 2009), Lozano et al. (2009), Zhao et al. (2010), Sun et al. (2014) and Liao et al. (2015).

Additionally, we observe that at country/region level the targeting indicators for allocation consist of both emission permits and emission reductions. At firm level, however, the targeting indicators are nearly all emission permits. This might be explained by the operating mechanism of CET in which a cap is set for each participating firm to fulfill the regional or national emission reduction targets.

### *4.2. Methodological Aspect*

As shown in Table A.1, the methodological aspect of a study is comprised of two components, namely allocation principle and method used. The former is broadly divided into fairness and efficiency principles as described in Section 2, and the latter consists of four groups of methods as described in Section 3, i.e. indicator, optimization, game theoretic and hybrid approaches.

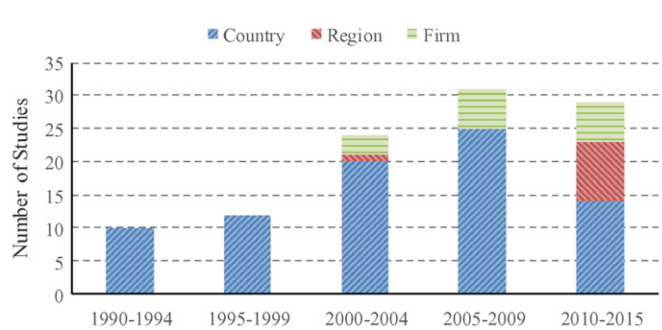


**Fig. 3.** Breakdown of studies by application level over time.

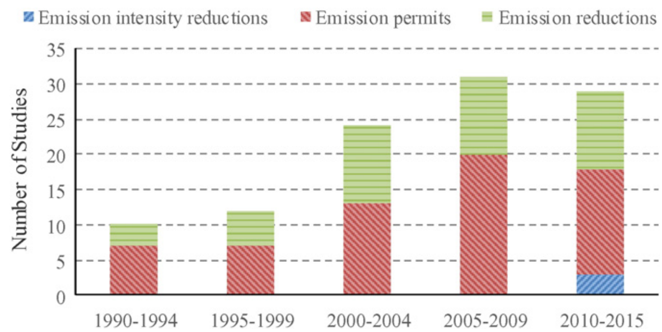


**Fig. 4.** Breakdown of studies by targeting indicator over time.

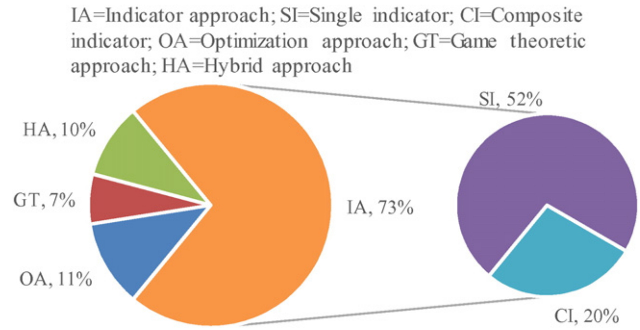


**Fig. 6.** Breakdown of studies by allocation method.

Fig. 5 shows the breakdown of studies by allocation principle. Not surprisingly, fairness principle plays a vital role in $CO_2$ emissions allocation. Of the studies reviewed, 67% follow fairness principle while 28% follow efficiency principle to examine emissions allocation. The remaining 5% take account of fairness and efficiency principles simultaneously. Since 2000, scholars have become more interested in the use of efficiency principle. A possible explanation is that earlier studies focus on emission mitigation burden sharing among different countries, for which most scholars sought for fairness in order to make the allocation results be easily accepted by different entities. Later, scholars became interested in economically achieving emission reduction targets, which led them to explore emissions allocation methods from the efficiency perspective.

As shown in Fig. 6, the indicator approach accounting for 73% of the studies represents the most popular group of methods in application. The single indicator approach seems to be more popular than the composite indicator approach, which should be attributed to its simplicity and transparency. Among different single indicators, population was most intensively used, e.g. Bertram (1992), Baer et al. (2000), Leimbach (2003), Persson et al. (2006), Böhringer and Helm (2008), Sørensen (2008) and Chakravarty et al. (2009). The share of the studies using the optimization approach is 11%, which is followed by the hybrid approach (10%) and game theoretic approach (7%). Within the optimization approach, DEA accounted for about four fifth of the studies, which should be attributed to the growing attention on efficiency principle in emissions allocation and the popularity of DEA in carbon emission analysis (Zhou et al., 2008). The game theoretic approach used for emissions allocation mainly consists of cooperative game, dynamic game and incomplete information game.

Fig. 7 shows the breakdown of studies by allocation method over time. It can be observed that the indicator approach, including single and composite indicator approaches, has been the most commonly used during all the five periods of time. Of the relevant studies, the allocation rules based on equal per capita emissions and equal per capita cumulative emissions have received much attention at country level, while grandfathering has been extensively examined and discussed at firm level. Whereas in the earlier time frames very few studies adopt the optimization approach, its share becomes as high as 30% in 2010–2015. A major contributor is DEA that has been widely applied to examine $CO_2$ emissions allocation at various levels (Zhou et al., 2008). The game theoretic approach seems not to receive much attention in recent years, which might be explained by its complexity and less transparency in application. The use of the hybrid approach in $CO_2$ emissions allocation has constantly been examined in the past years owing to its flexibility in taking account of multiple factors. Some latest developments on the hybrid approach, e.g. Yu et al. (2014) and Zhang et al. (2014), seem to be theoretically nice but too complicated to be applied in reality.

Additionally, we find that a majority of studies using the indicator approach follow the fairness principle. However, the studies using optimization approach are more likely to follow the efficiency principle. In contrast, the game theoretic approach often integrates both fairness and efficiency principles together so that its structure becomes more complicated.

### *4.3. Some Empirical Findings*

As summarized in the last section, a majority of past studies dealt with the allocation of $CO_2$ emissions at country level by the indicator approach. To shed additional insights for the potential impacts of indicator choice, in this section we conduct a comparison of the allocation results with alternative indicator methods used in earlier studies.[6] The allocation results for four major $CO_2$ emitters (i.e. China, EU, India and USA), which are based on ten popular indicator methods and taken from Pan et al. (2014b), are used for our comparative analysis.

Fig. 8 shows the cumulative $CO_2$ emission permits allocated for EU, USA, China and India by different allocation methods in 2001–2050.[7] It is observed that the choice of allocation method has a major impact on the allocation results, especially when the single indicator approach

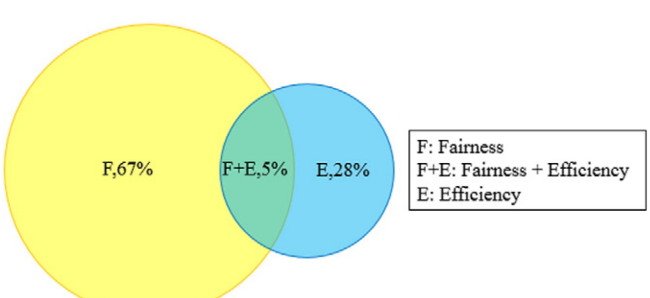


**Fig. 5.** Breakdown of publications by principle.

[6] Applications of other approaches tend to be diverse and case-dependent, so in this review study only the empirical results with indicator approach are compared and evaluated. Future research could be carried out by conducting a more comprehensive comparative study on different approaches given the availability of the data required.

[7] The abbreviations used in Fig. 8 are explained as follows: EPCE = equal per capita emission; EPCCE = equal per capita cumulative emission; C&C = contraction & convergence; CDC = common but differentiated convergence; HR = historical responsibility; GF = grandfathering; AP = ability to pay; EIT = emission intensity targets; TTA = Triptych approach; GDR = greenhouse development rights.

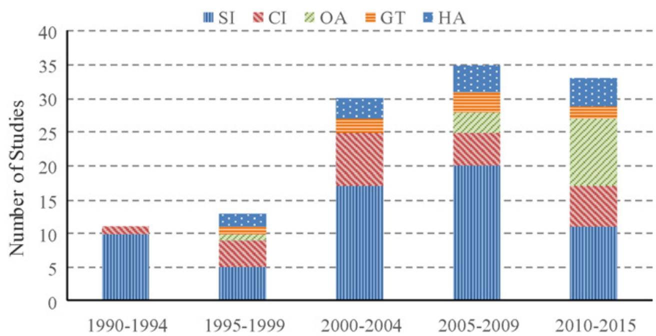


**Fig. 7.** Breakdown of studies by allocation method over time.

is used. Compared to the single indicator approach, the composite indicator approach (e.g. the Triptych) generates the allocation results with less discrepancy. One possible explanation is that the composite indicator approach incorporates multiple indicators which lead to relatively "balanced" allocation results. With reference to the baseline level, the developed countries are often required to take more efforts than the developing countries to reduce $CO_2$ emissions no matter which allocation method is adopted.

It can also be seen from Fig. 8 that China and India receive relatively higher emission permits than EU and USA when the population indicator is used. In particular, the emission permits of EU and USA are negative under the equal per capita cumulative emissions allocation rule. Of the allocation methods using emission indicator, the historical responsibility method is more favorable to China and India while grandfathering is more beneficial to EU and USA. By the ability to pay rule the EU and USA have to undertake more emission reductions.

In summary, different allocation methods often lead to different or even contradictive allocation results. While different parties argue for the use of different methods from their own perspective, a compromise solution could be reached by the use of composite indicator approach that is capable of incorporating multiple conflicting criteria (Vaillancourt and Waaub, 2004). Nevertheless, the choice of underlying indicators and the way to generate composite indicators would pose additional challenges to the use of composite indicator approach in international climate negotiation.


**Fig. 8.** $CO_2$ emission permits derived from different methods in 2001–2050 (Gt).

## 5. Conclusions

This paper provides a literature review of studies on $CO_2$ emissions allocation with emphasis on the evolution of methodological developments. We first introduce the fairness and efficiency principles in emissions allocation, under which some major allocation criteria are summarized. We classify the commonly used allocation methods into four groups, namely indicator approach, optimization approach, game theoretic approach and hybrid approach, and discuss the key ideas behind each of the four approaches. The main features and findings of past studies are summarized in both methodological and application aspects. Generally, the fairness principle plays a major role in the choice or design of $CO_2$ emissions allocation methods, whereas the efficiency principle has recently received increasing attention. Of the four groups of allocation methods, the indicator approach is most widely used owing to its simplicity and ease of understanding. Other approaches seem to be more encompassing but may reduce the transparency of the allocation results. We also present a comparative study on some empirical results by different indicators to show their characteristics in application.

Comparing the four groups of approaches, each one has its specific strengths and weaknesses and none of them dominates others in all respects. All the four approaches may be applied depending on the study purpose as well as the perspectives of policy makers. If the fairness principle is concerned, the indicator and hybrid approaches seem to be suitable. When the efficiency principle is concerned, the optimization approach is preferred. If interactions between different participants need to be taken into account, the game theoretic approach might be a good choice. In reality, the use of indicator approach seems to be a norm, but it is difficult to reach a consensus on the indicator used since the variation in the allocation results by different indicator methods is rather large.

The challenge in selecting an appropriate allocation method for use also provides opportunities for studying $CO_2$ emissions allocation in a deeper way. A general topic is on how to strike a balance between the fairness and efficiency principles in improving the existing allocation methods or developing new methods. Along this line of thought, the composite indicator approach is worth further investigating since it is relatively easier to understand and capable of incorporating multiple conflicting criteria so that the allocation results are more easily to be accepted by different participants. Second, previous studies mainly focus on the spatial allocation for a fixed period of time. However, emission reduction is a long-term and dynamic process and its inter-period characteristics need to be considered. Further research may be carried out by examining the dynamic allocation of $CO_2$ emissions in order to achieve the economic efficiency and allow for banking and borrowing permits. Third, since different allocation methods may have different impacts in terms of abatement cost and economic loss, it might be meaningful to develop novel allocation methods by considering such kinds of impacts.

## Acknowledgements

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## Appendix A

Table A.1 Summary of studies on $CO_2$ emissions allocation.

| Study | Principle | | Method | | | | | Application level | | | Targeting indicator | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fairness | Efficiency | SI | CI | OA | GT | HA | Country | Region | Firm | Emission permits | Emission reductions | Emission intensity reductions |
| Azar (2000) | √ | | √ | | | | | √ | | | √ | | |
| Baer et al. (2000) | √ | | √ | | | | | √ | | | √ | | |
| Baer et al. (2008) | √ | | | √ | | | | √ | | | | √ | |
| Beckerman and Pasek (1995) | √ | | | √ | | | | √ | | | √ | | |
| Berk and den Elzen (2001) | √ | | √ | | | | √ | √ | | | | √ | |
| Bertram (1992) | √ | | √ | | | | | √ | | | √ | | |
| Bode (2004) | √ | | √ | | | | | √ | | | √ | | |
| Bohm and Larsen (1994) | | √ | √ | | | | | √ | | | | √ | |
| Böhringer and Helm (2008) | √ | | √ | | | | | √ | | | √ | | |
| Bohringer and Lange (2005) | √ | | √ | | | | | | | √ | √ | | |
| Böhringer and Löschel (2005) | √ | | √ | | | | | √ | | | | √ | |
| Böhringer and Welsch (2004) | √ | | √ | | | | | √ | | | √ | | |
| Böhringer and Welsch (2006) | √ | | √ | | | | | √ | | | √ | | |
| Cantore and Padilla (2010) | √ | √ | | | √ | | | √ | | | √ | | |
| Chakravarty et al. (2009) | √ | | √ | | | | | √ | | | | √ | |
| Chiu et al. (2015) | | √ | | | √ | | | √ | | | √ | | |
| Cui et al. (2014) | √ | | √ | | | | | | √ | | | √ | |
| DeCanio (2009) | √ | | √ | | | | | √ | | | √ | | |
| Demailly and Quirion (2006) | √ | √ | √ | | | | | | | √ | √ | | |
| den Elzen (2002) | √ | | √ | √ | | | √ | √ | | | | √ | |
| den Elzen and Lucas (2005) | √ | | √ | √ | | | | √ | | | | √ | |
| den Elzen and Meinshausen (2006) | √ | | √ | | | | √ | √ | | | | √ | |
| den Elzen and schaeffer (2002) | √ | | √ | | | | | √ | | | | √ | |
| den Elzen et al. (1992) | √ | | √ | | | | | √ | | | √ | | |
| den Elzen et al. (2005a) | √ | | √ | | | | √ | √ | | | | √ | |
| den Elzen et al. (2005b) | √ | | √ | | | | | √ | | | | √ | |
| den Elzen et al. (2006) | √ | | | | | | √ | √ | | | | √ | |

(continued on next page)

**Table A.1** (*continued*)

| Study | Principle | | Method | | | | | Application level | | | Targeting indicator | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fairness | Efficiency | SI | CI | OA | GT | HA | Country | Region | Firm | Emission permits | Emission reductions | Emission intensity reductions |
| den Elzen et al. (2007) | √ | | | √ | | | | √ | | | | √ | |
| den Elzen et al. (2008a) | √ | | √ | | | | √ | √ | | | √ | | |
| den Elzen et al. (2008b) | √ | | | √ | | | | √ | | | | √ | |
| Ding et al. (2009) | √ | | √ | | | | | √ | | | √ | | |
| Edmonds et al. (1995) | √ | | √ | | | | | √ | | | √ | | |
| Edwards and Hutton (2001) | √ | √ | √ | | | | | | | √ | √ | | |
| Ekholm et al. (2010) | √ | | | √ | | | √ | √ | | | | √ | |
| Eyckmans and Tulkens (2003) | √ | √ | | | | √ | | √ | | | | √ | |
| Färe et al. (2012) | | √ | | | √ | | | √ | | | | √ | |
| Feng et al. (2015) | | √ | | | √ | | | √ | | | | √ | |
| Filar and Gaertner (1997) | √ | √ | | | √ | √ | | √ | | | | √ | |
| Germain and Steenberghe (2003) | √ | √ | | | | √ | | √ | | | √ | | |
| Ghersi et al. (2003) | √ | | √ | √ | | | | √ | | | | √ | |
| Gomes and Lins(2008) | | √ | | | √ | | | √ | | | √ | | |
| Groenenberg and Blok (2002) | | √ | √ | | | | | | | √ | √ | | |
| Groenenberg et al. (2001) | √ | | | √ | | | | √ | | | | √ | |
| Groenenberg et al. (2004) | √ | | | √ | | | | √ | | | | √ | |
| Grubb (1990) | √ | | √ | | | | | √ | | | √ | | |
| Grübler and Fujii (1991) | √ | | √ | | | | | √ | | | √ | | |
| Gupta and Bhandari (1999) | √ | | | | | | √ | √ | | | √ | | |
| Harvey (1995) | √ | | √ | | | | | √ | | | √ | | |
| Hof and Den Elzen (2010) | √ | | | √ | | | | √ | | | | √ | |
| Hof et al. (2010) | √ | | √ | √ | | | | √ | | | | √ | |
| Höhne et al. (2006) | √ | | √ | | | | | √ | | | √ | | |
| Janssen and Rotmans (1995) | √ | | | √ | | | | √ | | | √ | | |
| Jensen and Rasmussen (2000) | √ | √ | √ | | | | | | | √ | √ | | |
| Kuntsi-Reunanen and Luukkanen (2006) | √ | | √ | | | | | √ | | | √ | | |
| Kuosmanen et al. (2009) | | √ | | | √ | | | √ | | | | √ | |
| Kverndokk (1995) | √ | | √ | | | | | √ | | | √ | | |
| Larsen and Shah (1994) | √ | √ | √ | √ | | | | √ | | | √ | | |
| Leimbach (2003) | √ | | √ | | | | | √ | | | √ | | |
| Leimbach et al. (2010) | √ | √ | √ | √ | | | | √ | | | | √ | |
| Lennox and van Nieuwkoop (2010) | | √ | √ | | | | | | | √ | √ | | |
| Liao et al. (2015) | √ | | | | | √ | | | | √ | √ | | |
| Lozano et al. (2009) | | √ | | | √ | | | | | √ | √ | | |
| MacKenzie et al. (2008) | | √ | | | | √ | | | | √ | √ | | |
| MacKenzie et al. (2009) | | √ | | | | √ | | | | √ | √ | | |
| McKibbin and Wilcoxen (2009) | √ | | √ | | | | | √ | | | √ | | |
| Miketa and Schrattenholzer (2006) | √ | √ | √ | | | | | √ | | | √ | | |
| Neuhoff et al. (2006) | √ | √ | √ | | | | | | | √ | √ | | |
| Neumayer (2000) | √ | | √ | | | | | √ | | | √ | | |
| Pan et al. (2014a) | √ | | √ | | | | | √ | | | √ | | |
| Pang et al. (2015) | | √ | | | √ | | | √ | | | √ | | |
| Persson et al. (2006) | √ | | √ | | | | | √ | | | √ | | |
| Phylipsen et al. (1998) | √ | | | √ | | | | √ | | | | √ | |
| Ren et al. (2015) | | √ | | | | √ | | | | √ | | √ | |
| Ridgley (1996) | √ | | | | | | √ | √ | | | | √ | |
| Ringius et al. (1998) | √ | | | √ | | | | √ | | | | √ | |
| Ringius et al. (2002) | √ | | | √ | | | | √ | | | | √ | |
| Rose (1990) | √ | √ | √ | | | | | √ | | | | √ | |
| Rose and Stevens (1993) | √ | | √ | | | | | √ | | | √ | | |
| Rose and Zhang (2004) | √ | √ | √ | | | | | | √ | | √ | | |
| Rose et al. (1998) | √ | √ | √ | | | | | √ | | | √ | | |
| Rowlands (1997) | √ | √ | √ | | | | | √ | | | | √ | |
| Sijm et al. (2001) | √ | | | | | | √ | √ | | | | √ | |
| Smith (1991) | √ | | √ | | | | | √ | | | | √ | |
| Sørensen (2008) | √ | | √ | | | | | √ | | | √ | | |
| Sun et al. (2014) | | √ | | | √ | | | | | √ | √ | | |
| Torvanger and Godal (2004) | √ | | √ | √ | | | | √ | | | | √ | |
| Torvanger and Ringius (2002) | √ | | √ | √ | | | | √ | | | | √ | |
| Vaillancourt and Waaub (2004) | √ | √ | | √ | | | | √ | | | √ | | |
| Vaillancourt and Waaub (2006) | √ | √ | | √ | | | | √ | | | √ | | |
| van Ruijven et al. (2012) | √ | √ | √ | √ | | | | √ | | | √ | | |
| Viguier et al. (2006) | | √ | | | | √ | | √ | | | √ | | |
| Wang et al. (2013) | | √ | | | √ | | | | √ | | √ | | |
| Wei et al. (2012) | | √ | | | √ | | | | √ | | | √ | |
| Wei et al. (2014) | √ | | √ | | | | | √ | | | √ | | |
| Welsch (1993) | √ | | √ | | | | | √ | | | √ | | |
| Winkler et al. (2002) | √ | | √ | | | | | √ | | | √ | | |
| Yang and Sirianni (2010) | √ | √ | | | √ | | | √ | | | | √ | |
| Yi et al. (2011) | √ | | | √ | | | | | √ | | | | √ |
| Yu et al. (2011) | √ | | √ | | | | | √ | | | √ | | |
| Yu et al. (2014) | √ | | | | | | √ | | √ | | | | √ |

**Table A.1** (*continued*)

| Study | Principle | | Method | | | | | Application level | | | Targeting indicator | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fairness | Efficiency | SI | CI | OA | GT | HA | Country | Region | Firm | Emission permits | Emission reductions | Emission intensity reductions |
| Zetterberg et al. (2012) | √ | √ | √ | | | | | | | √ | √ | | |
| Zhang et al. (2014) | √ | | | | | | √ | | √ | | √ | | |
| Zhang and Hao (2015) | √ | | | | | | √ | | √ | | | | √ |
| Zhao et al. (2010) | | √ | √ | | | | | | | √ | √ | | |
| Zhou et al. (2013) | √ | √ | √ | | | | | | √ | | | √ | |
| Zhou et al. (2014) | | √ | | | √ | | | | √ | | √ | | |

Note: SI = single indicator; CI = composite indicator; OA = optimization approach; GT = game theoretic approach; HA = hybrid approach.

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