Assessment of possible global regulatory measures to reduce greenhouse gas emissions from international shipping

Misak Avetisyan[a]*, Jasper Faber[b], Tristan Smith[c]

[a]Texas Tech University, Department of Economics, Lubbock, TX 79409
[b]CE Delft, Oude Delft 180, 2611 HH Delft, The Netherlands
[c]UCL Energy Institute, University College London, WC1H 0NN, London, United Kingdom

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Abstract

During the last several years, there has been a significant increase in global merchandise trade and it is expected to grow especially between more distant countries. Subsequently, growing trade is likely to stipulate the use of international maritime transport, since roughly ninety percent of the world trade is carried via sea transport. International transportation is one of the substantial sources of global emissions, producing about 14% of global Greenhouse Gas Emissions (GHG), and growing trade is expected to further increase the share of transport emissions and contribute to climate change.

This issue has drawn more attention as the negative impacts of the GHG emissions become more serious and significant. The International Maritime Organization, a UN body, has adopted a Greenhouse Gas Strategy that sets the ambition to reduce GHG emissions by at least 50% in 2050 and phase them out altogether as soon as possible in this century.

In this paper we analyze which policy measures are able to achieve significant maritime transport emission reductions and then we develop assessment criteria for evaluation of the relative merits of the different mid- and long-term policy measures. We also develop a methodology based on the energy-environmental version of the Global Trade Analysis Project (GTAP-E) with transport mode substitution that enables an appropriate representation of the dynamics and responses of both the shipping system and global/national economies. Using our proposed analysis methodology in a number of case studies in order to produce outputs for small island states, developing and least developed countries, we illustrate the methodology and its capabilities, as well as produce evidence about how specific policy measures may have impacts on specific nations' economic development and security.

*Correspondence to be sent to: Misak Avetisyan, Texas Tech University, Department of Economics, Holden Hall Room 258, POB 41014, Lubbock, Texas 79409, phone: (806) 834-6156, email: misak.avetisyan@ttu.edu.

Introduction

The recent growth in international trade has significantly increased the use of international transportation, especially the maritime transport, which is essential to the world's economy, since the largest portion of the world trade is carried via international waterways. Moreover, it represents the most cost effective means of transportation to ship raw materials and goods around the world. As one of the significant sources of global Greenhouse Gas Emissions (GHG), international transportation is responsible for about 14% of world emissions, and the further growth in world trade is expected to increase the share of transport emissions contributing to climate change. Given the share of ships in international transport emissions the International Maritime Organization (IMO), has adopted a Greenhouse Gas Strategy aimed at reducing GHG emissions by 2050 and phasing them out altogether as soon as possible in this century consistent with the Paris Agreement temperature goals. To achieve these levels of abatement, short and long-term policy measures need to be implemented. A number of renewable energy options and efficiency improving options are available to be included in the emission reduction measures of each transport sector. However, in the long run a zero fossil carbon fuels policy needs to be applied in all transportation sectors to achieve full decarbonization. Currently, such fuels are available on a small scale, and therefore policy measures should consider incentives for the uptake and development of low or zero fossil carbon fuels. Moreover, even with learning and scaling effects, these fuels are likely to be more expensive, and thus the improvement of energy efficiency and application of other renewable energy options will still play an important role in the decarbonization of the transport sector.

In this paper we identify and analyze the direct and indirect economic effects of mid and long-term measures that reduce GHG emissions from international maritime shipping. We concentrate on policy measures that allow shipping sector decarbonization, and therefore omit certain policy measures and consider some of the measures as supporting or complementary. More specifically, the measures that consider the ship fuel consumption rather than the CO_2 emissions or the carbon content of the fuel are excluded from the analysis. Also, the policy measures aimed at improving the energy efficiency and reducing the speed of ships are considered supporting or complementary measures. Finally, the offset measures are excluded from our analysis, since these will become scarce in the long-run due to decarbonization of other sectors. Moreover, the IMO Greenhouse Gas Strategy considers the carbon intensity and the GHG emissions of international maritime shipping thus implying in-sector abatement for meeting its targets.

Literature review

It is essential to generate accurate estimates of international transport emissions related to global merchandise trade for efficient regulation of GHG emissions from international shipping. This was one of the reasons that the Kyoto Protocol did not address the issue of assigning international transport emissions to specific countries and regions. It suggested that emissions from air travel should be referred only to domestic air transport, and that signatory countries needed to deal with international air transport emissions according to the regulations of International Civil Aviation Organization (Transportation Research Board, 2009)[1].

[1] http://www.aci-na.org/static/entransit/acrp_guidebook_on_greenhouse_gases_april09.pdf

The International Maritime Organization (IMO, 2009) considered assigning the full amount of fuel to local consumption if the next destination of the vessel is in the same state, and if the next port is in another country then it should be recorded as international fuel consumption. Due to complexity of generating accurate estimates of international transport emissions the 2015 Paris Agreement did not address the regulation of GHG emissions from international aviation and maritime transport. According to Romera (2016), this issue was omitted from the Paris Agreement because transportation sectors are not considered essential economic sectors for all participating countries, and states conveying more importance on transport sectors have apparently exhibited reluctance to negotiate positions.

Transport emissions have not adequately been considered in international emissions regulations, and this becomes even more important with IMO's Greenhouse Gas Strategy targeting the reduction and then complete elimination of GHG emissions from international shipping in line with the Paris Agreement temperature goals.

According to IPCC (2014), very frequently the total benefits of mitigating transport emissions exceed the total implementation costs. The study also suggests that the assessment of co-benefits and welfare effects needs a more thorough analysis. Despite some challenges, countries have many opportunities for additional reduction of transport emissions at lower medium and long-run marginal costs. The IPCC (2014) report also states that despite some difficulties strategies including a combination of technological development, transport infrastructure modification, and co-benefits will lead to cost efficient abatement of international transport emissions.

Hoen et al. (2010) find that for bulky products, taxation of emissions substantially reduces emission levels when considering rail versus road or rail versus maritime transportation.

The findings also indicate that an emission tax can result in greater research activity and use of more efficient technologies within modes of transportation and different economic sectors (Dechezleprêtre et al., 2013, 2011; Dechezleprêtre and Sato, 2017).

The study by Kageson (2009) suggests that emission taxes or allowances may result in modal shifts by incentivizing cargo owners to substitute land transport for maritime shipping. The substitution may be larger for roll-on and roll-off vessels that carry wheeled cargo and container traffic shipments than for large liquid loads.

As stated by Bertaud et al. (2009), global transport emissions significantly contribute to the world GHG emissions. The study finds that from 1990 to 2003 global transport emissions increased by 31%[2]. Findings also indicate that transport sectors show the least progress on implementing effective emission reduction policies. Therefore, the authors emphasize the need for more sustainable and refined transport emission abatement policies to effectively tackle the issue of climate change.

The study of existing research reveals that reduction of global transport emissions has not been sufficiently considered in international emission abatement policies. This issue becomes even more important with the IMO's adoption of a Greenhouse Gas Strategy setting the ambition to reduce GHG emissions from international maritime shipping by at least 50% in 2050 and phasing them out completely in this century. Therefore, in this paper we identify and analyze the direct and indirect economic effects of mid and long-term measures that reduce GHG emissions from international maritime shipping. We concentrate on policy measures that address shipping sector decarbonization, and thus exclude certain policy measures and consider some of the

[2] Food and Agricultural Organization estimated that in 1990 the world transport emissions were 4,034,907.3 Gigagrams (http://www.fao.org/faostat/en/?#home). Ecofys estimates show that in 2012 world transport emissions were 7,257,600 Gigagrams (https://www.ecofys.com/files/files/world-ghg-emission-flow-chart-2012_v9-c-asn-ecofys-2016_02.pdf). Considering these two estimates we find that during the 1990-2012 period global transportation emissions increased by 80%.

measures as complementary or supporting. In most cases such measures include emission taxation, which lead to various direct and indirect economic impacts across regions due to differences in economic emissions intensities of transport modes.

The GTAP Model and Methodology

Until lately, the main modeling methods for analyzing the impacts of energy and environmental policies were the input-output (I-O)[3] and macroeconomic growth (MG)[4] models. The differences in scopes and assumptions of these modeling methods created limitations for making comparisons between their outcomes. The structure of I-O models allows consideration of cargo values and types, connectivity between markets, trade dependency and costs. These models have highly disaggregated sectoral representation, provide information about direct and indirect effects, and consider all inputs and economic interdependences (Robson et al., 2018). I-O models can estimate the impacts of energy and environmental policies by implementing a shock where changes in production, consumption, and trade will result in redistribution effects and changes in import, export, and production related emissions. The changes in production, consumption, and trade flows can also be used to determine other factors, such as the cost-effectiveness and socio-economic development. However, I-O models are unable to consider the behavioral component and provide information about prices. This creates limitations for implementing price shocks within these models (Bachmann et al., 2014). Using computable general equilibrium (CGE) models for analyzing the impacts of energy and environmental policies provides information about the economy-wide effects of such policies by disaggregating their impacts to sector specific direct and indirect effects.

[3] See Miller and Blair (2009).
[4] See Kydes et al (1995).

CGE models are multi-sector and multi-market economic models that consider individual consumer and producer behavioral responses to changes in prices, quantities, technology, and any other factors within the available labor, capital, and natural resource endowments (Dixon and Rimmer, 2002). Though CGE models have some similarities with the input-output models, such as highly disaggregated sectoral representation, consideration of all inputs and economic interdependences, they overcome the limitations of the input-output analysis by considering the non-linear relationships in markets, behavioral component, input substitution, and provide information on prices and markets (Rose, 1995). Being well suited for the analysis of energy and environmental policies, these models can be used to assess the direct and indirect economic and environmental impacts of such policies by linking emissions and other environmental factors to economic drivers within the model and simulating changes in trade and transport policies (Avetisyan et al., 2021; Avetisyan et al., 2014).

CGE models have been widely used in the analysis of trade and transportation policies. Using a spatial CGE model, Pilegaard and Fosgerau (2008) investigate the effect of lower transportation costs on increasing job search over larger distances. Sandoval et al. (2009) use a CGE model of the global economy to investigate the feasibility of hydrogen transportation and trade under various carbon stabilization and taxation policies. Winchester et al. (2013) examine the effects of carbon policies on U.S. aviation operations and emissions using a recursive dynamic CGE model. Finally, Avetisyan (2018) uses a modified version of the GTAP-E model with transport mode substitution to examine the implications of global carbon taxes on international trade, modal choice, and changes in emissions from international transport.

In this paper we estimate the direct and indirect impacts of the changes in maritime transportation costs using the modified version of the GTAP-E model, which allows for

substitution among modes within the composite transport good and carbon taxation of specific commodities for various source and destination country pairs. There are three transport industries in the model: other Transport, Water Transport, and Air Transport. The transport modal substitution is determined by a Constant Elasticity of Substitution (CES) production function. The CES elasticity of substitution, with a typical value of 0.57 to 2.14, governs modal choice changes in response to variations in the relative cost of different transport modes (Avetisyan et al., 2015; Avetisyan, 2018; Avetisyan et al., 2021). GTAP was developed in conjunction with the U.S. International Trade Commission (ITC) and the World Trade Organization (WTO) and is presently the most extensively used international CGE model. The aim of the GTAP methodology is to on one hand provide sector wide information about direct and indirect effects of changes in maritime transportation costs, and on the other to balance the need for simplicity with the need for comprehensiveness.

In the GTAP model the production structure uses Leontief specification to combine labor, capital, land, and intermediate inputs and it also incorporates the energy substitution nest. The latter is based on the constant elasticity of substitution (CES) formulation where the electricity and non-electricity goods, and non-electricity commodities are joined. In the next level of the production nesting structure the energy sub-product is combined with capital to generate the capital-energy sub-product. The latter is then combined with other factors using another CES function specification. Finally, in the top level of the production structure the final output is formed by combining the value added and intermediate inputs.

The structure of the household consumption is based on a constant-difference of elasticities (CDE) functional form. In the GTAP model consumption, government spending, and savings are combined through a Cobb-Douglas functional specification to form the household

preferences. According to the CDE theory, energy commodities that have similar substitution and income parameters can be joined into a composite good that will have parameters similar to the original energy commodities. The substitution between energy commodities is characterized by a CES functional specification.

The model structure includes origins and destinations for traded goods and not for transportation services. The water, air, and other transport services produced in all countries are combined into a composite international transportation commodity, which is later assigned to importing countries using the share of exported goods in each country in the world total exports of traded goods. With this specification the export or FOB price of a good transported from the origin to the destination is combined with the composite transportation commodity to form the import or CIF price of this good at the destination.

We summarize the structure of the GTAP model in Figure 1.

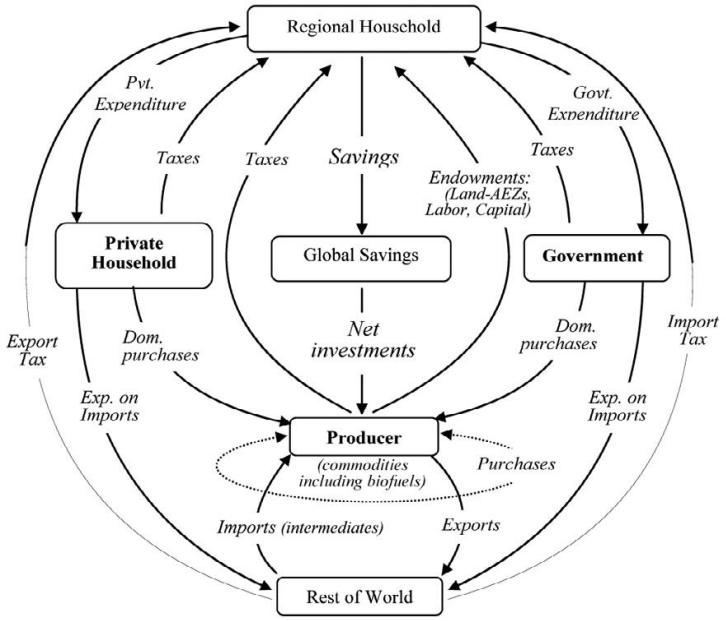

Figure 1. Structure of the GTAP model (source: Hertel et al., 2010)

We modify the GTAP-E model from Avetisyan (2018) that allows for substitution among modes of transport to account for changes in the cost and amount of transportation services necessary to transport a given product along a particular route through a given mode. The modal substitution in the model is described by Avetisyan and Hertel (2021), which incorporates modal substitution into the standard GTAP model (Hertel, 1997) after estimating the elasticities of modal substitution for land-air and water-air transport pairs. They estimate that a CES elasticity of modal substitution, with a typical value of 0.57 to 2.14, governs modal shifts driven by variations in the relative price of different transport modes. In most economic sectors the modal substitution elasticities between water and air transport dominate the elasticities of substitution between land and air transport modes. Avetisyan and Hertel (2021) validate their modified version of the GTAP model by analyzing the historical changes in world trade facilitation and their effect on transportation, by mode, between 2007 and 2012. The findings reveal that the historical improvement in logistics decreases the total cost of transport and amount of services necessary to ship a given good along a given route by a given transport mode. They also find that the reduction in modal cost leads to modal substitution. The model validation shows that both historical and GTAP-based changes in air and other transport use across regions show strong agreement in most cases.

There are two transport price variables in the GTAP-E model, $PTRAN_{i,r,s}$ and PT_m, which are determined endogenously. The variable $PTRAN_{i,r,s}$ represents the price of the composite transportation service used for transporting commodity i from origin r to destination s. PT_m represents the global transport services price index by transport mode m, without differentiating it by origin, destination, or industry. We modify the GTAP-E model to differentiate the price of

international transport services also by transport mode, and then we express it as a percent change variable $ptrans_{m,i,r,s}$ due to the linearized specification of the model. The modified version of the GTAP-E model allows modelling and simulating an emissions taxation scenario for maritime transport by varying water transportation costs for a commodity shipped from the origin to the destination. The change in transport costs results in modal substitution controlled by a CES elasticity of substitution shown in Equation (1), and generates changes in the use of water, air, and other transport services and emissions from transportation.

$$TRANS_{m,i,r,s} = EXP_{i,r,s} * TRTECH_{m,i,r,s}^{(\sigma_{i,r,s} - 1)} * \left(\frac{PTRAN_{i,r,s}}{PT_m}\right)^{\sigma_{i,r,s}} \quad (1)$$

where:

$TRANS_{m,i,r,s}$ is the usage of transportation mode m for shipping good i from source r to destination s;

$TRTECH_{m,i,r,s}$ is the transport technology of transportation mode m used for shipping good i from source r to destination s;

$EXP_{i,r,s}$ is the commodity i exports from source r to destination s;

$\sigma_{i,r,s}$ is the CES elasticity of transport mode substitution for shipping good i from source r to destination s;

PT_m is the global transport services price index by transport mode m;

$PTRAN_{i,r,s}$ is the price of the composite transportation service used for transporting commodity i from origin r to destination s.

As previously noted, GTAP uses linearized specification of model equations. Therefore, we represent Equation (1) in linearized (percent change) form, as illustrated in Equations (2) and (3):

$$trans_{m,i,r,s} = -trtech_{m,i,r,s} + exp_{i,r,s} - \sigma_{i,r,s} * \left(pt_m - trtech_{m,i,r,s} - ptran_{i,r,s}\right) \quad (2)$$

$$ptran_{i,r,s} = \sum_m [TRSHARE_{m,i,r,s} * \left(pt_m - trtech_{m,i,r,s}\right)] = \sum_m ptrans_{m,i,r,s} \quad (3)$$

where:

$trans_{m,i,r,s}$ is the percent change in the usage of transportation mode *m* for shipping good *i* from source *r* to destination *s*;

$trtech_{m,i,r,s}$ is the percent change in the transport technology of transportation mode *m* used for shipping good *i* from source *r* to destination *s*;

$exp_{i,r,s}$ is the percent change in the commodity *i* exports from source *r* to destination *s*;

$\sigma_{i,r,s}$ is the CES elasticity of transport mode substitution for shipping good *i* from source *r* to destination *s*;

pt_m is the percent change in the global transport services price index by transport mode *m*;

$ptran_{i,r,s}$ is the percent change in the price of the composite transportation service used for transporting commodity *i* from origin *r* to destination *s*;

$TRSHARE_{m,i,r,s}$ is the transport mode *m*'s share in the cost for shipping commodity *i* from source *r* to destination *s*;

$ptrans_{m,i,r,s}$ is the percent change in the price of transportation mode *m* used for transporting commodity *i* from source *r* to destination *s*.

In the modified GTAP-E model, an increase in the international water transport costs due to external factors, such as emission tax, can be modeled by making the transport cost variable $ptrans_{m,i,r,s}$ exogenous and then applying the cost increase scenario. This can be implemented by "swapping" the transport cost variable with another variable to preserve the balance between the

number of equations and endogenously determined variables. For this purpose we use the shipping technology variable for all goods shipped from an origin to destination by maritime transport. Since the technology of maritime transport is not changed, we expect the now endogenously determined water transport technology variable to be zero or close to zero.

There are many strengths and a few limitations in the GTAP model. The limitations include assumptions about the equilibrium adjustment, perfect information, and perfect competition. Though these assumptions are not realistic, their differences from reality can be taken as fairly small and not likely to substantially affect our results.

The GTAP Database and Aggregation

We use the GTAP-E version 9 database, which provides detailed information on energy use and carbon dioxide emissions by region and industry, and it is well suited for simulating maritime transport costs change scenarios.

The original GTAP-E version 9 database includes 140 regions, and 57 traded and non-traded sectors in each region. It also includes information about trade and transport connections among these economies. The GTAP database is usually aggregated to fewer regions and industries, since it is not computationally possible to perform simulations using the completely disaggregated 140 region and 57 sector version of the model. This approach enables performing a comprehensive analysis of specifically interesting subsets of countries and sectors. In this paper, we aggregate the database to 51 regions (generating 2601 bilateral trading region pairs)

and 29 industries. The aggregation schemes for both regions and industries are provided in Tables A1 and A2 in the Appendix.

Our model aggregation is based on several objectives. We analyze the impact of increased international maritime transport costs driven by emissions taxation on the Least Developed Countries (LDC) and Small Island Developing States (SIDS) based on the United Nations regional classification. Therefore, in the aggregated database we preserve some of these countries based on the availability in the original GTAP-E data. Next, we concentrate on low and high income countries based on the World Bank classification, and thus we also retain the subset of these countries in our aggregated database based on the availability in the original GTAP-E database. Lastly, our study addresses the impact of increased international maritime transport costs on the security and supply of food commodities in various countries, and therefore we preserve the original food sectors.

Economic Emission Intensities for International Maritime Transportation

It is difficult to differentiate between domestic and international transportation emissions in the GTAP model. Thus, using the GTAP emissions dataset to calculate economic emissions intensities of international transport services (emission intensities for each dollar of transportation output) would yield incorrect estimates. Also, the GTAP model does not include information about domestic transportation margins making it impossible to distinguish between domestic and international transportation emissions.

We overcome this issue by developing a methodology for separating domestic and international transportation emissions in the GTAP database. Using these new emission estimates we find emission intensities per dollar of international maritime transportation services for each trade route in the model. This enables estimation of increased maritime transportation costs due to carbon pricing along each route.

The estimation of economic emission intensities of international water transport is implemented in two steps:

1. Using the value of exported maritime transportation services by source and destination and the value of maritime transportation services in each region, we calculate the share of maritime transport services exports by trade route in the aggregate water transportation services output.
2. Adjust maritime transportation emissions in each region using the share of maritime transport services exports from step 1, and then divide it by the maritime transportation costs for shipping goods from the origin to destination.

Our methodology provides more accurate assessment of economic emissions intensities of international water transportation by origin and destination regions. Since transportation emissions in the GTAP database are not available by commodity, origin and destination, we cannot calculate economic emission intensities of international maritime transportation for each good shipped from the source to destination region.

Implications for Regulation of Emissions from International Maritime Shipping

As stated in the IMO Greenhouse Gas Strategy, maritime transport emissions should be reduced by 2050 and then completely eliminated during this century in line with the Paris Agreement temperature goals. However, the abatement of transport emissions will be a very difficult task under the projected increase in demand (IPCC, 2014). As suggested by IPCC (2014), under the existing growth rates of both passenger and freight transportation GHG emissions from the transport industry could possibly grow by 50% in 2035 and then double by 2050 if no emission abatement policies are enacted.

Reduction in maritime transport emissions can be implemented through the substitution of fossil fuels with renewable fuels assuming that biofuels are produced with electricity available from renewable sources. Due to higher prices of renewable resources the fuel substitution will result in higher maritime transportation costs. Additionally, some of the medium and long run measures, such as taxation, which raise government revenues will also contribute to increased transportation costs. According to the World Economic Forum (2021), 90% of the world trade is carried via water transport[5], and therefore international maritime transportation services will face the largest negative impacts of such an emissions tax. Therefore, we use our modified version of the GTAP-E model to analyze the emissions, trade, and other macroeconomic impacts of transport taxes imposed on any good that is shipped from a source to destination by international maritime transport.

More specifically, we study the impact of an emissions tax imposed on international maritime transportation services by converting it to the ad valorem impact on the transportation costs of traded commodities. The emission tax per ton of carbon dioxide emissions ($/t$CO_2$) is the same for all traded commodities shipped by water transport. However, the economic emissions intensities or emissions per dollar of maritime transport services output are different

[5] https://www.weforum.org/agenda/2021/10/global-shortagof-shipping-containers/

for all trading routes. Such variations in economic emissions intensities result in differential impacts across various trade route.

In this study we model low and high emissions taxation scenarios for international maritime transport. Specifically, we use \$250/tCO_2 and \$400/tCO_2, in the low and high carbon dioxide emissions tax scenarios, respectively. We use these two estimates based on the careful synthesis of recent literature on the amount of carbon dioxide tax that may be necessary to reach zero-carbon fuels substitution (Smith et al. 2019; Faber et al. 2020). In the literature assumes zero (or close to zero) operational or tailpipe emissions and zero (or close to zero) upstream emissions from the production, transportation, and storage. The emission tax is mostly driven by the fuel costs and not ship design modification and technology. The latter is driven mostly by the fuel feedstock costs, which include the cost of renewable electricity. The modeling simulations assume certain level of carbon pricing that will result in mass market utilization of zero-carbon fuels. It is possible to have lower emission tax in the beginning of the policy creating incentives only for small number of ships to use zero-carbon fuels. However, in this study we analyze the impacts of higher carbon pricing.

In our model simulations we assume that the emission tax revenues are invested in decarbonization of shipping, and the economic analysis of carbon pricing is implemented at the midpoint of the maritime fleet decarbonization. This refers to the fuel substitution stage at which about 50% of the shipping fleet would already be using zero-carbon fuels, while the rest of the ships still use fossil fuels. It will take some time for implementing fleet decarbonization assuming continuous substitution of fossil fuels with zero-carbon fuels. However, our modeling is based on a cross-sectional analysis, and the midpoint happens when 50% of the fleet uses zero-carbon fuels (without paying emission taxes and using highly priced zero-carbon fuel with some

of its high cost being subsidized by the government emission tax revenues) and the remaining half of the fleet uses fossil fuels and pays the emission tax. We use that state for calculating the effective emission taxes by reducing the initially low and high emission tax amounts (use \$250/tCO_2 and \$400/tCO_2) by 50%.

In the earlier stages of CO_2 abatement policy implementation the polluters may face lower price for emissions due to lower fuel subsidies. However, in the later stages the price of carbon can increase due to higher prices of zero-carbon fuels, but that increase may be compensated by the reduced costs of producing zero-carbon fuels due to economies of scale, technology advancements, etc. This is a conservative assumption based on current zero-carbon fuel cost estimates, and therefore can be considered a high carbon price scenario. It is worth to mention that in our analysis we do not concentrate on the details of policy design, such as how the emission tax is applied and what are its implications for tax revenues and their impacts. For instance, states can impose higher carbon prices in the beginning of the policy period to have more options for mitigating the disproportionately negative effects on their economies. It may also be possible to set lower carbon price initially to reduce the negative impacts on the state economies.

To understand the implications for regulation of emissions from international maritime shipping we start our analysis by converting the two emission taxes to *ad valorem* equivalents of increased maritime transportation costs for each bilateral trade route using Equation (4):

$$ptrans_{m,i,r,s} = 100\% * ECEMINTENS_{m,r,s} * CO2TAX \qquad (4)$$

where:

$ptrans_{m,i,r,s}$ is the percent change in the price of transportation mode m used for transporting commodity i from source r to destination s;

ECEMINTENS$_{m,r,s}$ is the economic emission intensity of transportation mode *m* by source *r* and destination *s* (tCO_2/$);

CO2TAX in the carbon dioxide tax imposed on transportation services ($/$tCO_2$).

As previously mentioned, we consider the following carbon price scenarios where the effective emission taxes are calculated by reducing the initially low and high emission tax amounts by 50%:

1. Low price of CO_2 abatement - $250/$tCO_2$ (effective emission tax $125/$tCO_2$)
2. High price of CO_2 abatement - $400/$tCO_2$ (effective emission tax $200/$tCO_2$)

These effective tax rates are converted to *ad valorem* equivalents of increased maritime transportation costs for any commodity shipped through any trade route, and serve as basis for determining possible scenarios to be simulated in our modified version of GTAP-E. With 51 trading regions the model will have 2,601 bilateral trade routes that will be affected by the emission tax imposed on international maritime transportation.

In Table 1 we present an example of the conversion of water transport emission taxes ($250/$tCO_2$ and $400/$tCO_2$ adjusted to $125/$tCO_2$ and $200/$tCO_2$, respectively) to *ad valorem* equivalents of increased maritime transportation costs for all commodities exported from the European Union to all other regions in the model. As previously mentioned, the *ad valorem* equivalents of emission tax impacts will vary by trading route due to the differences in economic emission intensities of water transportation across bilateral trade routes. It is important to realize that depending on the economic productivity or the value generated by maritime transport services per ton-kilometer ($/ton-km), trading routes with similar travel distances may have significantly different economic emission intensities. For instance, the economic emissions

intensity for the EU – China trading route is 0.068 kgCO2/$, while the EU – Rest of East and South East Asia trade route with a similar shipping distance has an economic emissions intensity of 2.781 kgCO2/$.

Table 1 - Ad valorem equivalents of adjusted $250/tCO$_2$ and $400/tCO$_2$ emission taxes on maritime transport for all exports from EU to rest of the regions

Regions importing from the European Union	Economic emissions intensity (kgCO$_2$/ $transport)	Emission tax $125/tCO$_2$		Emission tax $200/tCO$_2$	
		Emissions tax per $ of transport services ($tax/ $transport)	Change in transport costs (%)	Emissions tax per $ of transport services ($tax/ $transport)	Change in transport costs (%)
United States	0.038	0.005	0.47	0.008	0.75
Canada	0.323	0.040	4.04	0.065	6.46
European Union	1.357	0.170	16.96	0.271	27.13
Japan	1.253	0.157	15.66	0.251	25.06
China, Hong Kong	0.068	0.008	0.84	0.014	1.35
Brazil	0.727	0.091	9.08	0.145	14.53
India	0.735	0.092	9.19	0.147	14.71
Russia	0.199	0.025	2.49	0.040	3.98
Oceania countries	0.844	0.106	10.55	0.169	16.89
Dominican Republic	0.015	0.002	0.19	0.003	0.30
Puerto Rico	0.035	0.004	0.43	0.007	0.69
Trinidad and Tobago	1.493	0.187	18.66	0.299	29.86
Cambodia	0.120	0.015	1.50	0.024	2.40
Lao People's Dem. Republic	0.076	0.009	0.95	0.015	1.51
Malaysia and Indonesia	0.510	0.064	6.37	0.102	10.19
Afghanistan, Bhutan, Maldives	0.144	0.018	1.80	0.029	2.88
Bahrain	0.015	0.002	0.19	0.003	0.30
Benin	0.011	0.001	0.14	0.002	0.23
Burkina Faso	0.009	0.001	0.11	0.002	0.18
Guinea	2.356	0.294	29.45	0.471	47.11
Togo	0.013	0.002	0.16	0.003	0.26
Rwanda	0.283	0.035	3.54	0.057	5.66
Bangladesh	0.012	0.001	0.15	0.002	0.24
Madagascar	0.060	0.007	0.74	0.012	1.19
Malawi	0.866	0.108	10.83	0.173	17.33
Senegal	0.006	0.001	0.08	0.001	0.12
Tanzania	0.024	0.003	0.31	0.005	0.49
Zimbabwe	0.265	0.033	3.32	0.053	5.31
Rest of Europe and F. S. Union	0.767	0.096	9.59	0.153	15.35
Rest of East and South East Asia	2.781	0.348	34.76	0.556	55.62
Rest of South Asia	0.926	0.116	11.58	0.185	18.53
Rest of Oceania	0.377	0.047	4.72	0.075	7.55
Rest of Caribbean	0.277	0.035	3.46	0.055	5.54
Central and Caribbean Americas	0.079	0.010	0.99	0.016	1.58
South and Other Americas	0.758	0.095	9.47	0.152	15.16

Central Africa	0.049	0.006	0.62	0.010	0.99
Rest of Eastern Africa	0.068	0.009	0.85	0.014	1.36
Rest of Western Africa	0.018	0.002	0.22	0.004	0.35
Sub Saharan Africa	0.192	0.024	2.41	0.038	3.85
Middle Eastern and North Africa	0.190	0.024	2.38	0.038	3.80
Rest of the World	0.248	0.031	3.10	0.050	4.97

Results

The impacts vary depending on the differences and structure of interconnections between trade and regional economies. Despite increasing maritime transportation costs some economies benefit from the decarbonization policy, while others experience negative net effects. The total impact appears to be small. The aggregate impacts depend on the maritime transport economic emission intensities on various trading routes, modal substitution elasticities, the balance between exports and imports along with the resulting impacts on investment. For instance, in the European Union the Gross Domestic Product (GDP) declines by -0.022% driven mostly by reductions in consumption and exports. More specifically, the EU region experiences reduction in natural gas and oil exports, and the consumption of energy intensive industry commodities, oil, and oil products. Due to increased investment the Brazilian GDP increases by 0.001%, and we discuss the interactions that generate this results in the section on the Brazilian economy impacts. In Benin the GDP grows by 3.699% driven mainly by increased investment and consumption. Specifically, we find increased consumption of commodities produced by energy intensive sectors, non-tradable and other industrial services. The higher emission tax proportionately increases the impacts of carbon pricing. When comparing the impacts of the effective carbon price of \$125/tCO_2 shown in Table 2 to the results of the effective carbon price of \$200/tCO_2 reported in Table 3, we find about 160% increase in impacts with higher carbon pricing.

Impacts on High Income Economies

We analyze the impacts of maritime emission taxes on the four high income economies – United States, European Union, Canada, and Japan. For both carbon pricing scenarios the GDP in the United States and Japan increase, while it declines in the European Union and Canada. Under the lower carbon pricing policy we observe similar decline in all exports ranging from 0.1 to 0.2%. The variation in net GDP impacts is driven by different effects on investment. The largest negative effect due to increased maritime transport costs is on the investment in the EU region.

We find that the impacts of a maritime carbon pricing policy depend on specific region's economic conditions and circumstances. The generalized increase in transport costs results in substitution and increased market shares in countries that are closer compared to the more distant trading partners. Increased transportation costs also result in substitution of imports with local production and thus increase investments in the region. We concentrate on some of these examples in our discussion of results in India and Brazil.

Impacts Middle Income and Emerging Economies

Some of the larger and diversified economies experience GDP growth. For instance, China, India, Russia, and Brazil show positive economic effects under the two emission taxes. Generally, the increased local consumption and investment counterbalance the export and import flow impacts. This is due to the strength of some economic sectors of these economies that offset the negative effects in their other economic sectors through substitutions in production and trade, and subsequent rise in domestic consumption and investment.

In South America we observe net positive impacts under the two carbon pricing policies. An increase in investment counterbalances the small decline in exports. In the Malaysia and Indonesia region we find -0.004% reduction in GDP. There are negative impacts also in the South Asia and South East Asia regions with -0.03% and -0.05% GDP reduction under the low and high emission taxation policies, respectively. This shows that there is no generalizable rule for measuring the impacts of maritime transport carbon pricing in middle income and emerging economies and it is recommended to analyze individual country effects to find the range of impacts and their possible disproportionality. Regardless of the shipping distance, the magnitude of such impacts can be substantially larger in bilateral trade routes with higher economic emission intensities of maritime transport ($kgCO_2$/$) (Table 1).

<u>Impacts on SIDS and LDC</u>

The original GTAP database has generally poor coverage of SIDS and LDCs. There are only five SIDS available from the GTAP data – Dominican Republic, Jamaica, Mauritius, Singapore, and Trinidad and Tobago. All of these regions have negative GDP impacts between -0.014% and -0.28% under the low carbon pricing policy. These negative changes in GDP are driven mainly by reduced exports, imports, and in some regions also by decrease in investment. Moreover, the Rest of Caribbean region representing an aggregation of SIDS countries experiences negative GDP impacts.

Another aggregation of SIDS countries, Rest of Oceania, experience positive GDP impacts driven mainly by increased investments and changes in trade volumes. However, these GDP impacts may be less accurate due to the relatively poor quality of data available for these economies.

The rest of SIDS countries located along the Atlantic and Indian Oceans as well as South China Sea are included in aggregate regions in the original GTAP database, making the analysis of their individual impacts very difficult. Although for some of these economies the GTAP database provides limited information, we can see that generally all these SIDS countries experience negative GDP impacts due to the emission taxes imposed on international maritime transportation. Therefore, we can conclude that given the dependency of SIDS countries on maritime transportation, they will most likely experience similar negative impacts. Also, the availability of a higher quality data for SIDS countries will enable more comprehensive assessment of any disproportionate negative impacts.

For LDCs we observe both highly positive and negative net impacts, driven by larger changes in investment and trade. About 60% of individual LDCs in our model experience net negative impacts. This illustrates that similar to SIDS countries LDCs are not able to offset the negative impacts of increased maritime transportation costs through substitution with the positive effects from other economic sectors.

Addressing Some of the Impacts

We also analyze the costs for addressing some of the negative impacts. The uncertainty regarding the factors contributing to the disproportionate negative impacts together with data limitations prevent precise estimation of possible approaches to address such effects and the potential consequences of addressing these negative impacts. However, we are able to draw some insights from the results produced by our modified version of the GTAP-E model.

Under the low carbon pricing we observe net negative impacts (between -0.002% and -7.3%) for 20 SIDS and LDCs out of total 26 such countries. We can find an upper bound for addressing those impacts if these effects are completely addressed. This can be modeled as a group of transfers equal to GDP reductions of all negatively affected economies to compensate them for aggregate negative effects. This is just one approach to address disproportionate negative impacts for a specific group of countries with full compensation. The aggregate negative economic impact for all 20 SIDS and LDCs is $2.7 billion. Using the midpoint of decarbonization from the GTAP emissions database of 305Mt of carbon dioxide, we find that the upper bound for carbon costs is about $8.8 billion, while the lower bound is 7% of the total mitigation cost. There are total 76 SIDS and LDCs, therefore the sample we examine is about the third of all these countries available in the GTAP database. The rest of the LDCs and SIDS economies are not substantially larger than our selected sample, and therefore we conclude that the size of impacts for all LDCs and SIDS countries can be found by multiplying our previous estimates by three.

We observe relatively smaller impacts for middle income and emerging countries. In most of these regions the total economic impacts of increased international maritime transport costs are positive. The only negative GDP impact among the regions available in our model is observed in the Malaysia and Indonesia region despite their aggregate GDP being much larger than GDPs in LDCs and SIDS countries. When also find that some aggregate middle income and emerging regions, such as Asia, Central America, etc., experience negative GDP impacts. Therefore, disaggregating these original GTAP regions will help observe the negative GDP impacts of carbon pricing for individual economies. This will also help analyze and address possible disproportionately negative impacts in such countries.

Impact Uncertainties and their Effect on the Results

According to the GTAP database, domestic and international transport emissions were 610 Mt in 2011, which is lower than the shipping emissions of 850 Mt estimated by the Third IMO GHG Study. This means that either some portion of shipping emissions has not been included in the GTAP dataset or shipping emissions have been calculated at much lower carbon intensity levels than estimated by the IMO study.

GTAP-E is a static model and the database is based on 2011 data. Since then, the world economies and international shipping went through many developments and changes. Moreover, the carbon pricing scenarios described in our study will be implemented in future, and we should expect improvement in transportation efficiency and reduction in CO2 emission intensities over time. This will affect both the scale of impacts and the changes in the use of competing transport modes. Therefore, the results from our study can be useful for analyzing the indicative impacts on different types of economies, but these cannot provide precise information that can be used for implementation in future. The accuracy of the results from GTAP simulations depend on the quality of sectoral and regional data. For some LDCs and SIDS countries the data may have poor quality and thus the GDP impact results can be highly sensitive to that quality. The results for medium and large size economies tend to be more accurate both due to higher quality of data and higher sensitivity of model's output to these inputs. In some of the LDCs and SIDS countries analyzed in our study we observed both extreme negative and positive impacts partially due to the data quality issues. However, we cannot generalize the results for this type of economies without more detailed analysis and validation at the level of individual LDCs and SIDS countries. Therefore, we interpret the results as indicative for some types of LDCs and SIDS countries, and not as absolute impacts for these individual economies.

Regional Carbon Pricing Results

We summarize the results of low and high price of CO_2 abatement - \$250/tCO_2 and \$ 400/tCO_2 scenarios in Tables 2 and 3.

Table 2 - Low price CO_2 abatement results with \$250/tCO_2 emissions tax (effective CO_2 tax is \$125/tCO_2)

Regions	GDP, % change	Investment, % change	Exports, % change	Imports, % change	Emissions, % change	Land Transport, % change	Water Transport, % change	Air Transport, % change
United States	0.002	0.276	-0.27	0.313	0.037	0.106	0.171	0.253
Canada	-0.004	0.014	-0.181	-0.276	0.077	0.812	0.594	0.041
European Union	-0.022	-0.420	-0.159	-0.637	-0.038	0.968	0.822	0.367
Japan	0.001	0.155	-0.181	-0.028	0.010	0.017	0.738	0.462
China, Hong Kong	0.001	0.069	-0.131	-0.039	0.021	0.140	0.313	0.417
Brazil	0.001	0.161	-0.288	-0.048	-0.012	0.011	0.178	0.060
India	0.010	0.080	0.012	0.113	0.021	0.012	0.622	-0.017
Russia	0.005	0.222	-0.066	0.201	0.000	0.275	0.116	0.179
Oceania countries	-0.001	0.100	-0.163	-0.100	-0.009	0.063	0.156	-0.051
Dominican Republic	-0.020	0.008	-0.133	-0.357	-0.141	0.219	0.581	0.242
Jamaica	-0.278	-2.237	-0.575	-2.690	-0.799	1.259	1.108	1.484
Puerto Rico	0.000	0.229	0.043	0.287	0.050	0.152	0.628	0.414
Trinidad and Tobago	-0.014	-0.134	-0.128	-0.383	-0.060	0.054	0.230	0.089
Cambodia	-0.121	0.031	-0.165	-0.967	-0.879	0.286	0.381	0.519
Lao People's Dem. Republic	0.008	0.342	-0.087	0.257	-0.010	0.094	0.233	0.246
Malaysia and Indonesia	-0.004	0.087	-0.111	-0.081	0.003	0.012	0.166	0.151
Singapore	-0.039	-1.460	-0.344	-1.170	0.361	5.394	0.972	1.584
Afghanistan, Bhutan, Maldives	-0.002	0.127	-0.156	-0.024	-0.091	0.302	0.635	0.255
Bahrain	0.002	0.237	-0.065	0.051	0.104	1.070	0.667	0.517
Benin	3.699	19.867	-23.515	10.087	7.953	4.669	3.604	4.013
Burkina Faso	0.046	0.636	0.070	0.703	0.099	-0.010	0.016	-0.145
Guinea	-0.434	-0.792	-2.457	-2.409	-0.788	-0.223	-0.609	-0.403
Togo	-2.013	-18.217	7.239	-7.208	-4.546	-3.017	1.143	1.193
Mauritius	-0.048	-0.824	-0.418	-1.304	-0.319	0.479	0.553	-0.284
Mozambique	0.643	-13.632	-12.667	-35.169	-12.289	-6.900	-11.665	-7.642
Rwanda	-0.134	-0.211	-1.097	-1.189	-2.064	0.253	-0.289	0.091
Uganda	0.050	-3.635	-6.058	-15.098	-0.876	-1.728	-1.073	-0.908
Zambia	-0.225	-26.819	-12.070	-44.494	-11.153	-4.981	-7.694	-3.593
Ethiopia	-0.021	-0.055	-0.615	-0.496	0.059	0.095	0.102	-0.266
Nepal	-0.008	-0.025	-0.385	-0.333	-0.042	0.021	0.130	-0.017
Bangladesh	0.001	0.108	-0.076	0.011	0.005	-0.002	0.011	0.069
Madagascar	-0.002	0.211	-0.006	0.152	-0.044	0.028	0.354	0.085
Malawi	-0.226	-9.791	1.515	-3.524	-1.985	-0.923	-1.381	3.222
Senegal	0.000	0.148	0.012	0.022	0.065	0.574	0.095	-0.049
Tanzania	-7.275	-17.119	-14.647	-37.495	-8.563	20.611	0.782	5.057
Zimbabwe	-5.552	-4.935	-36.561	-45.644	-10.507	4.455	15.052	20.711
Other E. Europe and	0.014	0.187	0.018	0.201	0.015	0.780	0.247	0.124

Regions	GDP, % change	Investment, % change	Exports, % change	Imports, % change	Emissions, % change	Land Transport, % change	Water Transport, % change	Air Transport, % change
Rest of F.S.U.								
Rest of European Countries	-0.033	-0.427	-0.391	-1.110	-0.415	0.479	0.670	-0.260
East Asia	-0.020	-0.236	-0.112	-0.395	0.033	1.910	0.910	1.039
Rest of South East Asia	-0.031	-0.501	-0.043	-0.541	-0.070	0.404	0.391	0.522
Rest of South Asia	-0.032	-0.360	-0.488	-1.110	-0.165	-0.009	1.338	0.728
Rest of Oceania	0.013	0.225	0.088	0.203	0.147	0.159	0.564	1.148
Rest of Caribbean	-0.020	-0.065	-0.122	-0.254	-0.050	0.449	0.660	0.436
Central and Caribbean Americas	-0.001	-0.005	-0.198	-0.474	-0.034	0.054	0.389	0.267
South and Other Americas	0.002	0.181	-0.107	0.055	-0.014	0.119	0.476	0.268
Central Africa	0.111	0.392	0.849	1.909	0.804	0.119	-0.056	-0.528
Rest of Eastern Africa	-0.001	0.070	-0.011	0.098	0.006	0.038	0.031	0.196
Rest of Western Africa	0.025	0.128	0.008	0.087	0.067	0.336	0.430	0.131
Sub Saharan Africa	0.004	0.269	0.104	0.372	0.197	0.188	0.174	-0.064
Middle Eastern and North Africa	0.000	0.130	-0.049	0.054	0.062	0.476	0.712	0.285
Rest of the World	0.000	0.026	-0.110	-0.167	0.041	0.673	0.675	0.142

Table 3 - High price CO_2 abatement results with \$400/tCO_2 emissions tax (effective CO_2 tax is \$200/tCO_2)

Regions	GDP, % change	Investment, % change	Exports, % change	Imports, % change	Emissions, % change	Land Transport, % change	Water Transport, % change	Air Transport, % change
United States	0.004	0.441	-0.203	0.501	0.059	0.169	0.274	0.405
Canada	-0.006	0.022	-0.289	-0.441	0.123	1.295	0.952	0.065
European Union	-0.035	-0.673	-0.255	-1.020	-0.061	1.545	1.317	0.587
Japan	0.001	0.247	-0.289	-0.046	0.016	0.027	1.183	0.740
China, Hong Kong	0.002	0.110	-0.209	-0.063	0.033	0.224	0.501	0.668
Brazil	0.002	0.258	-0.461	-0.076	-0.018	0.017	0.285	0.096
India	0.016	0.127	0.019	0.180	0.033	0.020	0.997	-0.028
Russia	0.008	0.354	-0.105	0.320	0.000	0.439	0.186	0.287
Oceania countries	-0.001	0.160	-0.261	-0.160	-0.014	0.101	0.249	-0.082
Dominican Republic	-0.032	0.017	-0.210	-0.562	-0.225	0.344	0.927	0.382
Jamaica	-0.444	-3.572	-0.922	-4.298	-1.277	2.009	1.769	2.368
Puerto Rico	0.000	0.366	0.069	0.459	0.081	0.243	1.007	0.663
Trinidad and Tobago	-0.023	-0.215	-0.204	-0.611	-0.096	0.087	0.369	0.142
Cambodia	-0.194	0.050	-0.264	-1.547	-1.406	0.458	0.610	0.831
Lao People's Dem. Republic	0.012	0.544	-0.138	0.411	-0.016	0.150	0.373	0.393
Malaysia and Indonesia	-0.006	0.138	-0.177	-0.130	0.005	0.020	0.265	0.241
Singapore	-0.063	-2.338	-0.551	-1.873	0.576	8.608	1.557	2.534

Regions	GDP, % change	Investment, % change	Exports, % change	Imports, % change	Emissions, % change	Land Transport, % change	Water Transport, % change	Air Transport, % change
Afghanistan, Bhutan, Maldives	-0.003	0.202	-0.249	-0.039	-0.144	0.482	1.017	0.408
Bahrain	0.003	0.378	-0.102	0.086	0.166	1.707	1.068	0.826
Benin	5.907	31.726	-37.556	16.110	12.702	7.458	5.757	6.409
Burkina Faso	0.074	1.017	0.113	1.127	0.159	-0.017	0.026	-0.233
Guinea	-0.694	-1.266	-3.930	-3.853	-1.260	-0.358	-0.974	-0.644
Togo	-3.216	-29.101	11.563	-11.513	-7.262	-4.820	1.827	1.911
Mauritius	-0.077	-1.320	-0.669	-2.088	-0.510	0.765	0.885	-0.454
Mozambique	1.015	-21.674	-20.163	-55.937	-19.555	-10.974	-18.578	-12.175
Rwanda	-0.213	-0.340	-1.759	-1.925	-3.289	0.403	-0.458	0.144
Uganda	0.072	-5.770	-9.601	-23.944	-1.395	-2.749	-1.703	-1.442
Zambia	-0.371	-42.383	-19.107	-70.338	-17.654	-7.865	-12.184	-5.692
Ethiopia	-0.034	-0.089	-0.983	-0.792	0.095	0.152	0.163	-0.427
Nepal	-0.013	-0.040	-0.614	-0.533	-0.067	0.032	0.207	-0.028
Bangladesh	0.002	0.172	-0.120	0.017	0.009	-0.003	0.017	0.110
Madagascar	-0.003	0.335	-0.011	0.241	-0.071	0.044	0.566	0.135
Malawi	-0.362	-15.747	2.439	-5.688	-3.182	-1.465	-2.196	5.145
Senegal	0.000	0.237	0.019	0.035	0.105	0.916	0.152	-0.079
Tanzania	-11.409	-26.843	-22.968	-58.790	-13.388	32.456	1.235	7.932
Zimbabwe	-8.713	-7.747	-57.346	-71.637	-16.446	7.029	23.676	32.530
Other E. Europe and Rest of F.S.U.	0.022	0.298	0.029	0.321	0.024	1.245	0.395	0.199
Rest of European Countries	-0.053	-0.685	-0.627	-1.778	-0.664	0.764	1.074	-0.416
East Asia	-0.033	-0.378	-0.179	-0.632	0.052	3.048	1.458	1.663
Rest of South East Asia	-0.050	-0.802	-0.069	-0.865	-0.112	0.644	0.626	0.835
Rest of South Asia	-0.051	-0.576	-0.780	-1.776	-0.264	-0.015	2.140	1.164
Rest of Oceania	0.021	0.360	0.141	0.326	0.236	0.253	0.903	1.837
Rest of Caribbean	-0.032	-0.105	-0.195	-0.408	-0.081	0.716	1.058	0.697
Central and Caribbean Americas	-0.002	-0.008	-0.315	-0.757	-0.053	0.087	0.623	0.426
South and Other Americas	0.003	0.289	-0.170	0.087	-0.022	0.189	0.763	0.429
Central Africa	0.175	0.619	1.338	3.010	1.269	0.193	-0.078	-0.832
Rest of Eastern Africa	-0.001	0.111	-0.018	0.154	0.010	0.060	0.050	0.312
Rest of Western Africa	0.042	0.209	0.013	0.141	0.109	0.536	0.688	0.210
Sub Saharan Africa	0.006	0.426	0.162	0.586	0.310	0.299	0.278	-0.101
Middle Eastern and North Africa	0.000	0.207	-0.078	0.086	0.098	0.759	1.142	0.456
Rest of the World	0.000	0.041	-0.177	-0.268	0.066	1.074	1.082	0.226

Impacts of Carbon Pricing in India

The other industry and services is the largest sector of the Indian economy, generating about 44% of its domestic production. As shown in Figure 2, the next largest sectors are the energy intensive industries and other transport each generating about 9% of India's domestic output.

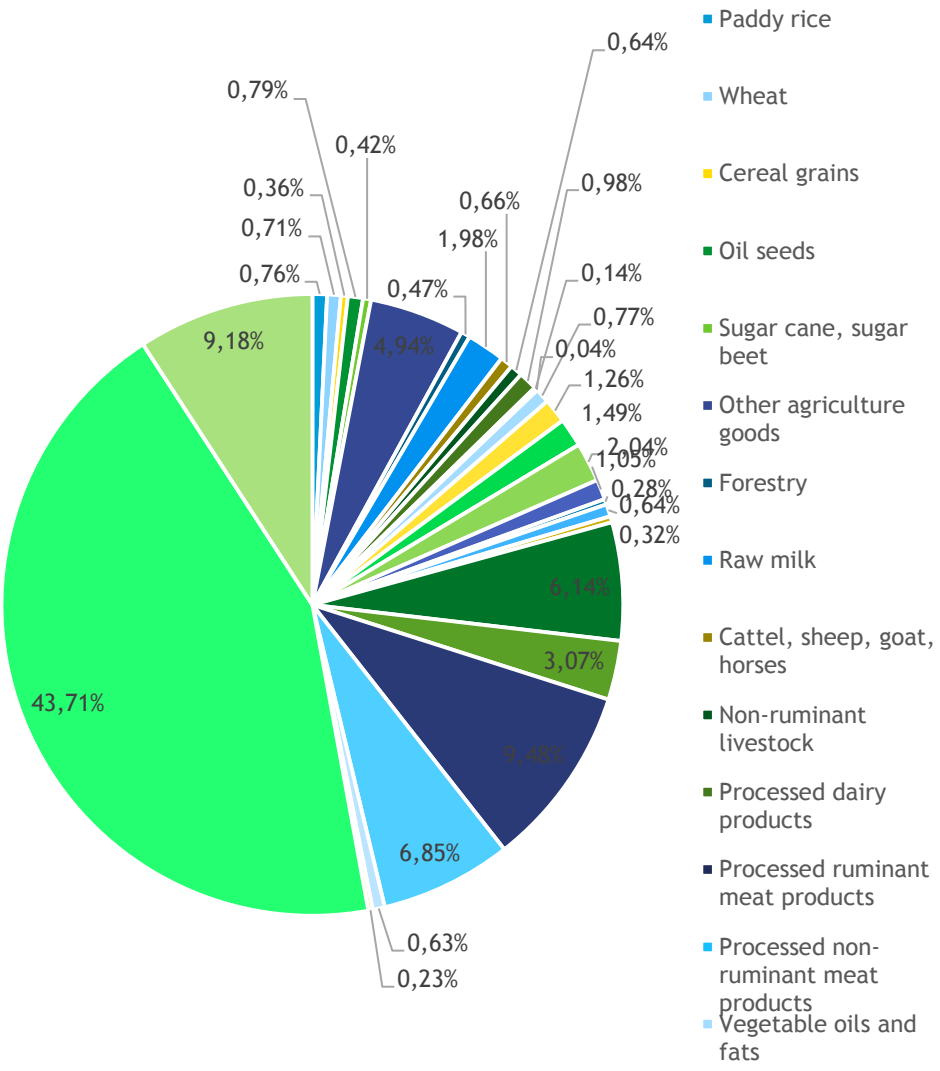

Figure 2 - Output by sector in India, percent

The increased maritime transport costs driven by carbon pricing results in GDP and domestic output growth by 0.01% and 0.02-0.03% increase, respectively. However, the sectoral disaggregation of results provides more interesting insights. As illustrated in Tables 4 and 5, some sectors experience reduction in output. Most of these negatively affected sectors export relatively low value commodities. Under the low carbon price scenario, ruminant meat products and other agricultural commodities experience the largest output reduction by 0.2% and 0.05%, respectively. We observe the largest increase in the output of oil seeds, energy intensive industries, and petroleum and coal products ranging from 0.06% to 0.2%. Some of the most affected sectors are small, while others are relatively larger, and thus the large relative effects of increased maritime transportation costs are not necessarily translated to large absolute impacts. Other industries and services and other agricultural products experience the largest decline in the output. We observe the largest output gains in the petroleum and coal products, and energy intensive industries.

The results in Tables 4 and 5 show positive correlation between the production and exports of some sectors, and negative relationship between production and imports for other sectors. In some sectors, such as the energy intensive industries, we find that both exports and imports increase due to growing international competitiveness of these sectors. One interpretation for such outcome is growing exports require more imports of intermediate goods or inputs. Due to increased competitiveness, the inputs of skilled and unskilled labor also increase in this sector. We observe the opposite outcome in the other industry and services sector, which experiences decline in international competitiveness because of reduced exports, growing imports, and decline in employment.

We find significant import substitution in the dairy products sector, which experiences reduction in imports and increase in output, exports, and employment. Processed dairy products that were initially imported are now produced by domestic producers, which ae also able to export some of their output. Similar changes are observed in the oil seeds and other food products sectors.

We observe similar impacts under the high price CO_2 abatement but larger than those with the low carbon pricing scenario (Table 5).

Table 4 - Changes in production, employment and trade in India under low price CO_2 abatement with \$250/tCO_2 emission tax (effective CO_2 tax is \$125/tCO_2), percent

Sectors	Output	Exports	Imports	Skilled labor	Unskilled labor
Paddy rice	0.021	3.254	9.291	0.018	0.016
Wheat	0.003	-1.893	0.965	-0.001	-0.003
Cereal grains	-0.017	-0.194	7.292	-0.025	-0.027
Oil seeds	0.065	1.045	-0.137	0.069	0.067
Sugar cane, sugar beet	0.010	-0.782	3.014	0.004	0.003
Other agriculture goods	-0.054	-0.224	1.570	-0.070	-0.072
Forestry	-0.007	-0.297	-0.018	-0.004	-0.006
Raw milk	0.015	-1.239	1.584	0.010	0.009
Cattel, sheep, goat, horses	-0.011	-0.622	0.147	-0.021	-0.022
Non-ruminant livestock	0.008	-0.222	0.650	0.001	0.000
Processed dairy products	0.026	0.602	-0.521	0.033	0.025
Processed ruminant meat products	-0.168	-0.306	1.947	-0.161	-0.168
Processed non-ruminant meat products	0.005	-0.026	0.470	0.012	0.005
Vegetable oils and fats	-0.048	0.552	0.132	-0.039	-0.046
Beverages, tobacco, sugar	0.007	-0.152	-0.037	0.015	0.007
Processed rice	-0.011	-0.252	2.457	-0.004	-0.012
Other food products	0.027	0.122	-0.054	0.033	0.026
Other Primary: Fishery and Mining	0.032	0.062	0.002	0.037	0.036
Coal	-0.009	-0.106	0.109	0.041	0.015
Crude oil	0.031	-0.039	0.123	0.044	0.041
Natural gas	-0.049	-0.134	0.359	-0.046	-0.048
Petroleum, coal products	0.109	0.306	-0.068	0.121	0.113
Electricity	0.037	-1.222	1.312	0.037	0.029
Energy intensive industries	0.229	0.984	0.020	0.236	0.228
Other transport	0.012	-0.085	0.211	0.027	0.016
Water transport	0.622	0.902	0.152	0.633	0.622
Air transport	-0.017	-0.029	0.085	-0.004	-0.015
Other industry and services	-0.037	-0.451	0.151	-0.029	-0.038
Non-tradable services	0.010	-0.702	0.201	0.014	0.006

Table 5 - Changes in production, employment and trade in India under high price CO_2 abatement with \$400/tCO_2 emission tax (effective CO_2 tax is \$200/tCO_2), percent

Sectors	Output	Exports	Imports	Skilled labor	Unskilled labor
Paddy rice	0.035	5.249	14.597	0.030	0.027
Wheat	0.004	-3.022	1.522	-0.002	-0.005
Cereal grains	-0.026	-0.309	11.443	-0.040	-0.042
Oil seeds	0.104	1.676	-0.223	0.111	0.108
Sugar cane, sugar beet	0.016	-1.219	4.754	0.008	0.005
Other agriculture goods	-0.085	-0.348	2.465	-0.110	-0.113
Forestry	-0.010	-0.447	-0.031	-0.006	-0.009
Raw milk	0.024	-1.967	2.498	0.017	0.014
Cattel, sheep, goat, horses	-0.017	-0.988	0.234	-0.032	-0.035
Non-ruminant livestock	0.012	-0.354	1.014	0.003	0.000
Processed dairy products	0.042	0.960	-0.834	0.052	0.040
Processed ruminant meat products	-0.267	-0.487	3.063	-0.256	-0.268
Processed non-ruminant meat products	0.008	-0.048	0.750	0.019	0.007
Vegetable oils and fats	-0.075	0.888	0.211	-0.062	-0.074
Beverages, tobacco, sugar	0.012	-0.234	-0.060	0.024	0.012
Processed rice	-0.018	-0.399	3.884	-0.007	-0.019
Other food products	0.042	0.195	-0.087	0.053	0.041
Other Primary: Fishery and Mining	0.052	0.101	0.002	0.059	0.057
Coal	-0.016	-0.170	0.174	0.065	0.022
Crude oil	0.049	-0.070	0.198	0.070	0.065
Natural gas	-0.080	-0.219	0.574	-0.076	-0.079
Petroleum, coal products	0.175	0.495	-0.109	0.194	0.180
Electricity	0.059	-1.942	2.071	0.060	0.046
Energy intensive industries	0.363	1.561	0.031	0.375	0.362
Other transport	0.020	-0.137	0.337	0.044	0.026
Water transport	0.997	1.445	0.243	1.015	0.997
Air transport	-0.028	-0.047	0.135	-0.007	-0.025
Other industry and services	-0.059	-0.720	0.241	-0.046	-0.061
Non-tradable services	0.016	-1.121	0.321	0.023	0.010

Impacts of Carbon Pricing in Brazil

The other industry and services is the largest sector of the Brazilian economy, generating about 47% of its domestic production. As shown in Figure 3, the next largest sectors are the energy intensive industries and non-tradable services generating about 10% and 20% of the Brazilian domestic output, respectively.

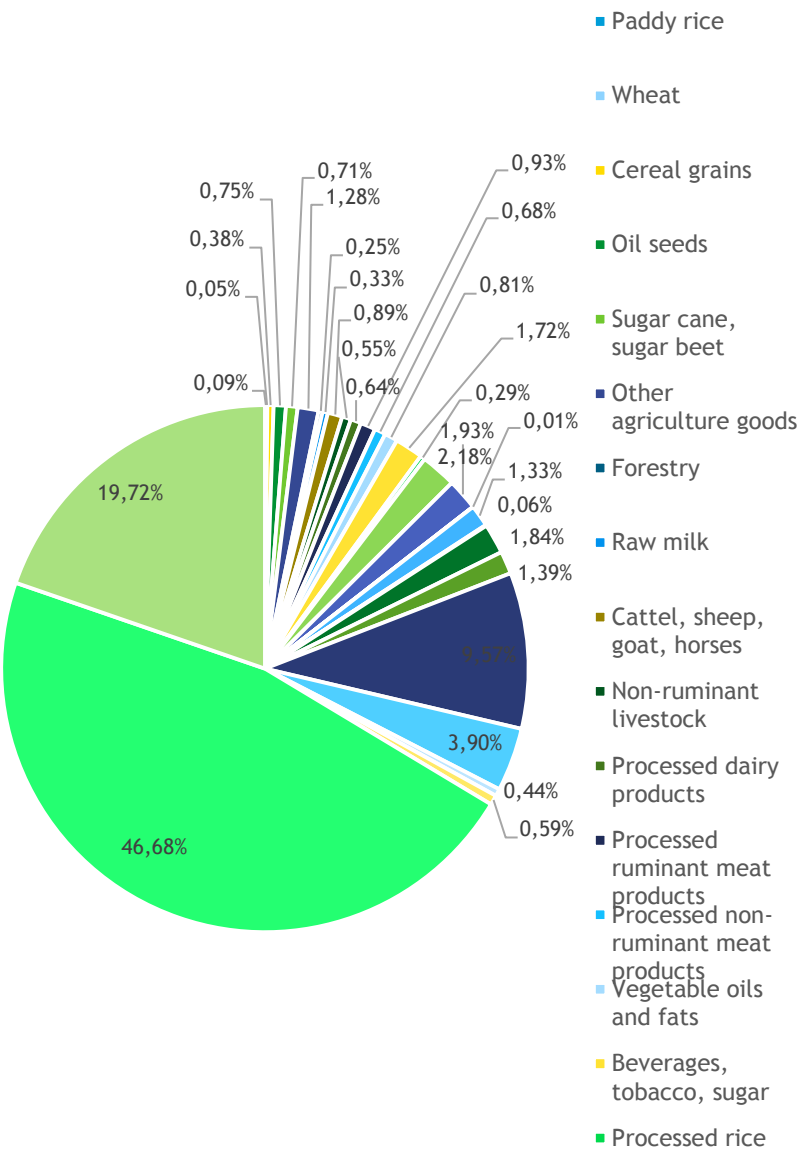

Figure 3 - Output by sector in Brazil, percent

Our results show that the increased water transport costs inducing the utilization of low and zero-carbon fuels have positive impact on the Brazilian output and GDP. However, a more detailed analysis reveals interesting insights about the potential changes.

As illustrated in Tables 6 and 7, some sectors experience reduction in output. Vegetable oil and fats, oil seeds, non-ruminant livestock, and processed non-ruminant meat products experience decrease in output ranging from 0.1% to 0.3%. Energy intensive industries, coal, and other agricultural goods sectors see the largest growth in output between 0.04% and 0.07%. Due to modal substitution the use of air transportation services increases by 0.06%, which contributes to increasing transportation emissions in Brazil. The largest reduction in absolute terms is observed in the output of petroleum and coal products, and oil seeds, while we find the largest output gains in other industry and services, and energy intensive industries.

Similar to the Indian economy case, we observe a positive correlation between the production and exports of some sectors, but contrary to the Indian case we do not find any negative relationship between production and imports for other sectors, as shown in Tables 6 and 7. The results also show import substitution in the energy intensive industries, fossil fuels, and processed dairy products sectors.

We find similar impacts under the high price CO_2 abatement, but larger than those with the low carbon pricing scenario (Table 7).

Table 6 - Changes in production, employment and trade in Brazil under low price CO_2 abatement with \$250/tCO_2 emission tax (effective CO_2 tax is \$125/tCO_2), percent

Sectors	Output	Exports	Imports	Skilled labor	Unskilled labor
Paddy rice	0.002	0.894	-0.036	-0.005	-0.005
Wheat	0.032	0.357	0.090	0.027	0.027
Cereal grains	-0.039	-0.102	0.012	-0.047	-0.048
Oil seeds	-0.335	-0.529	-0.017	-0.360	-0.361
Sugar cane, sugar beet	-0.014	-0.684	2.835	-0.021	-0.022
Other agriculture goods	0.067	0.216	-0.120	0.065	0.064

Sectors	Output	Exports	Imports	Skilled labor	Unskilled labor
Forestry	0.004	-0.330	2.760	0.005	0.005
Raw milk	0.002	-1.098	0.996	-0.005	-0.005
Cattel, sheep, goat, horses	0.003	-0.261	0.215	-0.003	-0.003
Non-ruminant livestock	-0.149	-0.178	-0.159	-0.164	-0.164
Processed dairy products	0.002	-0.883	-0.192	0.002	0.001
Processed ruminant meat products	-0.068	-0.638	0.053	-0.069	-0.070
Processed non-ruminant meat products	-0.301	-0.734	0.140	-0.301	-0.302
Vegetable oils and fats	-0.083	-0.430	-0.486	-0.084	-0.085
Beverages, tobacco, sugar	-0.036	-0.162	-0.210	-0.037	-0.038
Processed rice	-0.023	-0.570	-0.101	-0.023	-0.024
Other food products	-0.013	-0.247	-0.282	-0.014	-0.015
Other Primary: Fishery and Mining	-0.034	-0.068	-0.199	-0.033	-0.033
Coal	0.050	0.298	-0.050	0.076	0.074
Crude oil	0.036	0.137	-0.349	0.047	0.047
Natural gas	0.002	0.280	-0.022	0.007	0.007
Petroleum, coal products	-0.055	-0.650	-0.066	-0.012	-0.013
Electricity	-0.025	-0.949	0.914	-0.029	-0.030
Energy intensive industries	0.037	-0.358	-0.341	0.042	0.041
Other transport	0.011	0.760	0.198	0.025	0.023
Water transport	0.178	0.597	0.154	0.197	0.195
Air transport	0.06	1.002	0.064	0.083	0.081
Other industry and services	0.006	-0.559	0.088	0.005	0.003
Non-tradable services	-0.004	-0.553	0.271	-0.007	-0.008

Table 7 - Changes in production, employment and trade in Brazil under high price CO_2 abatement with \$400/tCO_2 emission tax (effective CO_2 tax is \$200/tCO_2), percent

Sectors	Output	Exports	Imports	Skilled labor	Unskilled labor
Paddy rice	0.004	1.456	-0.063	-0.006	-0.007
Wheat	0.051	0.570	0.143	0.044	0.044
Cereal grains	-0.062	-0.161	0.018	-0.075	-0.076
Oil seeds	-0.533	-0.842	-0.033	-0.573	-0.573
Sugar cane, sugar beet	-0.022	-1.060	4.470	-0.033	-0.034
Other agriculture goods	0.111	0.357	-0.193	0.107	0.107
Forestry	0.006	-0.511	4.321	0.009	0.008
Raw milk	0.002	-1.735	1.566	-0.008	-0.008
Cattel, sheep, goat, horses	0.005	-0.416	0.334	-0.005	-0.005
Non-ruminant livestock	-0.239	-0.283	-0.256	-0.263	-0.263
Processed dairy products	0.004	-1.417	-0.307	0.003	0.001
Processed ruminant meat products	-0.109	-1.020	0.081	-0.110	-0.112
Processed non-ruminant meat products	-0.482	-1.176	0.221	-0.482	-0.484
Vegetable oils and fats	-0.132	-0.686	-0.779	-0.133	-0.135
Beverages, tobacco, sugar	-0.057	-0.257	-0.335	-0.058	-0.060
Processed rice	-0.037	-0.908	-0.164	-0.037	-0.039
Other food products	-0.021	-0.396	-0.451	-0.022	-0.023
Other Primary: Fishery and Mining	-0.053	-0.108	-0.319	-0.052	-0.052
Coal	0.080	0.486	-0.080	0.122	0.117
Crude oil	0.056	0.216	-0.555	0.074	0.074
Natural gas	0.002	0.432	-0.033	0.011	0.010

Petroleum, coal products	-0.088	-1.041	-0.105	-0.019	-0.021
Electricity	-0.040	-1.510	1.443	-0.046	-0.048
Energy intensive industries	0.058	-0.573	-0.545	0.067	0.065
Other transport	0.017	1.212	0.317	0.040	0.037
Water transport	0.285	0.957	0.247	0.315	0.312
Air transport	0.096	1.604	0.104	0.133	0.130
Other industry and services	0.009	-0.897	0.142	0.008	0.005
Non-tradable services	-0.007	-0.885	0.433	-0.011	-0.013

Conclusions

In this paper we study the policy measures that can generate significant maritime transport emission reductions. We also develop a methodology based on the energy-environmental version of the Global Trade Analysis Project (GTAP-E) with transport mode substitution that enables an appropriate representation of the dynamics and responses of both the shipping system and global/regional economies. We use our proposed methodology in a number of scenarios to produce economic impacts of various policy measures converted to increased maritime transport costs for the global economy, small island states, developing and least developed countries[6]. We show the methodology and its capabilities, and illustrate how certain policy measures may affect economic development and security of different countries.

Our results indicate that increased maritime transport costs applied to the shipments of all goods transported along all routes negatively affects the GDP of most countries. The largest gain is experienced by Benin with a relatively large positive change in imports and even larger negative change in exports. This is explained by increased investments, as well as the other components of its GDP, such as consumption and government expenditures. However, uncertainty regarding the data limitations together with factors contributing to the

[6] In this version of the paper we have not specified our methodology of converting various transport emissions regulatory measures to change in cost of transportation. This is still work in progress and will be presented in the final version.

disproportionate impacts make it difficult to perform precise estimation of possible economic impacts for smaller countries. This is especially true in the case of SIDS countries, when poor data quality and uncertainty related to factors contributing to the disproportionate negative impacts prevent accurate estimation of possible approaches to address such effects and the potential consequences of addressing these negative impacts. However, in this study we were able to draw some useful insights from the results produced by our modified version of the GTAP-E model.

Emissions decline in most countries with significant reductions happening in countries and regions that experience larger GDP losses. Most regions with positive change in GDP generate more emissions, as expected. Some countries with decreasing GDP produce more emissions, because the decline in their exports is relatively smaller than the reduction in imports. Also, in some countries emissions from transportation increase explained by modal substitution resulting in relative increased supply of other and air transport services across all regions.

We also conclude that if the maritime transport cost increase is applied to specific countries, such as small island developing states, least developing countries, and countries that depend on the export of perishables over long distances, the total economic and environmental impacts are of smaller magnitude.

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Appendix A

Table A1. Regional aggregation

#	**Regions**
1	United States
2	Canada
3	European Union
4	Japan
5	China, Hong Kong
6	Brazil
7	India
8	Russia
9	Oceania countries
10	Dominician Republic[a]
11	Jamaica[a]
12	Puerto Rico[a]
13	Trinidad and Tobago[a]
14	Cambodia[b]
15	Lao People's Dem. Republic[b]
16	Malaysia and Indonesia
17	Singapore[a]
18	Afghanistan, Bhutan, Maldives[c]
19	Bahrain[a]
20	Benin[b]
21	Burkina Faso[b]
22	Guinea[b, c]
23	Togo[b]
24	Mauritius[a, c]
25	Mozambique[b]
26	Rwanda[b, c]
27	Uganda
28	Zambia[b, c]
29	Ethiopia[b, c]
30	Nepal[b, c]
31	Bangladesh
32	Madagascar[b, c]
33	Malawi[b, c]
34	Senegal[b, c]
35	Tanzania[b, c]
36	Zimbabwe[c]
37	Other East Europe and Rest of Former S. Union
38	Rest of European Countries
39	East Asia
40	Rest of South East Asia
41	Rest of South Asia
42	Rest of Oceania
43	Rest of Carribean
44	Central and Caribbean Americas
45	South and Other Americas
46	Central Africa[c]
47	Rest of Eastern Africa[c]
48	Rest of Western Africa[c]
49	Sub Saharan Africa
50	Middle Eastern and North Africa
51	Rest of the World

a. 7 SIDS (https://sustainabledevelopment.un.org/topics/sids/list)

b. 17 LDC (https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/ldc_list.pdf)

c. 15 LOW INCOME (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups)

Table A2. Sectoral aggregation

#	Sectors
1	Paddy rice
2	Wheat
3	Cereal grains
4	Oil seeds
5	Sugar cane, sugar beet
6	Other agriculture goods
7	Forestry
8	Raw milk
9	Cattel, sheep, goat, horses
10	Non-ruminant livestock
11	Processed dairy products
12	Processed ruminant meat products
13	Processed non-ruminant meat products
14	Vegetable oils and fats
15	Beverages, tobacco, sugar
16	Processed Rice
17	Food products other
18	Other primary products: Fishery & Mining
19	Coal
20	Crude oil
21	Natural gas
22	Petroleum, coal products
23	Electricity
24	Energy intensive Industries
25	Other transport
26	Water transport
27	Air transport
28	Other industry and services
29	Services generating Non-CO_2 Emissions