2017生產力與數據包絡分析研習會

DEA於碳交易與PM2.5之邊際減排成本分析
(一噸二氧化碳賣多少錢?)

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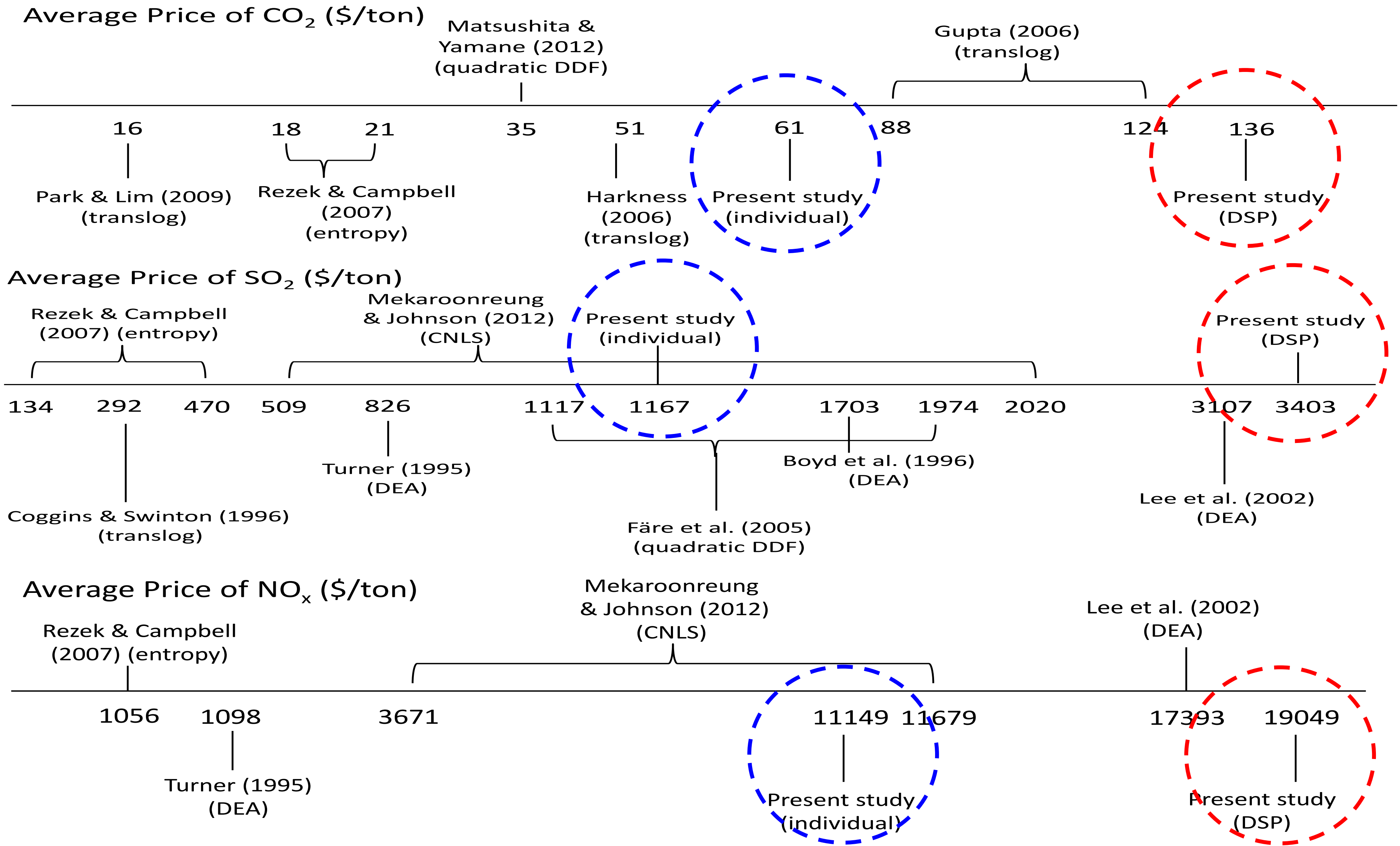
以2010年美國火力發電廠為例

- 估計邊際減排成本(marginal abatement cost, MAC)
  - On average, US$ 61 for CO2, 1167 for SO2, and 11149 for NOx (underestimated)



How much does it cost to abate per ton of CO_2, SO_2, and NO_x?

Outline

- Introduction
- Directional Marginal Productivity (DMP)
- Marginal Abatement Cost (MAC) Estimation
- Empirical Study
- Concluding Remarks

Introduction

- Productivity and Efficiency
  - Productivity
    - defined by the output level over the input level

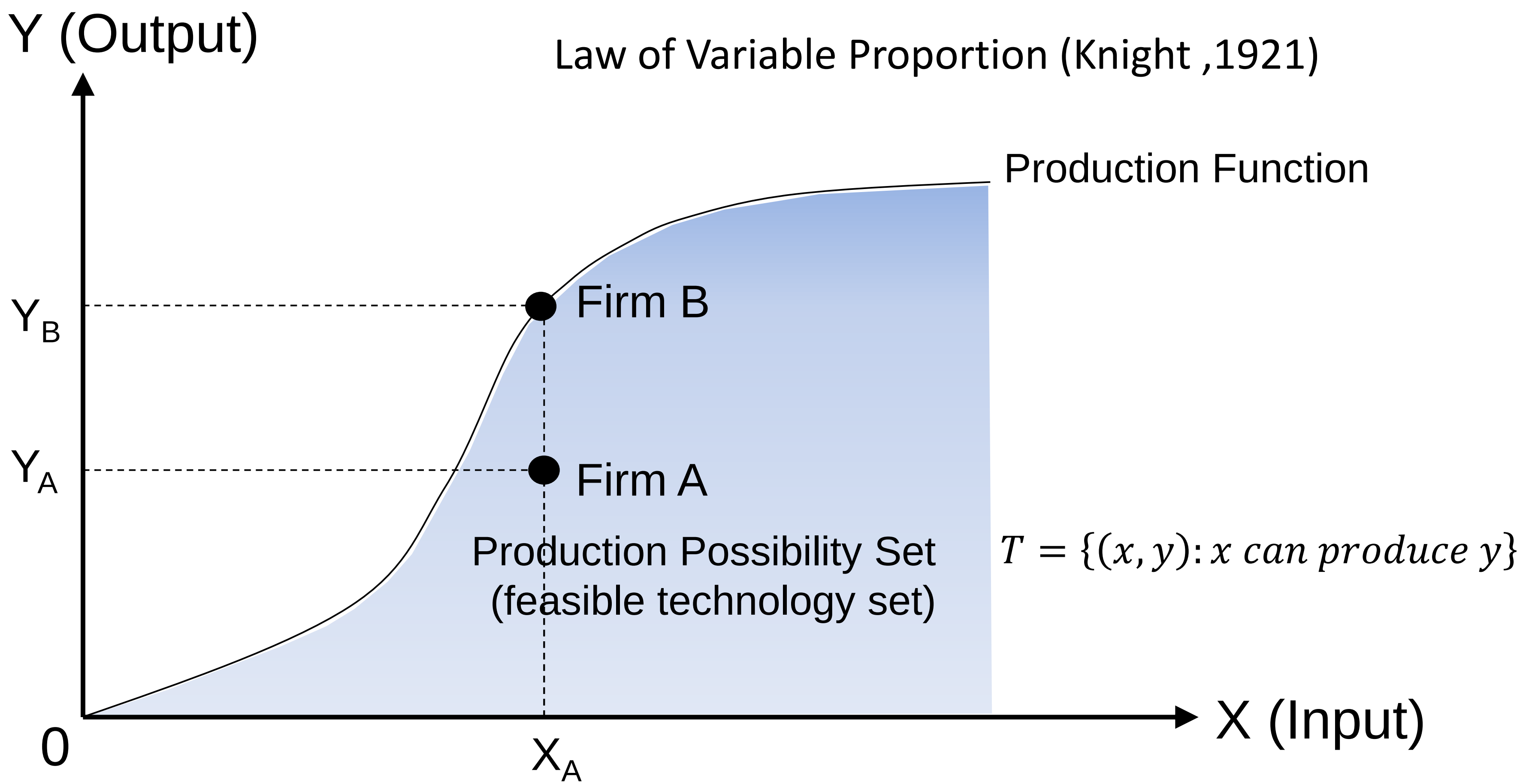
$$Prod_A = \frac{Y_A}{X_A}$$

  - Efficiency
    - The productivity benchmarking with best practice

$$Eff_A = \frac{Y_A / X_A}{Y_B / X_B}$$

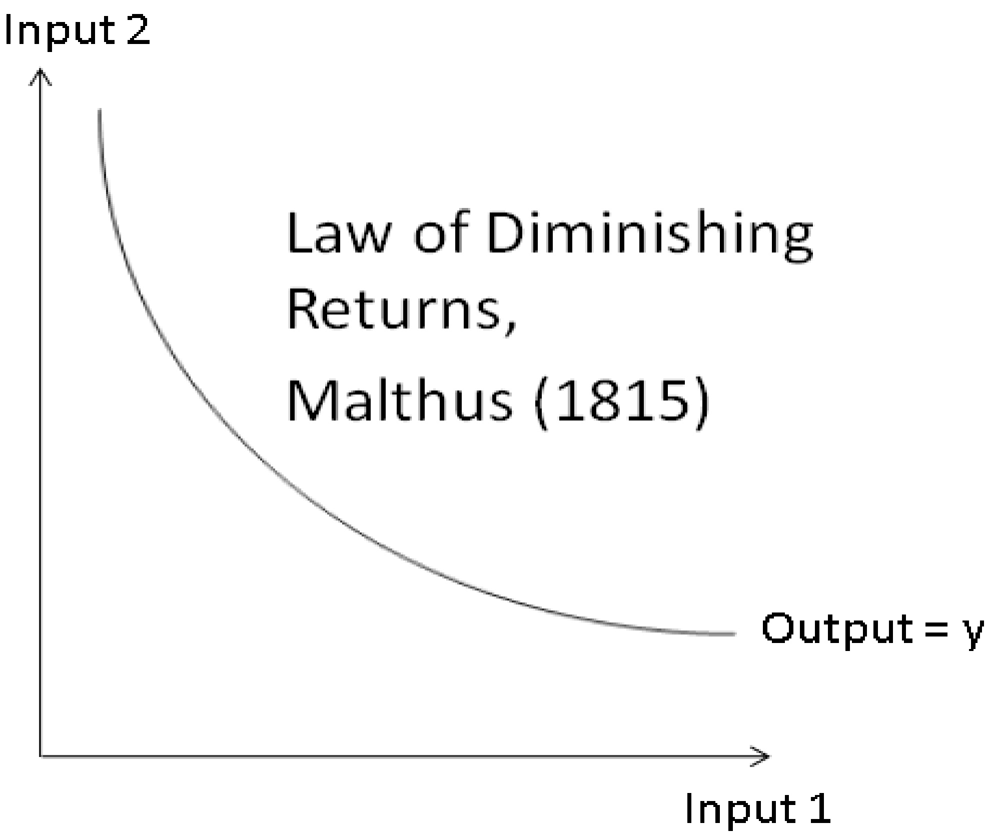
where B is the best practice

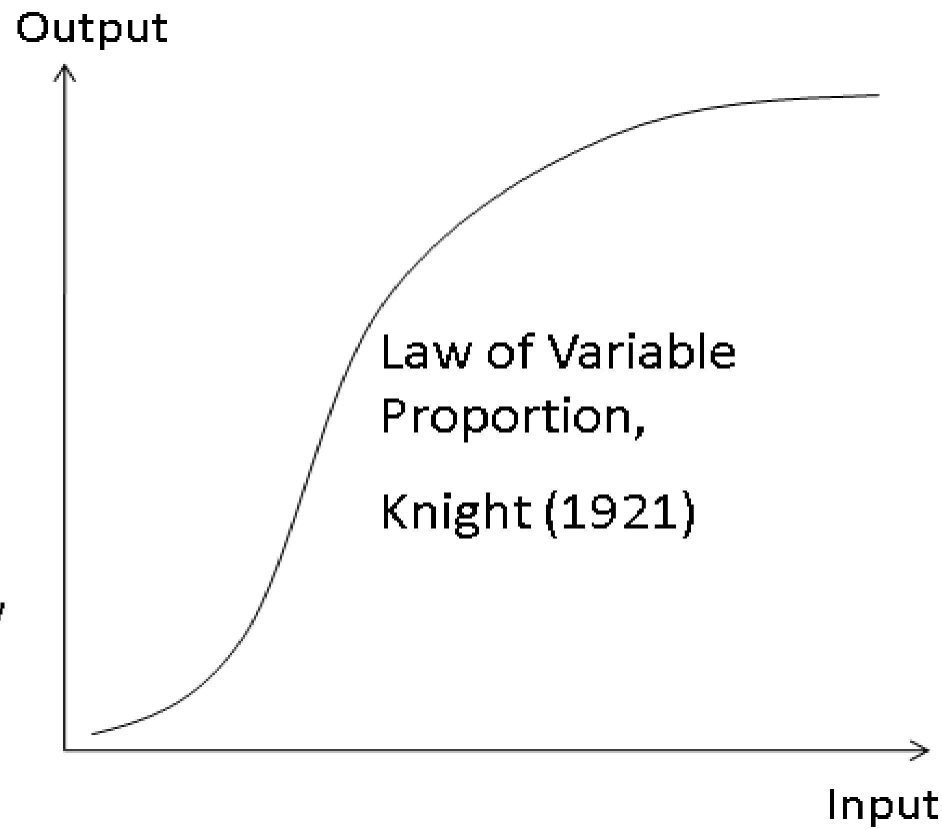
- Production Theory and Efficiency



A production function is a function that represents "maximum outputs" that can be achieved using input vector $\mathbb{x}$.

- Production Theory and Efficiency



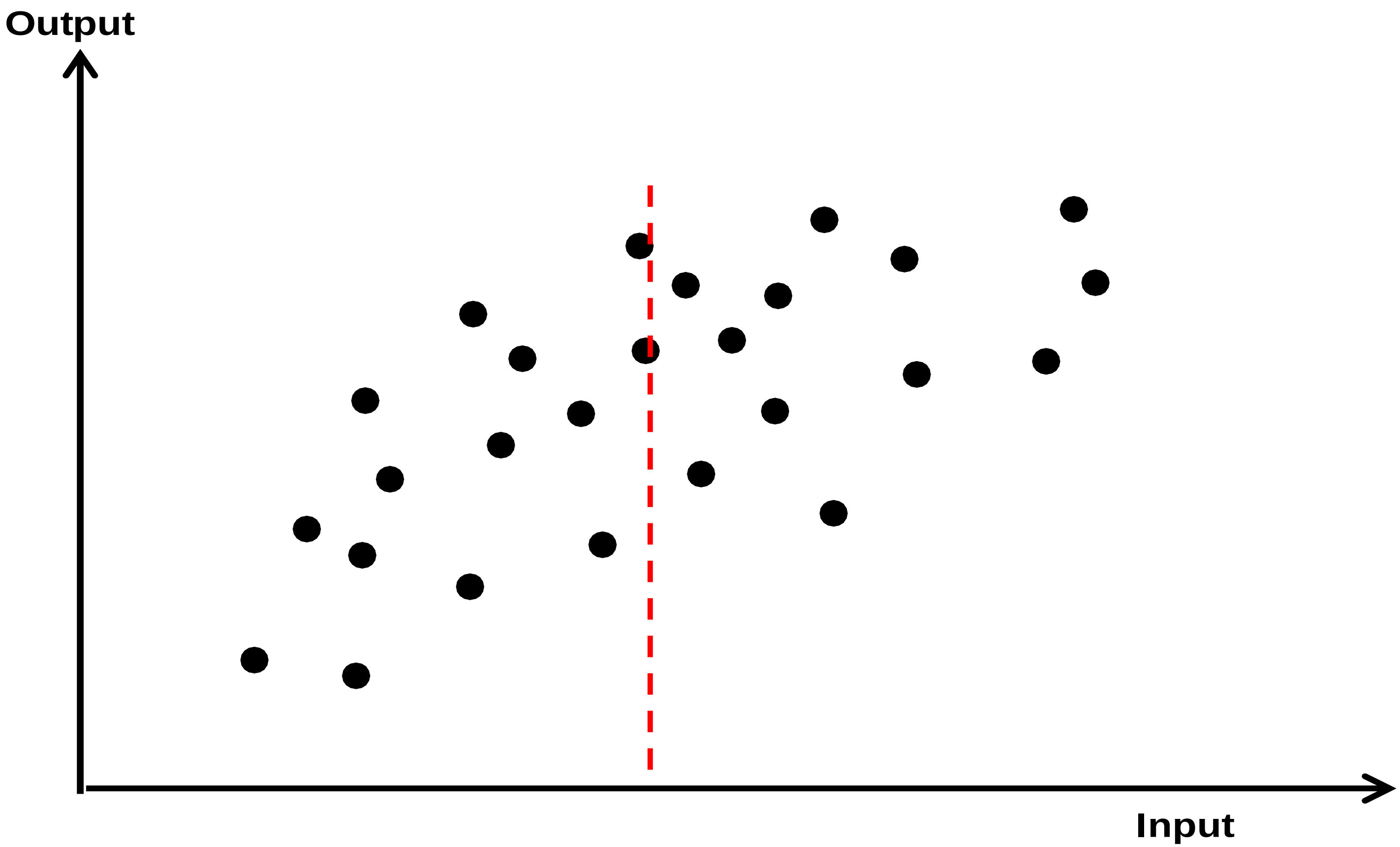


If we can observe the true production function, then the efficiency can be estimated. However, in practice, a **true production function is not observed** and must be estimated.

- Properties of Production Function
  - Chambers, 1988; Coelli, *et al.*, 2005
  - Nonnegativity: The production output is a finite, non-negative, real number.
  - Weak Essentiality: The production output cannot be generated without the use of at least one input.
  - Monotonicity: Additional units of an input will not decrease output; also called *nondecreasing* in $\mathbb{x}$.
  - Concavity: Any linear combination of the vectors $\mathbb{x}^0$ and $\mathbb{x}^1$ will produce an output that is no less than the same linear combination of $f(\mathbb{x}^0)$ and $f(\mathbb{x}^1)$. That is, $f(\lambda\mathbb{x}^0 + (1-\lambda)\mathbb{x}^1) \geq \lambda f(\mathbb{x}^0) + (1-\lambda)f(\mathbb{x}^1)$. This property implies the "law of diminishing marginal returns".

- Production Function Estimation
  - Productivity and efficiency analysis introduces the methodology to measure the performance of firms, which transforms input resources into output product or service (Coelli *et al*., 2005). $Y = \mathrm{F}(X)$
    - In practice, a **true production function** is not observed and must be estimated.
  - Approaches
    - Stochastic Frontier Analysis (SFA)
      - Parametric regression-based approach
      - Aigner et al., 1977; Meeusen and van den Broeck, 1977
    - Data Envelopment Analysis (DEA)
      - Nonparametric optimization-based approach
      - Charnes et al., 1978; Banker et al., 1984

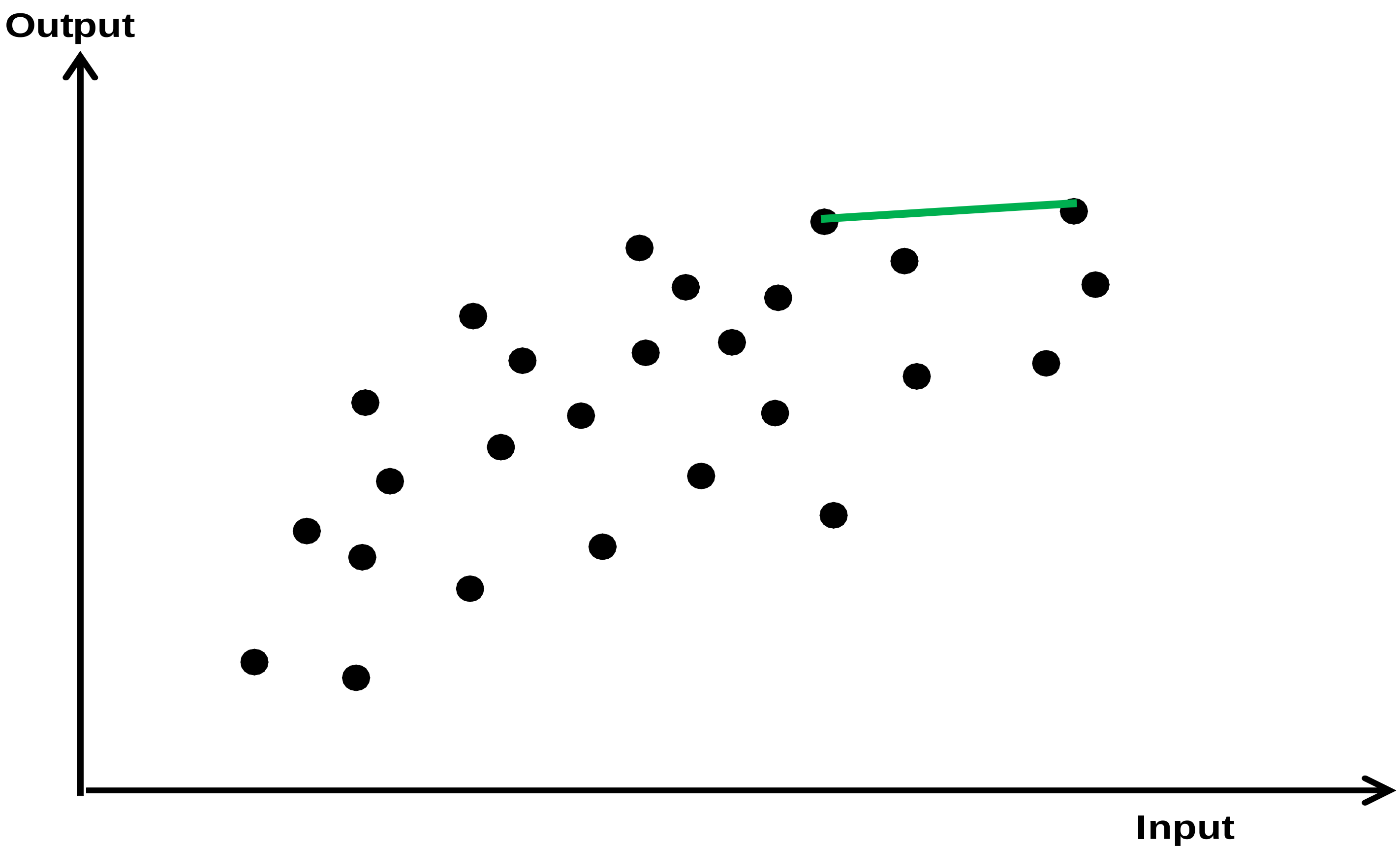
- Observed Production Data (26 points)



How to measure efficiency?

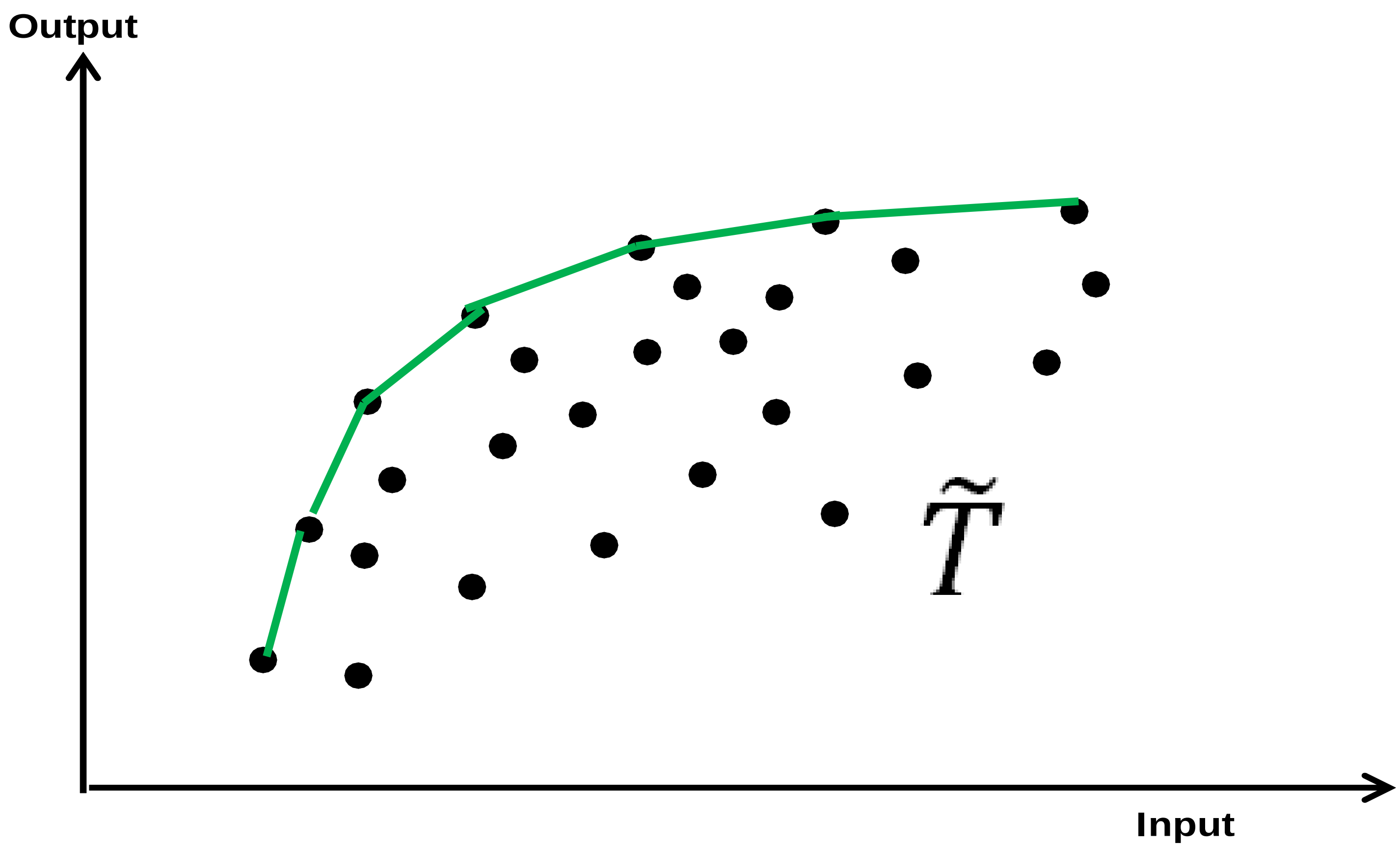
Introduction

- Data Envelopment Analysis (DEA)
  - Assumption1: Convexity



Introduction

- Data Envelopment Analysis (DEA)
  - Assumption1: Convexity
  - Assumption2: Monotonicity

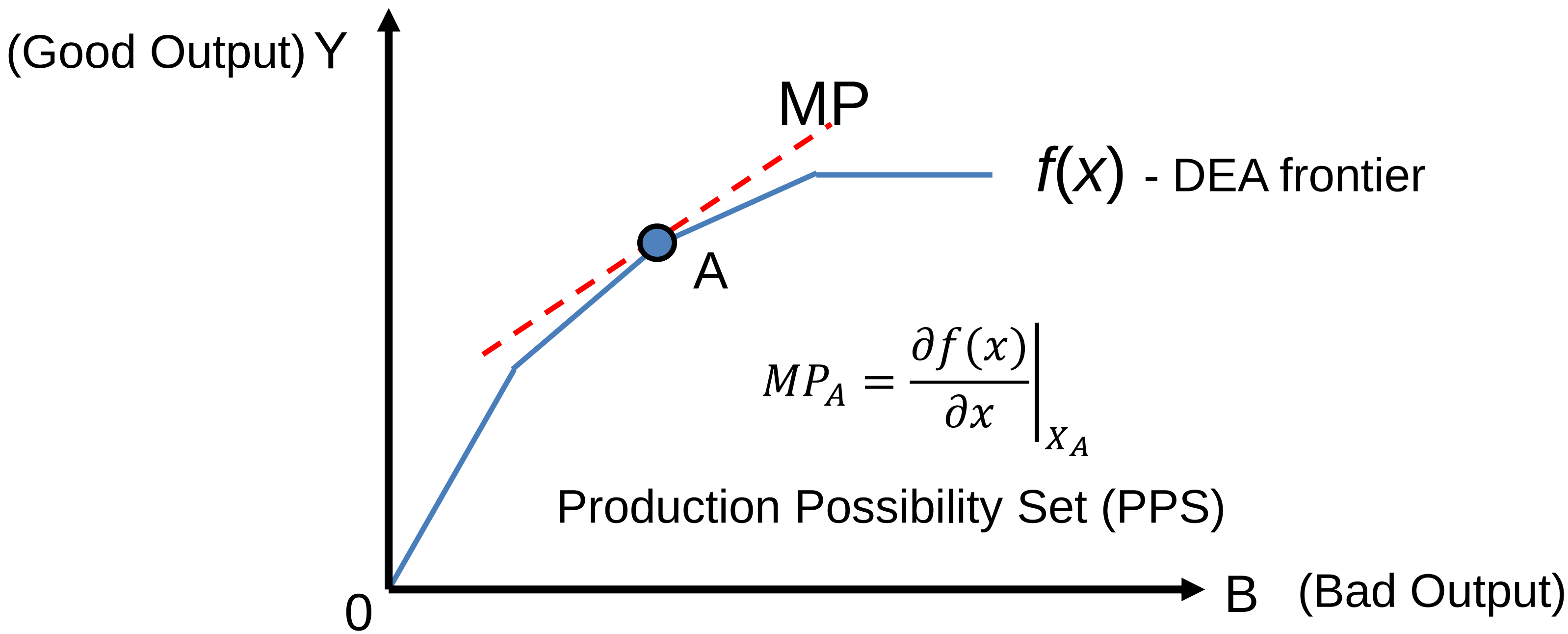


Directional Marginal Productivity (DMP)

Marginal Productivity

- The shadow prices (SP) of pollutants are used as a reference value to the allowance price in the trading market (Lee et al., 2002).

- Estimate the marginal product (MP) with respect to one efficient benchmark to derive the SP (Keilback, 1995), which is a differentiable characteristic of the production function.
  - Dual variables in data envelopment analysis (DEA)



$$MP_A = \left.\frac{\partial f(x)}{\partial x}\right|_{x_A}$$

- Marginal Productivity $MP_A = \left.\frac{\partial f(x)}{\partial x}\right|_{X_A}$
- Podinovski and Førsund (2010) propose a directional derivative technique to assess the marginal product of a nondifferential efficient frontier constructed by the data envelopment analysis (DEA)estimator.

$$\frac{\partial Y_{j^*r}}{\partial X_{i^*r}} = \beta_{i^*j^*r}^{+DEA} = \text{Min } v_{i^*}$$

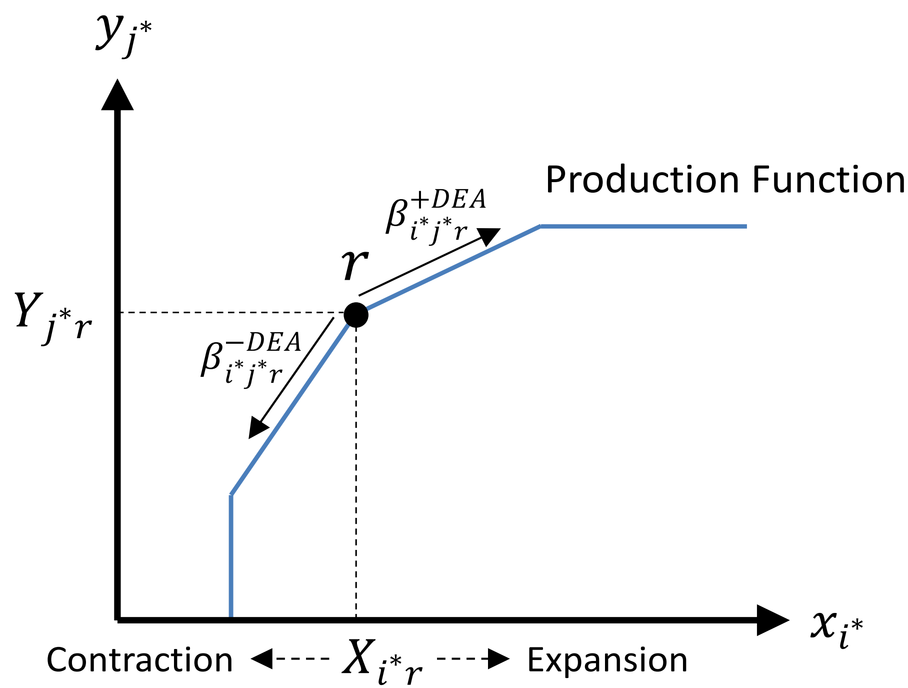
Subject to

$$\sum_i v_i X_{ir} - \sum_j u_j Y_{jr} + u_0 = 0$$

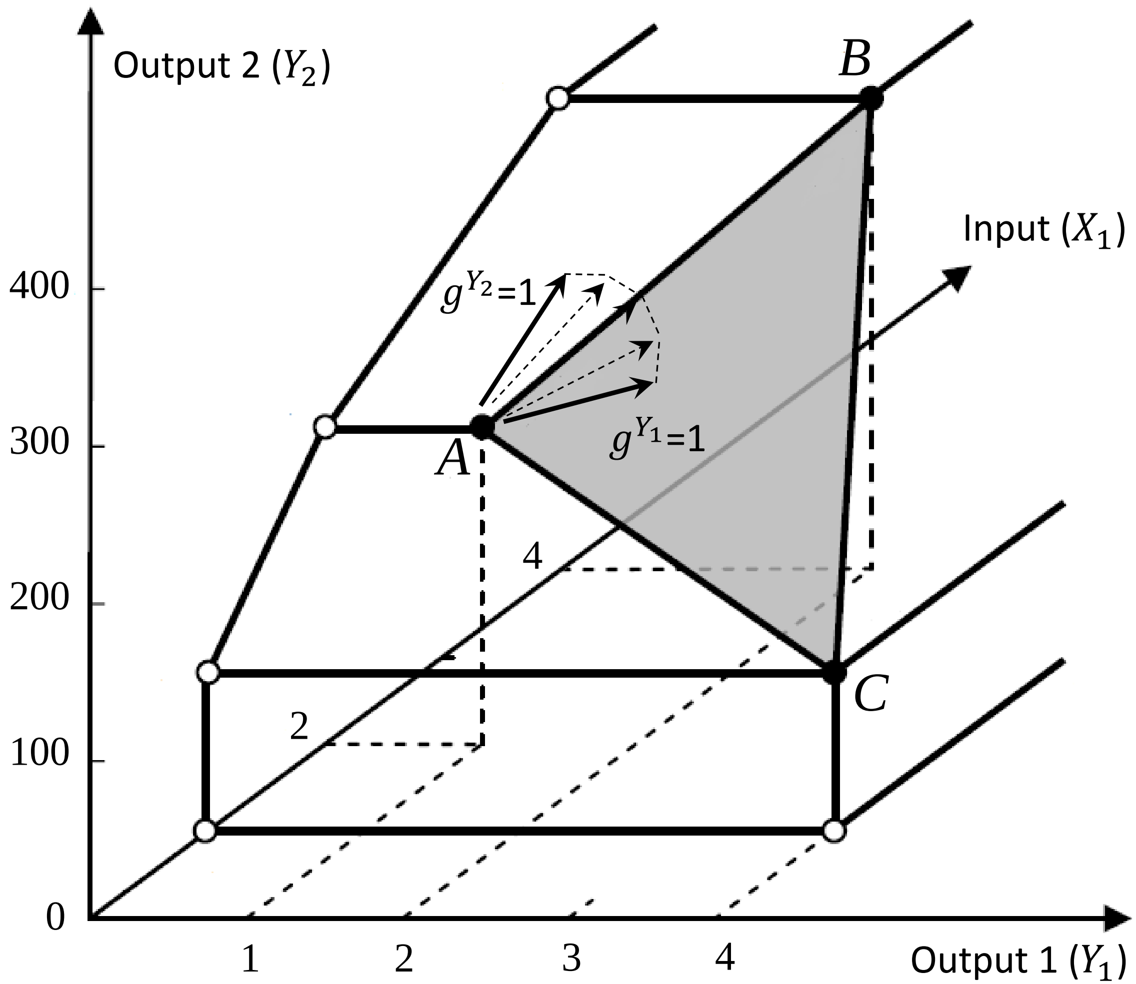
$$\sum_i v_i X_{ik} - \sum_j u_j Y_{jk} + u_0 \geq 0, \forall k$$

$$u_{j^*} = 1$$

$v_i, u_j \geq 0$, u_0 is free



- Desirable Output Substitution with One Extra Unit of Input



Lee (2013)

- How the change of single input X_{i^*} affects the multiple outputs
  - Let set $J^* \subset J$ be the outputs set investigated. Given the direction vector $(g^{X_{i^*}}, g^{Y_j})$ as parameters, where $g^{X_{i^*}} = 0$ and $\sum_{j \in J^*} g^{Y_j} = 1$ for unit simplex (Färe et al., 2013). Let $X_i^{Max} = \max\{X_{ik}\}$ and $Y_j^{Max} = \max\{Y_{jk}\}$

$$\alpha = \mathrm{Min}\ \frac{v_{i^*}}{X_{i^*}^{Max}}$$

s.t. $\sum_i v_i \frac{X_{ir}}{X_i^{Max}} - \sum_j u_j \frac{Y_{jr}}{Y_j^{Max}} + u_0 = 0$

$$\sum_i v_i \frac{X_{ik}}{X_i^{Max}} - \sum_j u_j \frac{Y_{jk}}{Y_j^{Max}} + u_0 \geq 0, \forall k$$

$$\sum_{j \in J^*} u_j g^{Y_j} = 1$$

$v_i, u_j \geq 0$, u_0 is free

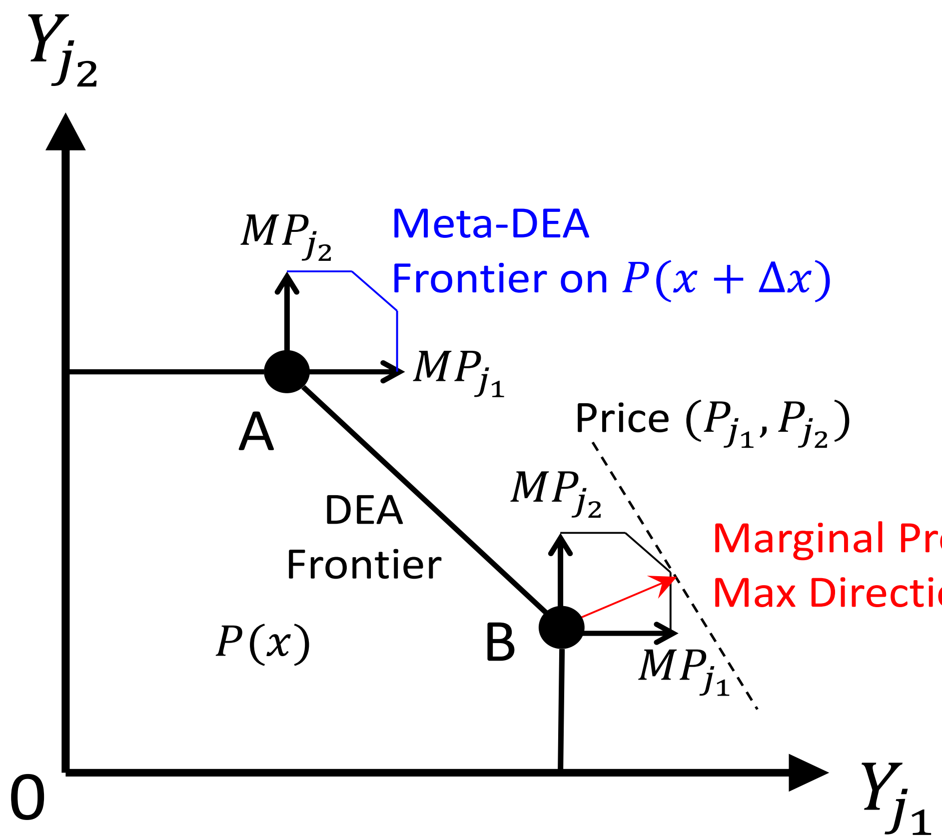
The reason for introducing unit simplex and eliminating the measurement units of inputs and outputs is to normalize the weight which presents a tradeoff among outputs.

  - increasing one extra unit of X_{i^*} of firm r, means that the vector of the DMP with respect to output Y_j is $\frac{\partial Y_{jr}}{\partial X_{i^*r}} = \alpha \times \left(g^{Y_j} Y_j^{Max}\right), \forall j \in J^*$.

Proposition 1: If the direction for MP estimation used in proposed model projects to the portion of free disposability with respect to inputs, then the DMP estimate will be equal to 0.

Proposition 2: The marginal productivity estimated by the proposed model with the objective function $\mathrm{Max}\ \frac{v_{i^*}}{X_{i^*}^{Max}} = \alpha$ is equivalent to the marginal productivity estimated, given a negative direction.

- Meta-DEA (Lee, 2014, EJOR)
  - Given (g^{y_1}, g^{y_2}) a variant of DDF can generate this "direction".
  - an approach to find a direction for an efficient firm to move towards its allocatively efficient benchmark based on maximization of the firm's marginal profits.



(Lee, 2014)

- DMP
  - Return to the example in Podinovski and Førsund (2010), which includes one input, two outputs, and three observations (units A, B, and C in following Table)

Unit	Input (X_1)	Output 1 (Y_1)	Output 2 (Y_2)
A	2	1	200
B	4	2	300
C	1	4	100

  - Formulation

$$\text{Min } \frac{v_1}{4} = \alpha$$

$$\text{s.t. } v_1\frac{2}{4} - u_1\frac{1}{4} - u_2\frac{200}{300} + u_0 = 0$$

$$v_1\frac{4}{4} - u_1\frac{2}{4} - u_2\frac{300}{300} + u_0 \geq 0$$

$$v_1\frac{1}{4} - u_1\frac{4}{4} - u_2\frac{100}{300} + u_0 \geq 0$$

$$u_1 g^{Y_1} + u_2 g^{Y_2} = 1$$

$$v_1, u_1, u_2 \geq 0,\ u_0 \text{ is free}$$

$$\frac{\partial(Y_{1A}, Y_{2A})}{\partial X_{1A}} = \alpha \times (4g^{Y_1}, 300g^{Y_2})$$

- DMP and meta-DEA of Y_1 and Y_2 in unit A

Case No.	Direction (normalized)		Objective Function	Multi-product MP	Meta-DEA
	g^{Y_1}	g^{Y_2}	α	$\frac{\partial(Y_{1A}, Y_{2A})}{\partial X_{1A}}$	$\frac{P_1}{P_2}$
Case 1	1	0	1	(4, 0)	[14.3198, ∞)
Case 2	0.9	0.1	0.70	(2.53, 21.05)	[14.26X, 14.3198)
Case 3	0.8	0.2	0.54	(1.73, 32.43)	[14.26X, 14.26X)
Case 4	0.7	0.3	0.44	(1.23, 39.56)	[14.26X, 14.26X)
Case 5	0.6	0.4	0.37	(0.89, 44.44)	[14.24, 14.26X)
Case 6	0.5	0.5	0.32	(0.64, 48.00)	[10, 14.24)
Case 7	0.4	0.6	0.28	(0.44, 50.00)	(0, 10)
Case 8	0.3	0.7	0.24	(0.29, 50.00)	
Case 9	0.2	0.8	0.21	(0.17, 50.00)	
Case 10	0.1	0.9	0.19	(0.07, 50.00)	
Case 11	0	1	0.167	(0.00, 50.00)	

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Decision Support

Meta-data envelopment analysis: Finding a direction towards marginal profit maximization

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ABSTRACT

This paper discusses a new meta-DEA approach to solve the problem of choosing direction vectors when estimating the directional distance function. The proposed model emphasizes finding the "direction" for productivity improvement rather than estimating the "score" of efficiency; focusing on "planning" over "evaluation". In fact, the direction towards marginal profit maximization implies a step-by-step improvement and "wait-and-see" decision process, which is more consistent with the practical decision-making process. An empirical study of U.S. coal-fired power plants operating in 2011 validates the proposed model. The results show that the efficiency measure using the proposed direction is consistent with all other indices with the exception of the direction towards the profit-maximized benchmark. We conclude that the marginal profit maximization is a useful guide for determining direction in the directional distance function.

Marginal Abatement Cost (MAC)

How to estimate the marginal effects of multiple good and bad outputs when increasing one extra unit of input?

- Introduction
  - Total U.S. energy-related emissions of carbon dioxide (CO_2) by the electric power sector in 2012 were 2,039 million metric tons, or about 77% of total U.S. CO_2 emissions.
  - CO2 emissions from U.S. electricity generation by source, 2012

Source	Million Metric Tons	Share of Total
Coal	1,514	74%
Natural gas	494	24%
Petroleum	19	1%
Other[2]	12	1%
Total	2,039	

[2]Miscellaneous wastes and from geothermal power generation.

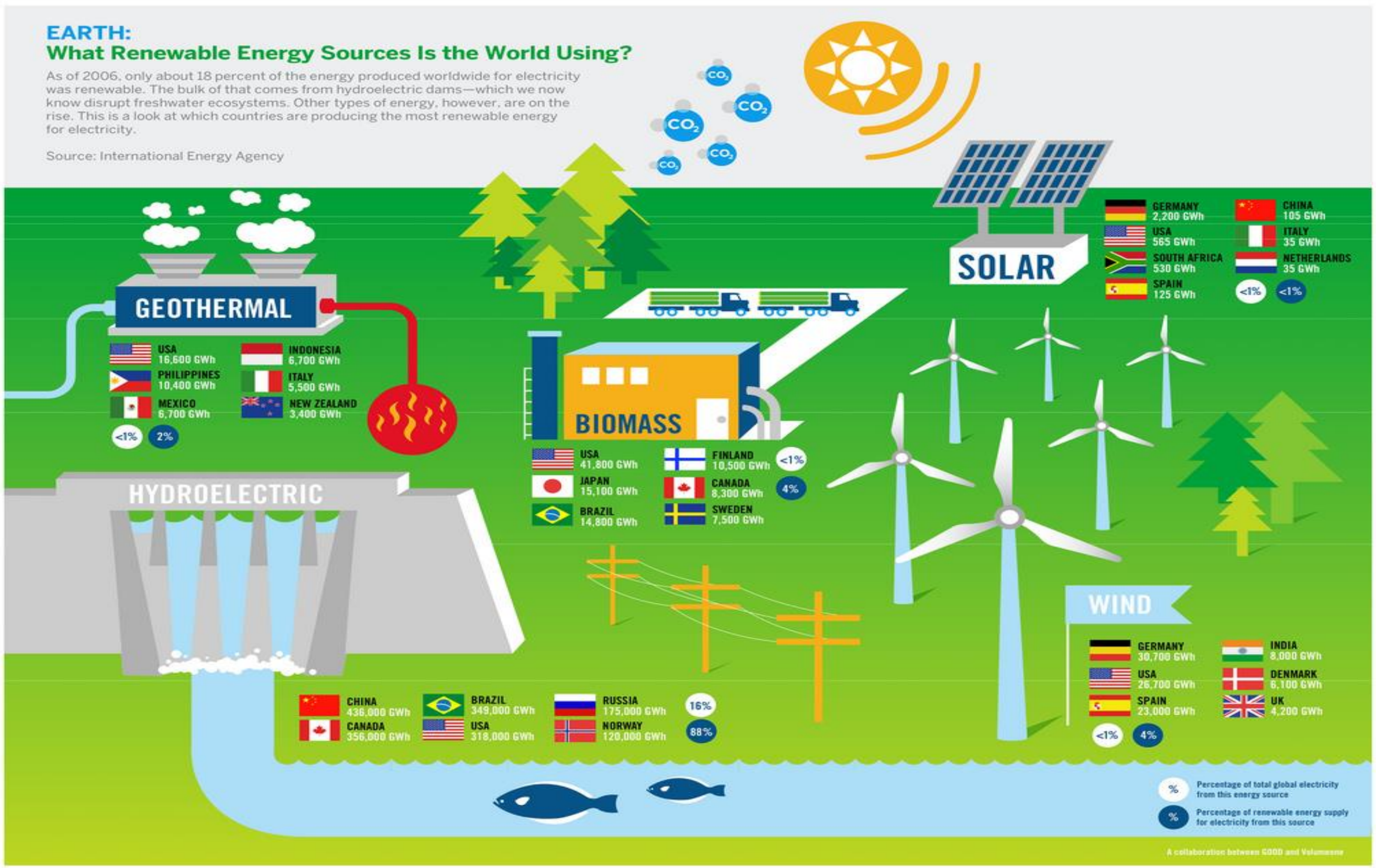
EIA, 2013. http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11
EIA, 2013. International Energy Statistics. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=90&pid=44&aid=8

Marginal Abatement Cost (MAC)

- Air Pollution in China
  - In 2012 China was the largest contributor to carbon emissions from fossil fuel burning and cement production, and responsible for 25 percent of global carbon emissions.
  - manufacturing and power generation are the major sectors contributing to China's carbon emissions, together these sectors accounted for 85 percent of China's total carbon emissions in 2012 (Liu, 2015).
  - In 2013-2015, China also struggled from the hazardous smog with the high concentration of PM 2.5.
  - Since 2013, seven pilot provinces and provincial cities, i.e. Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Chongqing and Hubei, have successively launched their emission trading scheme.

Emission Regulation

- Options to reduce emissions include:
  - ➢ Improved abatement technologies
  - ➢ Renewable energy
  - ➢ Tradable Permits for Emissions

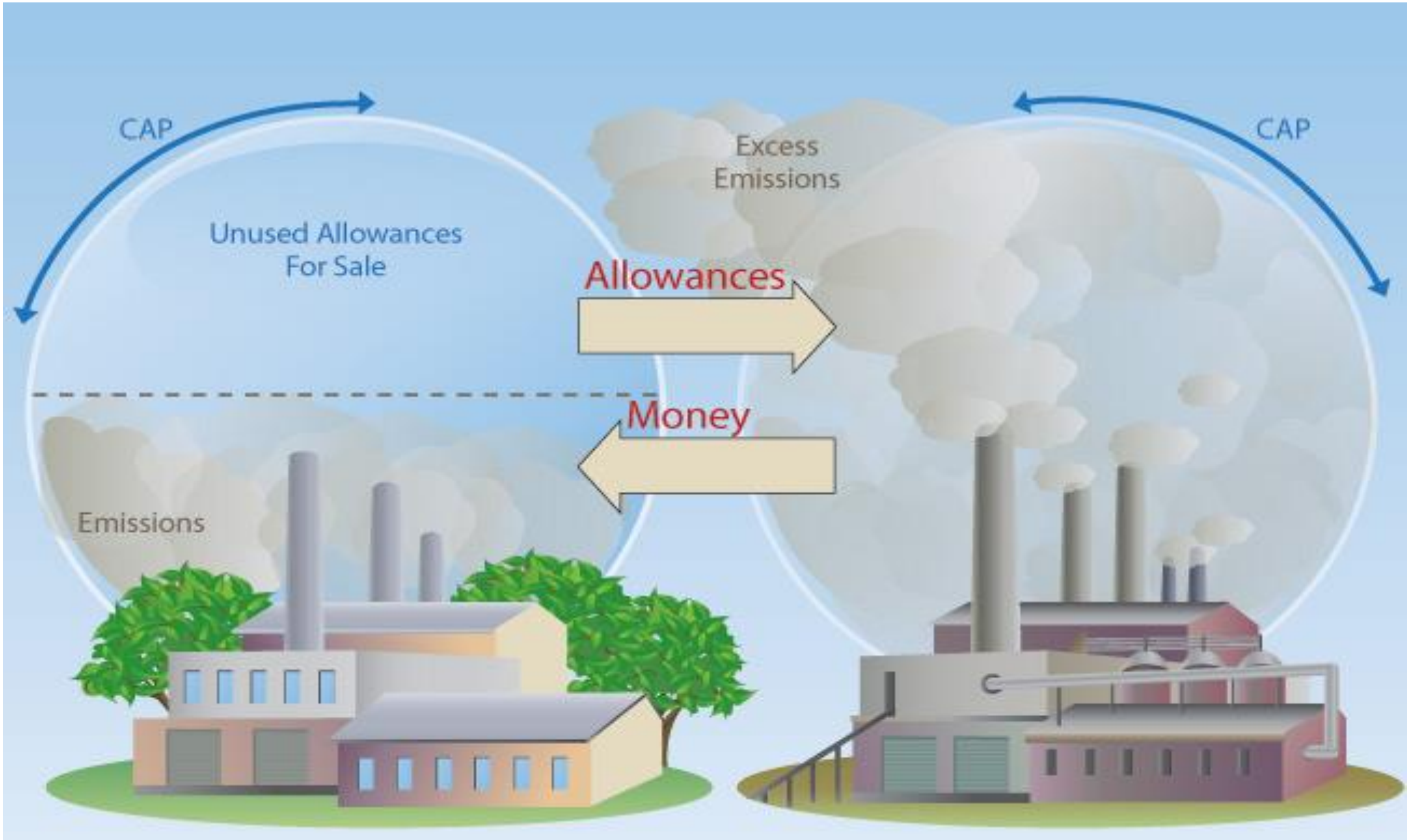


- Carbon Policy: carbon tax and cap-and-trade.

- 1) Carbon Tax is more about ‘Price’.
  - The carbon tax puts a direct price on each tonne of carbon (or GHG emitted) thereby sending a price signal that will, over time, elicit a market response across the economy to reduce carbon emissions.

- 2) Carbon Cap and Trade is more about ‘Quantity’.
  - The carbon cap system sets an absolute limit on the quantity of carbon emissions across specified industrial sectors. At the same time, the permits for each tonne of carbon emissions that specified industrial sectors get can be sold and transferred within the system.

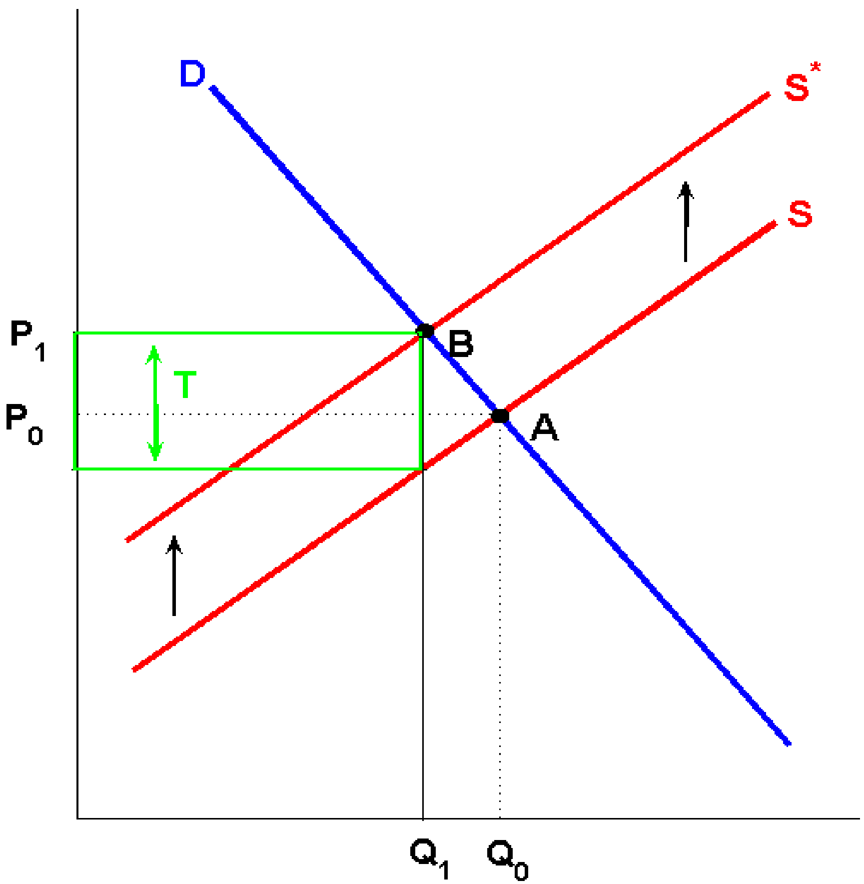
Idea is …



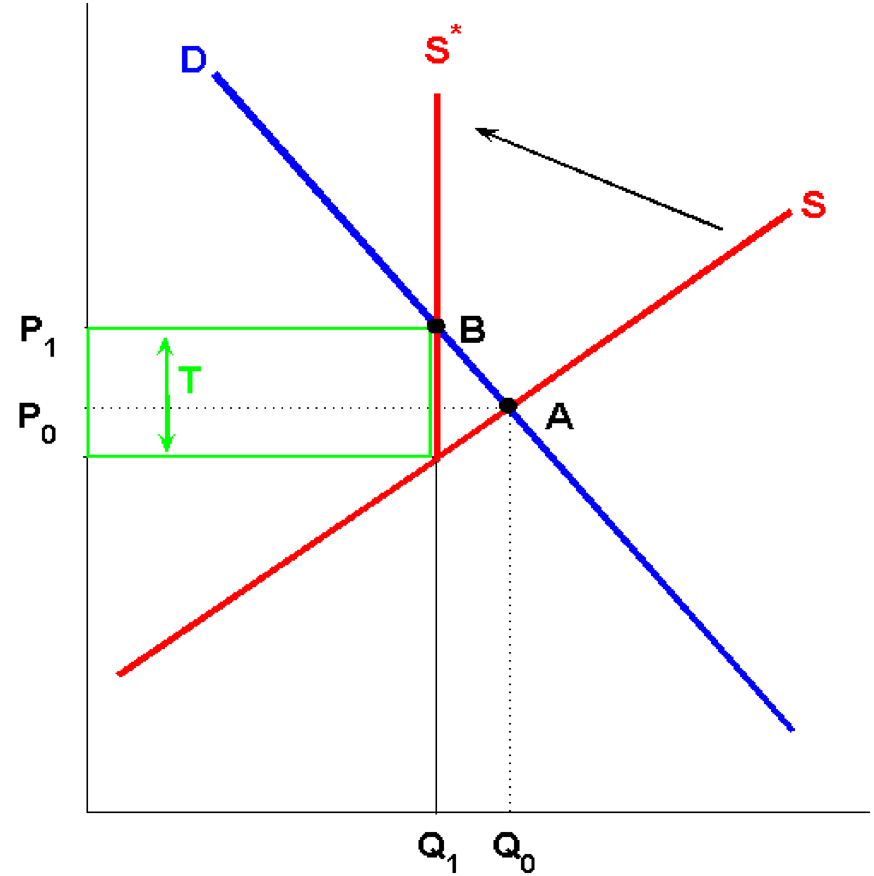
Calwatchdog.com (2013)

Tax vs. Cap-and-Trade

Carbon tax



Cap-and-trade



Cap-and-Trade

- Goal:
  - ➢ Reduce carbon dioxide and other greenhouse gas emissions economy-wide in a cost-effective manner.
- Cap (碳總量管制)
  - ➢ Each large-scale emitter (company)
  - ➢ A limit on the amount of greenhouse gas that it can emit.
    - Emission Permits
    - Over time more restrictive
- Trade (碳交易)
  - ➢ Some companies will reduce their emissions below their required limit more quickly and efficiently than others.
  - ➢ They can sell their extra permits to other companies.

Marginal Abatement Cost (MAC)

- Cap-and-Trade Regulation
  - Economic solutions to environmental externalities, such as the air pollution, often include emissions taxes and permit trading systems.
  - Policy-makers need to determine the marginal abatement costs (MAC) or shadow prices (SP) of pollutants to represent the costs of reducing one extra unit of pollutant.
  - The emission trading mechanism is based on Coase's assertion (Coase, 1960) that if trading in an externality and absent a transaction cost, bargaining will lead to an efficient outcome regardless of the initial allocation of property rights trading.
  - Since 2013, seven pilot provinces and provincial cities, i.e. Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Chongqing and Hubei, have successively launched their emission trading scheme.

How much does it cost to abate one ton of pollutant emission?

Literatures for MAC estimation

- Profit Maximization

Good Output, Bad Output, Input

$$\pi(p_y, p_b, p_x) = \max_{y,b,x} \underbrace{p_y' y}_{\text{Good Output}} - \underbrace{p_b' b}_{\text{Bad Output}} - \underbrace{p_x' x}_{\text{Input}}$$

$$\text{s.t. } F(x, y, b) = 0$$ (Production Transformation Function)

- Lagrange function: $\max_{y,b,x} p_y' y - p_b' b - p_x' x + \varphi F(x, y, b)$
- First-order conditions (FOCs):
  - $p_{y_j} + \varphi \frac{\partial F(x,y,b)}{\partial y_j} = 0$
  - $-p_{b_q} + \varphi \frac{\partial F(x,y,b)}{\partial b_q} = 0$
  - $-p_{x_i} + \varphi \frac{\partial F(x,y,b)}{\partial x_i} = 0$
  - $F(x, y, b) = 0$

- Marginal Abatement Cost

$$p_{b_q} = p_{y_j} \underline{\left(\frac{\partial F(x,y,b)}{\partial b_q} \Big/ \frac{\partial F(x,y,b)}{\partial y_j} \right)}$$

How to calculate the derivative of a production function?

- Stochastic Frontier Analysis (SFA) (Färe et al., 2005)
  - Parametric method
  - Translog functional form
  - Directional distance function

$$\ln D(x,y,b) = \alpha_0 + \sum_i \alpha_i \ln x_i + \sum_j \alpha_j \ln y_j + \sum_k \alpha_k \ln b_k$$
$$+ \frac{1}{2}\sum_i\sum_{i'}\gamma_{ii'} \ln x_i \ln x_{i'} + \frac{1}{2}\sum_j\sum_{j'}\gamma_{jj'} \ln y_j \ln y_{j'}$$
$$+ \frac{1}{2}\sum_k\sum_{k'}\gamma_{kk'} \ln b_k \ln b_{k'} + \sum_j\sum_k\gamma_{jk} \ln y_j \ln b_k$$
$$+ \sum_i\sum_j\beta_{ij} \ln x_i \ln y_j + \sum_i\sum_k\beta_{ik} \ln x_i \ln b_k \gamma_{ii'}$$
$$= \gamma_{i'i},\ i \neq i';\ \gamma_{jj'} = \gamma_{j'j},\ j \neq j';\gamma_{kk'} = \gamma_{k'k}, k \neq k$$

$$\text{Min} \sum_n \left[\vec{D}_o(x^n, y^n, b^n; g_y, -g_b) - 0\right]$$
$$\text{s.t. } \vec{D}_o(x^n, y^n, b^n; g_y, -g_b) \geqslant 0;$$
$$\partial\vec{D}_o(x^n, y^n, b^n; g_y, -g_b)/\partial y^n \leqslant 0;$$
$$\partial\vec{D}_o(x^n, y^n, b^n; g_y, -g_b)/\partial b^n \geqslant 0;$$
$$\partial\vec{D}_o(x^n, y^n, b^n; g_y, -g_b)/\partial x^n \geqslant 0;$$
$$g_y\sum_j \alpha_j - g_b\sum_k \alpha_k = -1;$$
$$g_y\sum_j\sum_{j'}\gamma_{jj'} - g_b\sum_j\sum_k\gamma_{jk} = 0;$$
$$g_y\sum_j\sum_k\gamma_{jk} - g_b\sum_k\sum_{k'}\gamma_{kk'} = 0;$$
$$g_y\sum_i\sum_j\beta_{ij} - g_b\sum_i\sum_k\beta_{ik} = 0;$$
$$g_y^2\sum_j\sum_{j'}\gamma_{jj'} + g_b^2\sum_k\sum_{k'}\gamma_{kk'} - g_y g_b\sum_j\sum_k\gamma_{jk} = 0;$$
$$\gamma_{ii'} = \gamma_{i'i},\ i \neq i';\ \gamma_{jj'} = \gamma_{j'j},\ j \neq j',\ \gamma_{kk'} = \gamma_{k'k},\ k \neq k'$$

Literatures for MAC estimation

- Data Envelopment Analysis (Lee et al. 2002)
  - Nonparametric method
  - Directional distance function
  - Dual variables

$$\vec{D}_o\left(x, y, b; g_y, g_b\right) = \max_{\lambda\beta} \beta$$

$$\begin{aligned} \text{s.t. } & Y\lambda \geqslant (1 + \beta g_y) y^n; \\ & B\lambda = (1 - \beta g_b) b^n; \\ & X\lambda \leqslant x^n; \\ & \beta, \lambda \geqslant 0 \end{aligned}$$

However…

Previous studies have estimated the shadow prices of individual undesirable outputs separately.

Marginal Abatement Cost (MAC)

- This equation $p_b = p_y \left(\frac{\partial \vec{D}_O(x,y,b;g^y,g^b)}{\partial b} \Big/ \frac{\partial \vec{D}_O(x,y,b;g^y,g^b)}{\partial y} \right)$, which takes derivatives with respect to one specific undesirable output to estimate its shadow price, implicitly assumes that a firm can generate only one type of pollutant at a time when increasing one extra unit of input.

- That is, estimating the shadow price of SO_2 is independent of estimating the shadow price of NO_x.

- In reality, the production process generates multiple undesirable outputs simultaneously when producing desirable outputs. Thus, estimating shadow prices separately may lead to an overestimation of marginal productivity and an underestimation of shadow price.

How to estimate the marginal effects of multiple bad outputs simultaneously when burning one extra unit of coal?

Directional Marginal Productivity (DMP)

Marginal Abatement Cost (MAC)

- DMP with Bad Outputs
  - Kuosmanen and Podinovski (2009) introduce the weak disposability property which forms a convex technology with undesirable outputs.
- MP for multiple outputs given a pre-determined direction (g^{Y_j}, g^{B_q})

$$\text{Min } v_{i^*}$$

$$\text{s.t. } \sum_i v_i \frac{X_{ir}}{X_i^{Max}} - \sum_j u_j \frac{Y_{jr}}{Y_j^{Max}} + \sum_q w_q \frac{B_{qr}}{B_q^{Max}} + u_0 = 0$$

$$\sum_i v_i \frac{X_{ik}}{X_i^{Max}} - \sum_j u_j \frac{Y_{jk}}{Y_j^{Max}} + \sum_q w_q \frac{B_{qr}}{B_q^{Max}} + u_0 \geq 0, \forall k$$

$$\sum_i v_i \frac{X_{ik}}{X_i^{Max}} + u_0 \geq 0, \forall k$$

$$\sum_{j \in J^*} u_j g^{Y_j} + \sum_{q \in Q^*} w_q g^{B_q} = 1$$

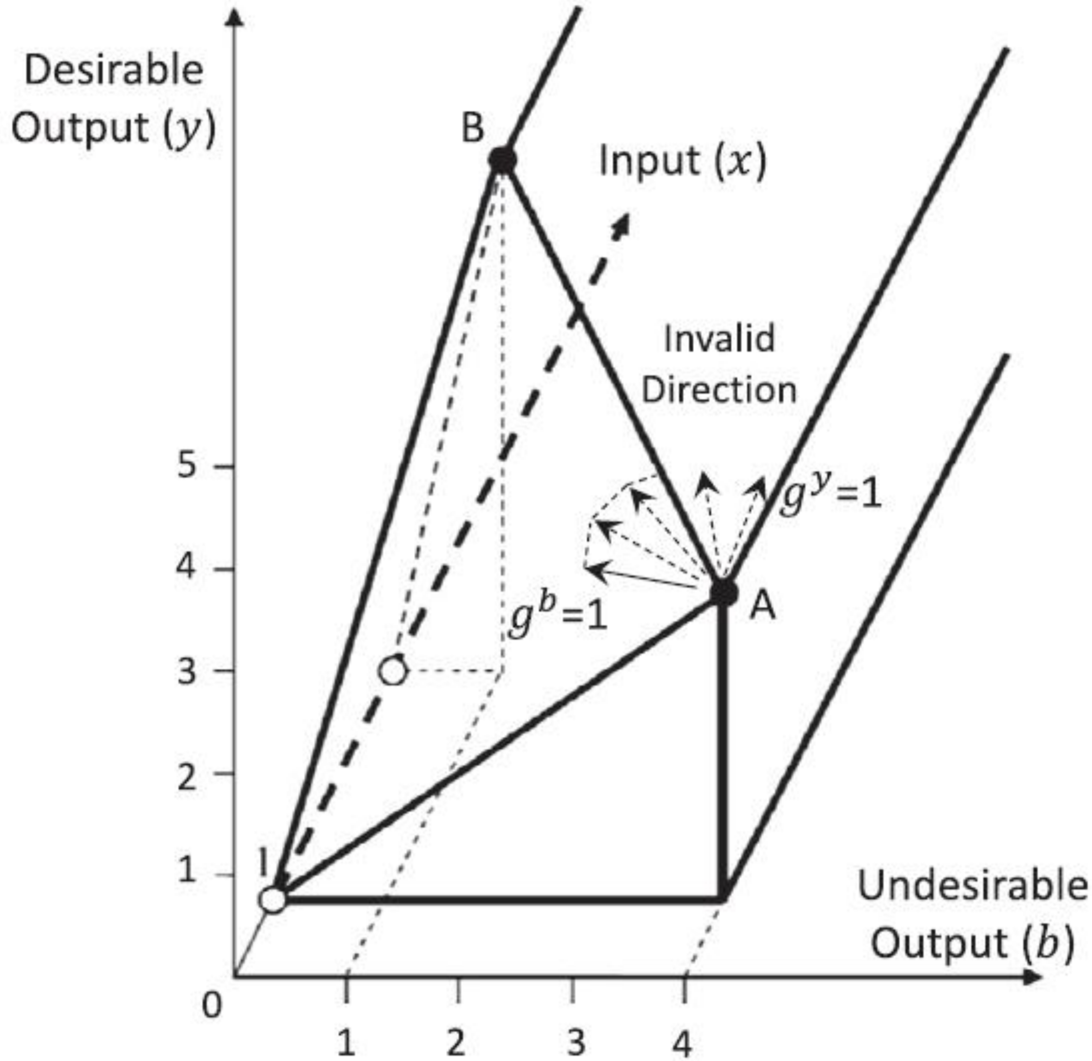
$$v_i, u_j \geq 0,\ w_q,\ u_0 \text{ are free}$$

$$\boxed{\frac{\partial (Y_{jr}, B_{qr})}{\partial X_{i^*r}} = v_{i^*}\left(g^{Y_j} Y_j^{Max}, -g^{B_q} B_q^{Max}\right) / X_{i^*}^{Max}}$$

Directional Marginal Productivity (DMP)

Note: $\sum_{j \in J^*} g^{Y_j} + \sum_{q \in Q^*} g^{B_q} = 1$ for unit simplex (Färe et al., 2013)

- DMP with Bad Output



Lee (2014)

Marginal Abatement Cost (MAC)

- Shadow Prices of Pollutants p_{b_q}
- $p_{b_q} = p_{y_j}\left(\frac{\partial F(x,y,b)}{\partial b_q} / \frac{\partial F(x,y,b)}{\partial y_j}\right) = p_{y_j}\left(\frac{\partial y_j}{\partial b_q}\right) = p_{y_j}\left(\frac{\partial y_j}{\partial x_i} / \frac{\partial b_q}{\partial x_i}\right)$

- Given direction vector (g^{Y_j}, g^{B_q})
- $\left(\frac{\partial y_j}{\partial x_i}, \frac{\partial b_q}{\partial x_i}\right)$: DMP of good output and bad output

$$\boxed{\frac{\partial(Y_{jr}, B_{qr})}{\partial X_{i^*r}} = v_{i^*}\left(g^{Y_j} Y_j^{Max}, -g^{B_q} B_q^{Max}\right) / X_{i^*}^{Max}}$$

Directional Marginal Productivity (DMP)

$\Downarrow$

Directional Shadow Price (DSP)

Empirical Study of Coal-Fired Power Plant in U.S.

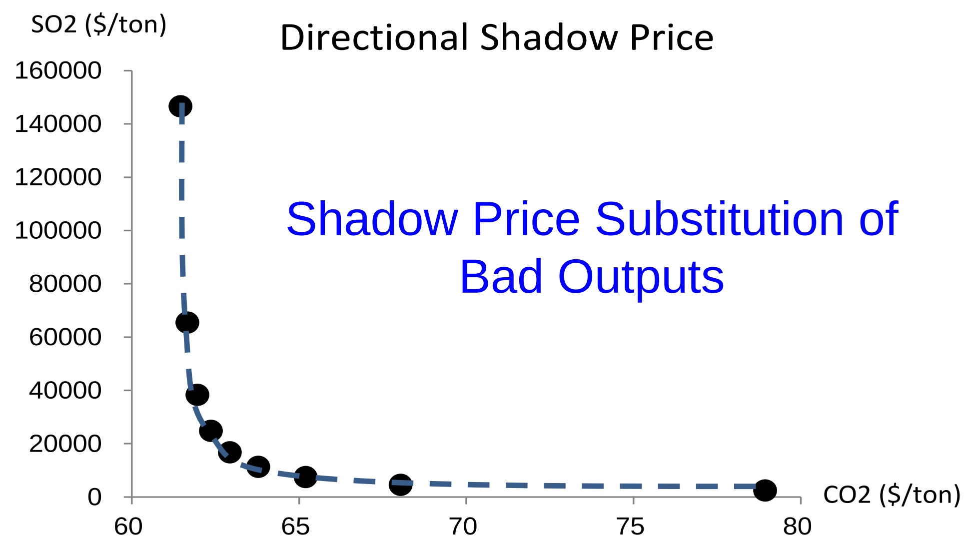
- Empirical Study: 2010 U.S. Coal Power Plants
- 48 observations of state-level dataset
- Inputs and Outputs
  - One desirable output: the annual amount of electricity generated by coal in Megawatt-hours (MWh).
  - Three undesirable outputs: the annual amount in tons of CO_2, SO_2 and NO_x.
  - One input: the annual amount in tons of coal consumption.
  - The average electricity price (p_y) is a weighted calculation among residential, commercial and industrial prices measured in dollars per MWh.

Empirical Study

- DMP and DSP of CO_2 and SO_2

Direction	DMP	DSP
$(g^{B_{CO_2}}, g^{B_{SO_2}}, g^{B_{NOx}})$	$\frac{\partial(B_{CO_2}, B_{SO_2}, B_{NOx})}{\partial X}$	$(p_{b_{CO_2}}, p_{b_{SO_2}}, p_{b_{NOx}})$
(1, 0, 0)	(2.0273, 0, 0)	(61.41, N/A, N/A)
(0.9, 0.1, 0)	(2.0060, 0.0008, 0)	(61.47, 146485, N/A)
(0.8, 0.2, 0)	(1.9755, 0.0019, 0)	(61.67, 65317, N/A)
(0.7, 0.3, 0)	(1.9615, 0.0032, 0)	(61.97, 38288, N/A)
(0.6, 0.4, 0)	(1.9545, 0.0049, 0)	(62.37, 24774, N/A)
(0.5, 0.5, 0)	(1.9502, 0.0074, 0)	(62.94, 16666, N/A)
(0.4, 0.6, 0)	(1.9472, 0.0110, 0)	(63.79, 11261, N/A)
(0.3, 0.7, 0)	(1.9450, 0.0171, 0)	(65.21, 7400, N/A)
(0.2, 0.8, 0)	(1.6151, 0.0244, 0)	(68.04, 4504, N/A)
(0.1, 0.9, 0)	(1.0208, 0.0294, 0)	(78.94, 2322, N/A)
(0, 1, 0)	(0, 0.0718, 0)	(N/A, 1167, N/A)

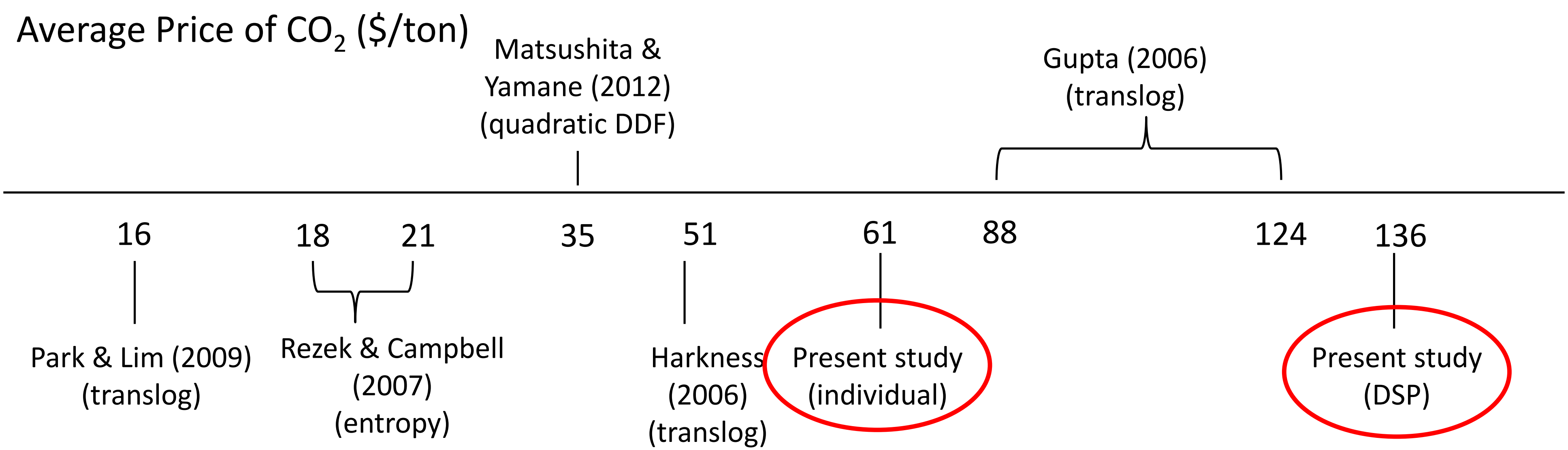
Individual Shadow Price (ISP)



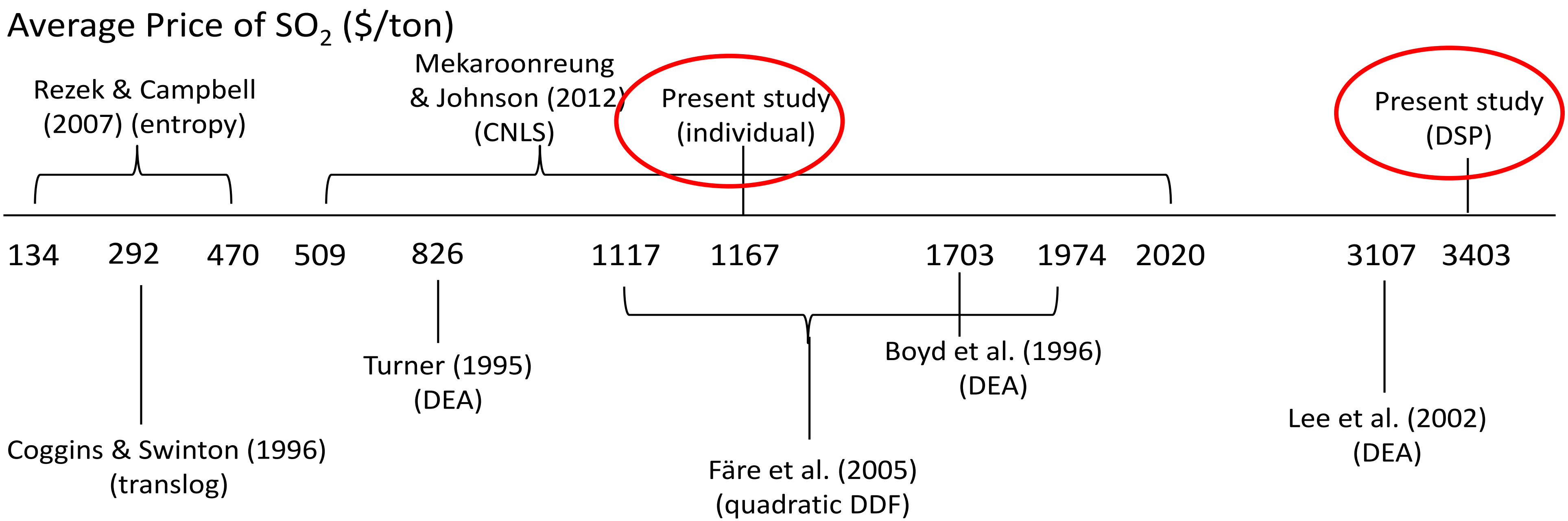
- Direction Generation ($g^{B_{CO2}}, g^{B_{SO2}}, g^{B_{NOx}}$)
  - Through a literature-based method, we found that the direction ($g^{B_{CO2}}, g^{B_{SO2}}, g^{B_{NOx}}$)=(0.048, 0.508, 0.444).

	Method	Literature-based			Method	Individual-SP		
	Direction ($g^{B_{CO2}}, g^{B_{SO2}}, g^{B_{NOx}}$)	0.048	0.508	0.444	Direction ($g^{B_{CO2}}, g^{B_{SO2}}, g^{B_{NOx}}$)	0.045	0.631	0.324
Boyd et al. (1996)	DSP	128	3212	17983	DSP	131	2478	23615
	Benchmarking Ratio (DSP/MSPL)	1.03	1.03	1.03	Benchmarking Ratio (DSP/ISP)	1.85	1.838	2.16
Turner (1995)	DSP	125	3121	17470	DSP	128	2410	22965
	Benchmarking Ratio (DSP/MSPL)	1.01	1.01	1.01	Benchmarking Ratio (DSP/ISP)	2.06	1.82	3.04

- Comparison of studies for shadow price estimations in electric power sectors

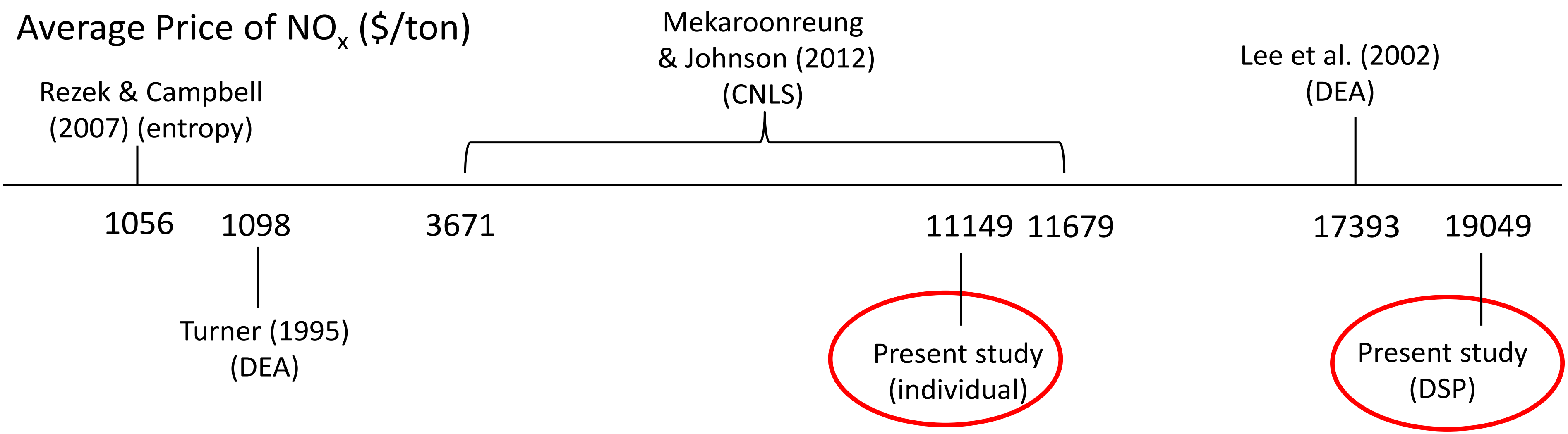


- Comparison of studies for shadow price estimations in electric power sectors

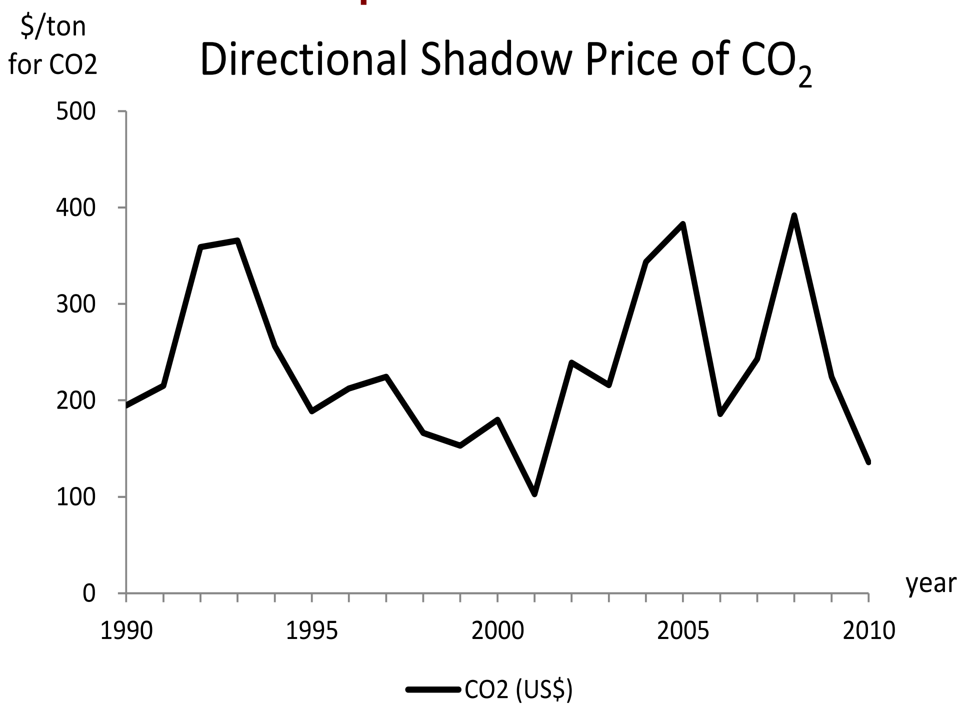


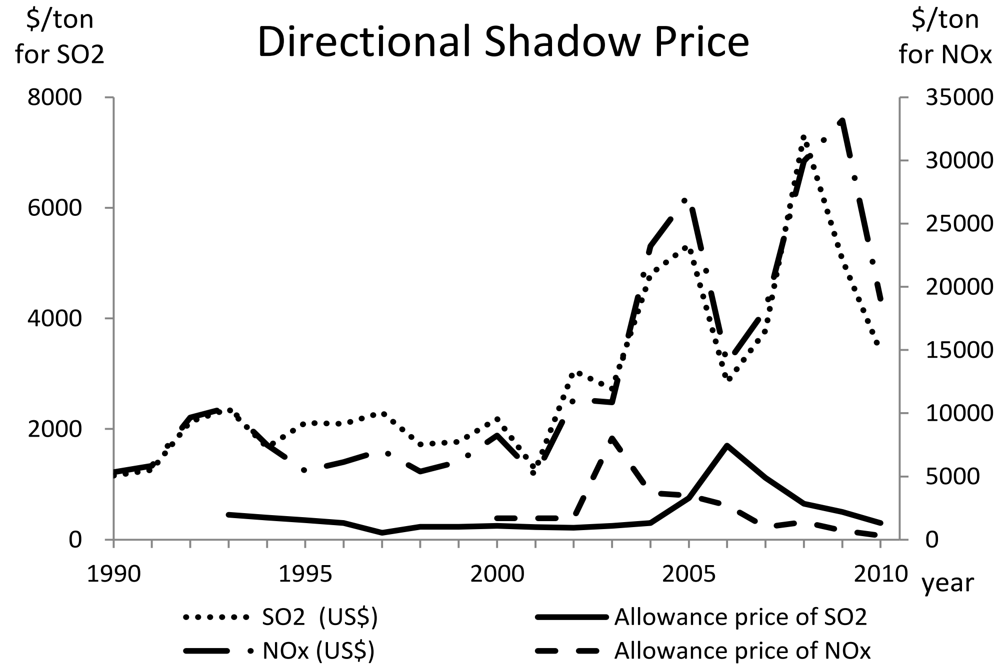
Empirical Study

- Comparison of studies for shadow price estimations in electric power sectors



- DSP of pollutants in 1990-2010

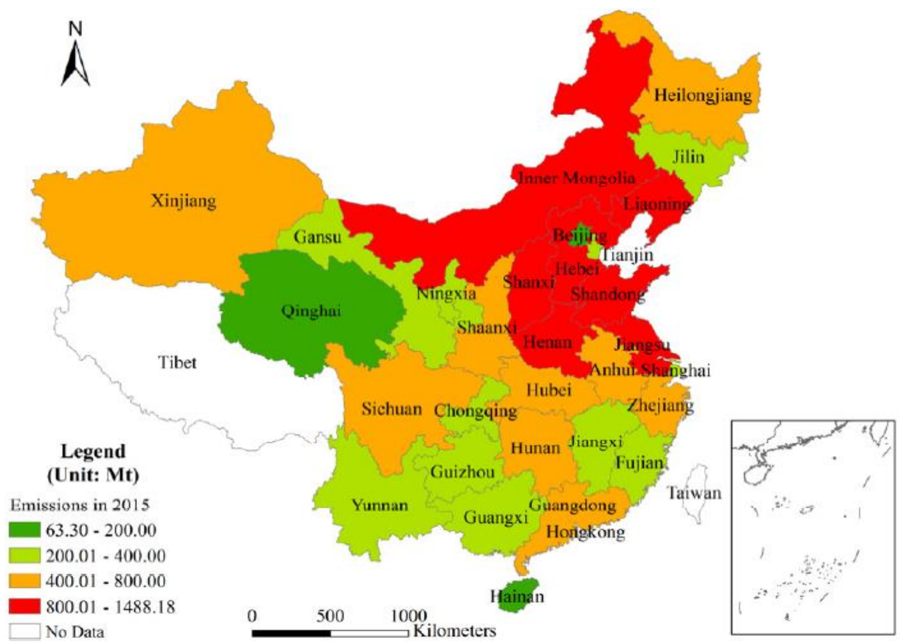




- The DSPs of SO_2 and NO_x rise gradually due to a successful emission reduction and Clean Air Interstate Rule (CAIR) beginning in 2010.
- Allowance prices rose in 2003 & 2006 since CAIR provided incentives for utilities to purchase allowances and bank them for future use.
- After 2005, emission levels fell because of the increased use of gas-fired boilers and pollution control equipment. Thus, an excess supply of allowances in the market caused allowance market prices to fall.

Empirical Study of
Coal-Fired Power Plant in China

2013 China Coal Power Plants in North and Northeast regions



Deng et al. (2015)

• Managerial Insights (Engineering Perspective)

- The higher MACs of SO_2 implies that the abatement technology of SO_2 in coal-fired power industry is urgent.
  - In fact, the key components of urban smog and acid rain are emissions of SO2 (Zhang and Samet, 2015).

- Nevertheless, it also implies the development of abatement technology on reducing SO_2 is not affordable. Thus, in the short run, the province should tend to purchase emission allowances of SO_2 from the market if the allowance price is much lower than MAC (in 2013 the average allowance price of carbon in Beijing is US$8.78 per tonne and US$5.18 in Tianjin, respectively).

- The lower MAC of NO_x implies that the plant is encouraged to invest the development of the NO_x abatement techniques at the present stage. Though the allowance price is lower than MAC, in the long run, when carbon regulation becomes more and more stringent, the MAC and allowance price is likely to rise.

- Managerial Insights (Market Perspective)
  - ➢ Allowance price significantly reflects the investors’ expectations regarding the environmental policy in the future.
  - ➢ In 2013, China issued an <Air Pollution Prevention and Control Action Plan> to control PM2.5 and reduce the number of smoggy days.
    - limits the emissions, energy use, and technology migration.
  - ➢ The sharp increase in SO_2 prices resulting from environmental policy, which caused an increase in the expected pollutant control costs in the future and provided incentives for utilities to purchase allowances and bank them for future use. (so…someone really in need cannot get it…)
  - ➢ In 2015, just before the Paris conference (Dec. 12), China submitted its INDC (Intended Nationally Determined Contributions)
    - (i) peak CO_2 emissions no later than 2030
    - (ii) increase the share of non-fossil fuels in the total energy supply to 20% by 2030
    - (iii) reduce the carbon intensity of GDP by 60-65% compared to 2005 levels by 2030

Concluding Remarks

- Theoretical Benefits
  - ➢ Directional marginal productivity (DMP)
  - ➢ Marginal abatement cost (MAC) of bad outputs
  - ➢ Shadow price substitution of bad outputs
  - ➢ Comparison of previous studies: addressing the issue
    - estimating shadow prices separately may lead to an overestimation of marginal productivity and an underestimation of shadow price

- Practical Benefits
  - ➢ Provide environmental policy guidelines and support Cap-and-Trade
    - the allowance price in emission trading markets
  - ➢ Bidding or Auction → Reasonable marginal abatement cost (MAC)
    - Reduce the **fluctuation** of the market price caused by the "**expectation**"

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Directional shadow price estimation of CO_2, SO_2 and NO_x in the United States coal power industry 1990–2010

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ABSTRACT

Shadow prices, also termed marginal abatement costs, provide valuable guidelines to support environmental regulatory policies for CO_2, SO_2 and NO_x, the key contributors to climate change. This paper complements the existing models and describes a directional marginal productivity (DMP) approach to estimate directional shadow prices (DSPs) which present substitutability among three emissions and are jointly estimated. We apply the method to a case study of CO_2, SO_2 and NO_x produced by coal power plants operating between 1990 and 2010 in the United States. We find that DSP shows 1.1 times the maximal shadow prices estimated in the current literature. We conclude that estimating the shadow prices of each by-product separately may lead to an overestimation of the marginal productivity and an underestimation of the shadow prices.

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Thanks for your attention!

Q&A