Supporting Information

Economic Impacts from $PM_{2.5}$ Pollution-Related Health Effect: A Case Study in Shanghai

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Summary

The supporting information includes 26 pages, 4 figures, 2 tables and 35 references.

GAINS MODEL

GAINS model is an integrated assessment model dealing with costs and potentials for air pollution control and greenhouse gas (GHG) mitigation, and assessing interactions between policies.[1,2] The GAINS-China model provides annual average $PM_{2.5}$ concentration, air pollutant emissions and pollution control costs data for Shanghai. The basic principles of calculating emissions and emission control costs in the model present in Eq. 1 and 2.

Equation 1:

$$Emissions = \sum_i Activity_i \times F \times (1-r) \times C$$

Equation 2:

$$Costs = \sum_i Activity_i \times U \times C$$

Components appearing on the right side of the equations are organized into three different data categories: activity pathways, emission vectors, and control strategies. Each emission scenario in GAINS is created through a combination of these three data categories. Emissions-generating economic *Activities* are organized into activity pathways which are divided into five groups: Agriculture (AGR), Energy (ENE), Mobile (MOB), Process (PROC), and VOC sources (VOCP). This study mainly focuses on Energy and Mobile sources activity. F (emission factors of activities), r (removal efficiencies of control technologies), U (unit cost of control technologies), together with all background information, form the so-called emission vectors. Finally, C (control technologies) for each activity are specified in control strategies. Emissions and control costs of each emission scenario are the sum of all i activities.

Based on the detailed spatial and sectoral GAINS emission inventory, GAINS computes fields of ambient concentrations of $PM_{2.5}$ with the help of source-receptor relationships derived from an atmospheric chemistry-transport model named TM5 model. The model computed contributions from (i) primary particulate matter released from anthropogenic sources, (ii) secondary inorganic aerosols formed from anthropogenic emissions of SO_2, NO_x and NH_3, (iii) particulate matter from natural sources (soil dust, sea salt, biogenic sources).

HEALTH MODULE

The health module is based on reference [3].

Health endpoint

All results are region r, year y, scenario s, and uncertainty range g specific. For simplification, they are omitted in the following description.

Exposure to incremental $PM_{2.5}$ pollutant leads to health problems called health endpoints, which are categorized into morbidity and chronic mortality (Table S1). Most studies[4-6] indicate that the Relative Risk (RR) for the endpoint is in a linear relationship with the concentration level, recent studies[7,8] argue that it is in a non-linear relationship, especially at high concentrations. As showed in Eq. 3 and 4, in this study, we adopted both linear and non-linear functions. When the concentration is lower than the threshold value of 10 μg/m^3, RR is 1, which causes no health impacts. Linear function assumes that the concentration-response function (CRF) is a constant. For mortality, we adopted China-specific linear function from ref [9] and cause-specific log-linear function based on the lookup table in.[7] The number of health endpoints is estimated by multiplying RR with population and reported cause-specific mortality rate.

Equation 3:

$$RR_{p,r,s,y,m,e,g}(C) = \begin{cases} 1, & & \text{if } C_{p,r,s,y} \le C0_p \\ 1 + CRF_{m,e,g} \times (C_{p,r,s,y} - C0_p), & \text{linear function,} & \text{if } C_{p,r,s,y} > C0_p \\ 1 + \alpha \times e^{(-\gamma \times (C_{p,r,s,y} - C0_p)^{\delta})}, & \text{nonlinear function,} & \text{if } C_{p,r,s,y} > C0_p \end{cases}$$

Equation 4:

$$EP_{p,r,s,y,m,e,g}(C) = \begin{cases} P_{r,y,m} \times (RR_{p,r,s,y,m,e,g}(C) - 1), & \text{for linear morbidity function} \\ P_{r,y,m} \times (RR_{p,r,s,y,m,e,g}(C) - 1) \times I_{r,\text{"all cause"}}, & \text{for linear mortality function} \\ P_{r,y,m} \times (RR_{p,r,s,y,m,e,g}(C) - 1) \times \hat{I}_{r,e}, & \text{for nonlinear mortality function,} \end{cases}$$

where

- **RR(C)**: Relative risk for endpoint at concentration C [case/person/year or day/person/year]
- **EP**: Health endpoint [case/year or day/year]
- **C**: Concentration level of pollutant
- **C0**: Threshold concentration that causes health impacts (10 μg/m^3 for $PM_{2.5}$)
- **CRF**: Concentration-response function

- **P**: Population, aged 14-65 for work loss day, age 25-65 for Ischemic heart disease and Stroke, and entire cohort for other endpoints
- $\hat{f}$: (cause-specific mortality rate) defined in ref [7]
- **I**: Reported average annual disease incidence (mortality) rate for endpoint
- $I_{r,\text{"all cause"}}$: Reported average annual natural death rate for endpoint
- α , γ , δ : Parameters that determine the shape of the non-linear concentration-response relationship for chronic mortality.
- Suffix p, r, s, y, m, e, g represent pollutant ($PM_{2.5}$), region, scenario, year, endpoint category (morbidity or mortality), endpoint, value range (medium, low and high), respectively.

Annual per capita work loss rate

Annual total work loss day (WLD) of a region is a summation of work loss day from morbidity and cumulative work loss day from chronic mortality aged from 14 to 65 years old (Eq. 5). Based on death rates for different age group and cause-specific mortality from China health statistics, we assume 4% of total chronic mortality is aged between 14 and 65 years old. Annual per capita work loss rate (WLR) is obtained by dividing WLD with working population and annual working days (Eq. 6). In the CGE model, WLR is used to calculate the actual labor force after subtracting the work loss (Eq. 7).

Equation 5:

$$WLD_{p,r,s,y,g} = \sum_{m} (EP_{p,r,s,y,m,\text{"wld"},g}) + \sum_{e,y\prime<y} (EP_{p,r,s,y\prime,\text{"mt"},e,g}) \times 0.04 \times DPY$$

Equation 6:

$$WLR_{p,r,s,y,g} = \frac{WLD_{p,r,s,y,g}}{DPY \times P_{r,y,\text{"14−65"}}}$$

Equation 7:

$$LAB_{p,r,s,y,g} = LAB0_{r,\text{"ref"},y}$$

Where

- **WLD**: Annual work loss day [day/year]
- **WLR**: Annual per capita work loss rate
- **"wld"**: Subset "Work loss day" of e
- **"mt"**: Subset "Chronic mortality" of m

- **LAB**: Labor force after considering work loss
- **LAB0**: Labor force in the reference scenario
- **DPY**: Per capita annual working days (5 day/week * 52 week/year = 260 day/year)

Health expenditure

Additional health expenditure is obtained by multiplying outpatient and hospital admission price with total endpoints (Eq. 8). The price is a function of per capita GDP of each province (Eq. 9), and the parameters β, θ are estimated through regression analysis of statistical price by disease and GDP of each province from 2003 to 2012. Additional medical expenditure is regarded as household expenditure pattern change, which means as more money is spent on medical services, less is available on other commodities.

Equation 8:

$$HE_{p,r,s,y,g} = PR_{r,s,y,e,g} \times EP_{p,r,s,y,m,e,g}$$

Equation 9:

$$PR_{r,s,y,e} = \beta \times GDPPC_{r,s,y} + \theta_{r,e}$$

Where:

- **HE**: Total additional health expenditure [billion Yuan/year]
- **PR**: Price of medical service [Yuan/case]
- **GDPPC**: Per capita Gross Domestic Production from CGE model
- β, θ: Parameters derived from regression analysis of medical service price

Table S1: Exposure-Response Functions for health endpoints

Category	Endpoint	Unit	Medium	C.I. (95%) Low	C.I. (95%) High
Morbidity	Work loss day	day/person	2.07E-02	1.76E-02	2.38E-02
	Respiratory hospital admissions	/μg-m^3/year	1.17E-05	6.38E-06	1.72E-05
	Cerebrovascular hospital admission	case/person	8.40E-06	6.47E-07	1.16E-05
	Cardiovascular hospital admissions	/μg-m^3/year	7.23E-06	3.62E-06	1.09E-05
	Chronic bronchitis		4.42E-05	-1.82E-06	9.02E-05
	Asthma attacks		1.22E-04	4.33E-05	1.21E-03
	Respiratory symptoms days		2.50E-02	2.17E-01	4.05E-01
Chronic mortality	All cause (International)		0.004	0.0003	0.008
	All cause (China-specific)		0.0009	-0.0003	0.0018
	Chronic obstructive pulmonary disease		Non-linear function		

Lung cancer
Ischemic heart disease (35-65 y)
Stroke (35-65 y)
Lower respiratory infections

Source: [7,9-11]

THE CGE MODEL

The CGE model

The CGE model could capture the full range of interaction and feedback effects between different agents in the economic system. It has been widely used to assess the economic and environmental impacts of different climate policies at global[12-14], national[15,16] levels. The model is a two-region dynamic CGE model that includes Shanghai and the Rest of China (ROC) based on the provincial CGE model developed by Dai et al.[17]

The CGE model applied in this study can be classified as a multi-sector, multi-region, recursive dynamic CGE model that covers 22 economic commodities and corresponding sectors, and eight power generation technologies. This CGE model is solved by MPSGE/GAMS[18] at a one-year time step. It has been used widely for assessing China's climate mitigation at the national[17,19,20] and provincial[3,21-27] levels.

Major model features are similar to the one-region version[17], including a production block, a market block with domestic and international transactions, as well as government and household incomes and expenditures blocks. The model is comprised of 42 sectors, which are classified into basic and energy transformation sectors, and seven power generation technologies. Activity output for each sector follows a nested constant elasticity of substitution (CES) production function. Inputs are categorized into material commodities, energy commodities, labor, capital and resources. Technical descriptions are provided in the Appendix.

Data collection and treatments

Data required by this model include the input-output table of Shanghai and China[28,29], energy balance tables[30,31], carbon emission factors of different fossil fuels, energy prices of coal, oil and gas for the year of 2012.

TECHNICAL INTRODUCTION OF THE CGE MODEL

The appendix provides a technical description of the CGE model used in this study based on ref [23].

Production

Each producer maximizes profit subject to the production technology. Activity output of each sector follows a nested constant elasticity of substitution (CES) production function. Each sector has two types of production function; one uses the existing capital stock, and another uses new investment.[32] The difference between these two subsectors is the efficiency and mobility of capital among the sectors. Inputs are categorized into material commodities, energy commodities, land, labor, capital and resource.

The producer maximizes its profit by choosing its output level and inputs use, depending on their relative prices subject to its technology. The producer's problem can be expressed as:

Equation 10:

$$max\colon \pi_{r,j} = p_{r,j} \cdot Z_{r,j} - (\sum_{i=1}^{N} p_{r,i} \cdot X_{r,i,j} + \sum_{f=1}^{F} \omega_{r,f} \cdot V_{r,f,j})$$

subject to:

Equation 11:

$$Z_{r,j} = \upsilon_{r,j}[X_{r,1,j}, X_{r,2,j}, \cdots, X_{r,N,j}; V_{r,1,j} \cdots, V_{r,f,j}]$$

Where

- $\pi_{r,j}$ Profit of j-th producers in region r,
- $Z_{r,j}$ Output of j-th sector in region r,
- $X_{r,i,j}$ Intermediate inputs of i-th goods in j-th sector in region r,
- $V_{r,f,j}$ f-th primary factor inputs in j-th sector in region r,
- $p_{r,j}$ Price of the j-th composite commodity,
- $\omega_{r,f}$ f-th factor price in region r.
- $\upsilon_{r,j}$ Share parameter in the CES production function.

Basic sectors

For the basic production functions, activity output is determined by a fixed coefficient aggregation of non-energy and energy intermediate commodities, and primary factors (Figure S1). The composite of non-energy inputs is in Leontief form. Energy and the value added bundle are nested by valued added and energy inputs. The value added bundle is a CES function of primary factors. The composite of energy inputs is a CES aggregation of electricity and fossil fuels. Fossil fuels are further disaggregated into five types.

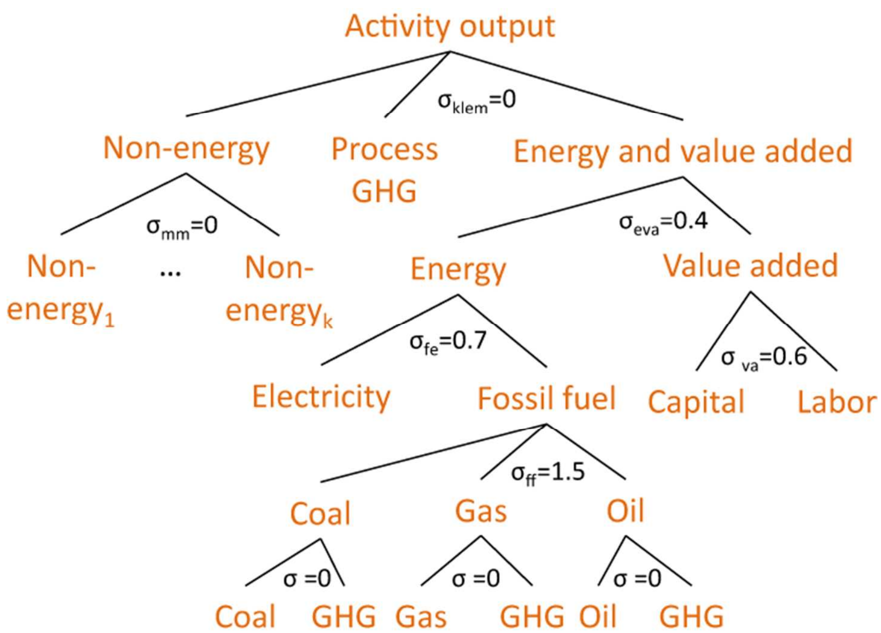

Figure S1: Production Tree of Basic Sectors. σ is elasticity of substitution for inputs

There are four levels in the above production tree. At each level a virtual firm is assumed, each of which aims to maximize the corresponding profit subject to the production technology. At the top-level, output is a Leontief function of the quantities of value-added and aggregate energy input and aggregate intermediate input, associated with process GHG emissions:

Equation 12:

$$max: \pi_{r,j} = p_{r,j} \cdot Z_{r,j} - (\sum_{i=1}^{N} p_{r,i} \cdot X_{r,i,j} + \sum_{f=1}^{F} \omega_{r,f} \cdot V_{r,f,j})$$

Equation 13:

$$max: \pi_{r,j}^{z} = p_{r,j}^{z} \cdot Z_{r,j} - (p_{r,j}^{vae} \cdot QVAE_{r,j} + p_{r,j}^{inta} \cdot QINTA_{r,j} + p_{r}^{ghg} \cdot QGHG_{r,j,act,ghg})$$

s.t.

Equation 14:

$$Q_{r,j} = min(\frac{QVAE_{r,j}}{qvae_{r,j}}, \frac{QINTA_{r,j}}{qinta_{r,j}}, \frac{QGHG_{r,j,act,ghg}}{qghg_{r,j,act,ghg}})$$

Where

- $\pi_{r,j}^{z}$ Profit of the j-th firm producing gross domestic output $z_{r,j}$ at the top level,
- $Z_{r,j}$ Gross domestic output of the j-th firm,
- $Q_{r,j}$ Output in sector j of region r,
- $QVAE_{r,j}$ Value added and energy composite input,
- $QINTA_{r,j}$ Composite intermediate input,
- $QGHG_{r,j,act,ghg}$ Process emissions of GHGs per unit of output,
- $p_{r,j}^{z}$ Price of j-th gross domestic output,
- $p_{r,j}^{vae}$ Price of composite goods of factor and energy,
- $p_{r,j}^{inta}$ Price of composite intermediate goods,
- p_{r}^{ghg} GHG emission price,
- $qvae_{r,j}$ Technical coefficient expressing the composite amounts of value added and energy inputs required per unit of $Q_{r,j}$,
- $qinta_{r,j}$ Technical coefficient expressing the composite amounts of non-energy intermediate inputs required per unit of $Q_{r,j}$,
- $qghg_{r,j,act,ghg}$ Technical coefficient expressing the process GHG emissions per unit of $Q_{r,j}$.

At the second level of the production tree, there are two virtual firms with profit-maximization problems. First, composite value added and energy input is CES aggregation of value added input and total energy input:

Equation 15:

$$max\colon \pi_{r,j}^{vae} = p_{r,j}^{vae} \cdot QVAE_{r,j} - (p_{r,j}^{va} \cdot QVA_{r,j} + p_{r,j}^{fe} \cdot QFE_{r,j})$$

s.t.

Equation 16:

$$QVAE_{r,j} = \alpha_{r,j}^{vae} \cdot (\delta_{r,j}^{vae} \cdot QVA_{r,j}^{-\rho_{r,j}^{vae}} + (1-\delta_{r,j}^{vae}) \cdot QFE_{r,j}^{-\rho_{r,j}^{vae}})^{\frac{-1}{\rho_{r,j}^{vae}}}$$

Second, aggregate non-energy intermediate input is defined as Leontief function of disaggregated intermediate input:

Equation 17:

$$max: \pi_{r,j}^{inta} = p_{r,j}^{inta} \cdot QINTA_{r,j} - (\sum_i p_{r,j}^q \cdot QINT_{r,i,j})$$

s.t.

Equation 18:

$$QINTA_{r,j} = min(\frac{QINT_{r,i,j}}{qint_{r,i,j}})$$

Where

- $\pi_{r,j}^{vae}$ Profit of j-th firm producing composite input of value added and energy,
- $\pi_{r,j}^{inta}$ Profit of j-th firm producing composite intermediate input,
- $QVA_{r,j}$ Aggregate value added input,
- $QFE_{r,j}$ Aggregate energy input (electricity and fossil energy),
- $QINT_{r,i,j}$ i-th non-energy inputs in j-th firm,
- $p_{r,j}^{va}$ Price of composite value added input,
- $p_{r,j}^{fe}$ Price of the composite energy input (including electricity and fossil fuel),
- $p_{r,j}^q$ Price of the i-th composite goods,
- $qint_{r,i,j}$ The amounts of each input required per unit of composite intermediate input,
- $\alpha_{r,j}^{vae}$ Shift (or efficiency) parameter in the CES function,
- $\delta_{r,j}^{vae}$ CES share parameter, $0 \leq \delta_{r,j}^{vae} \leq 1$, $\sum_i \delta_{r,j}^{vae} = 1$,
- $\rho_{r,j}^{vae}$ The CES substitution parameter, in which the elasticity of substitution between value added and energy, σ , equals $\frac{1}{(1+\rho)}$,
- $\sigma_{r,j}^{vae}$ Elasticity of substitution between value added bundle and energy.

At the third level of the production tree, there are two virtual firms with profit-maximization problems as well. First, composite value added input is CES aggregation of capital and labor input:

Equation 19:

$$max: \pi_{r,j}^{va} = p_{r,j}^{va} \cdot QVA_{r,j} - (pl_r \cdot QLAB_{r,j} + pk_{r,j} \cdot QCAP_{r,j})$$

s.t.

Equation 20:

$$QVA_{r,j} = \alpha_{r,j}^{va} \cdot (\delta_{r,j}^{cap} \cdot QCAP_{r,j}^{-\rho_{r,j}^{va}} + \delta_{r,j}^{lab} \cdot QLAB_{r,j}^{-\rho_{r,j}^{va}})^{\frac{-1}{\rho_{r,j}^{va}}}$$

And composite energy input is CES aggregation of electricity input and fossil fuel input:

Equation 21:

$$max: \pi_{r,j}^{fe} = p_{r,j}^{fe} \cdot QFE_{r,j} - (p_{r,\text{"ele"}}^{q} \cdot QELE_{r,j} + p_{r,j}^{fos} \cdot QFOS_{r,j})$$

s.t.

Equation 22:

$$QFE_{r,j} = \alpha_{r,j}^{fe} \cdot (\delta_{r,j}^{ele} \cdot QELE_{r,j}^{-\rho_{r,j}^{fe}} + (1 - \delta_{r,j}^{ele}) \cdot QFOS_{r,j}^{-\rho_{r,j}^{fe}})^{\frac{-1}{\rho_{r,j}^{fe}}}$$

Where

- $\pi_{r,j}^{va}$ Profit of j-th firm producing composite input of value added,
- $\pi_{r,j}^{fe}$ Profit of j-th firm producing composite input of energy,
- $QCAP_{r,j}$ Capital input required per unit of value added input,
- $QLAB_{r,j}$ Labor input required per unit of value added input,
- $QELE_{r,j}$ Electricity input required per unit of composite energy input,
- $QFOS_{r,j}$ Composite fossil fuel input required per unit of composite energy input,
- pl_r Labor price in region r,
- $pk_{r,j}$ Capital price in j-th sector of region r,
- $p_{r,\text{"ele"}}^{q}$ Price of the composite goods of electricity,
- $p_{r,j}^{fos}$ Price of composite fossil fuel input in j-th sector,
- $\alpha_{r,j}^{fe}$ Shift (or efficiency) parameter in the CES function,
- $\delta_{r,j}^{fe}$, $\delta_{r,j}^{cap}$, $\delta_{r,j}^{lab}$ CES share parameters, $0 \leq \delta_{r,j}^{*} \leq 1$, $\sum_i \delta_{r,j}^{*} = 1$

- $\rho_{r,j}^{fe}$ CES substitution parameter, in which the elasticity of substitution between electricity and composite fossil fuel, σ , equals $\frac{1}{(1+\rho)}$,
- $\sigma_{r,j}^{va}$ Elasticity of substitution between capital and labor,
- $\sigma_{r,j}^{vae}$ Elasticity of substitution between electricity and fossil fuel.

At the fourth level of the production function, composite fossil fuel is CES aggregation of coal, crude oil, natural gas, coke, petrol oil and manufactured gas:

Equation 23:

$$max\colon \pi_{r,j}^{fos} = p_{r,j}^{fos} \cdot QFOS_{r,j} - (\sum_{fos} p_{r,fos}^{q} \cdot QFF_{r,fos,j})$$

s.t.

Equation 24:

$$QFOS_{r,j} = \alpha_{r,j}^{ff} \cdot (\sum_{fos} \delta_{r,j}^{ff} \cdot QFF_{r,fos,j}^{-\rho_{r,j}^{ff}})^{\frac{-1}{\rho_{r,j}^{ff}}}$$

Where

- $\pi_{r,j}^{fos}$ Profit of j-th firm producing composite input of fossil fuel,
- $QFF_{r,fos,j}$ CES shift (or efficiency) parameter,
- $p_{r,fos}^{q}$ Price of fossil fuel input,
- $\alpha_{r,j}^{ff}$ Shift (or efficiency) parameter in the CES function,
- $\delta_{r,j}^{ff}$ CES share parameter, $0 \leq \delta_{r,j}^{ff} \leq 1$, $\sum_i \delta_{r,j}^{ff} = 1$
- $\rho_{r,j}^{ff}$ CES substitution parameter, in which the elasticity of substitution among fossil fuels, σ, equals $\frac{1}{(1+\rho)}$,
- $\sigma_{r,j}^{ff}$ Elasticity of substitution among fossil fuels.

Energy transformation sector (except power generation)

Energy transformation sectors include gas production and supply, petroleum and nuclear fuel processing, and coking. The energy bundle is linked at the top level in order to maintain the first-law of thermal efficiency of the conversion of primary energy to the secondary energy (Figure S2). Functions at other levels are the same as the basic sectors.

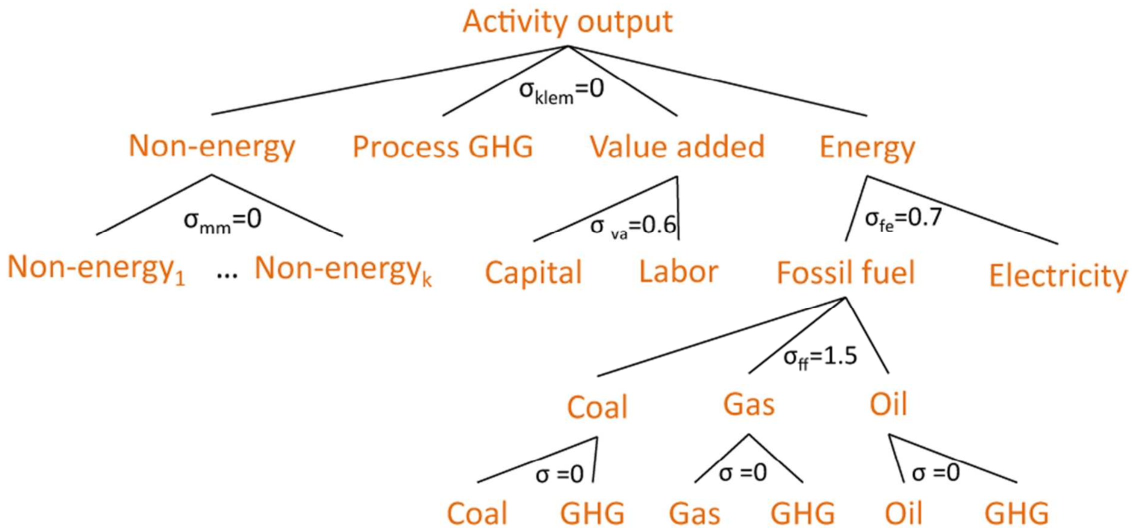

Figure S2: Production Tree of Energy Transformation Sectors. σ is elasticity of substitution for inputs

Thus the problem is expressed in:

Equation 25:

$$max: \pi_{r,j}^{z} = p_{r,j}^{z} \cdot Z_{r,j} - (p_{r,j}^{vae} \cdot QVAE_{r,j} + p_{r,j}^{fe} \cdot QFE_{r,j} + p_{r,j}^{inta} \cdot QINTA_{r,j} + p_{r}^{ghg} \cdot QGHG_{r,j,act,ghg})$$

s.t.

Equation 26:

$$Q_{r,j} = min(\frac{QVAE_{r,j}}{qvae_{r,j}}, \frac{QFE_{r,j}}{qfe_{r,j}}, \frac{QINTA_{r,j}}{qinta_{r,j}}, \frac{QGHG_{r,j,act,ghg}}{qghg_{r,j,act,ghg}})$$

Where

- $QFE_{r,j}$ Aggregate energy input (electricity and fossil energy),
- $qfe_{r,j}$ Technical coefficient expressing the aggregate energy inputs required per unit of $Q_{r,j}$.

Power generation sector

Electricity is generated by 7 technologies. Disaggregation of the electricity sector into 7 technologies in the base year follows the methodology developed by Sue Wing.[33,34] Production function of each technology is the same as that of energy transformation sectors. Each technology is perfectly substitutable with another. Electricity output is almost in a linear relationship with energy inputs (Figure S3).

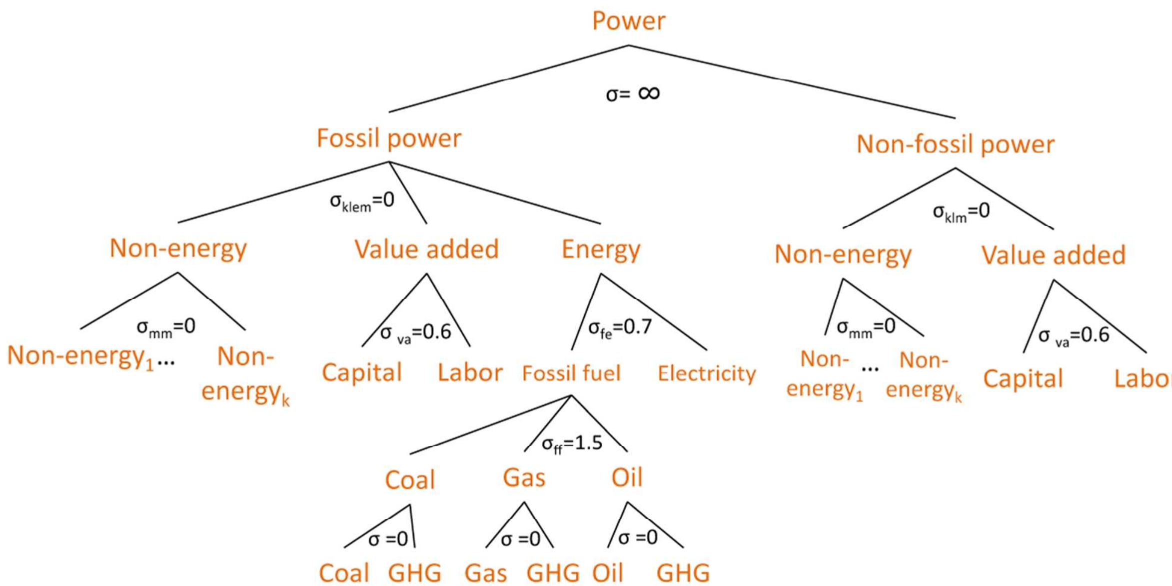

Figure S3: Production Tree of Electricity Generation Sectors. σ is elasticity of substitution for inputs

Household consumption

Household and government are final consumers. The representative household endows primary factors to the firms and receives income from the rental of primary factors (labor and capital), rents from fixed factors (land and natural resources) and lump- Sum transfer from the government (e.g. carbon tax revenue of government). The income is then used for either investment or final consumption. The objective of household consumption is to maximize utility by choosing levels of goods consumption following Cobb-Douglas preferences, subject to commodity prices and budget constraint. The agent's problem is expressed as:

Equation 27:

$$max\colon \mu_{r,h}[X_{r,1}^{p},\cdots,x_{r,i}^{p}] = A_r^p \cdot \prod_{i=1}^{N}(X_{r,i}^{p})^{\alpha_{r,i}^{p}}$$

s.t.

Equation 28:

$$EH_r = \sum_i p^q_{r,j} \cdot X^p_{r,i}$$

$$= \sum_{f=1}^{F} \omega_{r,f} \cdot V_{r,f} + \sum_j p\,ld_r \cdot QLAND_{r,j} + \sum_{res,j} p^{res}_{r,j} \cdot QRES_{r,j} + T^{cab}_r - T^d_r - S^p_r$$

Equation 29:

$$T^{cab}_r = pghg_{r,\text{"CO2"}} \cdot TEMS_{r,\text{"CO2"}}$$

Equation 30:

$$T^d_r = \tau^d_r \cdot \sum_f \omega_{r,f} \cdot V_{r,f}$$

Equation 31:

$$S^p_r = sr^p_r \cdot \sum_f \omega_{r,f} \cdot V_{r,f}$$

Where

- $\mu_{r,h}$ Utility function of households,
- EH_r Household expenditure,
- $X^p_{r,i}$ Household consumption of i-th commodity,
- $V_{r,f}$ fth primary factor endowment by household,
- S^p_r Household savings,
- $TEMS_{r,\text{"CO2"}}$ CO2 emissions in region r,
- $pghg_{r,\text{"CO2"}}$ Carbon price,
- T^d_r Direct tax,
- τ^d_r Direct tax rate,
- sr^p_r Average propensity to save by the household,
- $\omega_{r,f}$ Price of the f-th primary factor,,
- A^p_r Scaling parameter in Cobb-Douglas function,
- $\alpha^p_{r,i}$ Share parameter in Cobb-Douglas function, $0 \le \alpha^p_{r,i} \le 1$, $\sum_i \alpha^p_{r,i} = 1$.

Government

The government is assumed to collect taxes, including direct tax on household income, ad valorem production tax (indirect tax) on gross domestic output, ad valorem import tariff on imports and carbon tax. Based on a Cobb-Douglas demand function,[35] the government spends its revenue on public services which are provided to the whole society and on the goods and services which are provided to the households free of charge or at low prices. The model assumes that the revenue from carbon tax is recycled to the representative agent as a lump-Sum transfer.

Equation 32:

$$max: \mu_{r,g}[x^g_{r,1}, \cdots, x^g_{r,i}] = A^g_r \cdot \prod_{i=1}^{N} (x^g_{r,i})^{\alpha^g_{r,i}}$$

s.t.

Equation 33:

$$\sum_i p_{r,i} \cdot x^g_{r,i} = T^d_r + \sum_j T^z_{r,j} + \sum_j T^m_{r,j} - S^g$$

Equation 34:

$$T^z_{r,j} = \tau^z_{r,j} \cdot p_{r,j} \cdot Z_{r,j}$$

Equation 35:

$$T^m_{r,i} = \tau^m_{r,i} \cdot pm_{r,i} \cdot M_{r,i}$$

Equation 36:

$$S^g_r = sr^g_r \cdot (T^d_r + \sum_j T^z_{r,j} + \sum_j T^m_{r,j})$$

Where

- $\mu_{r,g}$ Utility function of government,
- $x^g_{r,i}$ Government consumption of i-th commodity,
- S^g_r Government savings,
- $T^z_{r,j}$ Production tax on the j-th commodity,
- $T^m_{r,j}$ Import tariff on the j-th commodity,
- $\tau^z_{r,j}$ Production tax rate on the j-th commodity,
- $\tau^m_{r,i}$ Import tariff rate on the i-th commodity,

- sr_r^g Average propensity to save by the government,
- $Z_{r,j}$ Gross domestic output of the j-th commodity,
- $M_{r,i}$ Import of the i-th commodity,
- $pm_{r,i}$ Price of the i-th imported commodity,
- A_r^g Scaling parameter in Cobb-Douglas function,
- $\alpha_{r,i}^g$ Share parameter in Cobb-Douglas function, $0 \leq \alpha_{r,i}^g \leq 1, \sum_i \alpha_{r,i}^g = 1.$

Investment and savings

Investment is an important part of final demand. In the CGE model a virtual agent is assumed for investment which receives all the savings from the household, government and the external sector to purchase goods for domestic investment. The virtual investment agent is assumed to maximize the utility based on a Cobb-Douglas demand function subject to its (virtual) income constraint. Mathematically, the investment problems can be described as follows:

Equation 37:

$$max: \mu_{r,v}[x_{r,1}^v, \cdots, x_{r,i}^v] = A_r^v \cdot \prod_{i=1}^{N} (x_{r,i}^v)^{\alpha_{r,i}^v}$$

s.t.

Equation 38:

$$\sum_i p_{r,i} \cdot x_{r,i}^v = S_r^p + S_r^g + \varepsilon \cdot S_r^f$$

Where

- $\mu_{r,v}$ Utility of virtual investment agent,
- S_r^f Current account deficits in foreign currency terms (or alternatively foreign savings),
- ε Foreign exchange rate,
- $x_{r,1}^v$ Demand for the i-th investment goods,
- A_r^v Scaling parameter in Cobb-Douglas function,
- $\alpha_{r,i}^v$ Share parameter in Cobb-Douglas function, $0 \leq \alpha_{r,i}^v \leq 1, \sum_i \alpha_{r,i}^v = 1.$

International transaction

The model is an open economy model that includes interaction of commodity trade with the rest of the world. Like most other country CGE models, this model assumes the small open economy, meaning that an economy is small enough for its policies not to alter world prices or incomes. The implicit implication of small-country assumption is that export and import prices are exogenously given for the economy. In this study, future international prices are fixed to be the same level for non-energy commodities whereas increase by 3% yearly for energy commodities compared to the 2005 level.

Two types of price variables are distinguished. One is prices in terms of the domestic currency p_i^e and p_i^m; the other is prices in terms of the foreign currency p_i^{We} and p_i^{Wm}. They are linked with each other as follows:

Equation 39:

$$p_i^e = \varepsilon \cdot p_i^{We}$$

Equation 40:

$$p_i^m = \varepsilon \cdot p_i^{Wm}$$

Furthermore, it is assumed that the economy faces balance of payments constraints, which is described with export and import prices in foreign currency terms:

Equation 41:

$$\sum_i p_i^{We} \cdot E_{r,i} \underset{\substack{f \\ r}}{+} = \sum_i p_i^{Wm} \cdot M_i$$

Where

- $E_{r,i}$ Export of i-th commodity in region r,
- $M_{r,i}$ Import of i-th commodity in region r,
- p_i^{We} Export price in terms of foreign currency,
- p_i^e Export price in terms of domestic currency,
- p_i^{Wm} Import price in terms of foreign currency,
- p_i^m Import price in terms of domestic currency.

Substitution between imports and domestic goods

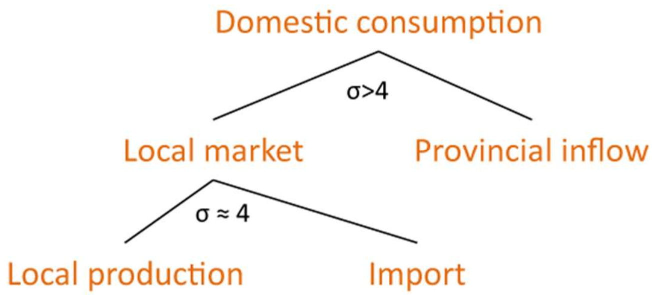

Figure S4: Nesting of Imported Goods, Locally Produced Goods and Goods Produced in Other Provinces. σ is elasticity of substitution for inputs

The Armington assumption is adopted, i.e., the domestic and imported goods are imperfectly substitutable for each other, which implies that households and firms don't directly consume or use imported goods but instead a so-called "Armington composite goods", which is made up of imported and locally produced goods as well as goods produced in other provinces by a two-level nested CES function (Figure S4).

Import activity is described by the bottom nesting of Figure S4. In the CGE model, the Armington composite goods at this level is created by virtual firms which maximize their profits by choosing a proper combination of imported and locally produced goods. The solution of their profit-maximization problem leads to their input demands for imported and domestic goods, which depend on the corresponding relative prices domestic and imported goods. Mathematically, this problem can be expressed as:

Equation 42:

$$max: \pi_{r,i}^{md} = p_{r,i}^{md} \cdot Q_{r,i}^{md} - [(1+\tau_{r,i}^{m}) \cdot p_{i}^{m} \cdot M_{r,i} + p_{r,i}^{d} \cdot D_{r,i}^{d}]$$

s.t.

Equation 43:

$$Q_{r,i}^{md} = \alpha_{r,i}^{md} \cdot (\delta_{r,i}^{m} \cdot M_{r,i}^{-\rho_{r,i}^{md}} + \delta_{r,j}^{d} \cdot D_{r,i}^{-\rho_{r,i}^{md}})^{\frac{-1}{\rho_{r,j}^{md}}}$$

Where

- $\pi_{r,i}^{md}$ Profit of the firm producing the i-th Armington composite goods of import and locally produced goods,
- $Q_{r,i}^{md}$ The i-th Armington composite goods of import and locally produced goods,
- $D_{r,i}^{d}$ The i-th locally produced goods,

- $p_{r,i}^{md}$ Armington price of the i-th imported and locally produced goods,
- $p_{r,i}^{d}$ Price of the i-th locally produced goods,
- $\tau_{r,i}^{m}$ Import tariff rate on the i-th commodity,
- $\alpha_{r,i}^{md}$ Shift (or efficiency) parameter in the Armington composite goods production function,
- $\delta_{r,i}^{m}, \delta_{r,j}^{d}$ Input share parameters in the Armington composite goods production function ($0 \leq \delta_{r,i}^{m} \leq 1, 0 \leq \delta_{r,j}^{d} \leq 1,\ \delta_{r,i}^{m} + \delta_{r,i}^{d} = 1$,
- $\rho_{r,i}^{md}$ The CES substitution parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{(1+\rho)}$.

Then the composite imported and locally produced goods will be further aggregated with the goods produced in other provinces to form the final Armington composite goods that are consumed by households, government and as intermediate inputs by firms.

Transformation between exports and domestic goods

On the supply side, the produced commodities are distributed to international market, local market and market in other provinces by a two-level nested constant elasticity of transformation function. Similar to the treatment of import, a virtual firm is assumed for each commodity which transforms the gross domestic output into exports and domestic goods as follows:

Equation 44:

$$max{:}\,\pi_{r,i}^{dx} = (p_i^{e} \cdot E_{r,i} + p_{r,i}^{dd} \cdot D_{r,i}^{s}) - (1 + \tau_{r,i}^{z}) \cdot p_{r,i}^{z} \cdot Q_{r,i}^{dx}$$

s.t.

Equation 45:

$$Q_{r,i}^{dx} = \alpha_{r,i}^{dx} \cdot (\delta_{r,i}^{e} \cdot E_{r,i}^{\rho_{r,i}{}^{dx}} + \delta_{r,j}^{d} \cdot D_{r,i}^{s\ \rho_{r,i}^{dx}})^{\frac{1}{\rho_{r,i}^{dx}}}$$

Where

- $\pi_{r,i}^{dx}$ Profit of the firm engaged in the i-th transformation,
- $Q_{r,i}^{dx}$ Gross domestic output of the i-th goods,

- $D_{r,i}^{s}$ i-th goods supplied to domestic market,
- $p_{r,i}^{z}$ Price of the i-th gross domestic output,
- $p_{r,i}^{dd}$ Price of domestically supplied goods,
- $\tau_{r,i}^{z}$ Production tax rate on the i-th commodity,
- $\alpha_{r,i}^{dx}$ Shift (or efficiency) parameter in the transformation function,
- $\delta_{r,i}^{e}$, $\delta_{r,j}^{d}$ Share parameters in the transformation function ($0 \leq \delta_{r,i}^{e} \leq 1$, $0 \leq \delta_{r,j}^{d} \leq 1$, $\delta_{r,i}^{e} + \delta_{r,i}^{d} = 1$),
- $\rho_{r,i}^{dx}$ Transformation elasticity parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{\rho-1}$.

It should be noted that the goods supplied to the domestic market at this level, $D_{r,i}^{s}$, will be further distributed to local market and market in other provinces through inter-provincial trade, which will be described in the next section.

Inter-provincial trade

An important feature of this model is that it is a country model in which inter-provincial trade is treated. Similar to the case of international trade, Armington assumption is adopted to distinguish between locally produced commodity and commodity produced by firms in other provinces, and CES and CET functions are employed to describe commodity inflow from and outflow to all provinces, respectively.

Substitution commodity between local market and inflow from other provinces

This section describes the top-level nesting of Figure S4 which treats inter-provincial inflow of commodity. By this stage the commodity in the local market is an aggregation of locally produced and imported goods, which needs to be further aggregated with goods produced in other provinces to form the final Armington composite goods to be consumed by final consumers and firms. The treatment is similar to import:

Equation 46:

$$max\colon \pi_{r,i}^{dd} = p_{r,i}^{a} \cdot Q_{r,i}^{dd} - [p_{r,i}^{md} \cdot Q_{r,i}^{md} + \sum_{rr} p_{rr,i}^{inf} \cdot D_{rr,r,i}^{inf}]$$

s.t.

Equation 47:

$$Q_{r,i}^{dd} = \alpha_{r,i}^{dd} \cdot (\delta_{r,i}^{md} \cdot Q_{r,i}^{md\,-\rho_{r,i}^{dd}} + \sum_{rr} \delta_{rr,r,i}^{inf} \cdot D_{rr,r,i}^{inf\ -\rho_{r,i}^{dd}})^{\frac{-1}{\rho_{r,i}^{dd}}}$$

Where

- $\pi_{r,i}^{dd}$ Profit of the firm producing the i-th Armington composite goods of local market and inflow from other provinces,
- $Q_{r,i}^{dd}$ Armington composite goods,
- $D_{rr,r,i}^{inf}$ The i-th goods inflowing from region rr to region r,
- $p_{r,i}^{a}$ Armington price taken by the final consumers and firms,
- $p_{rr,i}^{inf}$ Price of the i-th goods inflowing from province rr to region r,
- $\alpha_{r,i}^{dd}$ Shift (or efficiency) parameter in the Armington composite goods production function,
- $\delta_{r,i}^{md}$, $\delta_{rr,r,j}^{inf}$ Input share parameters in the Armington composite goods production function ($0 \leq \delta_{r,i}^{md} \leq 1, 0 \leq \delta_{rr,r,j}^{inf} \leq 1, \delta_{r,i}^{md} + \sum_{rr} \delta_{rr,r,i}^{inf} = 1$),
- $\rho_{r,i}^{dd}$ The CES substitution parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{(1+\rho)}$.

Transformation between goods sold in local market and outflowing to other provinces

Goods supplied to the domestic market, $D_{r,i}^{s}$, will be further distributed to local market and market in other provinces through, similar to the treatment of export, a CET function as follows:

Equation 48:

$$max\!: \pi_{r,i}^{pp} = (p_i^d \cdot D_{r,i}^{local} + \sum_{rr} p_{rr,i}^{out} \cdot D_{r,rr,i}^{out}) - p_{r,i}^{dd} \cdot D_{r,i}^{s}$$

s.t.

Equation 49:

$$Q_{r,i}^{pp} = \alpha_{r,i}^{pp} \cdot (\delta_{r,i}^{local} \cdot D_{r,i}^{local\rho_{r,i}^{pp}} + \sum_{rr} \delta_{r,rr,i}^{out} \cdot D_{r,rr,i}^{out\ \rho_{r,i}^{pp}})^{\frac{1}{\rho_{r,i}^{pp}}}$$

Where

- $\pi_{r,i}^{pp}$ Profit of the firm engaged in the i-th transformation,
- $Q_{r,i}^{pp}$ Out of the i-th goods supplied to local and other provinces' markets,
- $D_{r,i}^{local}$ i-th Goods supplied to local market,
- $D_{r,rr,i}^{out}$ i-th Goods outflowing from region r to other province rr,
- $p_{rr,i}^{out}$ Price of the i-th Goods outflowing to other province rr,
- $\alpha_{r,i}^{pp}$ Shift (or efficiency) parameter in the transformation function,
- $\delta_{r,i}^{local}$, $\delta_{r,rr,i}^{out}$ Share parameters in the transformation function ($0 \leq \delta_{r,i}^{local} \leq 1$, $0 \leq \delta_{r,rr,j}^{out} \leq 1$, $\delta_{r,i}^{local} + \sum_{rr} \delta_{r,rr,i}^{out} = 1$),
- $\rho_{r,i}^{pp}$ Transformation elasticity parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{\rho-1}$.

Market clearance conditions

The above sections describe the behavior of economic agents such as the households, firms, government, investment agents and the interactions with other provinces and the rest of the world. The final step is to impose the market-clearing conditions to all commodities and factor markets as follows:

Equation 50:

$$Q_{r,i} = x_{r,i}^{p} + x_{r,i}^{g} + x_{r,i}^{v} + \sum_{j} x_{r,i,j}$$

Equation 51:

$$\sum_{j} v_{r,f,j} = V_{r,f}$$

Macro closure

In a CGE model, the issue of macro closure is the choice of exogenous variables among all variables in the model, mainly including investment and saving macro closure, and current account balance macro closure. In this model, investment is exogenously assumed. In addition, foreign exchange rate is fixed and thus balanced of payment is an endogenous variable.

Table S2: GDP Loss, Welfare Loss and Sectoral Output Loss Rate Relative to Reference Scenarios in 2030

	BaU0	INDC1	INDC2	BaU3	INDC3
GDP	2.26%	0.95%	0.89%	0.37%	0.34%
Welfare	3.14%	1.07%	0.99%	0.51%	0.38%
Agriculture	9.26%	3.88%	3.62%	1.82%	1.41%
Mining	-0.24%	0.06%	0.06%	0.43%	0.02%
Food	3.05%	1.80%	1.68%	0.59%	0.65%
Textile	3.72%	2.08%	1.94%	0.74%	0.75%
Paper	0.00%	1.80%	1.68%	0.00%	0.65%
Oil Refinery	0.51%	0.14%	0.13%	0.03%	0.05%
Direct Energy	1.68%	0.61%	0.57%	0.19%	0.22%
Chemicals	2.81%	0.84%	0.79%	0.58%	0.30%
Cement	2.70%	0.54%	0.51%	0.55%	0.19%
Iron & steel	0.25%	-0.51%	-0.47%	0.12%	-0.18%
Metal Products	2.33%	0.26%	0.24%	0.40%	0.09%
Machinery	2.51%	0.60%	0.55%	0.52%	0.21%
Electronic	1.62%	0.93%	0.87%	0.36%	0.34%
Other Manufacture	1.72%	0.15%	0.14%	0.07%	0.05%
Electricity	1.82%	0.00%	0.00%	0.26%	0.00%
Construction	1.06%	0.29%	0.27%	0.21%	0.10%
Transport	0.82%	0.36%	0.33%	0.15%	0.13%
Service	3.27%	1.58%	1.47%	0.61%	0.57%

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