Journal of Cleaner Production 234 (2019) 306–314

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Centralized DEA-based reallocation of emission permits under cap and trade regulation

Ehsan Momeni [a], Farhad Hosseinzadeh Lotfi [b], Reza Farzipoor Saen [c, *], Esmaeil Najafi [a]

[a] Department of Industrial Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Department of Mathematics, Science and Research Branch, Islamic Azad University, Tehran, Iran
[c] Department of Industrial Management, Karaj Branch, Islamic Azad University, Karaj, Iran

ARTICLE INFO

*Article history:*
Received 18 July 2018
Received in revised form
5 April 2019
Accepted 17 June 2019
Available online 19 June 2019

Handling Editor: Xin Tong

*Keywords:*
Cap and trade
Data envelopment analysis (DEA)
Sustainability
Greenhouse gas emission

ABSTRACT

Cap-and-trade is regarded as the most effective approach to control and reduce greenhouse gas emission. How to perform the reallocation in a fair way is very critical to control total amount of emissions and improve trade mechanism. It has been proved that data envelopment analysis (DEA) is an effective way for reallocation. The objective of the present paper is to develop a centralized DEA model to reallocate emission permits in the cap and trade system based on countries efficiencies. Presented model considers all decision making units (DMUs) together and improves whole efficiency of them by reducing total emission permit as undesirable outputs. Also, this model determines amount of emitted gases that can be reduced without reducing other outputs. To demonstrate the applicability of model, a case study is presented. Sensitivity analysis is carried out to investigate the impact of the some parameters on the results.



## 1. Introduction

Economic development of countries has caused many environmental problems. Interconnection between economic development and environmental worsening has led to a key trend in environmental policy and socio-economic development (Redclift, 2005). Environmental problems have seriously threatened human survival and development (Cohen and Winn, 2007). Since 1970, level of total greenhouse gas emissions has reached to 80%.[1] Large amount of greenhouse gas emissions (mostly methane, carbon dioxide, and nitrous oxide) has changed chemical composition of atmosphere and, in turn, resulted into global warming and other related damages. Considerable damage could be caused by potential impacts of global warming (Mabey, 1997). To reach sustainable development, countries should focus on environmental, social, and economic aspects. Environmental performance is one of the significant research areas (Zhou et al., 2008). Growing public awareness on pernicious effects of greenhouse gas emissions on human life and pressure of environmentally friendly organizations in the world have led to approval of Kyoto protocol in December 1997. Based on Kyoto protocol, EU-15[2] committed to reduce six greenhouse gases including carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, fluorocarbons, and hydro fluorocarbon from 2008 to 2012. Following commitment of EU-15, Paris agreement was approved by 195 countries at 21st Conference of Parties based on United Nations Framework Convention on Climate Change (Sutter et al., 2015). Paris agreement deals with decrease of greenhouse gas emissions and it will be adopted in 2020. Countries agreed to mitigate greenhouse gas emissions with their national contributions and provide a green climate fund to control increase in global average temperature to no more than 2 °C, and preferably to 1.5 °C (Lee, 2016).

Reduction of greenhouse gas emissions attracts attention of both policy makers and researchers. In past decades, market-based approaches have been considered as the most efficient approaches for gas emissions reduction (Burtraw et al., 2014; Sacchi et al., 2014). Among them, tradable emission permit (TEP), pollution

* Corresponding author.
*E-mail addresses:* Ehs_momeni@yahoo.com (E. Momeni), Farhad@hosseinzadeh.ir (F.H. Lotfi), farzipour@yahoo.com (R.F. Saen), najafi1515@gmail.com (E. Najafi).

[1] https://www.iea.org.

[2] EU15 comprises following 15 countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and UK.

https://doi.org/10.1016/j.jclepro.2019.06.194
0959-6526/

tax, emission trading system (ETS), and cap and trade are worthwhile to mention. Cap and trade is the most preferred approach since it enables scientists and authorities to control reallocation and amount of gas emissions in different countries that are crucial for improving performance and sustainable development (Betsill and Hoffmann, 2011; Wagner, 2013).

Despite different approaches that have been proposed for allocating emission permits to countries, there is no reference addressing a centralized approach that incorporates cap of emissions on countries. In this paper, we propose a centralized approach based on data envelopment analysis (DEA) to deal with cap and trade policy for controlling emissions and trading emissions in countries. We consider total permitted amount of emissions as cap. If countries' emitted gases are higher than predetermined emission level, countries should reduce their gas emissions or they should buy emission allowances from trading market. On the other hand, countries with lower gas emissions can emit more or can sell their emission allowances to other buyers (Dong et al., 2016; Du et al., 2015). Thus, countries can trade their emission permits with each other. Objective of this paper is to present an approach for assessing performance of all countries based on their inputs and outputs to reallocate emission permits as an undesirable output so that total emissions are deducted from a predetermined cap. Also, in this approach highest emission deduction without damaging other outputs is determined. We believe that this paper has following contributions:

- All countries are considered simultaneously. Thus, reallocation of emission allowance is fair.
- Our proposed model considers cap for total emission permits.
- In our model, emission trade among countries is allowed.
- Price of buying and selling of emission permits can be given.
- Maximum amount of emission reduction without decreasing other outputs is determined.

The rest of this paper is organized as follows: literature review is described in Section 2. In Section 3, we develop a new DEA model for reallocation of emission permits. A case study and sensitivity analysis are discussed in Sections 4 and 5, respectively. Managerial implications are given in Section 6. Concluding remarks are provided in final section.

## 2. Literature review

### 2.1. Approaches for market based emission permits

Nowadays, due to harmful impact of excessive greenhouse gas emissions, trading market-based approaches are taken into account. Several models for carbon emission allowance in trading markets exist among which TEP, pollution tax, emission trading system (ETS), and cap and trade are the most preferred approaches (e.g., Baumol and Oates, 1988; Zhao, 2003; Eriksson and Vamling, 2006; Bulteau, 2012; Parry, 1995; Nannerup, 2001; Vossler et al., 2013; Clò et al., 2013; Bryant, 2016; Salant, 2016; Shen et al., 2016).

TEP system can result in considerable reduction of pollution with minimum cost as they balance marginal abatement costs using different sources (Baumol and Oates, 1988). Emission tax is another policy for environmental protection. Although appropriate level of tax can largely impact gas emission, determining right level of tax is complicated as it requires precise information on cost functions of marginal abatement (Ellerman, 2005). European Union Emissions Trading System (EUETS) is one of the first trading plans in greenhouse gas emissions in the world. It started in 2005 and aimed to face global warming (Ellerman and Buchner, 2007). EUETS is considered as the main foundation of EU climate policy (Wagner, 2004; EuropeanCommission, 2008). Wu et al. (2013) indicated that cap-and-trade mechanism is better than other control methods. Cap-and-trade mechanism is an effective way that focuses on efficient allocation of emission allowances to control harmful emissions. In this way, a cap is set on total amount of greenhouse gases. Within the cap, firms receive or buy emission allowances which can exchange with each other. In addition, they are permitted to get small amount of international credits from emission-saving projects around the world (European Commission, 2008). Therefore, we need to determine emission allowances given cap so that all countries agree on it. In such a case, 'allowances' for emissions are offered for selling or buying and as a result can be traded. Countries have to monitor and report their emissions and convince authorities to give enough allowances to cover their emissions. If reallocated of emission permits is lower than their current emissions, they should decrease emissions or should buy emission permits from others in trade market. In contrast, if environmental performance of a country is good and has lower gas emission than reallocated emission permit, it is allowed to emit more gas or it can sell its extra permit to other countries. This lets countries to find economic ways for reallocating and reducing emissions. Hence, for controlling total emission and improving environmental impacts, it is crucial to observe reallocation of emission permit.

### 2.2. Allocating emission allowance

A common approach in emission allocation is grandfathering (GF) method in which amount of gas emission is allocated based on historical data (Goulder et al., 1999). However, GF is not fair as "dirty" firms get more generous allocations than "clean" firms (Åhman et al., 2007). Europe is not willing to use GF method (Sterner and Muller, 2008).

Another allocation procedure is periodic reallocation of allowances. Periodic reallocation treats existing and new entrants units fairly and also it reduces incentives of existing units to profit from their own allowances. In this case, companies should adjust their outputs to get more allowance. However, as addressed by Lozano et al. (2009), this procedure has some weaknesses such as high administrative costs and more complexity.

Fischer and Fox (2004) presented output-based allocation (OBA) method to improve the disadvantages of previous methods. However, OBA is based on outputs and ignores inputs of production. As a result, OBA leads to increase of production and increase of emissions. Therefore, OBA increases total amount of emission. Consequently, it is needed to use an approach that takes into account both inputs and outputs. As a result, performance-based DEA procedure was suggested to resolve the problems (Amirteimoori and Kordrostami, 2005; Gomes and Lins, 2008). DEA is a linear programming technique which is used to assess relative efficiency of decision making units (DMUs). DEA was introduced by Charnes et al. (1978).

Andersen and Bogetoft (2007) proposed a DEA model to allocate catch allowance to a group of fisheries. They evaluated effect of tradable allowance on firm's ability to decrease inputs and increase outputs. Lozano et al. (2009) deal with centralized DEA approach for reallocating emission permits using three objectives separately: minimizing undesirable total emissions, maximizing aggregated desirable production, and minimizing consumption of inputs. Amirteimoori and Tabar (2010) presented a DEA-based method for allocating fixed resources or costs across a set of DMUs. Bi et al. (2011) introduced a model to assess targets and resource allocation based on DEA. Hosseinzadeh Lotfi et al. (2013) proposed an allocation method based on common dual weight. Wu et al. (2013) introduced bargaining game based DEA to make competition among DMUs and set a common weight for all DMUs. They also applied it in agricultural greenhouse gas emissions from 15 European Union members. They concluded that efficient countries are allowed to emit more and inefficient countries have to emit less. Sun et al. (2014) employed an allocation mechanism to control total emission level of DMUs in individual and central scenario, separately. It does not allow trading emission among DMUs and it only wants to cut it down. Wang et al. (2013) proposed zero sum gain DEA model to allocate $CO_2$ emission allowance over 30 administrative regions of China. Emissions allowance is allocated to realize national $CO_2$ emissions' reduction target. They applied model for several scenarios of economic growth, $CO_2$ emissions, and energy consumption. Feng et al. (2015) indicated that persuading DMUs into an agreement in centralized reallocation is difficult and they provided an improved two-step procedure to mitigate this problem. To help decision makers to allocate resources, Wu et al. (2016) combined context-dependent DEA and multiple objective linear programming (MOLP). Wu et al. (2018) presented a DEA model to allocate emission permits that ensures production stability of each DMU before and after allocation. In their model, total amount of emission permits remains constant and does not decrease. Also, their model does not take into account all DMUs together and cannot consider trading price.

In this paper, we develop a new DEA model in presence of cap and trade policy to reallocate emission permits among countries. We use DEA since it does not require weights of criteria from decision makers. Reallocation of emission permits among countries is performed based on results of DEA model. Note that total allowed emissions is considered as a cap. Here, amount of emitted gas is treated as undesirable output. If emitted gas of countries is higher than the reallocated amount, countries should reduce their emissions or they should buy emission permits from other countries in emissions trading market. On the other hand, countries with lower gas emissions can emit more gas or they can sell their emission permits. Thus, it is possible to have a trade among countries. In addition, we identify allowed reduction of total undesirable output such that this reduction does not damage other desirable outputs. Finally, a case study and sensitivity analysis will be discussed to reflect capability of proposed model.

## 3. Centralized DEA-based reallocation model

In traditional reallocation approaches, members (countries) are considered separately while the centralized approach brings members together. Emission permits are reallocated to countries based on their efficiencies and cap is total permitted amount of reallocated emission permits. In our model, the amounts that should be decreased or increased are determined. So, countries can trade their emission permits with each other. Our centralized DEA model not only can take into account undesirable output, but also can consider nondiscretionary inputs. Also, in our model, the highest emission reductions without damaging other outputs are determined.

Suppose that there are $N$ homogeneous DMUs (countries) that $DMU_j$ ($j = 1,2, \ldots,N$) and $DMU_p$ ($p = 1,2,..,N$) are controlled by a central authority. Each DMU consumes $M$ inputs $X_j = (x_{1j}, x_{2j}, \ldots, x_{Mj})$ to produce $S$-1 desirable outputs $Y_j = (y_{2j}, y_{3j}, \ldots, y_{Sj})$ and one undesirable output $y_{1j}$ (gas emission). Table 1 displays used nomenclatures in this paper.

In addition, central authority would like each country to produce desirable outputs as much as possible and undesirable outputs as low as possible for given levels of inputs. DMUs want to increase relative efficiency by augmenting production rate. To this end, they should use minimum inputs to produce maximum desirable outputs and minimum undesirable output so that total undesirable output should not exceed pre-determined amount ($\alpha$). Our proposed model is as follows:

$$
\begin{aligned}
MinZ = & \sum_{p=1}^{N}\theta_p + \varepsilon \times \left(\sum_{p=1}^{N} c.n_{1p}^{-} - \sum_{p=1}^{N} c.n_{1p}^{+}\right) + \varepsilon \times q \qquad (3)\\
st: \quad & \sum_{j=1}^{N}\lambda_{jp}x_{ij} = \theta_p x_{ip} - S_{ip}^{-} \quad i = 1,2,\ldots M \quad p = 1,2,\ldots,N\\
& \sum_{j=1}^{N}\lambda_{jp}y_{rj} = y_{rp} + S_{rp}^{+} \quad r = 2,3,\ldots S \quad p = 1,2,\ldots,N\\
& \sum_{j=1}^{N}\lambda_{jp}y_{1j} = y_{1p} + n_{1p}^{+} - n_{1p}^{-} \quad p = 1,2,\ldots,N\\
& \sum_{p=1}^{N}\sum_{j=1}^{N}\lambda_{jp}y_{1j} = \alpha - l + q\\
& \theta_p \le 1 \quad p = 1,2,\ldots,N\\
& \sum_{p=1}^{N} n_{1p}^{-} - \sum_{p=1}^{N} n_{1p}^{+} \ge \sum_{j=1}^{N} y_{1j} - \alpha\\
& \lambda_{jp} \ge 0,\ S_{ip}^{-} \ge 0,\ S_{rp}^{+} \ge 0,\ n_{1p}^{+} \ge 0,\ n_{1p}^{-} \ge 0,\ l \ge 0,\ q \ge 0
\end{aligned}
$$

Model (3) seeks to minimize all DMU's inputs radially (proportionally) and undesirable outputs without reducing desirable outputs. Here, $\theta_p$ is defined as relative efficiency score of $p$th DMU that is less than 1. Here, $\varepsilon$ is non-Archimedean infinitesimal value which is very small and positive real number and $c$ is selling or buying price. Variables$S_{ip}^{-}$, $S_{rp}^{+}$ in the first and second constraints are slack variables which express difference among virtual inputs/outputs and appropriate inputs/outputs of DMUs. Note that $\alpha$ should be less than total amount of undesirable output($\alpha \le \sum_{p=1}^{N}\sum_{j=1}^{N}\lambda_{jp}y_{1j}$).

**Theorem 1.** *Suppose that $\theta_p$ is optimal value. If$\theta_p = 1$, $DMU_p$ is efficient and $n_{1p}^{+} = n_{1p}^{-} = 0$.*

***Proof***: *$DMU_p$ is efficient if $\theta_p = 1$ and efficient frontier consists of efficient DMUs. Coordinates of projected DMUs on efficient frontier are same as their original coordinates (i.e. $\sum_{j=1}^{N}\lambda_{jp}^{*}y_{1j} = y_{1p}$). Given third constraint, we have$n_{1p}^{+} - n_{1p}^{-} = 0$. Since this model is linear programming, optimal solution is chosen from set of basic feasible solutions. Given that two linearly dependent variables cannot be both basic, at least one of them should be non-basic and its value is zero, i.e., $n_{1p}^{+}.\ n_{1p}^{-} = 0$. Hence, given$n_{1p}^{+} - n_{1p}^{-} = 0$, we have$n_{1p}^{+} = n_{1p}^{-} = 0$. This means that emission allowance for considered DMU is correct and there is no need to change it. Otherwise, DMU under evaluation is inefficient so it needs to trade emission allowance.*

*In the first constraint of model (3) the variable $\theta$ is proportional reduction applied to all inputs of $p^{th}$ DMU to improve efficiency. This reduction is applied to all inputs and results in a radial movement towards the envelopment surface while desirable outputs can simultaneously increase in the second constraint of model (3). Since all DMUs are considered comprehensively, each DMU does not determine its allocation separately. Consequently, model (3) determines DMUs that their initial emission allowances are lower than their reallocated amount of gas emission ($n_{1p}^{+} > 0$). Thus, these DMUs are allowed to increase their undesirable outputs so that other desirable outputs are also increased and they reach to efficiency level. On the other hand, these DMUs can sell their emission permits to other countries. Model (3) also determines DMUs which have extra gas emissions ($n_{1p}^{-} > 0$). These sorts of DMUs should reduce their gas emissions or buy additional emission allowance. These are included in third constraint of model (3). The fourth constraint indicates that total emitted gas by countries should not exceed predetermined cap $\alpha$ so that it does not damage other outputs. If specified reduction is higher than what can be realized, $q$will be positive to prevent too much pressure and it will*

**Table 1**
The nomenclatures used in this paper.

| Symbol | Definition | Symbol | Definition |
|---|---|---|---|
| j, p = 1,2, …,N | Set of DMUs | $\alpha$ | Cap of total undesirable output |
| i = 1,2, …,M | Set of inputs | $l$ | Reduction of total undesirable output |
| r = 1 | Index of undesirable outputs | $q$ | Over reduction of total undesirable output |
| r = 2,3 …,S | Set of desirable outputs | $x_{ij}$ | Amount of ith input for $DMU_j$ or $DMU_p$ |
| $\lambda_{jp}$ | The intensity vector corresponding to $DMU_j$ in benchmark of $DMU_j$ | $y_{rj}$ | Amount of ith desirable output for $DMU_j$ or $DMU_p$ |
| $s^-_{ip}$ | Excess usage of ith input for $DMU_j$ | $y_{1j}$ | Amount of undesirable output for $DMU_j$ or $DMU_p$ |
| $s^+_{rp}$ | Shortfall of rth desirable output for $DMU_p$ | $\theta_p$ | Relative efficiency score for pth DMU |
| $n^-_{1p}$ | Amount of undesirable output which has to be decreased for pth DMU | $\varepsilon$ | Non-Archimedean small and positive number |
| $n^+_{1p}$ | Amount of undesirable output which can be increased for pth DMU | c | Selling or buying price |

*damage other desirable output of DMUs. The fifth constraint emphasizes that relative efficiency scores should not be more than* 1. *The last constraint of model* (3) *ensures that difference between total amount that should be decreased and can be increased is at least as much as difference between total gas emissions and cap. Objective function of model* (3) *minimizes ratio of inputs*($\theta_p$), *total amount of emitted gas more than reallocated emission allowance* ($n^-_{1p}$), *and over-reduction of total allocation which disrupt production system and affect desirable outputs*($q$). *On the other hand, the objective function maximizes amount of allowances that can be sold* ($n^+_{1p}$).

**Theorem 2.** *The proposed model always has a feasible solution.*

***Proof***: *It is obvious that following expressions are feasible for all constraints of model* (3), $\theta_p = 1,\ \lambda_p = e_p,\ S^-_p = 0,\ S^+_p = 0,\ l = 0,\ q = \sum_{p=1}^N y_{1p} - \alpha,\ n^+_{1p} = 0,\ n^-_{1p} = 0$. *Therefore, model* (3) *has feasible solution.*

**Theorem 3.** *In every feasible solution for*$DMU_p$, *the relative efficiency score of model* (3) *is greater than* 0($\theta_p > 0$).

***Proof***: *Suppose that*$\theta_p \le 0$. *Then, given that inputs are positive, i.e.* $x_{ip} \ge 0$, *we have* $\theta_p x_{ip} \le 0$. *As* $S^-_{ip} \ge 0$, *according to the first set of constraints* $\sum_{j=1}^N \lambda_{jp} x_{ij} \le \theta_p x_{ip}$, $\sum_{j=1}^N \lambda_{jp} x_{ij} \le 0$. *Given that* $x_{ij}$ *is positive, then* $\sum_{j=1}^N \lambda_{jp} \le 0$. *However, since* $\lambda_{jp} \ge 0$ *then* $\lambda_{jp} = 0$. *On the other hand, in the second constraint, due to non-negativity of slacks,* $S^+_{rp} \ge 0$, *we have* $\sum_{j=1}^N \lambda_{jp} y_{rj} \ge y_{rp}$. *As* $\lambda_{jp} = 0$, *therefore* $\sum_{j=1}^N \lambda_{jp} y_{rj} = 0$. *This leads to* $0 \ge y_{rp}$ *which means that outputs are negative which is not correct. Thus,* $\theta_p > 0$.

**Theorem 4.** *Optimal value of objective function of model* (3) *is finite.*

***Proof***: *According to the fifth constraint of model* (3) *and* Theorem 3, *for each DMU there is* $0 < \theta_p \le 1$. *Then, for all intended DMUs we have*$0 < \sum_{p=1}^N \theta_p \le N$, *this means that the first part of the objective function* $\sum_{p=1}^N \theta_p$ *and* $Min \sum_{p=1}^N \theta_p$ *are finite.* $\varepsilon$ *is non-Archimedean small and positive value. Therefore,* $\varepsilon \times (\sum_{p=1}^N n^-_{1p} - \sum_{p=1}^N n^+_{1p}) + \varepsilon \times q$ *in the objective function approaches to zero. Consequently, the objective function is finite.*

## 4. Case study

In this section, to investigate applicability of the proposed models we apply model (3) for "Organisation for Economic Cooperation and Development (OECD)". This is a unique forum where governments work together to address the economic, social, and environmental challenges of globalization.[3] In addition, "Environmental Performance Review Program" of OECD provides assessments of country progress in achieving domestic and international environmental policy commitments (Lehtonen, 2005). It acts as a central authority that promotes coordinated and innovative international action to accelerate progress towards sustainable development in their members.[4] OECD has been widely used as benchmark for governments to facilitate and improve integration of environment and climate change into all aspects of development.[5] Hence, in the international level, OECD reports and guidelines and specially its policy recommendations have been broadly accepted by researchers, governments, and NGOs. Numerous related articles and researches, especially environmental scientists have considered OECD countries as a case study (Böhringer and Welsch, 2006; Richels et al., 2009; Oberheitmann, 2010; Feng et al., 2015; Rashidi et al., 2015).

Model (3) analyzes greenhouse gas emissions of 33 OECD countries (N = 33) and their total emitted gases. This model provides an efficient way to reallocate and trade emission permits in the cap and trade system. Also, it determines emitted gases that can be reduced without reducing other outputs. Difference between reallocated allowance and emitted gas should be traded among countries. Dataset consists of 4 inputs including population, labor force, total capital stock, and total energy consumptions. Also, there are 2 outputs including greenhouse gas (GHG) emissions and gross domestic product (GDP) which are regarded as undesirable and desirable outputs, respectively. Though we can use other inputs and outputs, the selected inputs and outputs are more common for evaluating performance of countries (Mavi et al., in press; Wu et al., 2018; Feng et al., 2015).

Our centralized DEA model creates an integrated set of DMUs and improves whole efficiency of DMUs though the efficiency of some DMUs may be reduced. Therefore, DMUs are not independent of one another and their efficiencies influence and are influenced by each other and whole set, simultaneously. Also, DMUs are assumed to be homogeneous; because they convert the same kinds of resources/inputs to the same kinds of products/outputs. We select 4 inputs (population, labor force, capital stock, and energy consumption) and 2 outputs (GHG emission and GDP) that their reliable data are available. It should also be noted that our proposed model can consider other inputs and outputs. Due to differences in the economic and environmental structure of countries, given their inputs and outputs, different reallocations for OECD members are determined (Table 3).

Dataset dates back to 2014 which is obtained from International Energy Agency (www.iea.org), Total Energy Statistical Year Book (www.yearbook.enerdata.net), Eurostat (www.europa.eu), and OECD.STAT (www.stats.oecd.org). Table 2 depicts dataset.

The proposed method can be used for each group of countries

[3] http://www.oecd.org/about/members and partners/.

[4] http://www.oecd.org/dac/.

[5] http://www.oecd.org/dac/environment-development/.

**Table 2**
Dataset of inputs and outputs for OECD countries (2014).

| Countries (DMUs) | Inputs | | | | Outputs | |
|---|---|---|---|---|---|---|
| | Population (1000 persons) | Labor force (1000 persons) | Capital stock (1000000$) | Energy consumption (1000000 tons) | GHG Emission (1000 tons) | GDP (1000000$) |
| Australia | 23491 | 12335.8 | 3944975.5 | 127.252 | 522397.1 | 1077535.2 |
| Austria | 8468.6 | 4357.7 | 1891024.38 | 32.671 | 76332.6 | 369329.5 |
| Belgium | 11227.3 | 4967 | 2300616 | 53.987 | 113866.6 | 459555.3 |
| Canada | 35540 | 19189.3 | 6097224.5 | 256.375 | 732418.9 | 1515437.6 |
| Chile | 17819.1 | 8442.7 | 1166427.75 | 38.841 | 97276.3 | 375593.3 |
| Czech Republic | 10524.8 | 5297.9 | 1733171.12 | 41.293 | 123650.7 | 313253.4 |
| Denmark | 5627.2 | 2889.8 | 1079511.12 | 16.905 | 52166.8 | 253126.2 |
| Estonia | 1315.8 | 682.8 | 150939.28 | 6.726 | 21059.2 | 34181.7 |
| Finland | 5472 | 2699 | 1003242.06 | 34.592 | 59029 | 207831.4 |
| France | 64062.3 | 29499.5 | 12076728 | 243.521 | 464417.8 | 2455870 |
| Germany | 80896 | 41943 | 15146735 | 310.713 | 900202.2 | 3473467.5 |
| Greece | 10926.8 | 4819.2 | 2004816.37 | 24.429 | 101403.3 | 255977.8 |
| Hungary | 9863 | 4444.1 | 1065811.75 | 22.772 | 57223.6 | 235520 |
| Iceland | 327.4 | 187 | 59350.67 | 6.058 | 4596.8 | 13980 |
| Ireland | 4609.9 | 2156.1 | 991600.87 | 13.562 | 58253.7 | 269794.2 |
| Italy | 60447.9 | 25514.9 | 13027931 | 151.027 | 418587.2 | 2013578.9 |
| Japan | 127298 | 65770 | 18236474 | 443.354 | 1363862.3 | 4436993.5 |
| Korea | 50424 | 26535.9 | 6839375 | 276.69 | 697707.98 | 1741967.1 |
| Luxembourg | 549 | 396.1 | 180698.06 | 4.215 | 10770.6 | 49821 |
| Mexico | 119713 | 51836.8 | 6677512 | 189.113 | 701360.1 | 1939052.3 |
| Netherlands | 16804.8 | 8964.8 | 3507223.25 | 76.807 | 186845.4 | 769031.7 |
| New Zealand | 4509.7 | 2455 | 459617.12 | 20.894 | 81104.4 | 151788 |
| Norway | 5137 | 2734 | 1294501.25 | 30.697 | 53155.8 | 307690.7 |
| Poland | 38484 | 17428 | 2073986.87 | 94.456 | 380037.6 | 931796 |
| Portugal | 10457.3 | 5225.6 | 1937154.75 | 21.396 | 64492.1 | 276229.6 |
| Slovak Republic | 5415.9 | 2715.3 | 522355.84 | 16.18 | 40638.7 | 152340.8 |
| Slovenia | 2061.6 | 1015.4 | 338292.25 | 6.681 | 16582.3 | 58189.6 |
| Spain | 46464.1 | 22954.6 | 8438931 | 116.68 | 328926.3 | 1472316.5 |
| Sweden | 9609 | 5153.6 | 1774148 | 48.168 | 54382.7 | 432516.4 |
| Switzerland | 8140 | 5102.6 | 1907268.12 | 25.057 | 48605.2 | 446085.7 |
| Turkey | 76902.9 | 28786 | 4605440.5 | 124.013 | 467550.4 | 1424172.3 |
| United Kingdom | 63650 | 32638.9 | 11811327 | 189.34 | 527203.4 | 2476524.3 |
| United States | 316498 | 156772.2 | 52849892 | 2216.787 | 6870454.4 | 17348070 |

and for each percent reduction in each period. Since countries in Kyoto protocol pledged to reduce GHG emission by 8% between 2008 and 2012,[6] we assume that OECD countries want to reduce their total emission with the same percentage. On the other hand, 2014 is the most recent year in which all necessary data are available. In 2014, total GHG emission for these countries was 15696561 thousand tons. So these countries should reduce 8% GHG emissions, i.e. 1255725 thousand tons. This means that cap is 14440836 thousand tons. We want to know whether there is a need to change initial allocation of emission permits and how countries should trade with their unused allowances. We consider price of trading to be one hundred thousand per ton gas emission. By running model (3), the efficiency scores of countries and amount of increasing or decreasing the emission allowance are reported in Table 3.

As is seen in the second column of Table 3, the efficiency score of countries are less than or equal to 1. Therefore, they are classified into inefficient and efficient countries. Inefficient countries should seek to improve their efficiency status. Third column shows reduction of emissions which their sum is equal to 1635913. The last column reports amounts that countries can add to their emissions or sell their emission quota which their sum is equal to 380188. Therefore, total amount of emission permits that countries should reduce (1635913) is more than total amount that countries can sell (380138). As a result, difference between them (i.e., 1255725) is equal to the amount which should be reduced from total GHG emissions. Therefore, total centralized emission reallocation level is 14440836 thousand tons.

We also focus on the relation between the countries' efficiency and the reallocation level. It is seen that countries like Ireland, Luxembourg, Poland, and United States are efficient ($\theta_p = 1$) and there is no need to change their emission levels. Other countries such as Australia, Belgium, and Canada are inefficient ($\theta_p < 1$) which have to decrease their emission ($n^-_{1p} > 0$) or should buy emission allowance. Other countries such as Austria, Chile, and Denmark are allowed to increase their emissions or can sell their emission allowance($n^+_{1p} > 0$). There is no over-reduction of total allocation($q$) which disrupts production system.

## 5. Sensitivity analysis

Optimum solution of model (3) depends on $\alpha$ (cap) which is determined in protocols and agreements. Here, we assess impact of variations of $\alpha$ on relative efficiency scores of countries. Therefore, sensitivity analysis is performed. Table 4 reports results given different $\alpha$ values.

As is seen in Table 4, efficiency scores of countries are increased by decreasing the alpha. If a DMU is efficient for an alpha, it is also efficient for smaller ones. Therefore, it is not sensitive to alpha variations. In addition, by reducing alpha, number of efficient DMUs are increased. Fig. 1 depicts changes in countries efficiencies based on $\alpha$ variations. As is seen in Fig. 1, when absolute values of variations are increased, relative efficiency scores are increased. When $\alpha$ becomes less than $-0.4$, there is no change in relative efficiency scores.

On the other hand, by changing $\alpha$, amount of emission trading among countries is changed. Here, another sensitivity analysis is

[6] www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends/greenhouse-gas-emission-trends-assessment.

**Table 3**
Relative efficiency scores of countries and amounts of trade among them.

| Countries | Relative efficiency scores | $n_{1p}^{-}$: Amount of emission allowance which should be reduced (1000 tons) | $n_{1p}^{+}$: Amount of emission allowance which can be sold (1000 tons) |
|---|---|---|---|
| Australia | 0.869 | 176744 | |
| Austria | 0.705 | | 6530 |
| Belgium | 0.736 | 14517 | |
| Canada | 0.808 | 299460 | |
| Chile | 0.845 | | 36140 |
| Czech Republic | 0.599 | 37718 | |
| Denmark | 0.836 | | 6112 |
| Estonia | 0.639 | 7410 | |
| Finland | 0.67 | | 11502 |
| France | 0.723 | | 97470 |
| Germany | 0.79 | 52490 | |
| Greece | 0.527 | 46132 | |
| Hungary | 0.702 | | 9194 |
| Iceland | 0.736 | | 592 |
| Ireland | 1 | | |
| Italy | 0.67 | | 16182 |
| Japan | 0.955 | 693051 | |
| Korea | 0.789 | 194870 | |
| Luxembourg | 1 | | |
| Mexico | 0.821 | 65318 | |
| Netherlands | 0.763 | | 5945 |
| New Zealand | 0.905 | 20319 | |
| Norway | 0.895 | | 13362 |
| Poland | 1 | | |
| Portugal | 0.649 | 4848 | |
| Slovak Republic | 0.827 | | 8945 |
| Slovenia | 0.582 | 1843 | |
| Spain | 0.639 | 8842 | |
| Sweden | 0.808 | | 68429 |
| Switzerland | 0.922 | | 47718 |
| Turkey | 0.894 | 12351 | |
| United Kingdom | 0.742 | | 52067 |
| United States | 1 | | |
| Sum | | 1635913 | 380188 |

run to determine impact of $\alpha$ on emission trading. Changes of $\alpha$ is between $-0.01$ and $-0.5$. Results are reported in Table 5. In Table 5 amounts that should be decreased ($n_{1p}^{-}$) and amounts that can be sold ($n_{1p}^{+}$) are shown with negative and positive signs, respectively. As is seen, emission trading is affected by $\alpha$.

Given different alpha values, Table 5 indicates the amounts of emission trading for countries. By decreasing the alpha, countries emission reduction is increased. However, there is no change in the permit of Ireland, Luxembourg, Poland, and the United States. Therefore, it does not affect trading volume of efficient countries. In 39th row of Table 5, difference between amount that should be decreased and amount that could be sold is exactly equal to amount that should be deducted from cap (2nd row). This implies that our model works well. In last row of Table 4, when $\alpha$ exceeds $-0.3$, $n_{1p}^{-}$ and $n_{1p}^{+}$ remain constant and variable $q$ takes value. This indicates that $\alpha$ has exceeded acceptable amount. If the OECD looks for another percentage reduction, Table 5 can help it to make a suitable decision about emission permit of each country.

## 6. Managerial implications

Based on international protocols, countries should control their greenhouse emissions. In this paper, we categorize countries into three categories. The first category consists of countries that exceed acceptable amount of gas emission. This sort of countries should reduce their emitted gas or purchase emission permits. The second category consists of counties that their emitted gas is less than acceptable emission gas. This sort of countries may increase their gas emission or sell their emission permits. The third category consists of countries that are not required to change their amount of gas emissions.

The main objective of this study is to develop a novel reallocation method to help managers to determine reduction of gas emissions or selling allowance of gas emissions. There is also a way to trade emission permits among countries and they can determine amount of trades. Furthermore, our approach determines maximum reduction of gas emission for all countries.

There has been an implicit trade-off between greenhouse gas emission reduction and economic growth. Since large amount of greenhouse gas emissions has led to a lot of issues, national and international organizations have developed some protocols and agreements to force countries to reduce their greenhouse gas emissions and also to reach sustainable development. Our proposed approach reallocates greenhouse gas based on economic and environmental considerations. Countries may encounter practical political barriers to implement the results. However, it is very difficult to access political barriers of each country and their dataset. This is part of the research limitation that cannot be dealt with.

Bargaining game and common set of weight (CSW) models evaluate all DMUs with a set of weight (Hosseinzadeh Lotfi et al., 2000). It can help us to identify the efficient when all DMUs are in an identical condition. Countries have different features and characteristics which affect the amounts of inputs and outputs. Although the kind of inputs and outputs are same and countries are homogeneous but in order to evaluate performance and obtain the efficiency of each country, it is necessary to assign different weights corresponding to the different amounts of inputs and outputs for each country. So assigning a common set of weights to the all inputs and outputs of these countries cannot imply the real amount of efficiencies of countries.

**Table 4**
Relative efficiency scores of countries based on different α

| Countries | Variations of α (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | −0.5 | −0.4 | −0.3 | −0.2 | −0.15 | −0.1 | −0.05 | −0.02 | −0.01 | 0 |
| Australia | 1 | 1 | 1 | 0.905 | 0.874 | 0.869 | 0.869 | 0.869 | 0.869 | 0.873 |
| Austria | 0.969 | 0.969 | 0.969 | 0.705 | 0.705 | 0.705 | 0.705 | 0.705 | 0.705 | 0.705 |
| Belgium | 1 | 1 | 1 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 |
| Canada | 1 | 1 | 1 | 0.847 | 0.822 | 0.822 | 0.79 | 0.764 | 0.764 | 0.764 |
| Chile | 1 | 1 | 1 | 0.845 | 0.845 | 0.845 | 0.845 | 0.845 | 0.845 | 0.845 |
| Czech Republic | 0.773 | 0.773 | 0.773 | 0.599 | 0.599 | 0.599 | 0.599 | 0.599 | 0.599 | 0.599 |
| Denmark | 1 | 1 | 1 | 0.836 | 0.836 | 0.836 | 0.836 | 0.836 | 0.836 | 0.836 |
| Estonia | 0.668 | 0.668 | 0.668 | 0.639 | 0.639 | 0.639 | 0.639 | 0.639 | 0.639 | 0.639 |
| Finland | 0.886 | 0.886 | 0.886 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| France | 0.952 | 0.952 | 0.952 | 0.864 | 0.79 | 0.723 | 0.723 | 0.711 | 0.709 | 0.709 |
| Germany | 0.98 | 0.98 | 0.98 | 0.98 | 0.964 | 0.879 | 0.79 | 0.79 | 0.792 | 0.793 |
| Greece | 0.608 | 0.608 | 0.608 | 0.527 | 0.527 | 0.527 | 0.527 | 0.527 | 0.527 | 0.527 |
| Hungary | 0.945 | 0.945 | 0.945 | 0.702 | 0.702 | 0.702 | 0.702 | 0.702 | 0.702 | 0.702 |
| Iceland | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 |
| Ireland | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Italy | 0.903 | 0.903 | 0.903 | 0.686 | 0.686 | 0.686 | 0.67 | 0.67 | 0.67 | 0.67 |
| Japan | 1 | 1 | 1 | 1 | 1 | 0.955 | 0.821 | 0.781 | 0.785 | 0.8 |
| Korea | 1 | 1 | 1 | 0.982 | 0.789 | 0.789 | 0.789 | 0.751 | 0.751 | 0.752 |
| Luxembourg | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Mexico | 1 | 1 | 1 | 0.967 | 0.821 | 0.821 | 0.821 | 0.821 | 0.821 | 0.821 |
| Netherlands | 0.981 | 0.981 | 0.981 | 0.769 | 0.769 | 0.763 | 0.763 | 0.763 | 0.763 | 0.763 |
| New Zealand | 1 | 1 | 1 | 0.905 | 0.905 | 0.905 | 0.905 | 0.905 | 0.905 | 0.905 |
| Norway | 1 | 1 | 1 | 0.895 | 0.895 | 0.895 | 0.895 | 0.895 | 0.895 | 0.895 |
| Poland | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Portugal | 0.725 | 0.725 | 0.725 | 0.649 | 0.649 | 0.649 | 0.649 | 0.649 | 0.649 | 0.649 |
| Slovak Republic | 1 | 1 | 1 | 0.827 | 0.827 | 0.827 | 0.827 | 0.827 | 0.827 | 0.827 |
| Slovenia | 0.71 | 0.71 | 0.71 | 0.582 | 0.582 | 0.582 | 0.582 | 0.582 | 0.582 | 0.582 |
| Spain | 0.746 | 0.746 | 0.746 | 0.744 | 0.639 | 0.639 | 0.639 | 0.639 | 0.639 | 0.639 |
| Sweden | 1 | 1 | 1 | 0.808 | 0.808 | 0.808 | 0.808 | 0.808 | 0.808 | 0.808 |
| Switzerland | 1 | 1 | 1 | 0.922 | 0.922 | 0.922 | 0.922 | 0.922 | 0.922 | 0.922 |
| Turkey | 1 | 1 | 1 | 0.894 | 0.894 | 0.894 | 0.894 | 0.894 | 0.894 | 0.894 |
| United Kingdom | 0.896 | 0.896 | 0.896 | 0.896 | 0.886 | 0.742 | 0.742 | 0.742 | 0.742 | 0.742 |
| United States | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

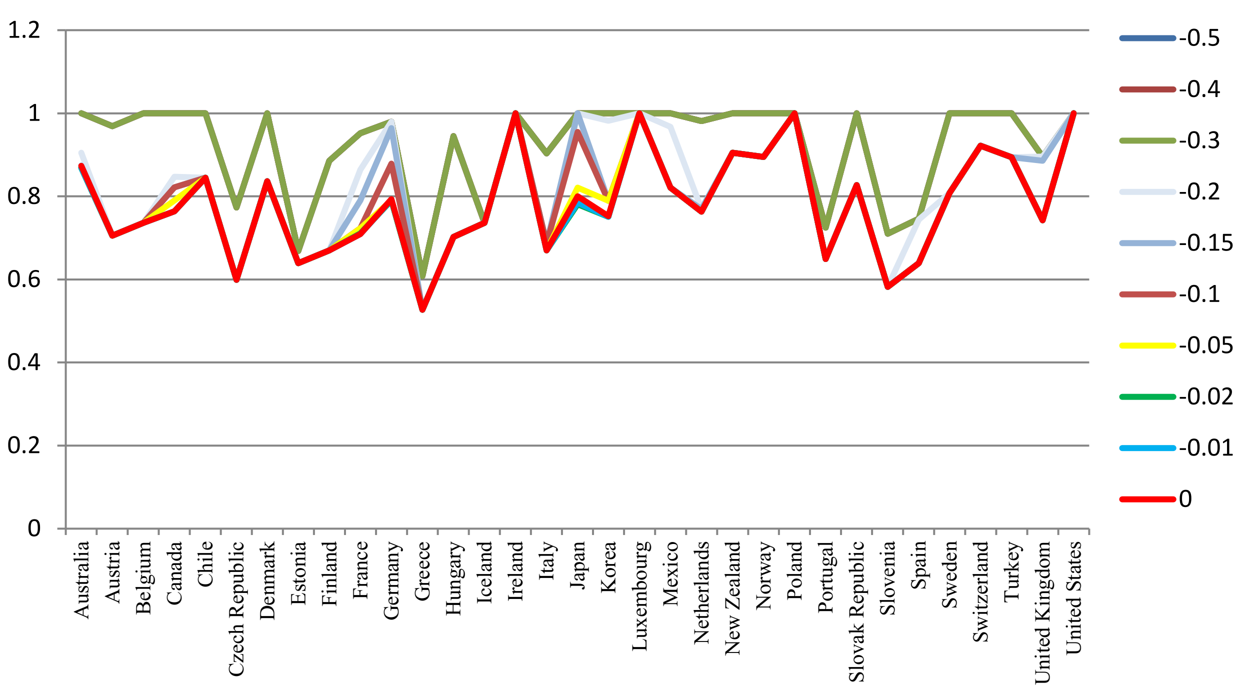


**Fig. 1.** Changes in countries efficiencies given α variation.

**Table 5**
Impact of $\alpha$ variation on emission trading.

| 1 | Variations of $\alpha$ (%) | −0.5 | −0.4 | −0.3 | −0.2 | −0.15 | −0.1 | −0.05 | −0.02 | −0.01 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | **Amounts that should be decreased from the cap** | 4359422 | 4359422 | 4359422 | 3139313 | 2354485 | 1569657 | 784828 | 313932 | 156967 |
| 3 | Australia | −308048 | −308048 | −308048 | −243176 | −187564 | −176744 | −176744 | −176744 | −176744 |
| 5 | Austria | −36090 | −36090 | −36090 | 6530 | 6530 | 6530 | 6530 | 6530 | 6530 |
| 6 | Belgium | −56555 | −56555 | −56555 | −14517 | −14517 | −14517 | −14517 | −14517 | −14517 |
| 7 | Canada | −524709 | −524709 | −524709 | −365394 | −338439 | −338439 | −248459 | −144754 | −144754 |
| 8 | Chile | | | | 36140 | 36140 | 36140 | 36140 | 36140 | 36140 |
| 9 | Czech Republic | −89518 | −89518 | −89518 | −37718 | −37718 | −37718 | −37718 | −37718 | −37718 |
| 10 | Denmark | −24209 | −24209 | −24209 | 6112 | 6112 | 6112 | 6112 | 6112 | 6112 |
| 11 | Estonia | −10493 | −10493 | −10493 | −7410 | −7410 | −7410 | −7410 | −7410 | −7410 |
| 12 | Finland | −36383 | −36383 | −36383 | 11502 | 11502 | 11502 | 11502 | 11502 | 11502 |
| 13 | France | −196827 | −196827 | −196827 | −131501 | −41546 | 97470 | 97470 | 170752 | 184755 |
| 14 | Germany | −521735 | −521735 | −521735 | −521735 | −497340 | −283418 | −52490 | −52490 | −6313 |
| 15 | Greece | −73512 | −73512 | −73512 | −46132 | −46132 | −46132 | −46132 | −46132 | −46132 |
| 16 | Hungary | −31561 | −31561 | −31561 | 9194 | 9194 | 9194 | 9194 | 9194 | 9194 |
| 17 | Iceland | 592 | 592 | 592 | 592 | 592 | 592 | 592 | 592 | 592 |
| 18 | Ireland | | | | | | | | | |
| 19 | Italy | −199188 | −199188 | −199188 | −27841 | −27841 | −27841 | 16182 | 16182 | 16182 |
| 20 | Japan | −805006 | −805006 | −805006 | −805006 | −805006 | −693052 | −273156 | −142944 | −46156 |
| 21 | Korea | −437749 | −437749 | −437749 | −421486 | −194870 | −194870 | −194870 | −31175 | −31175 |
| 22 | Luxembourg | | | | | | | | | |
| 23 | Mexico | −284953 | −284953 | −284953 | −255115 | −65318 | −65318 | −65318 | −65318 | −65318 |
| 24 | Netherlands | −103052 | −103052 | −103052 | −6839 | −6839 | 5945 | 5945 | 5945 | 5945 |
| 25 | New Zealand | −36889 | −36889 | −36889 | −20319 | −20319 | −20319 | −20319 | −20319 | −20319 |
| 26 | Norway | | | | 13362 | 13362 | 13362 | 13362 | 13362 | 13362 |
| 27 | Poland | | | | | | | | | |
| 28 | Portugal | −34394 | −34394 | −34394 | −4848 | −4848 | −4848 | −4848 | −4848 | −4848 |
| 29 | Slovak Republic | −7147 | −7147 | −7147 | 8945 | 8945 | 8945 | 8945 | 8945 | 8945 |
| 30 | Slovenia | −9254 | −9254 | −9254 | −1843 | −1843 | −1843 | −1843 | −1843 | −1843 |
| 31 | Spain | −168503 | −168503 | −168503 | −167240 | −8842 | −8842 | −8842 | −8842 | −8842 |
| 32 | Sweden | | | | 68429 | 68429 | 68429 | 68429 | 68429 | 68429 |
| 33 | Switzerland | | | | 47718 | 47718 | 47718 | 47718 | 47718 | 47718 |
| 34 | Turkey | −106863 | −106863 | −106863 | −12351 | −12351 | −12351 | −12351 | −12351 | −12351 |
| 35 | United Kingdom | −257362 | −257362 | −257362 | −257362 | −244264 | 52067 | 52067 | 52067 | 52067 |
| 36 | United States | | | | | | | | | |
| 37 | Total amount should decrease, $n_{1p}^{-}$ | 4360014 | 4360014 | 4360014 | 3347843 | 2563015 | 1933670 | 1165024 | 767410 | 624447 |
| 38 | Total amount can be sold, $n_{1p}^{+}$ | 592 | 592 | 592 | 208530 | 208530 | 364013 | 380195 | 453478 | 467480 |
| 39 | Difference between the two above | 4359422 | 4359422 | 4359422 | 3139313 | 2354485 | 1569657 | 784828 | 313932 | 156967 |
| 40 | $q$ | 3488859 | 1919203 | 349547 | 0 | 0 | 0 | 0 | 0 | 0 |

## 7. Conclusions and future research

Today, there is a deep concern over environmental protection and sustainability in national and international levels. In this sense, greenhouse gases emission is the main issue that causes global warming, climate change, and related disasters. This problem has led to a worldwide effort to reduce greenhouse gases emission and countries should observe it as an undesirable output. Market based approaches have been applied effectively to provide intensity for reducing greenhouse gas emissions and making countries more sustainable. Cap-and-trade policy is one of the most important, practical, and cost-effective market based approaches (Betsill and Hoffmann, 2011; Wagner, 2013). Upper limit of emission is considered as cap and countries can trade their allocated emission allowances. Fair reallocation of emission allowance among countries is a crucial subject in controlling emission permit and trade mechanism.

This paper developed a centralized DEA model for reallocation of emission allowances of countries. Our proposed model considered all countries in an integrated way so that emission allowances were reallocated according to their inputs and outputs. Note that countries emission and total of them were considered as undesirable output and cap. Countries with lower emission than their reallocated permit could emit more or sell their extra permits in emissions trading market. On the other hand, when countries' emission was higher than their reallocated permit they should reduce their emissions or buy permits from other countries. Reallocation of emission permit among OECD countries was conducted to illustrate the applicability of proposed model. Finally, sensitivity analysis was run to determine impact of variations in caps on relative efficiency scores and amount of reallocated emission allowances.

We recommend similar researches for centralized reallocation in presence of imprecise data. Another research can be repeated in presence of stochastic data.

## Acknowledgments

Authors would like to thank two anonymous Reviewers for their valuable suggestions and comments.

## References

Åhman, M., Burtraw, D., Kruger, J., Zetterberg, L., 2007. A Ten-year rule to guide the allocation of EU emission allowances. Energy Policy 35 (3), 1718–1730.
Amirteimoori, A., Kordrostami, S., 2005. Allocating fixed costs and target setting: a DEA-based approach. Appl. Math. Comput. 171 (1), 136–151.
Amirteimoori, A., Tabar, M.M., 2010. Resource allocation and target setting in data envelopment analysis. Expert Syst. Appl. 37 (4), 3036–3039.
Andersen, J.L., Bogetoft, P., 2007. Gains from quota trade: theoretical models and an application to the Danish fishery. Eur. Rev. Agric. Econ. 34 (1), 105–127.
Baumol, W.J., Oates, W.E., 1988. The Theory of Environmental Policy. Cambridge University Press.
Betsill, M., Hoffmann, M.J., 2011. The contours of "cap and trade": the evolution of emissions trading systems for greenhouse gases. Rev. Pol. Res. 28 (1), 83–106.
Bi, G., Ding, J., Luo, Y., Liang, L., 2011. Resource allocation and target setting for parallel production system based on DEA. Appl. Math. Model. 35 (9), 4270–4280.
Böhringer, C., Welsch, H., 2006. Burden sharing in a greenhouse: egalitarianism and sovereignty reconciled. Appl. Econ. 38 (9), 981–996.

Bryant, G., 2016. Creating a level playing field? The concentration and centralisation of emissions in the European Union Emissions Trading System. Energy Policy 99, 308–318.

Bulteau, J., 2012. Tradable emission permit system for urban motorists: the neo-classical standard model revisited. Res. Transport. Econ. 36 (1), 101–109.

Burtraw, D., Linn, J., Palmer, K., Paul, A., 2014. The costs and consequences of clean air act regulation of CO2 from power plants. Am. Econ. Rev. 104 (5), 557–562.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2 (6), 429–444.

Clò, S., Battles, S., Zoppoli, P., 2013. Policy options to improve the effectiveness of the EU emissions trading system: a multi-criteria analysis. Energy Policy 57, 477–490.

Cohen, B., Winn, M.I., 2007. Market imperfections, opportunity and sustainable entrepreneurship. J. Bus. Ventur. 22 (1), 29–49.

Dong, C., Shen, B., Chow, P.-S., Yang, L., Ng, C.T., 2016. Sustainability investment under cap-and-trade regulation. Ann. Oper. Res. 240 (2), 509–531.

Du, S., Ma, F., Fu, Z., Zhu, L., Zhang, J., 2015. Game-theoretic analysis for an emission-dependent supply chain in a 'cap-and-trade' system. Ann. Oper. Res. 228 (1), 135–149.

Ellerman, A.D., 2005. A note on tradeable permits. Environ. Resour. Econ. 31 (2), 123–131.

Ellerman, A.D., Buchner, B.K., 2007. The European Union emissions trading scheme: origins, allocation, and early results. Rev. Environ. Econ. Pol. 1 (1), 66–87.

Eriksson, M., Vamling, L., 2006. Heat pumps and tradable emission permits: on the carbon dioxide emissions of technologies that cross a tradable emission market boundary. Energy Convers. Manag. 47 (20), 3510–3518.

European Commission, 2008. Questions and Answers on the Commission's Proposal to Revise the EU Emissions Trading System.

Feng, C., Chu, F., Ding, J., Bi, G., Liang, L., 2015. Carbon emissions abatement (CEA) allocation and compensation schemes based on DEA. Omega 53, 78–89.

Fischer, C., Fox, A., 2004. Output-based Allocations of Emissions Permits: Efficiency and Distributional Effects in a General Equilibrium Setting with Taxes and Trade. Resources for the Future, Washington, DC.

Gomes, E., Lins, M.E., 2008. Modelling undesirable outputs with zero sum gains data envelopment analysis models. J. Oper. Res. Soc. 59 (5), 616–623.

Goulder, L.H., Parry, I.W.H., Williams Iii, R.C., Burtraw, D., 1999. The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. J. Public Econ. 72 (3), 329–360.

Hosseinzadeh Lotfi, F., Hatami-Marbini, A., Agrell, P.J., Aghayi, N., Gholami, K., 2013. Allocating fixed resources and setting targets using a common-weights DEA approach. Comput. Ind. Eng. 64 (2), 631–640.

Hosseinzadeh Lotfi, F., Jahanshahloo, G., Memariani, A., 2000. A method for finding common set of weights by multiple objective programming in data envelopment analysis. SW. J. Pure Appl. Math. 2000 (1), 44–54.

Lee, D.-H., 2016. Evaluation of the development of biobutanol with reference to continental level: the rebound effect and effectiveness of the Paris Agreement. Int. J. Hydrogen Energy 41 (46), 21600–21616.

Lehtonen, M., 2005. OECD environmental performance review programme: accountability or learning? Evaluation 11 (2), 169–188.

Lozano, S., Villa, G., Brännlund, R., 2009. Centralised reallocation of emission permits using DEA. Eur. J. Oper. Res. 193 (3), 752–760.

Mabey, N., 1997. Argument in the Greenhouse: the International Economics of Controlling Global Warming. Taylor & Francis US.

Mavi, R. K., Farzipoor Saen, R., & Goh, M. ((in press)). "Joint analysis of eco-efficiency and eco-innovation with common weights in two-stage network DEA: a big data approach". Technol. Forecast. Soc. Change.

Nannerup, N., 2001. Equilibrium pollution taxes in a two industry open economy. Eur. Econ. Rev. 45 (3), 519–532.

Oberheitmann, A., 2010. "A new post-Kyoto climate regime based on per-capita cumulative CO 2-emission rights—rationale, architecture and quantitative assessment of the implication for the CO 2-emissions from China, India and the Annex-I countries by 2050. Mitig. Adapt. Strategies Glob. Change 15 (2), 137–168.

Parry, I.W.H., 1995. Optimal pollution taxes and endogenous technological progress. Resour. Energy Econ. 17 (1), 69–85.

Rashidi, K., Shabani, A., Farzipoor Saen, R., 2015. Using data envelopment analysis for estimating energy saving and undesirable output abatement: a case study in the Organization for Economic Co-Operation and Development (OECD) countries. J. Clean. Prod. 105, 241–252.

Redclift, M., 2005. Sustainable development (1987–2005): an oxymoron comes of age". Sustain. Dev. 13 (4), 212–227.

Richels, R.G., Blanford, G.J., Rutherford, T.F., 2009. International climate policy: a second best solution for a second best world? Clim. Change 97 (1–2), 289–296.

Sacchi, S., Riva, P., Brambilla, M., Grasso, M., 2014. Moral reasoning and climate change mitigation: the deontological reaction toward the market-based approach. J. Environ. Psychol. 38, 252–261.

Salant, S.W., 2016. What ails the European Union's emissions trading system? J. Environ. Econ. Manag. 80, 6–19.

Shen, L., Song, X., Wu, Y., Liao, S., Zhang, X., 2016. Interpretive Structural Modeling based factor analysis on the implementation of Emission Trading System in the Chinese building sector. J. Clean. Prod. 127, 214–227.

Sterner, T., Muller, A., 2008. Output and abatement effects of allocation readjustment in permit trade. Clim. Change 86 (1), 33–49.

Sun, J., Wu, J., Liang, L., Zhong, R.Y., Huang, G.Q., 2014. Allocation of emission permits using DEA: centralised and individual points of view. Int. J. Prod. Res. 52 (2), 419–435.

Sutter, J.D., Berlinger, J., Ellis, R., 2015. Obama: Climate Agreement 'best Chance We Have'to Save the Planet. Cable News Network (CNN). Available at. http://www.cnn.com/2015/12/12/world/global-climate-change-conference-vote. accessed 17 January 2016.

Vossler, C.A., Suter, J.F., Poe, G.L., 2013. Experimental evidence on dynamic pollution tax policies. J. Econ. Behav. Organ. 93, 101–115.

Wagner, G., 2013. Carbon Cap and Trade A2 - Shogren, Jason F. Encyclopedia of Energy, Natural Resource, and Environmental Economics. Elsevier, Waltham, pp. 1–5.

Wagner, M., 2004. Firms, the Framework Convention on Climate Change & the EU Emissions Trading system." Corporate Energy Management Strategies to Ad-Dress Climate Change and GHG Emissions in the European Union, vol. 12. Centre for Sustainability Management, Lüneburg.

Wang, K., Zhang, X., Wei, Y.M., Yu, S., 2013. Regional allocation of CO2 emissions allowance over provinces in China by 2020. Energy Policy 54, 214–229.

Wu, H., Du, S., Liang, L., Zhou, Y., 2013. A DEA-based approach for fair reduction and reallocation of emission permits. Math. Comput. Model. 58 (5–6), 1095–1101.

Wu, H., Zhang, D., Chen, B., Yang, M., 2018. Allocation of emission permits based on DEA and production stability. INFOR Inf. Syst. Oper. Res. 56 (1), 82–91.

Wu, J., Zhu, Q., Chu, J., An, Q., Liang, L., 2016. A DEA-based approach for allocation of emission reduction tasks. Int. J. Prod. Res. 54 (18), 5618–5633.

Zhao, J., 2003. Irreversible abatement investment under cost uncertainties: tradable emission permits and emissions charges. J. Public Econ. 87 (12), 2765–2789.

Zhou, P., Ang, B.W., Poh, K.L., 2008. A survey of data envelopment analysis in energy and environmental studies. Eur. J. Oper. Res. 189 (1), 1–18.