ATHENS2017
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"Impacts of Outdoor $PM_{2.5}$ and Deployment of Decentralized Gasification Systems"

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National University of Singapore

Solid Waste Management Methods

(1) Landfill

Advantages: cheap, applicable for different wastes, land reclamation, material recycling, methane harvesting, etc.

Disadvantages: noxious gas emission, dust and leachate production, rodent infestation, land space requirement, etc.

(2) Incineration

Advantages: 80 – 95% waste volume reduction, free of leachate issue, electricity and heat production, etc.

Disadvantages: expensive, toxic by-products (e.g., acid gases, nitrogen oxide, heavy metals, particulates, and dioxin) emission, not appropriate for wastes with high moisture content, etc.

(3) Gasification

Advantages: low emissions, cost effective solution, electricity and heat production, suitable for decentralization, etc.

Disadvantages: sensitive (biomass dependent), frequent refueling, strict requirement for fuel size, moisture, ash content, etc.

Image from calacademy.org

Image from greentumble.com

Image from prmenergy.com

2030 Singapore Vision of Sustainable Solid Waste Management

- Achieving 70% of overall recycling rate

Further covert residual waste streams into resources:

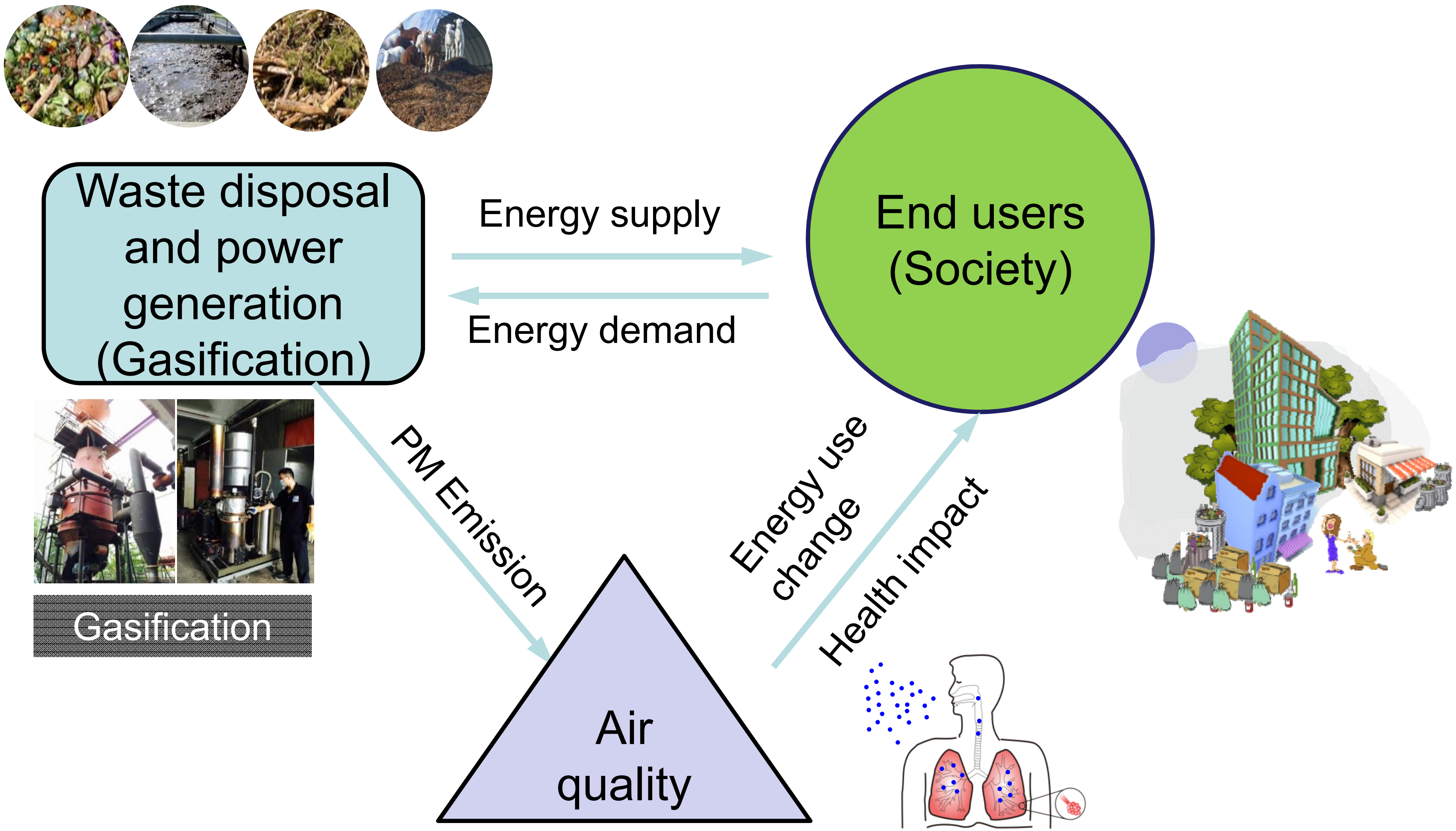
- Plastic waste to resources, e.g. carbon nanotubes and fuel
- Paper waste to cellulose aerogels, butanol etc.
- Incineration ash to valuable materials

- Embedding alternative technologies in the solid waste management infrastructure to *maintain* ***high level of public health*** and ***minimize environmental impacts***

- Explore alternative thermal treatment process, e.g. gasification and pyrolysis

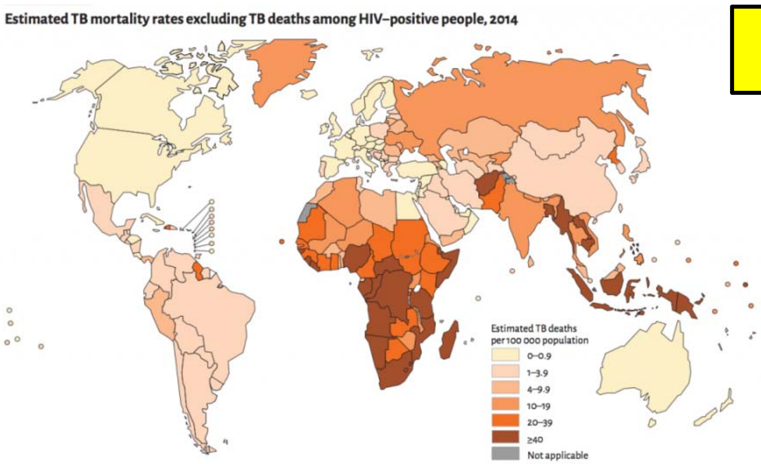
Source: Solid Waste Management Technology Roadmap

Environmental and Energy Impacts, and Economic Feasibility of Decentralized Gasification Systems

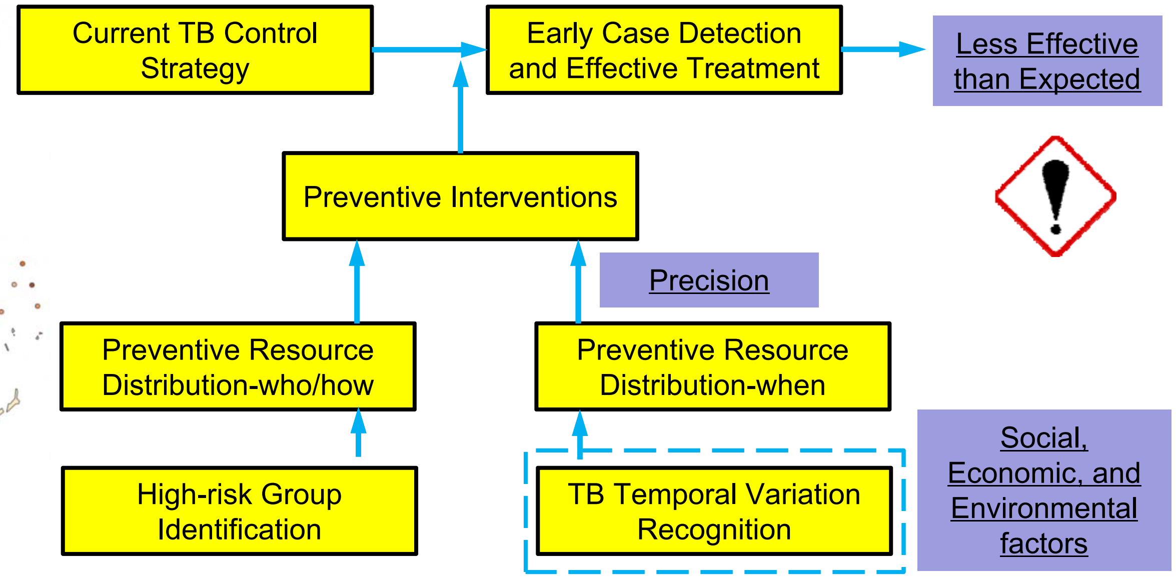


On the Association between Outdoor $PM_{2.5}$ Concentration and the Seasonality of Tuberculosis

S. You, YW Tong, K.G. Neoh, Y. Dai, C.H. Wang, "On the Association between Outdoor PM2.5 Concentration and the Seasonality of Tuberculosis for Beijing and Hong Kong", Environmental Pollution, 218, 1170-1179, (2016).



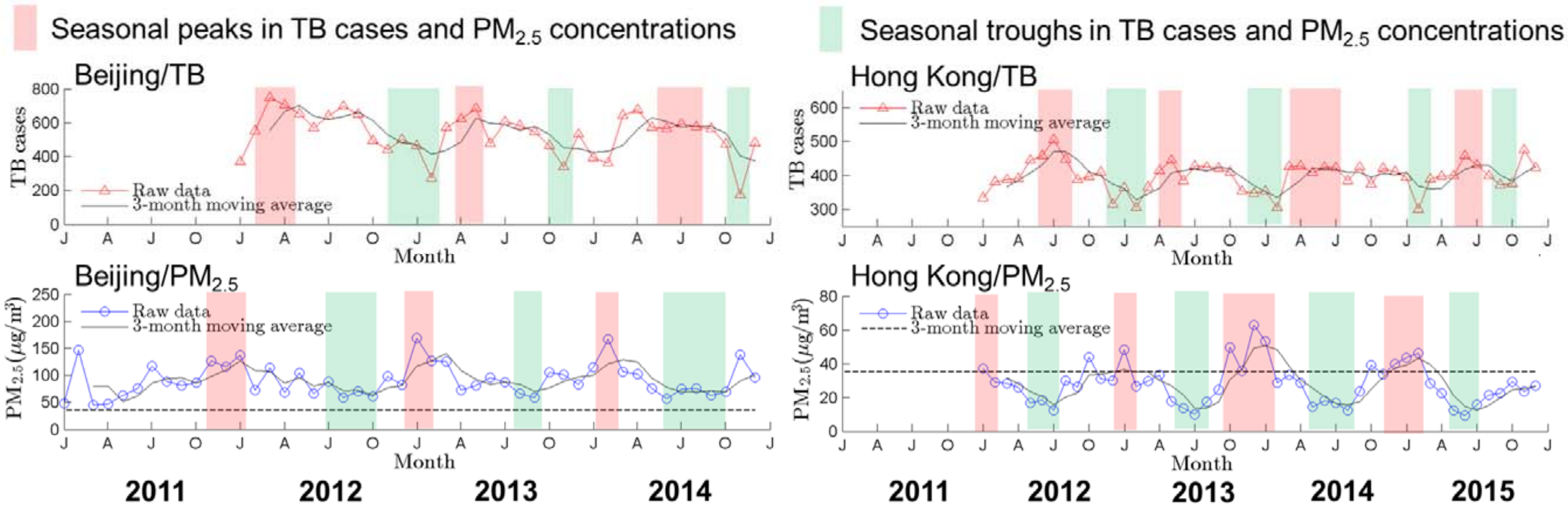
9.6 million new TB cases and 1.5 million deaths in 2014 (WHO, Global TB Report, 2015).



Methods-Ecologic Study

Beijing

Hong Kong



- Poisson regression analysis: TB incidence could be represented by Poisson distributions:

$$\Pr\{Y=y\}=(e^{-\mu}\mu^{y})/y!$$

- Poisson regression model:

$$\mathrm{Log}(\mu)=\alpha+\boldsymbol{X'\beta}$$

Results and Discussion

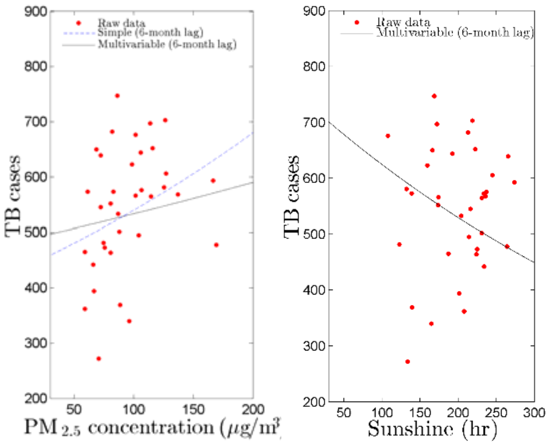
Regression Analysis

Results of regression analysis of TB cases and PM2.5 concentration for Beijing and Hong Kong

City	Variable	β_i							
		Simple analysis				Multivariable analysis			
		3 month	4 month	5 month	6 month	3 month	4 month	5 month	6 month
Beijing	Intercept	6.07 (6.02-6.12)a**	5.95 (5.90-5.99) **	5.99 (5.94-6.04) **	6.06 (6.00-6.11) **	5.92 (5.80-6.03) **	5.52 (5.40-5.65) **	5.95 (5.83-6.07) **	6.51 (6.39-6.63) **
	$PM_{2.5}$ concentration ($\times 10^{-3}$ μg/m^3)	2.26 (1.78-2.75) **	3.54 (3.06-4.02) **	3.08 (2.59-3.57) **	2.31 (1.82-2.81) **	2.66 (2.11-3.22) **	4.73 (4.15-5.31) **	3.19 (2.61-3.77) **	1.01 (0.42-1.59)**
	Sunshine duration ($\times 10^{-3}$ hrs)	-	-	-	-	0.576 (0.184-0.968) **	1.54 (1.13-1.95) **	0.155 (-0.254-0.564)	-1.65 (-2.06--1.24) **
Hong Kong	Intercept	6.01 (5.98-6.05) **	6.00 (5.96-6.03) **	5.93 (5.89-5.96) **	5.89 (5.85-5.92) **	6.07 (6.02-6.12) **	6.12 (6.07-6.18) **	6.03 (5.98-6.08) **	5.96 (5.90-6.01) **
	$PM_{2.5}$ concentration ($\times 10^{-3}$ μg/m^3)	-0.705 (-1.89-4.81)	-0.0921×10^{-5} (-1.28-1.09)	2.25 (1.07-3.43) **	3.47 (2.28-4.66) **	-0.489 (-1.69-0.71)	0.477 (-0.74-1.69)	2.84 (1.62-4.05) **	3.93 (2.70-5.15) **
	Sunshine duration ($\times 10^{-3}$ hrs)	-	-	-	-	-0.422 (-0.70--0.14)	-0.998 (-1.28--0.71) **	-0.842 (-1.13--0.55) **	-0.572 (-0.86--0.28) **

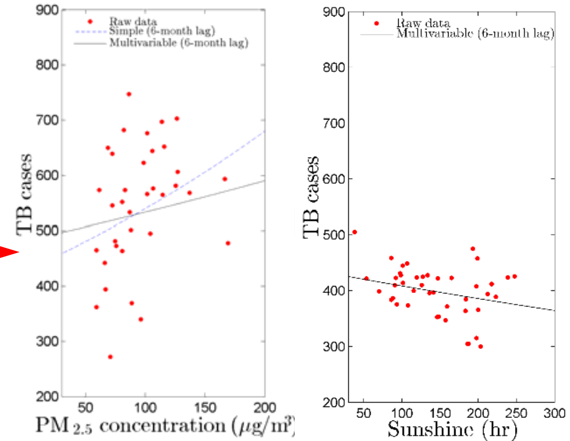
a: Values in brackets denotes 95% confidence intervals.

** denotes the regression coefficients with P<0.001.



Beijing

Number of TB cases plotted against $PM_{2.5}$ concentration and sunshine duration

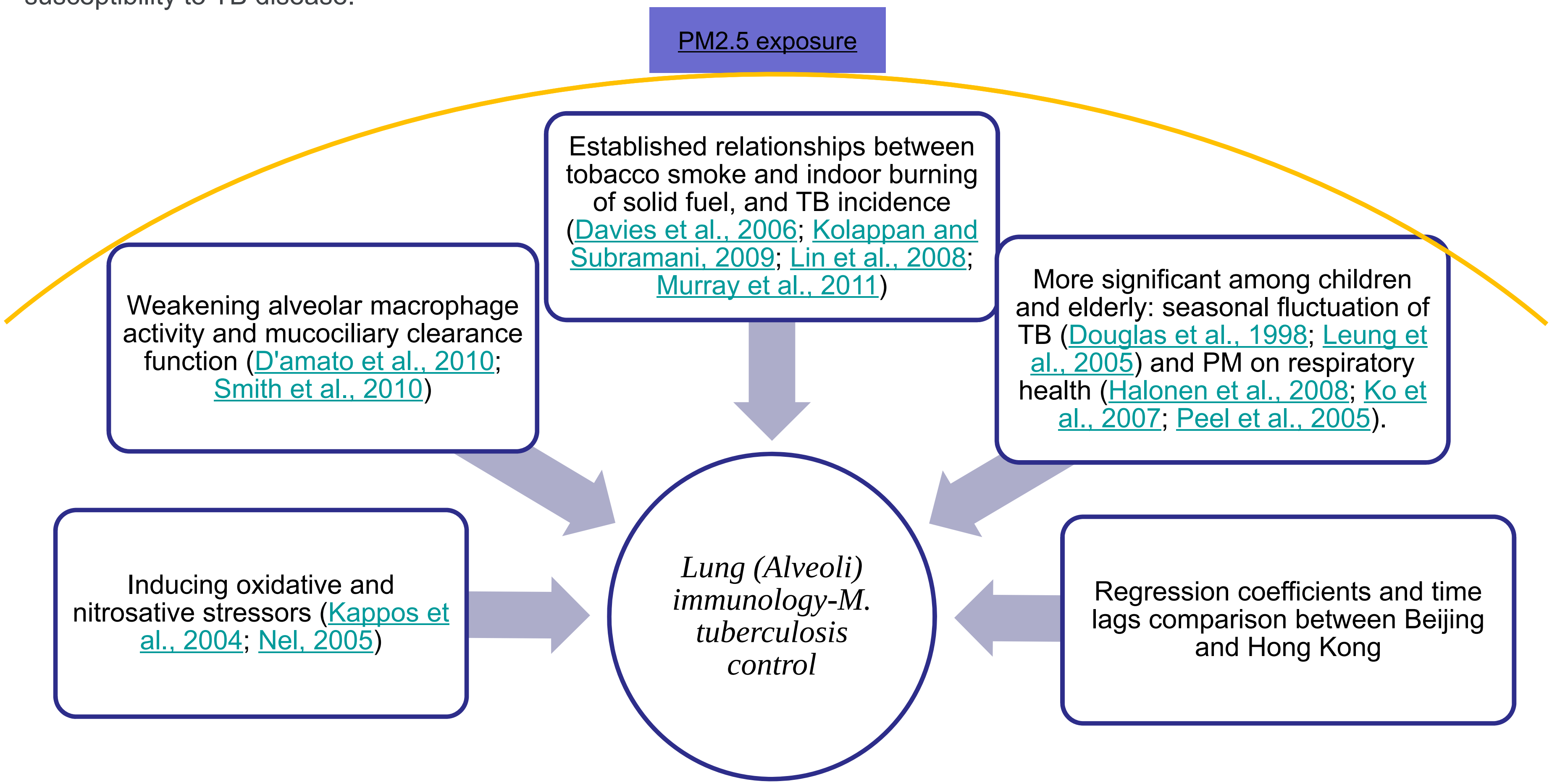


Hong Kong

Results and Discussion

Potential Mechanisms

(1) $PM_{2.5}$ exposure could directly impair or modify the immunology of the human respiratory system which increases people's susceptibility to TB disease.



Results and Discussion

3. Potential Mechanisms

(2) Increased indoor activities in the case of high outdoor $PM_{2.5}$ concentrations (household crowding has been long regarded as a risk factor for TB).

High $PM_{2.5}$ Concentration → people are advised to stay indoors → Increased indoor activities → TB: solely airborne-mode-transmittable → Increased risk of TB transmission

(3) The variation of $PM_{2.5}$ concentration may be related to the variation of other risk factors (confounders) of TB seasonality: (a) the direct seasonal change of immune system function (humoral and cellular immunity)

Experimental studies on rodents, birds and humans have suggested that the immune system is weakened during the winter (Altizer et al., 2006), while a down-regulation of interleukin (IL)-6, TNF-α, interferon (IFN)-γ, and interleukin (IL)-10 production happened during summer compared to winter as observed by other studies (Khoo et al., 2011).

(b) the existence of other air pollutants

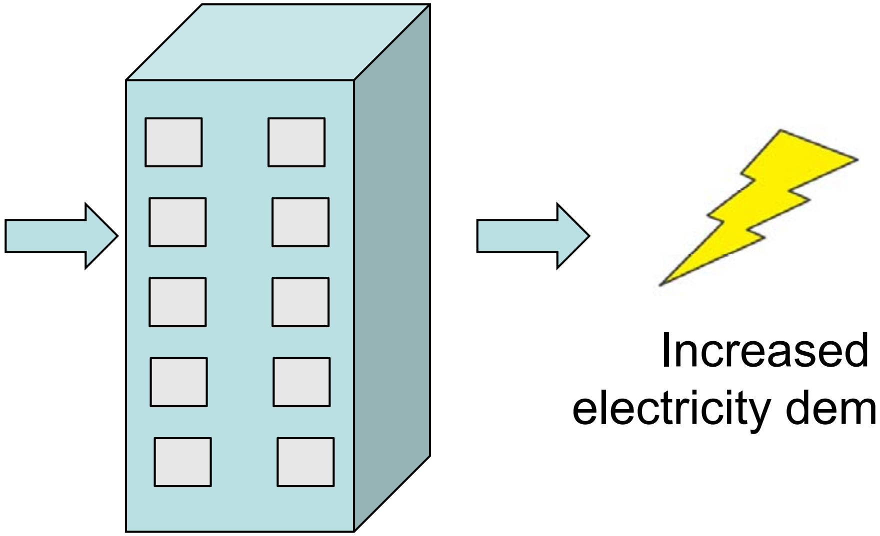
Some air pollutants pose similar health effects on the human respiratory system with $PM_{2.5}$ (Bascom et al., 1996; Fuertes et al., 2015; Sram et al., 2013).

Variation of household electricity consumption and potential impact of outdoor PM2.5 concentration

S. You, K.G. Neoh, Y.W. Tong, Y. Dai, C.H. Wang, "Variation of household electricity consumption and potential impact of outdoor PM2.5 concentration: A comparison between Singapore and Shanghai", Applied Energy, 188, 475-484

https://commons.wikimedia.org/wiki/File:Haze_in_Kuala_Lumpur.jpg

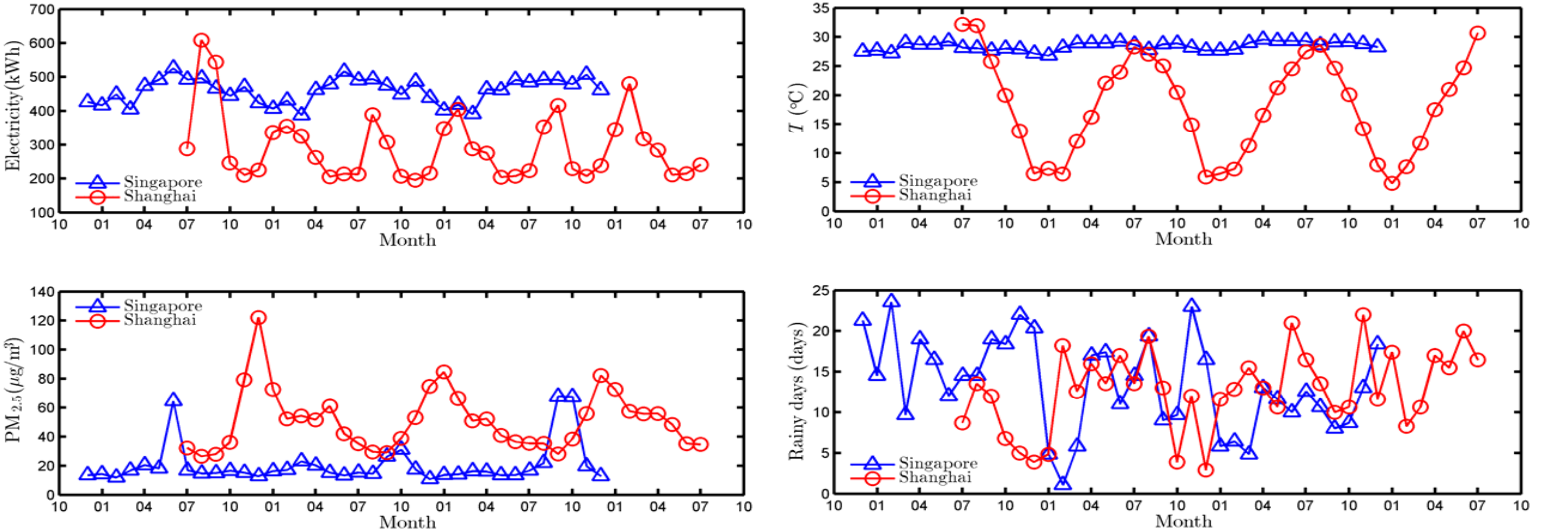
Haze



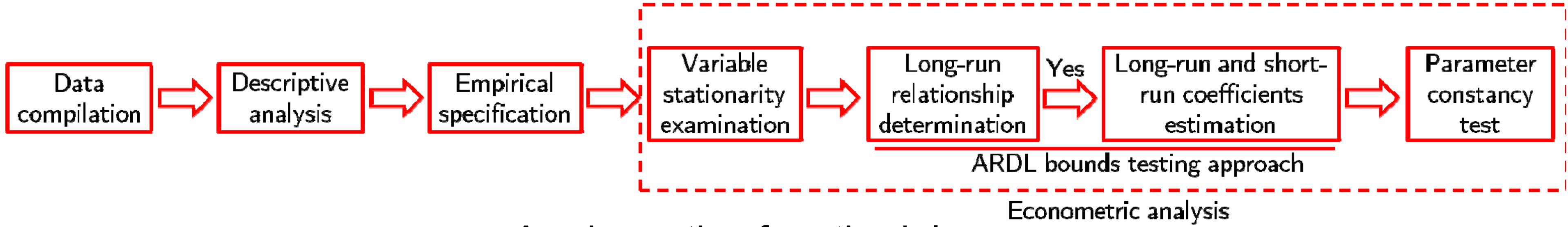
Increased indoor activities and use of air-conditioners and purifiers

Increased electricity demand

Methods



The temporal variation of monthly household electricity consumption, PM2.5 concentration, temperature, and the number of rainy days, for Singapore and Shanghai.



A schematic of methodology

Methods

Empirical specification

Singapore

The electricity consumption per household (*EC*) is specified as a function of $PM_{2.5}$ concentration (*PM*), temperature (*T*), and the number of rainy days (*RD*)

$$\ln EC_t = \alpha_0 + \alpha_1 \ln PM_t + \alpha_2 T_t + \alpha_3 RD_t + \alpha_4 t + \varepsilon_t$$

where ln[*x*] denotes the natural log of variable *x*; *t* denotes the time trend; *ε* denotes a random error, i.e. a normally and identically distributed white noise.

Shanghai

The electricity consumption per household (*EC*) is specified as a function of $PM_{2.5}$ concentration (*PM*), *HCDD*, and the number of rainy days (*RD*)

$$\ln EC_t = \beta_0 + \beta_1 \ln PM_t + \beta_2 HCDD + \beta_3 RD_t + \beta_4 t + \varepsilon_t$$

$HCDD = (HDD + CDD)/2$ with $HDD = \sum_i^n \mathrm{Max}(0, T_{ref} - T_{tmin})$ and $CDD = \sum_i^n \mathrm{Max}(0, T_{tmax} - T_{ref})$, respectively. T_{tmin} and T_{tmax} denote the minimum and maximum temperature on day i of a month. T_{ref} is the reference temperature which is set to be 10 °C and 25 °C for HDD and CDD, respectively.

Methods

Econometric analysis

Stationarity of variable series

- The stationarity of each variable is firstly examined based on Augmented Dickey-Fuller (ADF) unit root tests. The Akaike Information Criterion (AIC) is used to select the optimal lag length: both *I(0)* and *I(1)*) variables are involved and none of the variables are integrated of order *I(2)*.

ARDL bounds testing approach

A series of unrestricted error correction models (UECM) were constructed and estimated. Specifically, the models with electricity consumption as the dependent variable (DV) are

$$\Delta \ln EC_t = a_0 + a_1 \ln EC_{t-1} + a_2 \ln PM_{t-1} + a_3 \ln T_{t-1} + a_4 RD_{t-1} + \sum_{i=1}^{p} a_{5i} \Delta \ln EC_{t-i} + \sum_{j=0}^{p} a_{6j} \Delta \ln PM_{t-j} + \sum_{j=0}^{p} a_{7j} \Delta \ln T_{t-j} + \sum_{j=0}^{p} a_{8j} \Delta RD_{t-j} + a_9 t + \varepsilon_t$$

And

$$\Delta \ln EC_t = b_0 + b_1 \ln EC_{t-1} + b_2 \ln PM_{t-1} + b_3 HCDD_{t-1} + b_4 RD_{t-1} + \sum_{i=1}^{p} b_{5i} \Delta \ln EC_{t-i} + \sum_{j=0}^{p} b_{6j} \Delta \ln PM_{t-j} + \sum_{j=0}^{p} b_{7j} \Delta HCDD_{t-j} + \sum_{j=0}^{p} b_{8j} \Delta RD_{t-j} + b_9 t + \varepsilon_t$$

for Singapore and Shanghai, respectively. Δ denotes the first difference operator and *p* denotes the number of lags.

The significance *F*-test of the lagged levels of the variables is used to test the null hypothesis of no cointegration among the variables (i.e. H_0: *a1=a2=a3=a4=0* and H_0: *b1=b2=b3=b4=0*). The ARDL bounds testing analysis was conducted using Eviews (IHS Global Inc.).

Test of parameter constancy

The coefficient stability of the models was tested using the cumulative sum of recursive residuals (CUSUM) and the CUSUM of squares (CUSUM-SQ) tests, respectively.

Results and Discussion

ARDL cointegration analysis

Summary of *F*-tests

City	F-statistics			
Singapore ($k = 3$)#	F_2(EC|PM, T, RD) =18.5824***	F_{PM}(PM|EC, T, RD) =4.8879	F_T(T|EC, PM, RD) =12.8042***	F_{RD}(RD|EC, PM, T) =10.3305***
Shanghai ($k = 3$)	F_{EC}(EC|PM, HCDD, RD) =21.1659***	F_{PM}(PM|EC, HCDD,, RD) =4.7218	F_{HCDD}(HCDD|EC, PM, RD) =3.1649	F_{RD}(RD|EC, PM, HCDD) =5.2070**

Critical values&					
Significance level=1%		Significance level=5%		Significance level=10%	
Lower bound ($I(0)$)	Upper bound ($I(1)$)	Lower bound ($I(0)$)	Upper bound ($I(1)$)	Lower bound ($I(0)$)	Upper bound ($I(1)$)
5.654	6.926	3.936	4.918	3.290	4.176

k is the number of regressors.

& Critical values are from Narayan (2005) (unrestricted intercept and restricted trend) with respect to 35 observations.

** denote statistical significance at 5% level.

*** denote statistical significance at 1% level.

- The null hypothesis of no cointegration is rejected and there is a long-run relationship between household electricity consumption and other regressors (temperature, outdoor $PM_{2.5}$ concentration, and the number of rainy days) for both Singapore and Shanghai.
- In view of the long-run relationships between the household electricity consumption and other variables in the models, the long-run and short-run elasticities are further examined. The corresponding ARDL specifications of the long-run models are

$$\ln EC_t = c_0 + \sum_{i=1}^{m1} c_{1i} \ln EC_{t-i} + \sum_{i=1}^{m2} c_{2i} \ln PM_{t-i} + \sum_{i=1}^{m3} c_{3i} T_{t-i} + \sum_{i=1}^{m4} c_{4i} RD_{t-i} + \mu_t$$

and

$$\ln EC_t = d_0 + \sum_{i=1}^{m1} d_{1i} \ln EC_{t-i} + \sum_{i=1}^{m2} d_{2i} \ln PM_{t-i} + \sum_{i=1}^{m3} d_{3i} HCDD_{t-i} + \sum_{i=1}^{m4} d_{4i} RD_{t-i} + \mu_t$$

for Singapore and Shanghai, respectively.

Results and Discussion

Elasticities

Long-run and short-run elasticity of household electricity consumption for Singapore and Shanghai

Singapore	Long-run elasticity (DV[&]: $\ln EC_t$)			Short-run elasticity (DV: $\Delta\ln EC_t$)			
	$\ln PM_t$	T_t	RD_t	$\Delta\ln PM_t$	ΔT_t	ΔRD_t	ECM_{t-1}
Coefficient	0.0401***	0.1272***	0.0046**	0.0134	0.0405***	0.0060***	-1.3343***
Standard error	0.0122	0.0111	0.0020	0.0125	0.0098	0.0011	0.1273
t-statistics	3.297	11.5073	2.3360	1.0691	4.1354	5.3055	-10.4788
Shanghai	Long-run elasticity (DV: $\ln EC_t$)			Short-run elasticity (DV: $\Delta\ln EC_t$)			
	$\ln PM_t$	$HCDD_t$	RD_t	$\Delta\ln PM_t$	$\Delta HCDD_t$	ΔRD_t	ECM_{t-1}
Coefficient	0.0981***	0.0074***	0.0112***	0.0856	0.0006	0.0075***	-3.1597***
Standard error	0.0179	0.0005	0.0020	0.0459	0.0004	0.0021	0.2764
t-statistics	5.4638	16.5367	5.5454	1.8623	1.4103	3.6619	-11.4337

& DV denotes dependent variable.
** denote statistical significance at 5% level.
*** denote statistical significance at 1% level.

Singapore

- The error correction term (ECM_{t-1}) is statistically significant at the level of 1% with a negative sign → a long-run equilibrium relationship exists between the household electricity consumption and the other variables.
- Only the long-run elasticity is significant at the level of 1% → People will not immediately realize the severity of PM2.5 spike episodes and people's response may be modest during an initial period in Singapore.
- A 20% increase in $PM_{2.5}$ concentration is related to a 0.8% or 4.1 kWh increase in the electricity consumption per household for an average monthly electricity consumption per household of 460 kWh → an electricity overconsumption of 5.0 GWh and a total of 1.0 – 1.4 million SGD (or 0.7 – 1.0 million USD for an exchange rate of 0.73) in household electricity cost → 2.1 kilotons of CO_2 emission associated with electricity generation.

Results and Discussion

Elasticities

Long-run and short-run elasticity of household electricity consumption for Singapore and Shanghai

Singapore	Long-run elasticity (DV[&]: $\ln EC_t$)			Short-run elasticity (DV: $\Delta\ln EC_t$)			
	$\ln PM_t$	T_t	RD_t	$\Delta\ln PM_t$	ΔT_t	ΔRD_t	ECM_{t-1}
Coefficient	0.0401***	0.1272***	0.0046**	0.0134	0.0405***	0.0060***	-1.3343***
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Coefficient	0.0981***	0.0074***	0.0112***	0.0856	0.0006	0.0075***	-3.1597***
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& DV denotes dependent variable.
** denote statistical significance at 5% level.
*** denote statistical significance at 1% level.

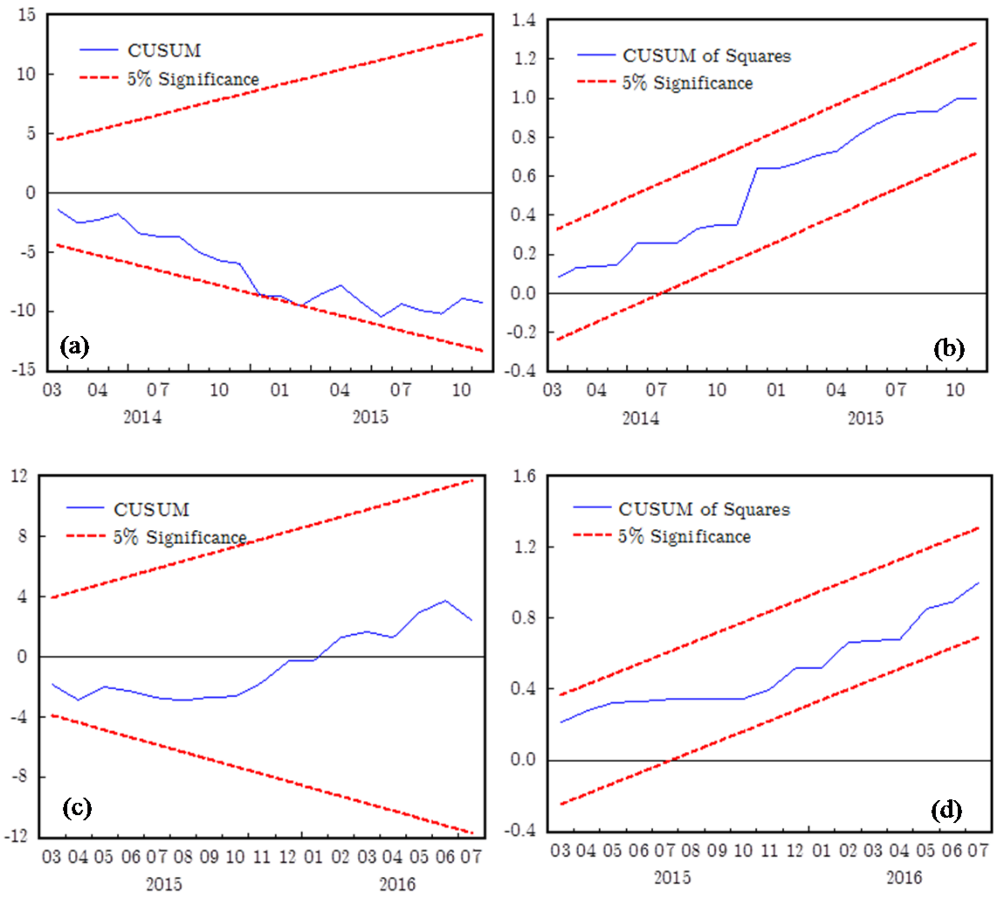
Shanghai

- A long-run equilibrium relationship exists between the household electricity consumption and the other variables.
- Similar to the case of Singapore, people's response to $PM_{2.5}$ concentration variation is not immediate.
- The larger long-run elasticity for the case of Shanghai than Singapore may be related to the fact that Shanghai suffers from significantly severer $PM_{2.5}$ pollution than Singapore.
- A 20% decrease of monthly $PM_{2.5}$ concentration is related to a 2.2% or 6.5 kWh decrease in the household electricity consumption → The overall household electricity consumption and bill are 35.0 GWh and 1.6 – 5.1 million USD, respectively. → 17.5 kilotons CO_2 emission if an emission factor of 500 tons per GWh is assumed for electricity generation.

Results and Discussion

Parameter constancy

Both the CUMSUM and CUSUM-SQ are generally falling within the 5% critical bounds of parameter stability as denoted by the red dash lines → the estimated coefficients of the models are stable at the significance level of 5%.



Model stability based on CUSUM and CUSUM-SQ tests for Singapore ((a) and (b)) and Shanghai ((c) and (d)). The red lines denote the critical bounds of parameter stability at the significance level of 5%.

The co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification- and incineration-based waste treatment schemes: A Singapore case study

S. You, W. Wang, Y. Dai, Y. W. Tong, C.H. Wang, "Comparison of the co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification- and incineration-based waste treatment schemes", Bioresource Technology, 218, 595-605 (2016).

Solid Wastes in Singapore

(1) Food wastes and sewage sludge need to be paid special attention.

- Food wastes: one of the major solid wastes generated; recycling rate among one of the lowest.
- Sewage sludge: an unavoidable product from water reclamation plants (WRP); comprising of harmful substances such as heavy metals, bacteria, viruses, poorly biodegradable organic compounds, dioxins etc. In Singapore, the disposal of sewage sludge and food wastes mainly relies on incineration. However, the high moisture content in the wastes makes them not ideal fuels for incineration.


Food waste

Is the gasification technology an alternative method for disposing of food wastes and sewage sludge?

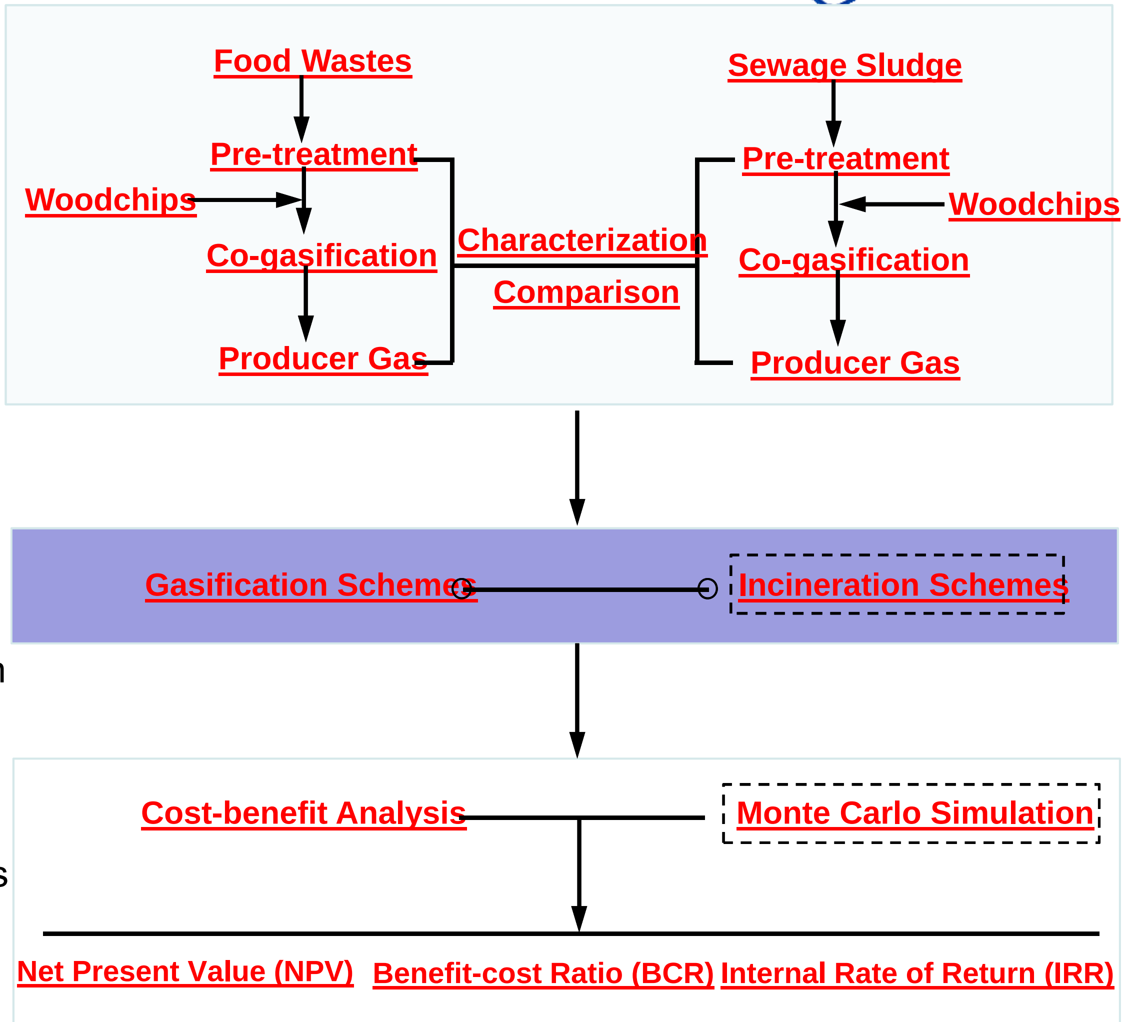

Sewage sludge

Techno-economic Analysis

Step 1: The relative pros and cons of food wastes vs. sewage sludge for co-gasification: important for the practical designing and management of gasification-based waste disposal.

Step 2: Proposing gasification-based waste disposal schemes to handle the sewage sludge and food wastes in Singapore.

Step 3: Cost-benefit analysis (CBA) considering both private and environmental costs: whether a proposed project or program is worthwhile; an effective tool for making reasonable decisions on the utilization and distribution of society's resources; critical to the decision-making process of policy-makers and investors.



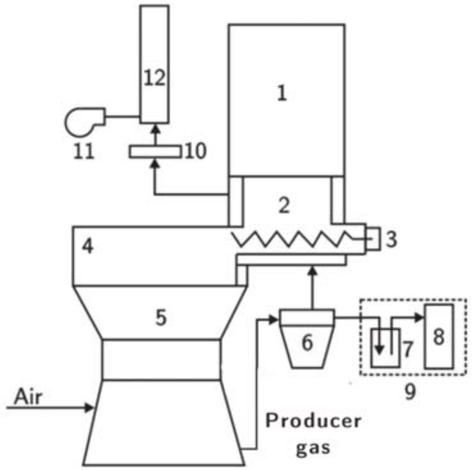
Methods

Feedstock Materials and Characterization

- Food wastes should be divided into subcategories: e.g., carbohydrate (rice, potato, noodle, pasta, vegetables, etc), protein (chicken, fish, egg, etc), fats and bones, based on their nutrient composition.
- The moisture content of wastes could be determined by the freeze-drying method (freezing followed by sublimation).
- Woodchips could be used as the co-gasification agent.
- Proximate, ultimate, and inductively coupled plasma (ICP) analysis were conducted to characterize the compositions of the feedstocks.

Co-gasification Experiments

- The moisture content of gasification feedstock could not be too high: e.g., lower than 25 wt.% for a downdraft fixed-bed gasifier.
- Feedstock drying: solar-drying.
- The size of feedstock : 2.5 cm in diameter for food waste balls and 1 to 4 cm for woodchips



A schematic diagram of downdraft gasifier. 1 Hopper, 2 Heat exchanger drying bucket, 3 Motorized screw feeder, 4 Pyro-coil heat exchanger, 5 Reactor, 6 Cyclone, 7 Gas conditioning system, 8 Gas analyzer, 9 Gas analysis system, 10 Filter, 11 Air blower, 12 Flare.

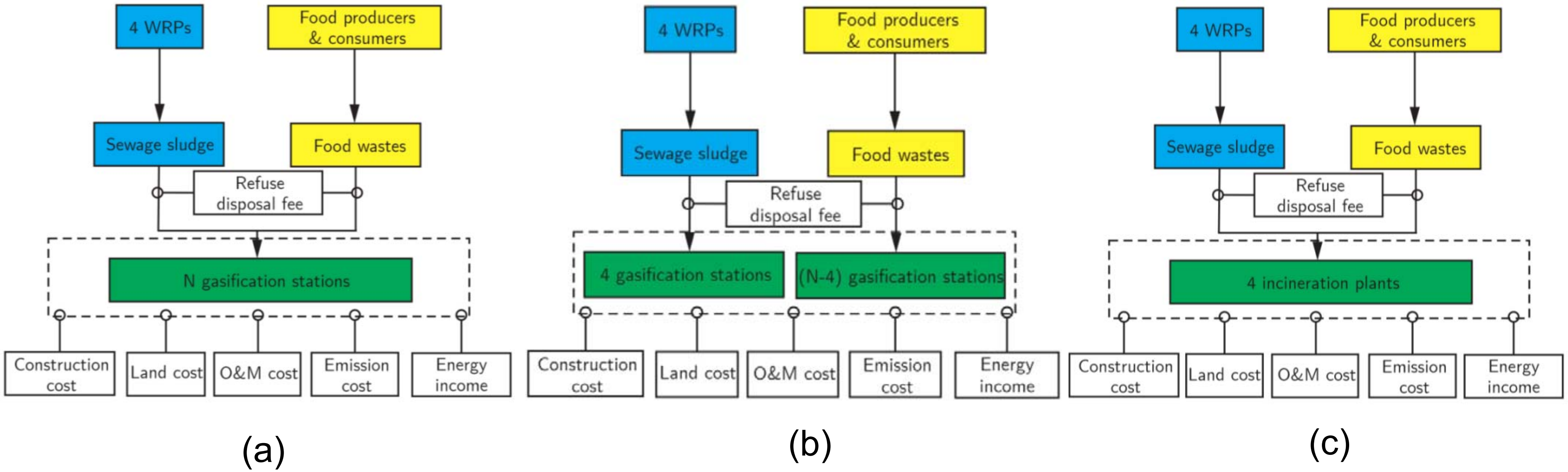
Methods

3. Cost-benefit Analysis

(1) Scheme proposal

• Gasification-based (1) N (e.g., N=100, 500, and 1000) decentralized gasification stations without differentiating the gasification of food wastes and sewage sludge; (2) each WRP has its own gasification station catering for the demand of its sewage sludge disposal while food wastes are gasified by other (N-4) gasification stations.

• Existing incineration scheme



Two gasification-based schemes: (a) and (b) vs. a third scheme (c) based on incineration.

Methods

3. Cost-benefit Analysis

(2) Indicators

- Net present value (NPV)

$$\mathrm{NPV} = \sum_{t}^{LT} \frac{C_{it}}{(1+r)^t} - C_0$$

C_{it} is the net cash inflow during a year t; C_0 is the total initial investment including the construction and land costs; LT=20 years denotes the life time of facilities; r is the discount rate. A near-zero discount rate means that the cost of borrowing from the future is low, and future benefits and costs are worth about the same as today.

- Benefit-cost ratio (BCR)

$$\mathrm{BCR} = \mathrm{NPV}/(\sum_{t}^{LT} \frac{C_{et}}{(1+r)^t} + C_0)$$

C_{et} is the expenditure cost (O&M and emission costs) during a year t.

- Internal rate of return (IRR): corresponds to a discount rate that leads to a zero NPV. IRR could not be calculated analytically and could be calculated using software algorithms (e.g., Matlab, irr(CashFlow)).

Triangular distributions are assumed for the potentially variable parameters and modeled by Monte Carlo simulation.

Methods

3. Cost-benefit Analysis

(1) Cost and benefit parameters

	Distribution	Parameters	Scheme 1	Scheme 2	Scheme 3
Construction cost (US$/kW)	Triangular	Lower	1000	1000	3000
		Mode	1500	1500	6000
		Upper	2000	2000	9000
Land cost (US$/m^2)	Triangular	Lower	500	500	-
		Mode	1500	1500	
		Upper	2500	2500	
O & M cost/capital cost*	Triangular	Lower	0.008	0.008	0.01
		Mode	0.014	0.014	0.03
		Upper	0.02	0.02	0.05
Electricity efficiency	Triangular	Lower	20%	20%	15%
		Mode	30%	30%	20%
		Upper	40%	40%	25%
CO_2 emission cost (US$/kg)	Triangular	Lower	6.4×10^{-4}	6.4×10^{-4}	6.4×10^{-4}
		Mode	1.18×10^{-2}	1.18×10^{-2}	1.18×10^{-2}
		Upper	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-2}
Dioxins emission cost (US$/kg)	Triangular	Lower	1.13×10^{7}	1.13×10^{7}	1.13×10^{7}
		Mode	1.47×10^{8}	1.47×10^{8}	1.47×10^{8}
		Upper	2.82×10^{8}	2.82×10^{8}	2.82×10^{8}
CO_2 emission (g/ton)	-	-	-	-	861800
Dioxin emission (g/ton)	-	-	0	0	5.15×10^{-7}
Electricity tariff (US$/kWh)	Triangular	Lower	0.1	0.1	0.1
		Mode	0.2	0.2	0.2
		Upper	0.3	0.3	0.3
Refuse disposal fee (US$/ton)	Triangular	Lower	50	50	50
		Mode	60	60	60
		Upper	70	70	70
Facility life-time (years)	-	-	20	20	20
Discount rate	Triangular	Lower	1%	1%	1%
		Mode	8%	8%	8%
		Upper	15%	15%	15%

List of parameters considered in the cost-benefit analysis

Results and Discussion

Food Wastes vs. Sewage Sludge

Compositions of food waste, sewage sludge, and woodchips

		Carbohydrate food waste	Protein food waste	Sewage sludge*	Woodchips
Freeze-drying (received basis wt.%)	Moisture	66.8	53.8	80&	8.2
Proximate analysis (wt.%)	Moisture	10.8	12.2	7.6	8.2#
	Volatiles	70.7	67.6	50.8	69.2
	Fixed carbon	15.8	13.9	15.1	16.2
	Ash	2.7	6.3	26.5	6.4
Ultimate analysis (dry basis wt.%)	Carbon	41.8	48.2	35.0	44.2
	Hydrogen	6.2	7.1	4.8	6.0
	Oxygen	46.9	29.0	27.8	41.6
	Nitrogen	2.0	8.9	5.2	0.9
	Sulfur	<0.50	<0.50	1.7	1.0
HHV (MJ/kg)		17.01	21.99	14.7	18.2

- The moisture content of food wastes and sewage sludge dropped to around 10 wt.% after drying.
- High ash contents in sewage sludge may pose problems such as slagging and clinker formation in the reactor.
- HHV: Food waste is a more favorable feedstock for gasification than sewage sludge in terms of energy content.

Results and Discussion

Food Wastes vs. Sewage Sludge

- The carbohydrate food waste has the highest Ca content.
- The sewage sludge has a significant more amount of Cu and Fe, which would limit its gasification ash's application as fertilizers.

Metallic compositions

	Cd	Co	Cr	Cu	Fe	Mn	Ca	Pb	Hg
Carbohydrate food waste	<0.1*	<0.1	<0.1	<0.1	<0.1	<0.1	12.5	<0.1	<0.1
Protein food waste	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	9.9	<0.1	<0.1
Sewage sludge&	-	<0.1	<0.1	1.9	8.5	<0.1	6.0	<0.1	-
Woodchips&	-	-	-	<0.1	0.2	<0.1	3.7	<0.1	<0.1

Producer gas compositions

Feedstock		Food waste + Woodchips	Sewage sludge + Woodchips*	Pure woodchips*
Gas composition (vol.%)	CO	16.4	15.6	17.1
	CO_2	14.5	12.7	11.9
	CH_4	2.5	2.1	1.7
	H_2	16.5	16.8	17.3
	O_2	0.82	1.0	1.3
	Total	50.6	48.2	49.1
LHV (MJ/Nm^3)	-	4.8	4.5	4.7

- The volume fraction of syngas ($CO+H_2$): Food wastes (32.9 vol.%) vs. Sewage sludge (32.4 vol.%).
- The energy output of the mixture of food waste and woodchips is similar to that of the gasification of pure woodchips.
- The food wastes serves as a better co-gasification agent than sewage sludge in terms of energy output.

Results and Discussion

Cost-benefit Analysis

Cost and benefit components

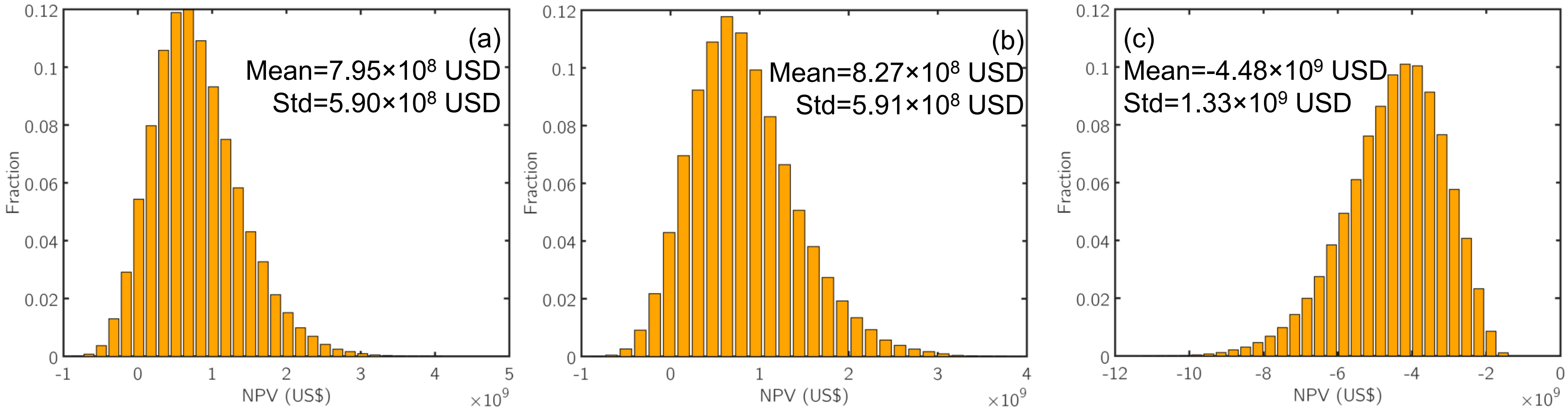
Components (US$)	Scheme 1			Scheme 2			Scheme 3
Number of stations	100	500	1000	100	500	1000	-
Construction cost	7.31×10^{8} (9.97×10^{7})&	1.18×10^{9} (1.61×10^{8})	1.46×10^{9} (1.99×10^{8})	7.18×10^{8} (9.76×10^{7})	1.13×10^{9} (1.55×10^{8})	1.38×10^{9} (1.88×10^{8})	1.09×10^{9} (2.23×10^{8})
Land cost	1.09×10^{8} (2.97×10^{7})	1.09×10^{8} (2.97×10^{7})	1.09×10^{8} (2.98×10^{7})	1.09×10^{8} (2.97×10^{7})	1.09×10^{8} (2.97×10^{7})	1.09×10^{8} (2.97×10^{7})	-*
O&M cost	1.44×10^{9} (4.49×10^{8})	2.21×10^{9} (6.91×10^{8})	2.69×10^{9} (8.46×10^{8})	1.41×10^{9} (4.43×10^{8})	2.13×10^{9} (6.69×10^{8})	2.54×10^{9} (7.98×10^{8})	4.02×10^{9} (1.67×10^{9})
Energy income#	2.44×10^{9} (6.52×10^{8})	2.44×10^{9} (6.49×10^{8})	2.44×10^{9} (6.55×10^{8})	2.44×10^{9} (6.51×10^{8})	2.44×10^{9} (6.52×10^{8})	2.44×10^{9} (6.52×10^{8})	3.16×10^{8} (7.89×10^{7})
Waste income§	6.64×10^{8} (1.48×10^{8})	6.64×10^{8} (1.47×10^{8})	6.65×10^{8} (1.48×10^{8})	6.64×10^{8} (1.48×10^{8})	6.64×10^{8} (1.48×10^{8})	6.65×10^{8} (1.48×10^{8})	3.18×10^{8} (7.06×10^{7})
Carbon dioxide emission cost	3.42×10^{7} (1.55×10^{7})	3.43×10^{7} (1.55×10^{7})	3.44×10^{7} (1.56×10^{7})	3.43×10^{7} (1.56×10^{7})	3.43×10^{7} (1.55×10^{7})	3.43×10^{7} (1.56×10^{7})	1.65×10^{7} (7.49×10^{6})
Dioxins emission cost	0	0	0	0	0	0	1.22×10^{5} (5.46×10^{4})

- The construction and O&M costs of scheme 1 and 2 increases as the number of gasification stations.
- The construction and O&M costs in scheme 2 are 2% - 5% lower than those in scheme 1.
- The capital cost of scheme 3 is about 130%, 85%, and 70% of that of scheme 1 with 100, 500, and 1000 stations, respectively.
- The O&M cost of scheme 3 is about 150% - 290% of that of scheme 1 and 2.
- The incineration-based scheme 3 is less profitable compared to the gasification-based scheme 1 and 2.
- The O&M costs are the highest among the cost components for all the schemes.
- The environmental externalities are negligible compared to the other cost and benefit components.

Results and Discussion

Cost-benefit Analysis

The distributions of NPV for (a) scheme 1, (b) scheme 2 of 100 stations, and (c) scheme 3, respectively.

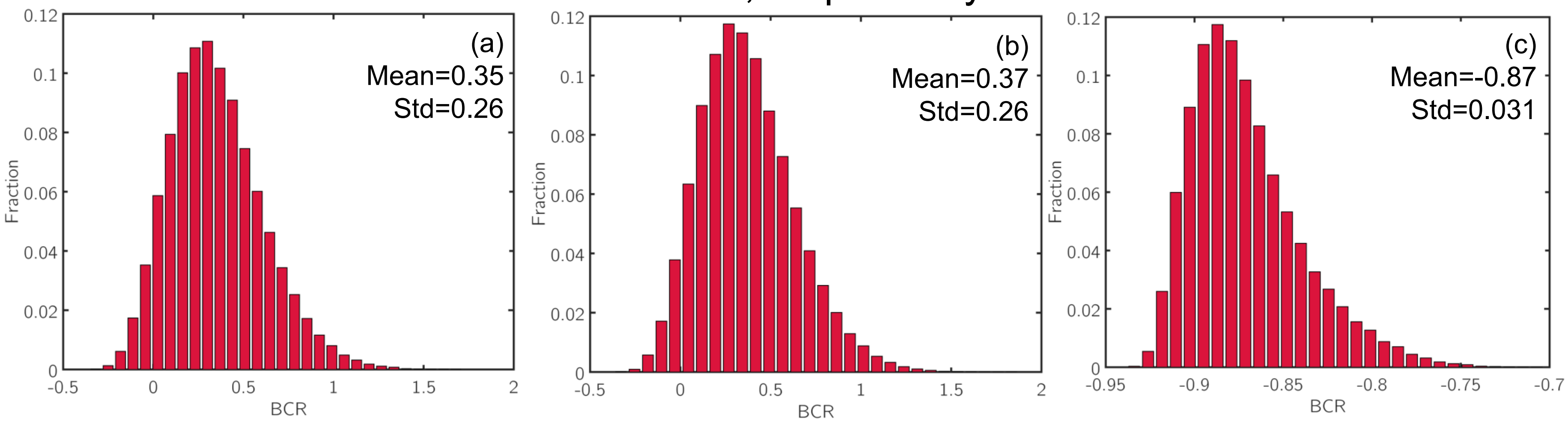


- The NPV distribution of scheme 1 is similar to that of scheme 2 in shape but has a smaller mean.
- The gasification-based schemes could be economically efficient and viable for disposing of food waste and sewage sludge.
- Statistically, there is around 80% of chance for the gasification-based schemes to be profitable.
- The values of the NPV distribution for the incineration-based scheme 3 are all negative with a mean of -4.48 billion, suggesting that the incineration-based scheme 3 is not financially viable.

Results and Discussion

Cost-benefit Analysis

The distributions of BCR for (a) scheme 1, (b) scheme 2 of 100 stations, and (c) scheme 3, respectively.

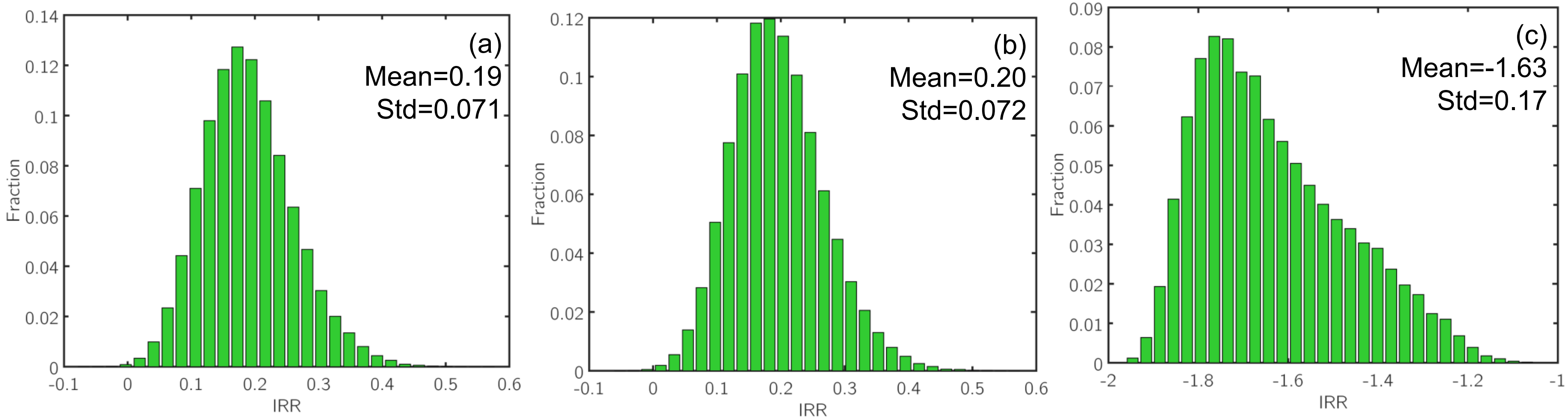


- The distribution of scheme 1 is similar to that of scheme 2 in shape but has a smaller mean.
- The mean BCRs of 0.35 and 0.37 suggest that the mean net profit would be around 35% and 37% of the overall cost for scheme 1 and 2, respectively.
- The BCR of scheme 3 has a mean of -0.87, meaning that the income from incineration could only cover about 13% of the overall cost, re-emphasizing the need to reduce the construction and O&M costs and increase the efficiency of the incineration-based scheme.

Results and Discussion

2. Cost-benefit Analysis

The distributions of IRR for scheme 1 (a), scheme 2 (b) of 100 stations, and scheme 3 (c), respectively.



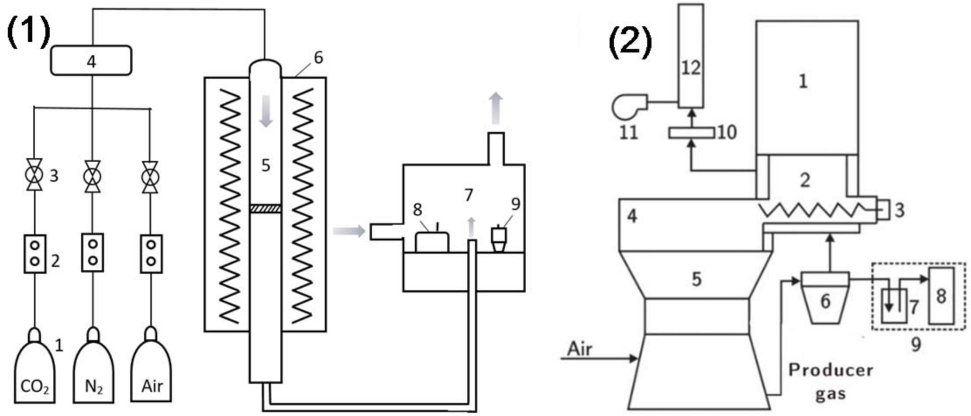
• The IRRs of scheme 1 and 2 are similar to each other and the fraction of positive IRRs is more than 95%, which suggests the potential for the gasification-based schemes to be profitable.

• The values of IRR for the incineration-based scheme 3 are all negative with a mean of -1.63, meaning the benefits from scheme 3 could not repay the investment during the designated life-cycle.

Particulate Emission from the Gasification of Solid Wastes: Impact of Feedstock and Operating Conditions

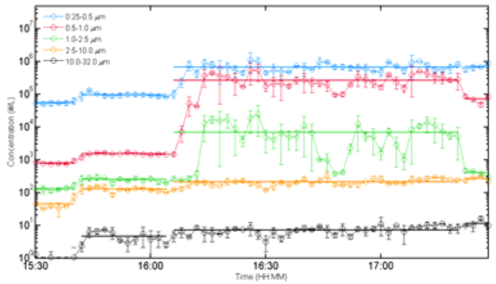
Methods

(1) Lab-scale gasifier. 1 Gas cylinder, 2 Mass flow controller, 3 Valve, 4 Gas mixer, 5 Gasifier reactor, 6 Heater, 7 Fume hood, 8 Aerosol spectrometer, 9 Sioutas Cascade Impactor. (2) Pilot-scale downdraft gasifier (capacity: 10 kg/hr). 1 Hopper, 2 Heat exchanger drying bucket, 3 Motorized screw feeder, 4 Pyro-coil heat exchanger, 5 Reactor, 6 Cyclone, 7 Gas conditioning system, 8 Gas analyzer, 9 Gas analysis system, 10 Filter, 11 Air blower, 12 Flare.

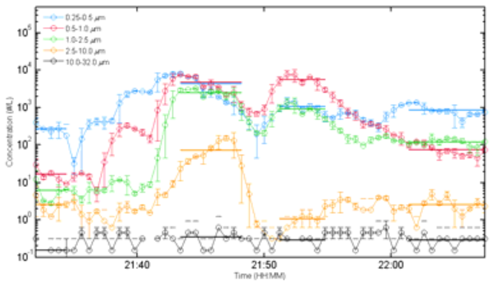


- Two types of gasifier reactors were used, i.e. lab-scale gasifier (ca. 1g/min) and pilot-scale gasifier (ca. 10kg/h).
- Woodchips and sewage sludge were used the feedstock.
- Particle number concentrations are measured using two aerosol spectrometers (GRIMM 1.109), while particle mass concentrations are measured using a Sioutas Cascade Impactor (SKC, Inc.).

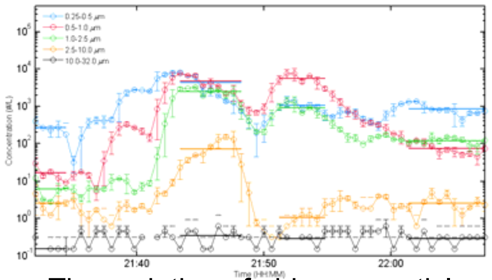
Results and Discussion



The variation of airborne particle concentrations during the pilot-scale gasification experiments (woodchips and air).



The variation of airborne particle concentrations during the lab-scale gasification experiments (woodchips and N_2).



The variation of airborne particle concentrations during the lab-scale gasification experiments (woodchips and Air)

- The particles emitted by the gasification system are mainly $PM_{0.25-2.5}$, suggesting potential exposure risk for users because these particles have a greater potential of penetrating deeply into the human respiratory system.
- Particle concentrations increase by a few times during the preparation stage compared to the background stage.
- Orders of magnitude increases occurs during the gasification stage compared to the background stage.
- For the case of pilot-scale gasifier, the concentration of $PM_{0.25-2.5}$ is increased most significantly during the gasification stage, suggesting the intermediate-sized particles are most difficultly removed by the existing particle reduction system (cyclone and filter).

Overall Conclusions

- For both Beijing and Hong Kong, a 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration months ago is significantly associated with a 3% increase in the number of TB cases. Preliminary evidence from the analysis of this work favors the mechanism based on the immunity-impairing effect of $PM_{2.5}$ exposure.
- For the case of Singapore, a 20% increase in the $PM_{2.5}$ concentration is significantly related to a 0.8% or 4.1 kWh increase in the electricity consumption per household in the long-run.
- For the case of Shanghai, a 20% decrease in the $PM_{2.5}$ concentration is significantly related to a 2.2% or 6.5 kWh decrease in the household electricity consumption in the long-run.
- Food wastes are more favorable than sewage sludge for co-gasification in terms of residue generation and energy output.
- Using the Monte Carlo simulation-based cost-benefit analysis, it was found that the gasification-based schemes are financially superior to the incineration-based scheme to handle food waste and sewage sludge.
- The environmental externalities are generally negligible compared to the other cost and benefit components for both the gasification and incineration-based schemes.
- Reducing the construction and O&M costs and increasing the electricity efficiency would be critical to improve the economics of the schemes.
- Both lab-scale and pilot-scale experiments showed that the particles emitted by the gasification system are mainly in the intermediate range ($PM_{0.25-2.5}$)

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