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An input–output linear programming model for assessing climate policy considering economic growth

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Abstract
Deploying new strategies to reduce the effect of climate change may constrain economic growth. It is thus necessary to develop a model which evaluates the trade-off between economic and environmental influences prior to a policy implementation. Recent studies have proved the effectiveness of input–output linear programming model in identifying the optimal solutions when different climate policies are considered. However, analyzing sectoral linkage to give priority sectors and then finding optimal solutions through reducing pollution from these sectors, which help avoid the economic losses from low-polluting sectors, have not been figured out in previous works. This study first uses input–output an (IO) analysis to provide a measure of structural interdependence among economic sectors and present priority sectors. An IO optimization model is then developed for minimizing the total greenhouse gas (GHG) emissions, in order to identify strategies for GHG intensity reduction in Vietnam, focusing on the priority sectors. In addition, the effect of GHG emissions on human health using the disability adjusted life years (DALY) is further evaluated. Six scenarios are considered to identify the potentials of highest GHG intensity reduction that can be obtained by the year 2020. These scenarios encompass BAU, the consideration of different GDP growth rates, differentiated economic sector growth, economic restructure, and the adaptation of lower-pollution technology implementation for the priority sectors. Each scenario quantifies sectoral final demand, sectoral gross domestic output, sectoral GHG emissions, GHG intensity, and DALY. The linkage analysis results indicate that agriculture, fishery and forestry, transport and communication, personal, community and household, manufacturing of non-metallic mineral products, and mining and quarrying are priority sectors. The optimization solutions present that the best strategy is by taking advantages of identified measures. The best solution obtains 20.3% reduction in GHG intensity compared to baseline. These obtained results become the useful suggestions for decision makers and environmental management in designing successful environmental regulations.

Keywords Greenhouse gas emissions · Input–output analysis · Linear programming · Optimization problem · Climate policy · DALY

1 Introduction

The impact of environment resulting from economic production activities has caused serious global problems (i.e., global warming). Increasing atmospheric concentrations of greenhouse gas (GHG) emissions from the continued consumption of fossil fuels remains a main contributor to climate change, which is a global threat to people's health and ecosystems (de Schryver et al. 2009). In order to reduce climate change, the 1992 UN Framework Convention on Climate Change (UNFCCC) developed the Kyoto Protocol, which required member countries to lower GHG emissions including CO_2, CH_4, and N_2O (UNFCCC 1998). However, the deployment of climate policies to meet these targets may have adverse effects on social welfare and economic growth. These effects are different from country to country depending upon the state of economic structure and economic growth (Fan et al. 2010).

Vietnam is now in the last process of rapid industrialization and going to pass an innovation period of growth (Marzyin 2013). PricewaterhouseCoopers (2017) reported that the Vietnam's economy has positively thrived with annual economic growth rates reaching more than 5%. According

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to MNRE (2014), this rapid economic growth has been accompanied by increased energy consumption and has resulted in corresponding increases through GHG release from energy sectors. Nguyen et al. (2009) reported that the GHG generation from energy combustion is projected to go up tremendously by 14% per year, reaching approximately 400 million tonnes of CO_2 (Mt CO_2) by 2030. Furthermore, in addition to the energy sectors, the agriculture sectors, industrial sectors, and waste treatment also contribute to the large amounts of GHG emissions (MNRE 2014). As a non-annex I country under Kyoto Protocol, Vietnam is not commanded to mitigate GHG generation. However, the country has ratified an agreement to make efforts to mitigate GHG amount from agriculture, energy, industry, and transportation sectors (KEPA and GreenID 2014).

In response to this, the Vietnamese Government paid great attention to GHG control with a target which required to reduce GHG intensity by 8–10% lower than the 2010 level by 2020, according to Decision 1393 (VNGGS 2012). There are several measures proposed to reduce GHG intensity including adjustment of economic structure or application of low-carbon technologies (KEPA and GreenID 2014). However, the implementation of measures to reduce GHG emissions may have constraining impacts on Vietnam's economy (KEPA and GreenID 2014), especially if sectors having the most economic productivity are also the most polluting. Hence, it is particularly relevant for the government, manufactures, and decision makers to assess how the implementation of pollution mitigation policies influences the economic development (Oliveira et al. 2016). The best way to assess the economic and environmental impacts is to apply input–output (IO) analysis proposed by Leontief (1936, 1970). The IO analysis provides a framework for capturing the interrelationship among various sectors of an economy or a region. This is done by considering the product from each economic sector both as commodities for final consumption and as raw material in the production of goods in the same or in other sectors (Miller and Blair 2009; Tan et al. 2017). The IO model can be extended to take into account other aspects of this economic system. For instance, Hoa et al. (2016) used the inoperability IO model (IIM) proposed by Haimes and Jiang (2001) and the vulnerable index given by Yu et al. (2014) to develop a multi-criteria model for disaster vulnerability evaluation due to the implementation of a biofuel policy. The extension of IO framework which captures environmental influences has been used for measuring environmental protection in China's industries (Fan et al. 2016), and in developing a tool for simultaneous management of production activities and waste resulting from the construction industry (Golzarpoor et al. 2017). The environmental IO approach is also considered a useful tool in measuring structural interdependence of an economy and in identifying key sectors in terms of both monetary and environmental performances through forward and backward inter-sectoral linkages (Lenzen 2003; Piaggio et al. 2012). Shmeleve (2013) then used these economic and environmental linkage coefficients to trade-offs between economic growth and environmental protection. Recently, Nguyen et al. (2018) applied the environmental IO model for evaluating the trend and impact of water pollution in Vietnam within a time series. In addition, Nguyen et al. (2018) also measured the inter-sectoral linkages to indicate the role of sectors as either key polluting sectors, polluting pushers/producers, or polluting pullers/consumers, in terms of their contribution to water pollution.

The value of IO model is further strengthened when it is integrated with linear programming (LP), and it is called IO-LP (Vogstad 2009). A recent review work of the IO-LP indicates the strong point of this integrated approach comparing to the conventional IO framework (Oliveira et al. 2016). The IO-LP can identify the suitable productivity of sectors to seek optimum solutions for a desired objective function (i.e., maximize gross domestic product, GDP) while satisfying the balance of sectoral activity as defined by the IO model. Furthermore, IO-LP may provide a more comprehensive assessment of efficient production probabilities and economic impacts of potential regulations, which allows to study trade-offs among conflicting objectives (Oliveira et al. 2016). For example, the IO-LP has been applied for quantifying the macro-economic costs of CO_2 mitigation in China's economy (Fan et al. 2010), and in evaluating the economic, energy, and environment (E3) trade-offs in Brazil's economy (de Carvalho et al. 2016). This model was also used to optimize GDO in the Greek economy in consideration of integrated impacts of solid waste and other pollutants (Hristu-Varsakelis et al. 2012). Recently, Cayamanda et al. (2017) modified the IO-LP model into a fractional programing IO model indicating the potential CO_2 intensity reductions for the Philippines' economy.

In general, these previous studies (i.e., Oliveira et al. 2016; de Carvalho et al. 2016 and among others) were successful in dealing with multi-objective problems regarding detailed economic–environmental concerns for each country. They, however, failed to highlight the prioritization of sectors in both terms of economic and environmental performance. The assessment of the environmental impact on an economic system, which focuses on priority sectors having higher impacts on both economy and environment, may help avoid the economic losses from low-polluting sectors. It is because once the ranking of sectors in consideration of environmental and economic factors is known, the economic performance will be adjusted in the direction which prioritizes the growth of low-polluting sectors and limits the production of high-polluting sectors to some extents. Therefore, the prioritization of sectors is important for trade-off economic–environmental objectives. However, this has not been figured out in these previous studies of multi-objective optimization model. Another limitation of these previous works is that the impacts of human health and the ecosystem due to climate change resulting from different environmental pollutants have not been involved. According to Forster et al. (2007), pollutant emissions can be translated into environmental end-point indicators such as disability adjusted life years (DALY) for measuring impact on human health damage (Hofstetter 1998) and the loss of species diversity for evaluating the damage of the ecosystem (Kollner 1999).

In Vietnam, studies on analyzing the potentials of reducing environmental pollutants in consideration of desired economic growth at the sectoral level, evaluating human health impact, and analyzing inter-sectoral linkages in consideration of pollutant factors have not been done comprehensively. To supplement these research gaps, this context first uses IO analysis to measure the structural interdependence between sectors of Vietnamese economy considering both economic and environmental flows. The priority sectors which have higher impact on economic and GHG emissions are indicated. An IO-LP optimization model is then developed to minimize the total GHG emissions. From the solution of optimization model, maximum reduction of GHG intensity focusing on these priority sectors in the trajectories to 2020 is estimated. This is a new finding of this study. In addition, this study extends the model to account for GHG impact on human health using DALY indicator. Different scenarios based on economic growth targets and given climate policies are considered to compare the business as usual (BAU) scenario. This framework uses 18-sector IO table and GHG emission data in 2011 as necessary data which serve as the baseline to compute for the growth trajectories to 2020. The rest of the paper is organized as follows. The methodology is explained in Sect. 2. Section 3 mentions data collection, while the results and discussions are given in Sect. 4. Finally, the conclusions and recommendations for future work are discussed.

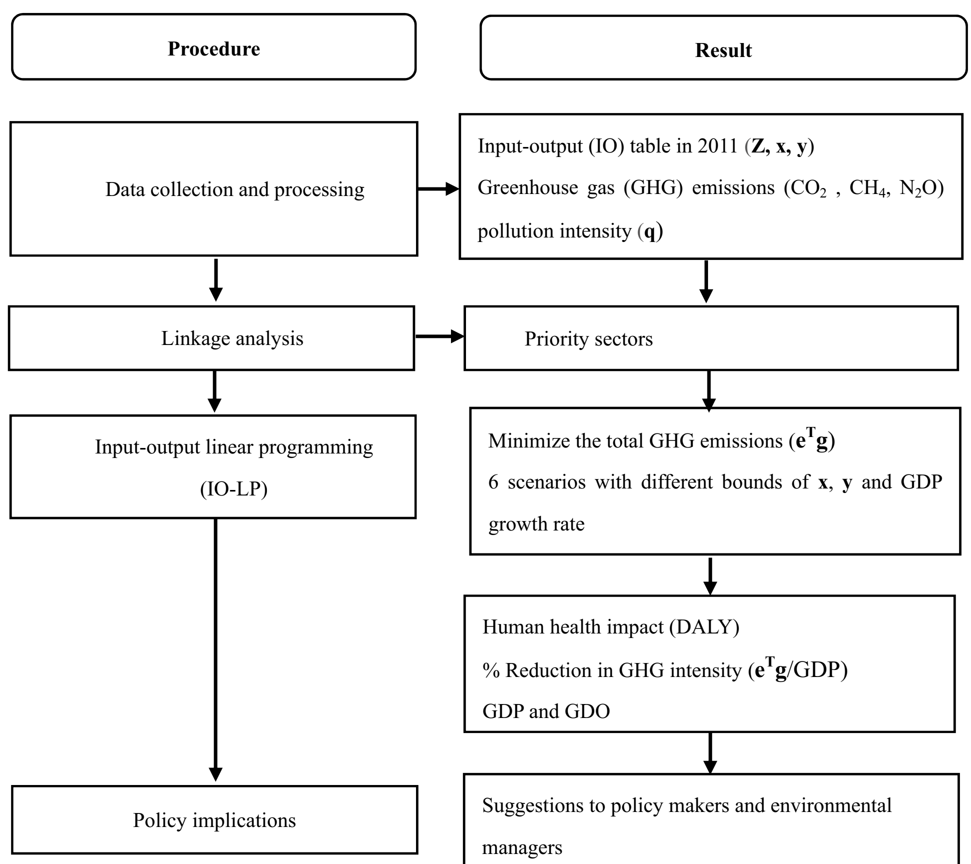
1.1 Methods

The framework developed to achieve the objectives of study is illustrated in Fig. 1:

1.2 Generic IO analysis

The IO framework has been conventionally applied to describe the relationship among various economic sectors in an economy or a region. Basically, it consists of a system of linear equations where total GDO is equal to intermediate demand, which is consumed internally by this system, plus

Fig. 1 Research framework



the amount used by final customers (final demand) (Leontief 1985). A more complete discussion of IO analysis can be found in Miller and Blair (2009), while a brief explanation can be obtained from Tan et al. (2017). For an economy with n sectors, the parameter $\mathbf{x}$ represents the $n \times 1$ GDO vector, $\mathbf{y}$ is the $n \times 1$ vector for final demand, and $\mathbf{Z}$ is the $n \times n$ matrix for IO transaction. Note that the total final demand is equal to the GDP of this economy. In a matrix notion, the IO framework can be stated as (Miller and Blair 2009):

$$\mathbf{x} = \mathbf{Ze} + \mathbf{y}, \quad (1)$$

where $\mathbf{e} = [1, 1, \ldots, 1]^{\mathrm{T}}$ is the $n \times 1$ vector with elements of value 1; $\mathbf{A}$ denotes the $n \times n$ technology coefficient matrix with elements a_{ij} ($a_{ij} = Z_{ij}/x_j$) representing the amount of product from the ith sector required to make one unit of GDO from the jth sector. Relying on this, Eq. (1) can be written again as follows:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y}. \quad (2a)$$

Consequently, Eq. (2a) is equivalent to Eq. (2b)

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y}, \quad (2b)$$

where $\mathbf{I}$ denotes the $n \times n$ identity matrix.

1.3 Environmental impact

The extension of IO model which accounts for the environmental intervention associated with each sector is mentioned in Miller and Blair (2009). Given that there are m pollutants considered (in our case $m = 3$ which includes CO_2, CH_4, and N_2O), the amount of environmental intervention of each pollutant in response to a sector is proportional to the sector size (i.e., GDO). Let $\mathbf{q}$ represent the $m \times n$ pollution intensity matrix; its elements, q_{kj}, is defined as the amount of pollutant k emitted by the jth sector so that the $m \times 1$ total intervention vector, $\mathbf{g}$, can be expressed as

$$\mathbf{g} = \mathbf{qx}. \quad (3)$$

1.4 DALY

According to McMichael et al. (2003), the GHG emissions, which contribute towards climate change, further cause an increase in different diseases (i.e., diarrhea, malaria, and heat stress). This decreases peoples' longevity or healthy life years. The assessment of the impact of GHG emissions can be carried out at mid-point and end-point. At mid-point, GHG emissions are evaluated based on infra-red forcing indicator or global warming potential (GWP), while at the end-point, the effects of GHG emissions are translated into damage indicators. The most common end-point indicator for human damage is put in terms of DALY. DALY is defined as years of life lost to early death and years of life with disability due to loss of function (Murray and Lopez 1996). The characterization factors of pollutants for quantifying DALY have been estimated for many kinds of diseases, including non-communicable diseases, vector-borne diseases, and various cancer types (Murray and Lopez 1996). There were several methods to obtain these characterization factors including the Eco-indicator 99 methodology (Goedkoop and Spriensma 2001) quantifying human health, Environmental Priority System (EPS) accounting for impacts on both human health and ecosystem damages (Steen 1999), and life cycle assessment (LCA) methods capturing human health damage (Goedkoop et al. 2009). de schryver et al. (2009) developed new characterization factors for 63 GHG pollutants affecting on both human and terrestrial ecosystems. This research used the characterization factors (DALY per ktonne of emissions) obtained from de schryver et al. (2009) to assess the impact of GHG emissions emitted from each economic activity. The total DALY expressed in number of lost years is given by Eq. (4):

$$\mathrm{DALY} = \mathbf{cg}, \quad (4)$$

where $\mathbf{c}$ is the $1 \times m$ characterization factor vector corresponding to m pollutants.

1.5 Forward and backward linkages

The assessment of inter-sectoral linkages and identification of key sectors using IO analysis have been performed by many researchers (Rasmussen 1956; Dietzenbacher 2005). These authors used Gosh inverse (Gosh 1958) or Leontief inverse to measure the linkages between sectoral monetary transactions. The approach was then developed to identify the key sectors and linkages when environmental impacts resulting from economic sectors were taken into account using the IO model (Lenzen 2003; Nguyen et al. 2018). These key sectors may cause high environmental impact to other sectors, since economic sectors are connected to all other economic sectors by virtue of its supply chain network (Leontief and Ford 1972). Shmeles (2013) stated that sectors having a forward linkage coefficient greater than one tend to create a greater than average effect on downstream sectors in the supply chain. Meanwhile, sectors having a backward linkage coefficient greater than one tend to have a higher than average effect on upstream sectors in the supply chain. Key sectors are those having both forward linkage and backward linkage coefficients greater than one.

Lenzen (2003) indicated that priority sectors from linkage analysis in terms of environmental impacts are different from the ranking achieved from purely monetary terms. Evaluating sector linkages, while accounting for both economic and environmental impacts, provides a better perspective for sustainable development. These authors computed forward and backward linkage coefficients for both sides for two scenarios including weighting linkage coefficients with final demand and value added, and vice versa (unweighting). The comparison of unweighted and weighted results was then performed and identified that the later one has more advantage to assess the economic and environmental impacts among sectors. Therefore, this paper uses a generalized framework introduced by Lenzen (2003) to obtain linkage coefficients, then weighting them with final demand and value added to identify key sectors.

1.6 Optimization problem

The implementation of climate policies which assists to reduce GHG generation will have an impact in the growth of some economic sectors because of the need to adjust the economic structure or due to limitations of the productivity of carbon-intensive sectors. This can interfere with an economy's macro-economic development. The contradiction between economic growth and GHG emission reduction needs to be balanced by decision makers. In the work, IO-LP is used to study the relationship between the Vietnam's continued economic development and GHG emission reduction resulting from the readjustment of economic structure or the implementation of low-carbon measures.

The optimization problem is set up to seek the minimization of total GHG emissions in consideration of Vietnam's different GDP growth rates, and subject to the bound of sectoral final demand. Furthermore, this model allows economic sectors to obtain different levels of productivity. The following is a notation form of objective function:

$$\text{Min } \mathbf{e}^{\mathbf{T}}\mathbf{g}, \quad (5)$$

where $\mathbf{e}^{\mathbf{T}}$ is the $1 \times m$ vector with elements of value 1.

This objective function is subject to economic, environmental constraints and health impact which are expressed in Eqs. (2b), (3), and (4), respectively.

$$\text{Production bound}: \mathbf{x}_{\mathbf{L}} \leq \mathbf{x} \leq \mathbf{x}_{\mathbf{u}}, \quad (6)$$

where $\mathbf{x}_{\mathbf{L}}$, $\mathbf{x}_{\mathbf{u}}$ are the $n \times 1$ column vectors containing the lower and upper limits on GDO. In every sector, GDO must be non-negative.

$$\text{Final demand bound}: \mathbf{y}_{\mathbf{L}} \leq \mathbf{y} \leq \mathbf{y}_{\mathbf{u}}, \quad (7)$$

where $\mathbf{y}_{\mathbf{L}}$, $\mathbf{y}_{\mathbf{u}}$ are the $n \times 1$ column vectors for the lower and upper limits of final demand.

The bounds in sector size (GDO) and in sectoral final demand given in Eq. (6) and Eq. (7) are placed to avoid solutions, which push the production of some sectors to unfeasible levels, ensuring the economic growth target.

2 Data collection

This section contains the empirical data used to illustrate our model. The data consist of (i) economic data including the Vietnamese IO table, and (ii) air pollution including CO_2, CH_4, and N_2O.

2.1 IO table

The newest IO table for the Vietnamese economy was from the year 2011, which was obtained from the Vietnamese General Statistical Office (GSO) website (GSO 2013). This IO table has 138 rows and columns with four value-added rows and six final consumption columns. The framework of the year of 2011 IO table is detailed in Nguyen et al. (2018). The original IO table is aggregated and categorized into 18 economic sectors using established IO techniques (Miller and Blair 2009). This is more convenient for accounting environmental emissions. This classification of sectors is compatible with that given in the 2011 IO table from GSO (2013) and the classification found in the International Standard Industrial Classification version 3 (ISIC 3) (UN 2002). The nomenclature of the 18 economic sectors, sectoral GDO in million Vietnamese dongs (Million VND) in 2011, and the percentage of GDO contribution from each sector are shown in Table 1, while the numerical values of **A** matrix are presented in Table 5 in Appendix. Table 1 shows that sectors, which contribute to the largest amount of total GDO, are Sector 1 (agriculture, fishery and forestry) accounting for 13.4%, Sector 10 (manufacturing of fabricated metal products, machinery and equipment) with 12.3%, and Sector 3 (food, beverage, and tobacco) with 11.6%. Besides GDO, the aggregated IO provides the IO matrix **Z** and final demand vector **y**, which are needed for the calculation and assessment of environmental–economic impact.

2.2 Pollution load and DALY

The data for CO_2 generation from fuel combustion in Vietnam are achieved from the International Energy Agency (IEA 2016). Since electricity generation produced by power and heat sectors is mainly used by other economic sectors, CO_2 emissions from electricity should be allocated to all other sectors based on their electricity consumption (Hsu and Chou 2000). The data of other air emissions were reported by the Vietnamese Ministry of Natural Resources and Environment (MNRE 2014) in fulfillment of the UNFCCC obligation. European Environment Agency indicates that there are three main issues on air pollution. These include GHGs which promote global warming, pollutants

Table 1 Nomenclature of sectors, GDO, percentage of GDO, and pollution intensity of GHG emissions

Sector number	Economic sector	GDO (*x*, trillion VND)	% GDO	Pollution intensity of GHG emissions (*q*, kg CO_2e/million VND)		
				CO_2	CH_4	N_2O
1	Agriculture, fishery, and forestry	1029	13.4	2.91813	81.34052	42.76569
2	Mining and quarrying	339	4.4	5.77364	61.66947	0.01437
3	Food, beverage, and tobacco	891	11.6	14.88240	1.51200	0.07004
4	Textile, wearing apparel, and leather industries	479	6.2	25.90904	0.02610	0.07004
5	Manufacture of wood and wood products	55	0.7	8.37145	0.02610	0.07004
6	Manufacture of paper and paper products, printing and publishing	98	1.3	26.80138	10.08224	0.07004
7	Manufacture of industrial chemicals	221	2.9	16.96586	0.02955	0.07004
8	Manufacture of non-metallic mineral products	200	2.6	254.66759	0.02610	0.07004
9	Basic metal industries	157	2	22.00112	0.04792	0.07004
10	Manufacturing of fabricated metal products, machinery and equipment	945	12.3	8.37145	0.02610	0.07004
11	Other manufacturing industries	474	6.2	28.79517	0.02723	0.07004
12	Electricity, gas, and water	175	2.3	9.47642	0.00343	0.02348
13	Construction	684	8.9	0.00000	2.44716	0.04930
14	Trade and repairing services	615	8	10.05966	2.44270	0.03019
15	Transportation and communication	543	7.1	71.16232	2.66868	0.20523
16	Finance, real estate, and business services	401	5.2	3.38932	2.42531	0.00840
17	Government services	146	1.9	3.38932	2.42531	0.00840
18	Personal, community, and household services	244	3.2	111.99322	37.68895	9.41169

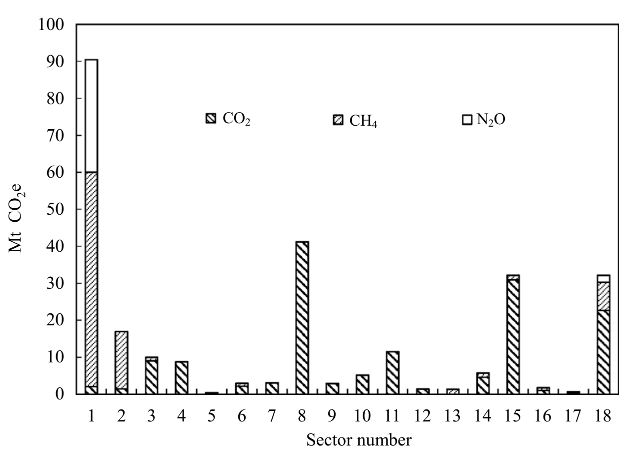


Fig. 2 GHG emissions of sectors

which induce acidification (ACID), and those which have tropospheric ozone forming potential (TOFP). However, the analysis employed by Hristu-Varsakelis et al. (2010) has highlighted that the effect of the last two impacts were much smaller than that of GHG. For this reason, only GHG emissions particularly CO_2, CH_4, and N_2O, estimated in million tonnes of CO_2 equivalents (Mt CO_2e), are considered in this work. The pollution intensity of each GHG pollutant for various sectors in the year 2011 is listed in Table 1, while the GHG emissions for each sector are shown in Fig. 2. The total GHG emissions in 2011 is 357 Mt CO_2e, in which 188 Mt CO_2e is contributed by CO_2 emissions. Three sectors, Sector 8 (manufacturing of non-metallic mineral products), Sector 15 (transport and communication), and Sector 18 (personal, community, and household services) are together responsible for 62.25% of the CO_2 emissions; 27.13% of these emissions comes from Sector 8 (manufacturing of non-metallic mineral products) and 20.58% of CO_2 emissions corresponds to the Sector 15 (transport and communication). Sector 2 (mining and quarrying) is responsible for 17.12% of CH_4 emissions in 2011, while Sector 1 (agriculture, fishery, and forestry) is responsible for 68.52% of the CH_4 emissions. The same sector is the main emitter of N_2O emissions accounting for 94.15% of total N_2O emissions.

To quantify the effect of each type of GHG emission on people's health, the characterization factors for DALY should be known. In this paper, the characterization factors for human damage due to climate change corresponding to CO_2, CH_4, and N_2O for hierarchical perspective were obtained from de Schryver et al. (2009) and expressed in DALY/ktonne units (DALY per thousand tonnes of pollutant). The hierarchical perspective coincides with the point of view that effects can be avoided with appropriate management, and that the selection in this model is relied on the level of scientific consensus (Goedkoop and Spriensma 2001). Thus, data based on this perspective are considered as standard to assess people health damage and ecosystem

Table 2 Characterization factors of greenhouse gas emissions (Sources: de Schryver et al. 2009)

Pollutants	(DALY/ktonnes)	GWP
CO_2	0.255	1
CH_4	5.04	21
N_2O	83.3	310

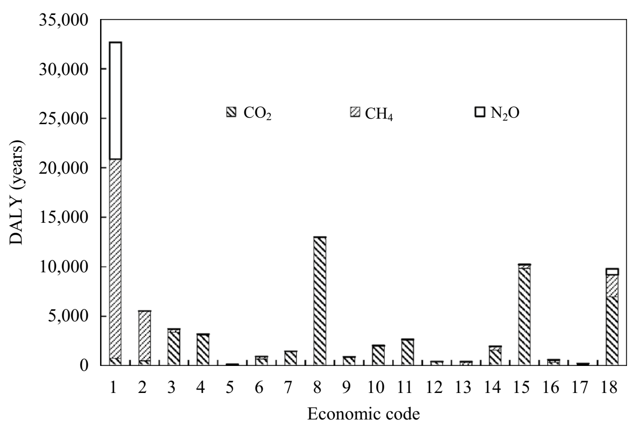


Fig. 3 DALY of sectors in 2011

damage. The global warming potentials (GWP) (MNRE 2014) are used to convert the amount of each GHG emitted into CO_2 amount which results in an equivalent effect to that of the actual gas emitted. Table 2 shows the characterization factors of pollutants and GWP. The generation of 1 ktonnes of CH_4, for example, has the same GWP as 21 ktonnes of CO_2e. Based on the total GHG emissions shown in Fig. 2 and these characterization factors, the DALY values of each sector corresponding to each pollutant are obtained using Eq. (4). These values are shown in Fig. 3. The calculation indicates that the total DALY induced by total GHG emissions in 2011 is 89,768 lost years, in which Sector 1 causes the highest impact on human health with 32,697 lost years. Sector 8 ranks 2 in terms of DALY with 12,991 lost years, followed by Sector 15 with 10,230 lost years and Sector 18 with 9784 lost years.

3 Results and discussion

3.1 Backward and forward linkages

Using formulas introduced by Lenzen (2003), forward and backward linkage coefficients of sectors in monetary terms and in GHG terms in consideration of weighting with final demand and value added are obtained. Figure 4 shows sectoral linkage coefficients in monetary terms, while Fig. 5 illustrates coefficients in terms of GHG. In these diagrams,

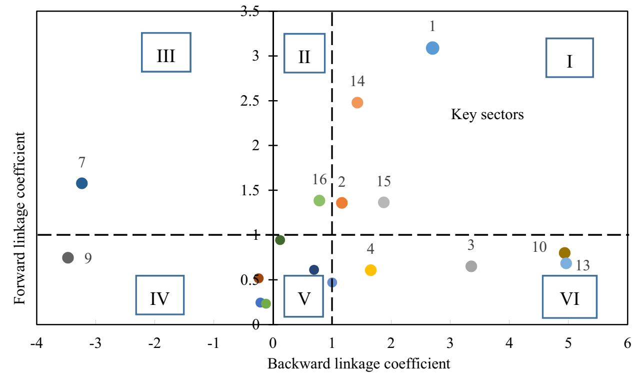


Fig. 4 Sectoral linkage coefficients in monetary term

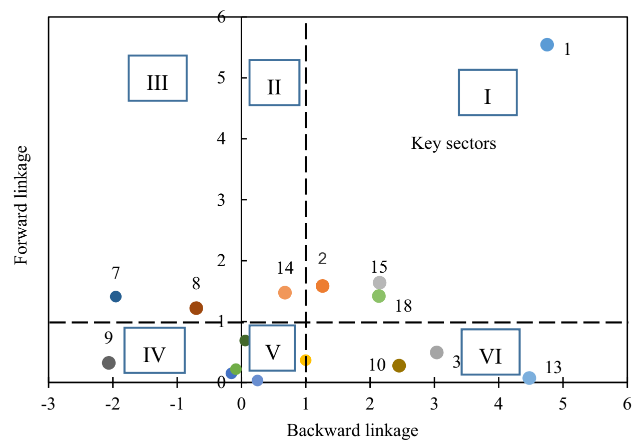


Fig. 5 Sectoral linkage coefficients with GHG emission factor

the forward linkage coefficients are set on the vertical axis, while the backward coefficients are on the horizontal axis. Sectors 5–9 have negative backward values (regions III and IV) because these sectors have negative values of final demand. This was caused by negative net investment and high imports while values of other final demand categories are low (Nguyen-Huu and Nguyen-Khac 2017). Net investment is equal to gross investment minus depreciation, in which depreciation is value of capital assets lost over their life. A sector, which has decreasing productive capacity, may have lower gross investment than depreciation. Since computation of coefficients was weighted by final demand, the negative final demand results in negative backward coefficients for these sectors.

Key sectors are those which are in the upper right corner of figure (region I). In monetary terms, key sectors in 2011 include Sector 1 (agriculture, fishery, and forestry), Sector 15 (transport and communication), Sector 14 (trade and repairing services), and Sector 2 (mining and quarrying) (Fig. 4). These sectors have the strongest economic connection with the rest of the economy; thus, they are capable of stimulating economic growth. Meanwhile, key sectors, in terms of GHG emissions, are Sector 1 (agriculture, fishery, and forestry), Sector 15 (transport and communication), Sector 18 (personal, community, and household services), and Sector 2 (mining and quarrying) (Fig. 5). These results demonstrate that a translation of key sectors from monetary terms into GHG terms may give different rankings. Sector 1 has very high linkage coefficients, especially in terms of GHG emissions with 4.7 for backward linkage and 5.4 for forward linkage. Sector 1 is thus considered as the most important sector in the country in terms of GHG emissions followed by Sector 15 then Sector 18 and Sector 2. Besides these four sectors, Sector 8 (manufacture of non-metallic mineral products) as backward linkages, which has the second highest GHG generation after Sector 1, should be considered as priority sector for pollution reduction (Fig. 2). Thus, great attention should be given to these five priority sectors when implementing GHG abatement strategies. The next section will mention different scenarios for optimization problem, which are considered for analyzing the potential of GHG emission mitigation, in the Vietnamese economic context. Out of scenarios, there are scenarios indicating how the change of technology state from these priority sectors influences the reduction of GHG intensity.

3.2 Scenario analysis

Vietnamese government ratified the Kyoto Protocol through proposed the National Green Growth Strategy (Decision No. 1393, 2012) which mandates the reduction of 8–10% GHG intensity (total GHG emissions per GDP) by 2020 relative to 2010 level (VNGGS 2012). Based on this policy, this work considers six scenarios corresponding to the different average economic growth rates from 2011 to 2020 and the change of technology state to indicate how the reduction of GHG intensity in 2020 compared to 2011 level (baseline) is. The results from different scenarios also provide the insights of the effect in reduction of GHG intensity on GDO, GDP, and human health damage.

- Scenario 1 serves as the business as usual (BAU) scenario which is expected to have the annual GDP and sectoral final demand growth rate as the historical trend. According to the statistical data, the average annual GDP growth rate from the year 2011 to the year 2017 is 6% (CEIC 2017). Therefore, this scenario considers that Vietnam has an annual GDP growth rate of 6% from 2011 level (3030 trillion VND) to 2020. Furthermore, the growth in the sectoral final demand in this scenario is assumed to vary from 5.5 to 6.5% per year during 9-year modeling horizon. The state of technology factor is assumed to be constant in this scenario (i.e, constant **A** and **q**).
- Scenario 2, Scenario 3, and Scenario 4 are assumed to have the annual GDP growth of 7, 8, and 5%, respectively. These figures are based on historical trend found in CEIC (2017) and projections of GDP growth rate during period of 2011–2030 (DEA 2017), which indicate that Vietnam GDP growth rate from 2000 to 2030 is varied from 5 to 8%. These scenarios also consider the adjustment of economic structure at wider ranges, and thus the sectoral final demand growth varies at wider ranges. The bounds of sectoral GDO are placed to correspond to accumulated changes, which result from a different sector growth.
- In scenario 5, the annual GDP growth and bounds of sectoral final demand are the same as BAU scenario, but the state of technology is changed to reduce GHG pollution intensity in the priority sectors, which are mentioned in backward and forward linkages. In light of this, the pollution intensities of Sector 1, 8, 15, and 18 are reduced by 12, 15, 5, and 4%, respectively. Such reductions of the agriculture and transportation sectors are based on the emissions reduction plans given in a study on management of GHG emissions and management of business of carbon credits (SMGGEMBCC), approved by government under Decision 1755 in 2011 (KEPA and GreenID 2014). Meanwhile, a reduction in Sector 8 can be obtained by using advanced energy efficiency technologies or reducing energy consumption which were found in nationally appropriate mitigation action (NAMA 2015). The 4% reduction in GHG pollution intensity from Sector 18 can be achieved by improving energy efficiency. This is one of strategies to achieve low-carbon development path (LCDP), published by the World Bank (Audinet et al. 2016).
- Scenario 6 combines the measures given in scenario 3 and 5 including high growth rate of GDP, differentiated sector growth, and reduction of pollution intensity in the priority sectors. The six scenarios are summarized in Table 3.

The IO-LP is solved for Eq. (2b) to (7) for each of the six scenarios using a linear solver in Lingo 17. The overall results are summarized in Table 4, while the contributions of the sectoral GDO and sectoral GHG emissions are shown in Tables 6 and 7 in Appendix. The results indicate that solving Scenario 1 as BAU scenario for the year 2020 gives a GDP of 5119 trillion VND (in 2011 currency), a total GDO of 12,977 trillion VND, a DALY of 136,966 years, and 590 Mt CO_2e. The corresponding intensity is 115.3 kg CO_2e per million Vietnamese dongs, which expresses 2% reduction compared to baseline (the 2011 level). These results imply that the climate policy of 8–10% reduction in GHG intensity by 2020 cannot be achieved with a BAU scenario.

Table 3 Scenarios

	Scenario 1 (BAU)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Annual GDP growth	6%	7%	8%	5%	6%	8%
Variation of sectoral final demand	5.5 to 6.5%	4 to 10%	5 to 12%	3 to 7%	5.5 to 6.5%	5 to 12%
Variation of sector size (GDO)	N/A	−22.6 to 28.3%	−22.4 to 38.7%	−16 to 18.5%	N/A	−22.4 to 38.7%
State of technology	Constant	Constant	Constant	Constant	Change **q** (Pollution intensities of sector 1, 8, 15, and 18 are reduced by 12, 15, 5, and 4%, respectively)	Change **q** (Pollution intensities of sector 1, 8, 15, and 18 are reduced by 12, 15, 5, and 4%, respectively)

Table 4 Result summary of modeling scenarios

	Baseline (2011)	Scenario 1 (BAU)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Total GDO (trillion VND)	7698.4	12,976.6	14,042.7	14,910.1	11,860.3	12,990.26	14,888.13
GDP (trillion VND)	3030	5118.8	5571.9	6061.3	4697.5	5118.797	6061.334
CO_2 emissions (Mt CO_2e)	356.7	590.0	573.9	609.6	505.4	546.6	568.2
GHG intensity (kg CO_2e/million VND)	117.6	115.3	103.0	100.6	107.6	106.8	93.7
Reduction in GHG intensity (%)	n/a	2.0	12.4	14.5	8.5	9.2	20.3
DALY (years)	89,768	148,451.1	144,311.1	153,199.8	127,118.9	137,527	142,786

With different average annual GDP growth rates, differentiated growth rates of economic sectors, and variation of sector size, scenarios 2, 3, and 4 contribute to reduce GHG intensity by 12.4, 14.5, and 8.5%, respectively, relative to the baseline year. Such reductions are due to the variation of sector size at wider range which allows to restructure in sectoral productivity by limiting the growth of high-emission sectors. Results show that the priority sectors, mentioned in backward and forward linkage section (Sector 1, 15, 18 and 8), experience the reduction in total GDO, resulting in 9, 5, 10, and 17% reduction in total GDO compared to BAU, respectively (Table 6). Meanwhile, most of low-polluting sectors (i.e., Sector 17, 16, and 5) achieve the increase in total GDO. The corresponding DALY results are 144,311 years for scenario 2, 153,200 years for scenario 3, and 127,119 years for scenario 4. The results from these scenarios indicate that higher growth rate in GDP achieves higher reduction in GHG intensity. However, the economy will suffer from increase in total GHG emissions when GDP growth rate increases. The total GHG emissions in scenario 4 (5% of GDP growth rate), scenario 2 (7%), and scenario 3 (8%) are 505 Mt CO_2e, 574 Mt CO_2e, and 610 Mt CO_2e, respectively.

Solving scenario 5, which considers GDP growth rate as BAU, but the pollution intensities of priority sectors are reduced, achieves a 9.2% reduction in GHG intensity relative to the year 2011. While total GDO and GDP remain the same as BAU, total GHG emissions and DALY are reduced to 547 Mt CO_2e and 137,527 years. The results highlight that application of low-carbon technology for polluting sectors considerably reduces GHG intensity, total GHG emissions, and human health damage, while keeping the economic productivity at a desired level (BAU).

Finally, the solution of scenario 6, which combines scenarios 3 and 5, greatly reduces GHG intensity by 20.3% compared to 2011. This scenario allows to reduce total GHG emissions and DALY to 568 Mt CO_2e and 142,786 years compared to BAU. Based on these results, the best measure for mitigating GHG intensity is scenario 6 which reduces up to 20.3% by 2020 relative to 2011, followed by scenario 3 by 14.5%, scenario 2 by 12.4%, scenario 5 by 9.2%, scenario 4 by 8.5%, and finally BAU by 2%. It can be concluded that scenario 6 achieves the highest reduction in GHG intensity because it combined the most advantages of all measures.

3.3 Policy implications

From the analytical modeling results for the six scenarios theorized, there are significant insights regarding GHG emission mitigation policies in pursuit of continued economic growth. These scenarios analyze the potentials of reduction in GHG intensity for Vietnamese economy. This includes (i) BAU scenario; (ii) the combination of different GDP growth rates, differentiated sector growth, and the variation of economic sector size which allows to readjust economic productivity such as production of high-polluting sectors is constrained to a certain extent while low-polluting sectors are prioritized; and (iii) application of technology to reduce pollution intensity in carbon-intensive sectors (energy efficiency improvement, implementation of energy saving strategies, and so on). From the results of these scenarios, there are several suggestions provided for policy makers and manufacturers in proposing the strategies to reduce GHG emissions per GDP:

1. The best way to reduce GHG intensity is to combine the advantages of all measures (scenario 6) including the increase in GDP growth rate as high as possible (i.e., 8% for scenario 3), allowing of economic restructure at wide range (i.e., − 22.4 to 38.7% growth/contraction of sectors for scenario 3), and use of low-carbon technology for carbon-intensive sectors (scenario 5). These combinations can achieve up to 20.3% reduction in GHG intensity.
2. If the GDP growth rate can be obtained at only BAU or lower than BAU level, the adjustment of economic structure may be useful to significantly reduce the GHG intensity (i.e., 8.5% for scenario 4).
3. If the GDP growth rate can be achieved at only BAU level and adjustment of economic productivity is difficult to deploy, the application of low-carbon energy technology for polluting sectors is a good suggestion (i.e., 9.2% for scenario 5).

4 Conclusion and recommendations

This study examines the potentials of GHG intensity reduction in response to a climate policy given by Vietnamese government considering different economic growth rates and the change of technology state from economic activities. Such a reduction in GHG intensity can potentially contribute towards decreasing negative human health impacts induced by climate change. First, the approach of forward–backward linkages is used to indicate the backward linkage sectors, forward linkage sectors, and key sectors in terms of economic and GHG emission performance. The sectors are prioritized as follows: Sector 1 (agriculture, fishery, and forestry), Sector 15 (transportation and communication), Sector 18 (personal, community, and household services), Sector 8 (manufacture of non-metallic mineral products,) and Sector 2 (mining and quarrying), which have high impact in terms of both economy and GHG emissions. These sectors need to focus on pollution mitigation strategies; thus, the consideration of their pollution intensity reduction is proposed in optimization model. Second, an optimization approach based on IO-LP is developed and solved in order to minimize the total GHG emissions (in Mt CO_2e) under the constraints of desired GDP growth rates. The IO table and GHG emission data in 2011 are used as economic and environmental data which serve as the baseline to compute for the growth trajectories to 2020. The reduction of GHG intensity in 2020 relative to the year 2011 is then given to compare to the given policy. The results reveal that the combination of increased GDP growth rate, readjustment of economic structure, and application of low-carbon techniques in the priority sectors can achieve the highest reduction potential of GHG intensity (by 20.3%). This figure exceeds the target outlined in Decision No. 1393 which mandates the reduction of GHG intensity by 8–10% during 2010–2020 in comparison to the 2010 level. In addition, these combined measures do not only contribute to the increase in 1911 trillion VND of total GDO, 943 trillion VND of GDP compared to BAU scenario, but they also help save 21,150 Mt CO_2e of total GHG emissions and 5533 years of DALY.

This work will be helpful for policy makers in analyzing the potential effectiveness of applying various measures for reducing different pollutants. This study focuses on the case of Vietnam, but the same methodology can be easily adapted for applying in other economies if IO tables and environmental data are available. The disadvantage of this work is that it just focuses on GHG emissions in domestic production, while emissions from import–export activities between Vietnam and other countries have not yet been considered. Therefore, future work can consider the further potential effectives of GHG reduction by applying the changes of different technology factors such as energy efficiency improvement, widespread deployment of energy conservation strategies, or other measures. Furthermore, other types of emissions should be focused on while taking into account trade effects. This will provide a more comprehensive assessment of the impact on environment resulting from Vietnamese economic activities. Besides, tools for dealing with data uncertainty should be integrated in this framework to assess the variation range in collected data for overall performance of an economy system.

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Appendix

See Tables 5, 6, and 7.

Table 5 Technical coefficient matrix of the Vietnamese economy in 2011 (**A**) (GSO 2013)

Sector code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.1463	0.0000	0.3400	0.0089	0.2024	0.0115	0.0158	0.0034	0.0000	0.0001	0.0220	0.0002	0.0008	0.0148	0.0648	0.0022	0.0010	0.0030
2	0.0008	0.0425	0.0029	0.0008	0.0017	0.0098	0.0576	0.0821	0.0272	0.0021	0.0131	0.0757	0.0174	0.0009	0.0023	0.0011	0.0000	0.0005
3	0.1286	0.0001	0.3232	0.0002	0.0018	0.0015	0.0116	0.0003	0.0000	0.0001	0.0003	0.0002	0.0001	0.0130	0.0868	0.0006	0.0014	0.0033
4	0.0021	0.0005	0.0016	0.5590	0.0106	0.0372	0.0014	0.0045	0.0001	0.0085	0.0216	0.0023	0.0025	0.0100	0.0017	0.0031	0.0022	0.0025
5	0.0008	0.0002	0.0004	0.0005	0.2948	0.0175	0.0021	0.0026	0.0000	0.0018	0.1524	0.0001	0.0075	0.0005	0.0006	0.0007	0.0010	0.0010
6	0.0003	0.0002	0.0181	0.0118	0.0117	0.4505	0.0099	0.0369	0.0003	0.0036	0.0180	0.0015	0.0056	0.0039	0.0137	0.0072	0.0231	0.0146
7	0.1011	0.1233	0.0263	0.1036	0.0672	0.0765	0.5440	0.0658	0.0228	0.0339	0.2472	0.0369	0.0514	0.0349	0.1176	0.0214	0.0285	0.0933
8	0.0010	0.0012	0.0024	0.0007	0.0201	0.0013	0.0134	0.2954	0.0129	0.0125	0.0089	0.0018	0.2098	0.0023	0.0018	0.0015	0.0013	0.0025
9	0.0003	0.0291	0.0036	0.0015	0.0160	0.0015	0.0052	0.0142	0.7657	0.1737	0.0202	0.0014	0.1421	0.0010	0.0008	0.0022	0.0004	0.0006
10	0.0041	0.0098	0.0112	0.0099	0.0112	0.0155	0.0105	0.0220	0.0155	0.4024	0.0433	0.0344	0.0465	0.0134	0.0179	0.0092	0.0227	0.0182
11	0.0032	0.0062	0.0311	0.0258	0.0106	0.0714	0.0384	0.0309	0.0008	0.1011	0.1857	0.0354	0.0165	0.0176	0.0160	0.0050	0.0145	0.0180
12	0.0075	0.0090	0.0118	0.0202	0.0185	0.0377	0.0167	0.0651	0.0194	0.0165	0.0226	0.1511	0.0058	0.0201	0.0220	0.0186	0.0174	0.0208
13	0.0008	0.0051	0.0005	0.0009	0.0006	0.0003	0.0002	0.0006	0.0003	0.0012	0.0051	0.0060	0.0436	0.0030	0.0094	0.0024	0.0202	0.0067
14	0.0275	0.0172	0.0507	0.0370	0.0325	0.0448	0.0375	0.0417	0.0157	0.0496	0.0429	0.0170	0.0300	0.0165	0.0332	0.0054	0.0156	0.0138
15	0.0086	0.0462	0.0271	0.0148	0.0209	0.0303	0.0311	0.0193	0.0112	0.0203	0.0183	0.0122	0.0231	0.0448	0.0823	0.0457	0.0590	0.0316
16	0.0025	0.0088	0.0101	0.0094	0.0086	0.0057	0.0217	0.0115	0.0068	0.0128	0.0101	0.0206	0.0139	0.0270	0.0328	0.2981	0.0397	0.0510
17	0.0000	0.0001	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0001	0.0001	0.0313	0.0007
18	0.0004	0.0017	0.0009	0.0006	0.0012	0.0008	0.0008	0.0017	0.0003	0.0007	0.0006	0.0305	0.0010	0.0016	0.0018	0.0020	0.0165	0.0675

Table 6 Sectoral gross domestic output (GDO, trillion VNDs) and % change compared to BAU scenario

Sector code	Scenario 1 (BAU)	Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	GDO (**x**)	GDO (**x**)	% Change GDO	GDO (**x**)	% Change GDO	GDO (**x**)	% Change GDO	GDO (**x**)	% Change GDO	GDO (**x**)	% Change GDO
1	1681	1524	−9	1639.2	−2.5	1380	−18	1681	0	1650	−2
2	591	756	28	865.8	46.5	599	1	591	0	862	46
3	1454	1308	−10	1421.1	−2.3	1187	−18	1454	0	1422	−2
4	840	1097	31	788.8	−6.1	866	3	840	0	790	−6
5	98	125	28	75.7	−22.6	106	8	98	0	124	27
6	168	163	−3	161.2	−3.8	156	−7	168	0	161	−4
7	618	899	46	851.4	37.7	703	14	618	0	782	26
8	322	268	−17	281	−12.7	251	−22	322	0	281	−13
9	202	16	−92	15.8	−92.2	32	−84	202	0	16	−92
10	1646	2104	28	2430	47.7	1669	1	1646	0	2429	48
11	620	704	14	720.7	16.2	611	−1	620	0	718	16
12	298	337	13	362.1	21.6	280	−6	298	0	362	21
13	1110	982	−12	1072.6	−3.4	896	−19	1110	0	1073	−3
14	1066	1320	24	1494.9	40.3	1060	−1	1066	0	1494	40
15	916	874	−5	951.3	3.9	781	−15	916	0	950	4
16	695	867	25	988.2	42.1	694	0	695	0	987	42
17	256	343	34	402.9	57.3	268	4	256	0	403	57
18	396	355	−10	387.6	−2.2	322	−19	396	0	388	−2

Table 7 Sectoral GHG emissions (Mt CO_2e) and % change compared to BAU scenario

Sector code	Scenario 1 (BAU)	Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	% Change $\mathbf{e}^T\mathbf{g}$	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	% Change $\mathbf{e}^T\mathbf{g}$	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	% Change $\mathbf{e}^T\mathbf{g}$	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	% Change $\mathbf{e}^T\mathbf{g}$	GHG emissions ($\mathbf{e}^T\mathbf{g}$)	% Change $\mathbf{e}^T\mathbf{g}$
1	214	194	−9	208	−2.5	175	−18	188	−12	184	−14
2	40	51	28	58	46.5	40	1	40	0	58	45
3	23	21	−10	23	−2.3	19	−18	24	2	23	0
4	22	29	31	21	−6.1	23	3	22	1	21	−6
5	1	1	28	1	−22.6	1	8	1	−3	1	33
6	6	6	−3	6	−3.8	6	−7	6	−3	6	−5
7	11	15	45	15	37.7	12	14	11	0	13	26
8	82	68	−17	72	−12.7	64	−22	71	−13	61	−26
9	4	0	−92	0	−92.2	1	−84	5	7	0	−93
10	14	18	28	21	47.7	14	1	14	0	21	47
11	18	20	14	21	16.2	18	−1	18	0	21	16
12	3	3	13	3	21.6	3	−6	3	−1	3	20
13	3	2	−12	3	−3.4	2	−19	3	8	3	−3
14	13	17	24	19	40.3	13	−1	13	0	19	40
15	68	65	−4	70	3.9	58	−15	63	−7	67	−1
16	4	5	25	6	42.1	4	0	4	−1	6	41
17	1	2	34	2	57.2	2	4	2	1	2	54
18	63	56	−10	62	−2.2	51	−19	61	−4	59	−6

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