Urban Metabolism

1. Definition & History
2. Applications of UM
3. Metabolism of Megacities
4. City GHG accounting

Metabolism

“the sum total of the chemical processes that occur in living organisms, resulting in growth, production of energy, elimination of waste, etc.”

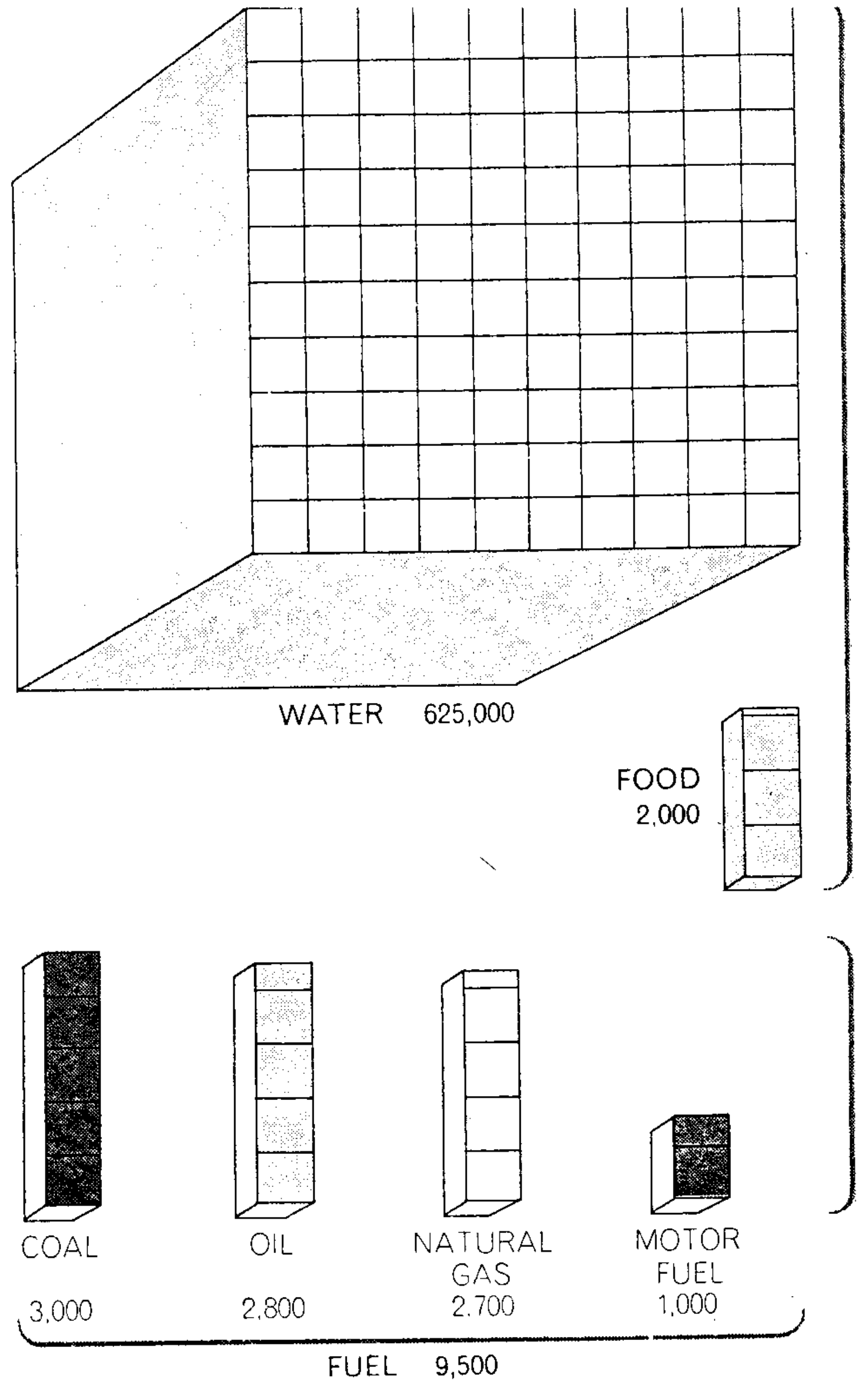
Urban Metabolism

"the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste."

(Kennedy et al, The changing metabolism of cities,
J. Industrial Ecology, 11(2), 43- 59, 2007)

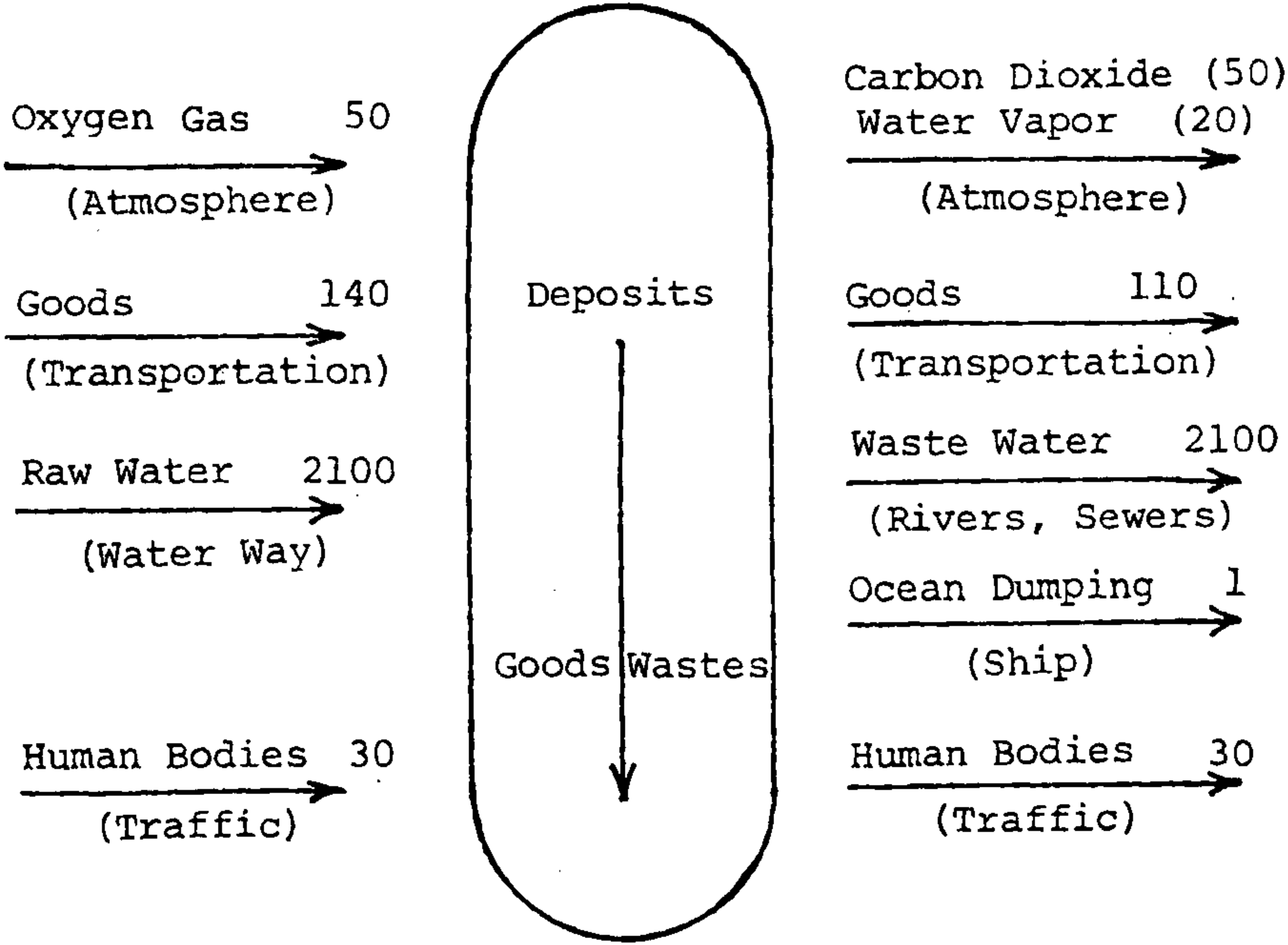
Early studies

- **av. US. City** (Wolman, 1965)
- **Tokyo** (Hanya and Ambe, 1976)
- **Brussels** (Duvigneaud and De Smet, 1977)
- **Hong Kong** (Newcombe et al., 1978)
- **Miami** (Zucchetto, 1975)
- **1850's Paris** (Stanhill, 1977)



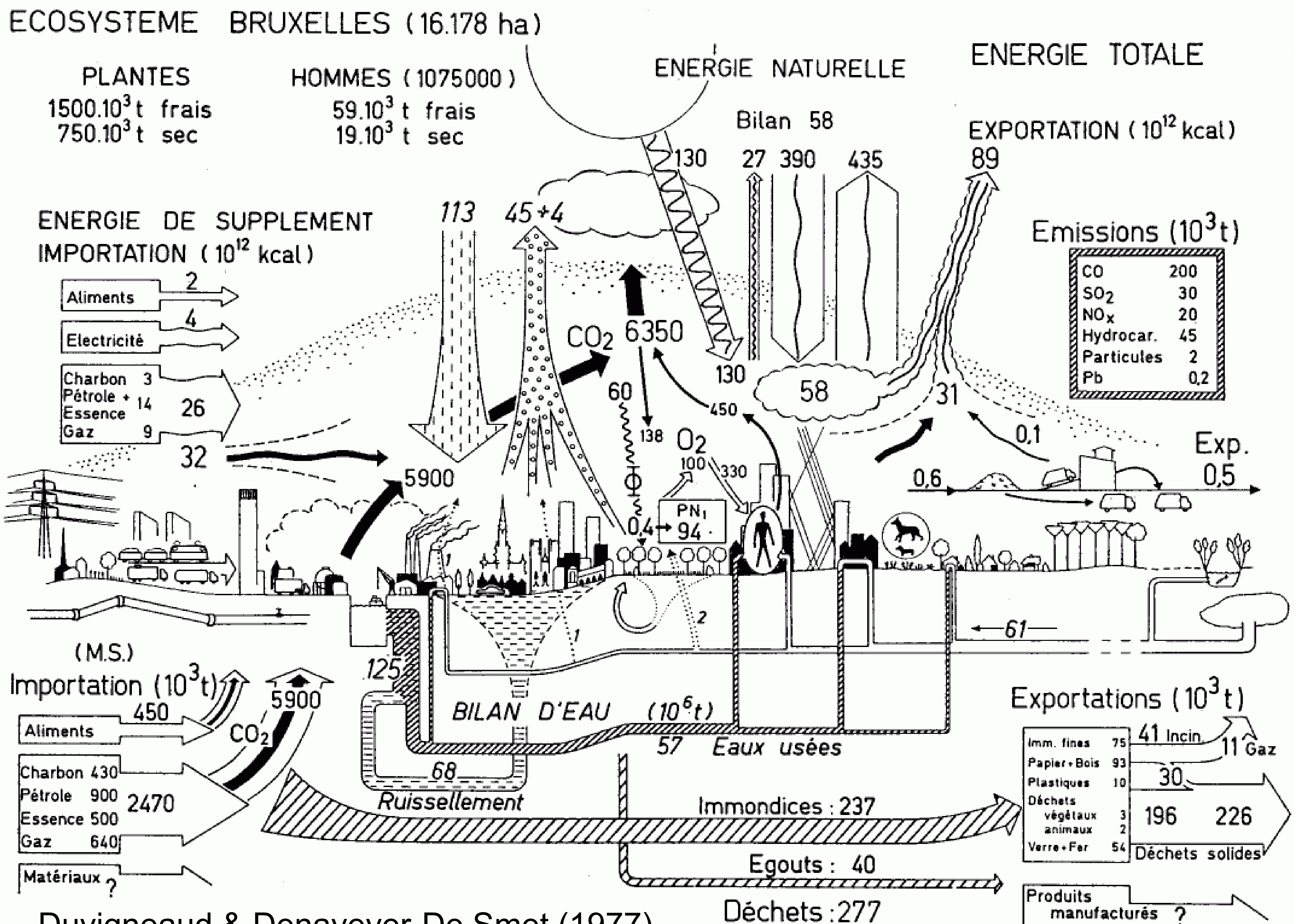
tons/day

Wolman (1965)

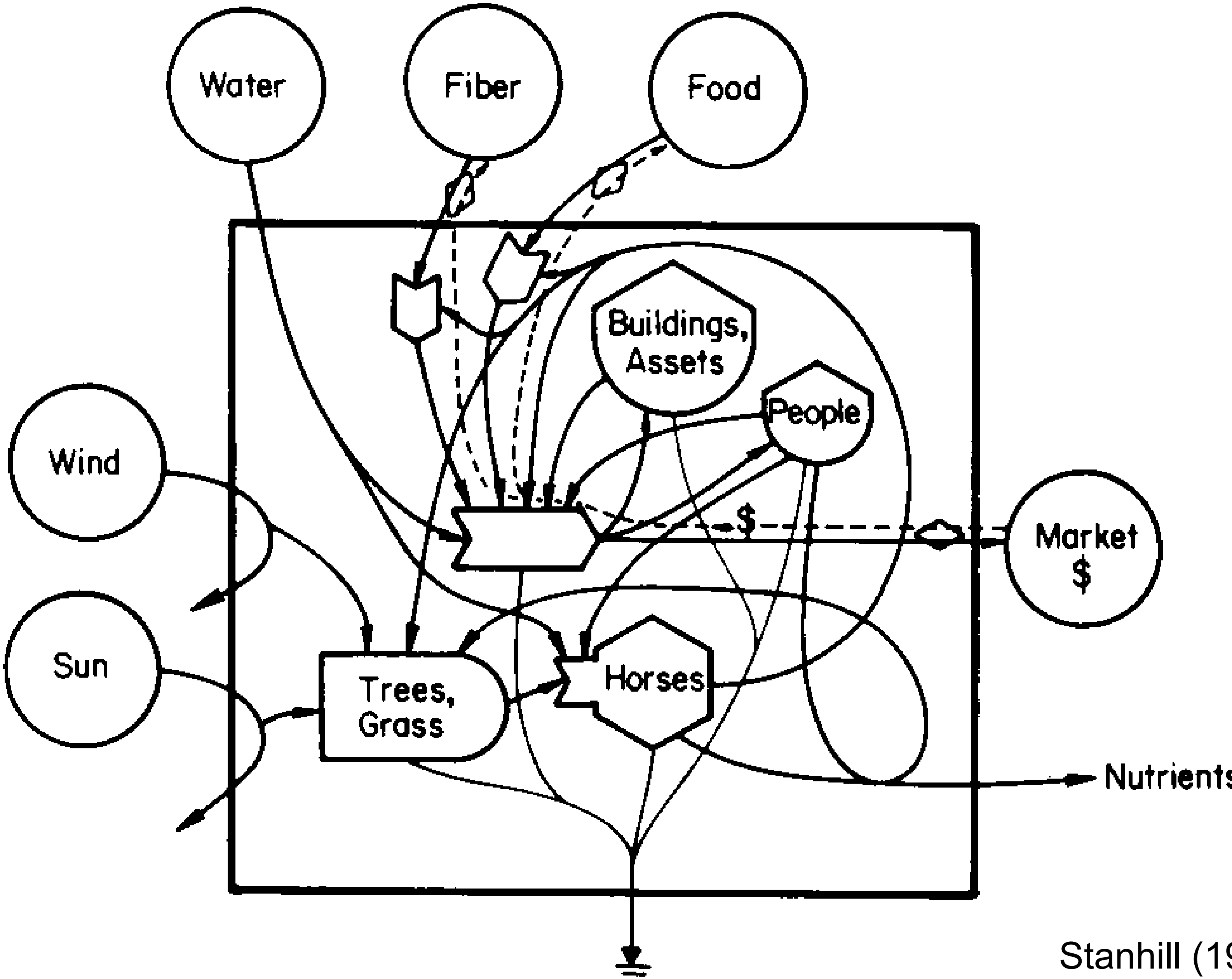


10^9 tons/year

Hanya & Ambe (1976)



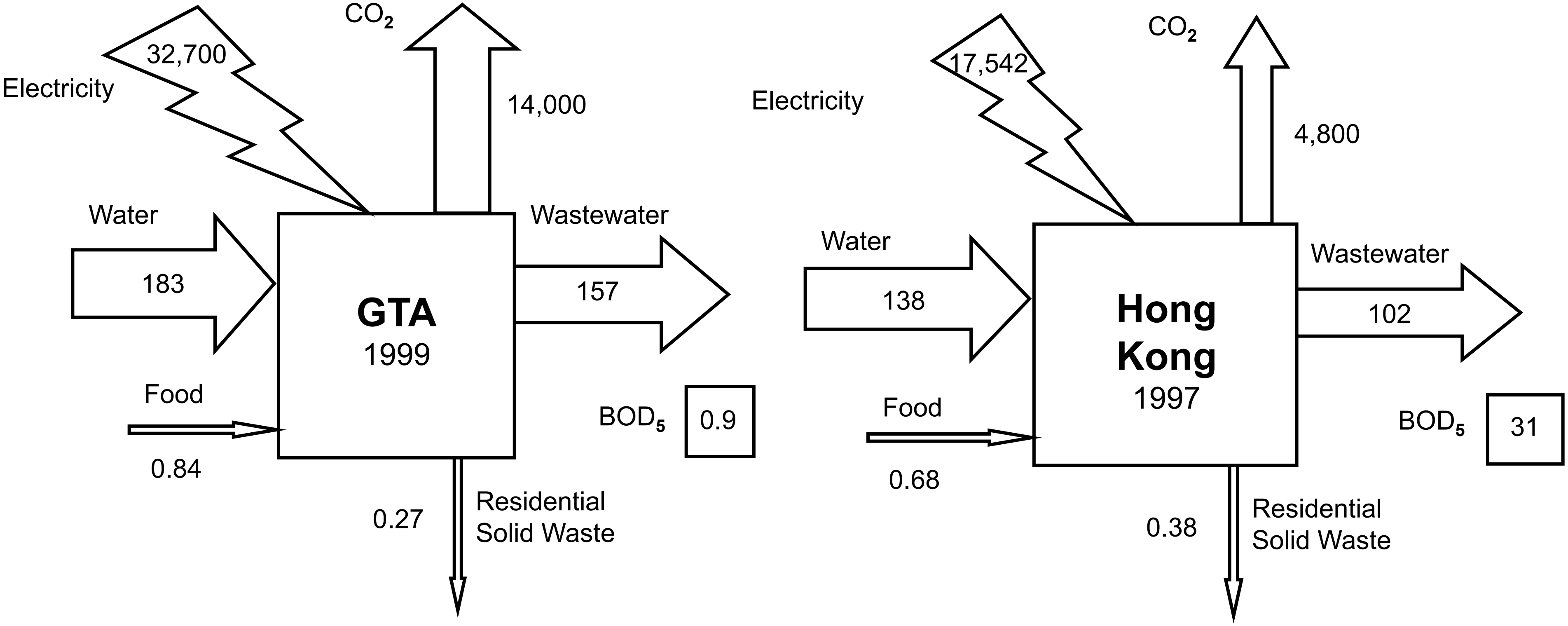
Duvigneaud & Denayeyer-De Smet (1977)



Stanhill (1977)

Early second-era studies (examples)

- **London** (Girardet, 1995; CIWM, 2002)
- **Swiss Lowlands** (Baccini, 1997)
- **Sydney** (Newman, 1999)
- **Vienna** (Hendricks et al., 2000)
- **Hong Kong** (Warren-Rhodes and Koenig, 2001)
- **Toronto** (Sahely et al., 2003)
- **Taipei** (Huang, 1998)



Comparison of urban metabolism: Hong Kong 1997 and Greater Toronto 1999 (all units in tonnes/cap, except electricity MJ/cap, CO_2 kg/cap, BOD_5 kg/cap).

Two Schools of Urban Metabolism

Odum (Systems ecology)

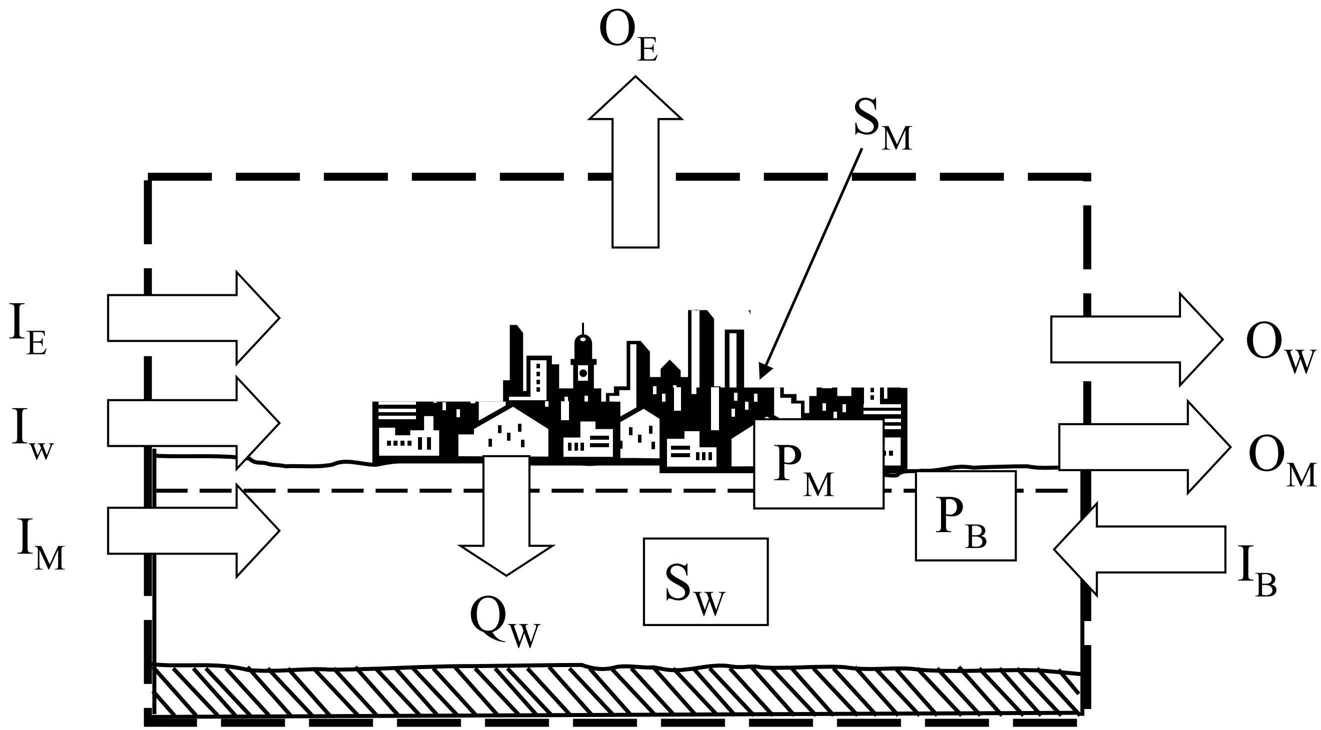
- focus of representing urban processes in terms of embodied solar energy

Baccini & Brunner (+ others before, i.e., Wolman)

Analysis of 4 key resources:

- Water
- Food (biomass)
- Construction materials
- Energy

UM framework



Urban systems boundary broadly showing inflows (I), outflows (O), internal flows (Q), storage (S) and production (P) of biomass (B), minerals (M), water (W), and energy (E).

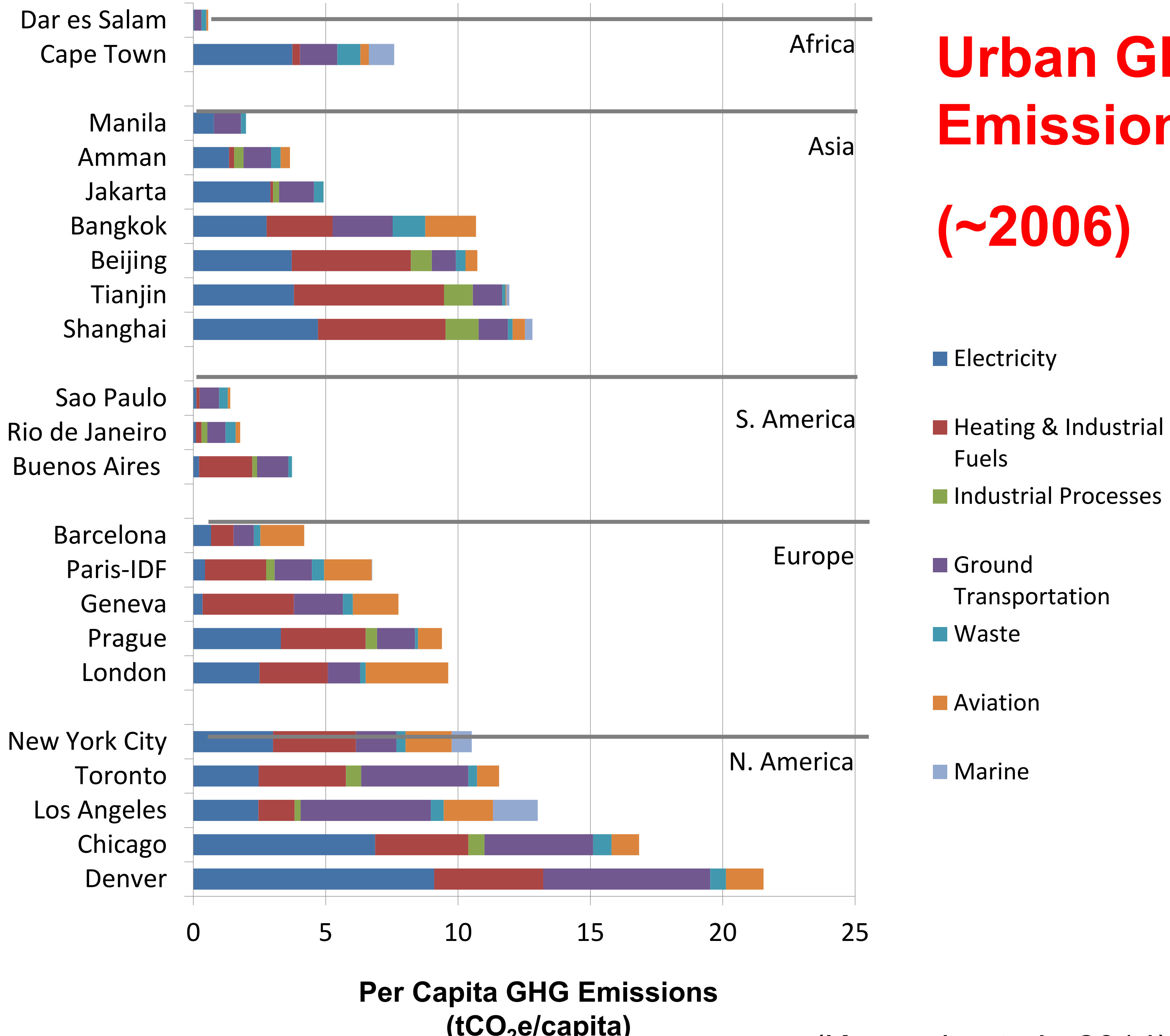
(Kennedy & Hoornweg, 2012)

2. Applications of Urban Metabolism

1. Sustainability Indicators
2. Data input to city GHG inventories
3. Mathematical models for policy analysis
4. A basis for sustainable urban design
5. Measures of resilience

Urban GHG Emissions

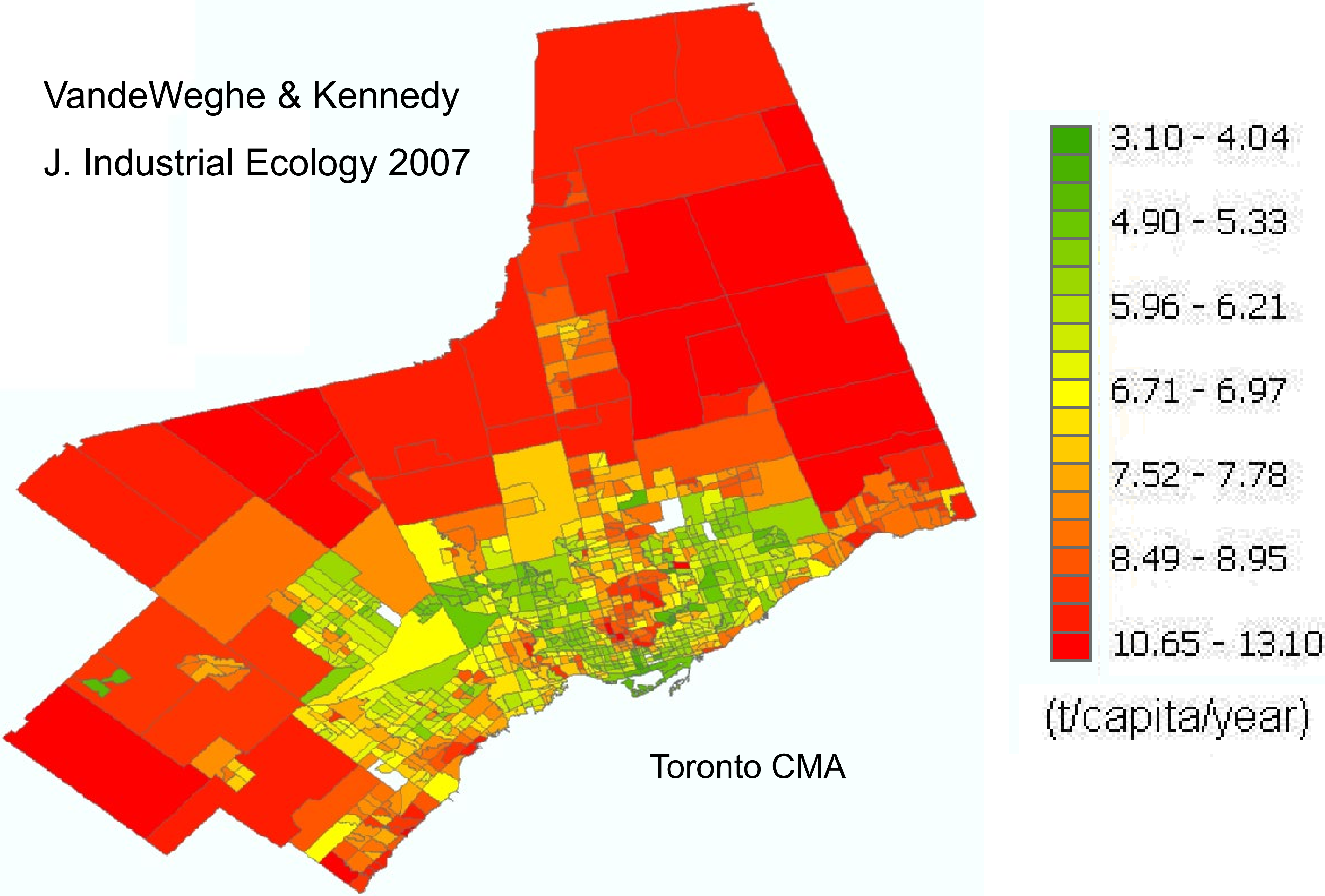
(~2006)



(Kennedy et al., 2014)

VandeWeghe & Kennedy

J. Industrial Ecology 2007



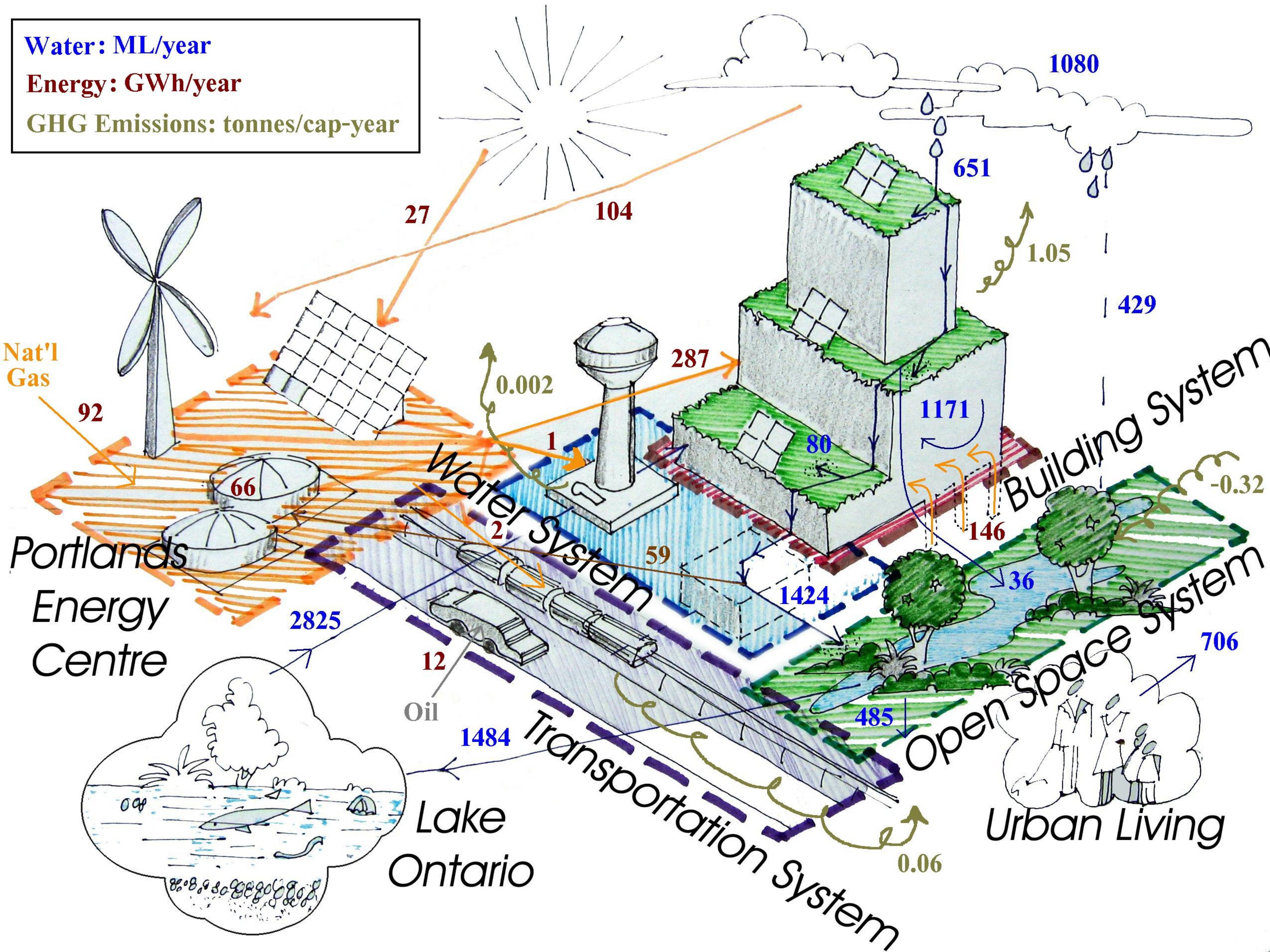
Annual per capita GHG emissions from residential activities

A Mathematical Model of Urban Metabolism
(Kennedy, 2012)

Develops set of ~25 equations to:

Represent essential relationships between components of metabolism (materials, water, nutrients, energy)

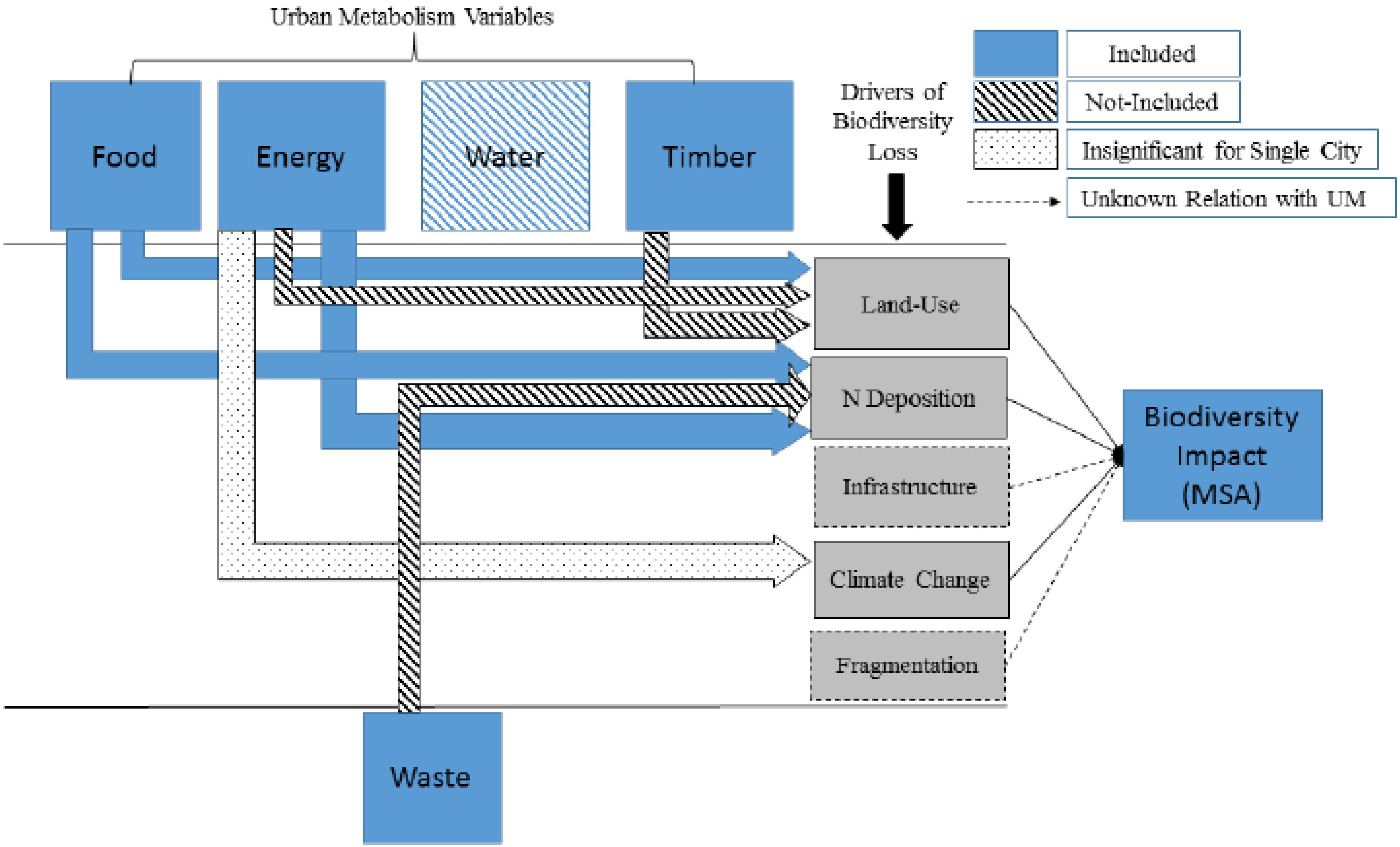
How does the material stock, i.e., infrastructure, impact the other components?



Water: ML/year
Energy: GWh/year
GHG Emissions: tonnes/cap-year
1080
651
27
104
1.05
429
Nat'l Gas
92
287
0.002
1171
1
80
-0.32
66
Building System
Water System
2
146
59
36
Portlands Energy Centre
1424
Open Space System
2825
706
12
Oil
485
1484
Transportation System
Lake Ontario
0.06
Urban Living

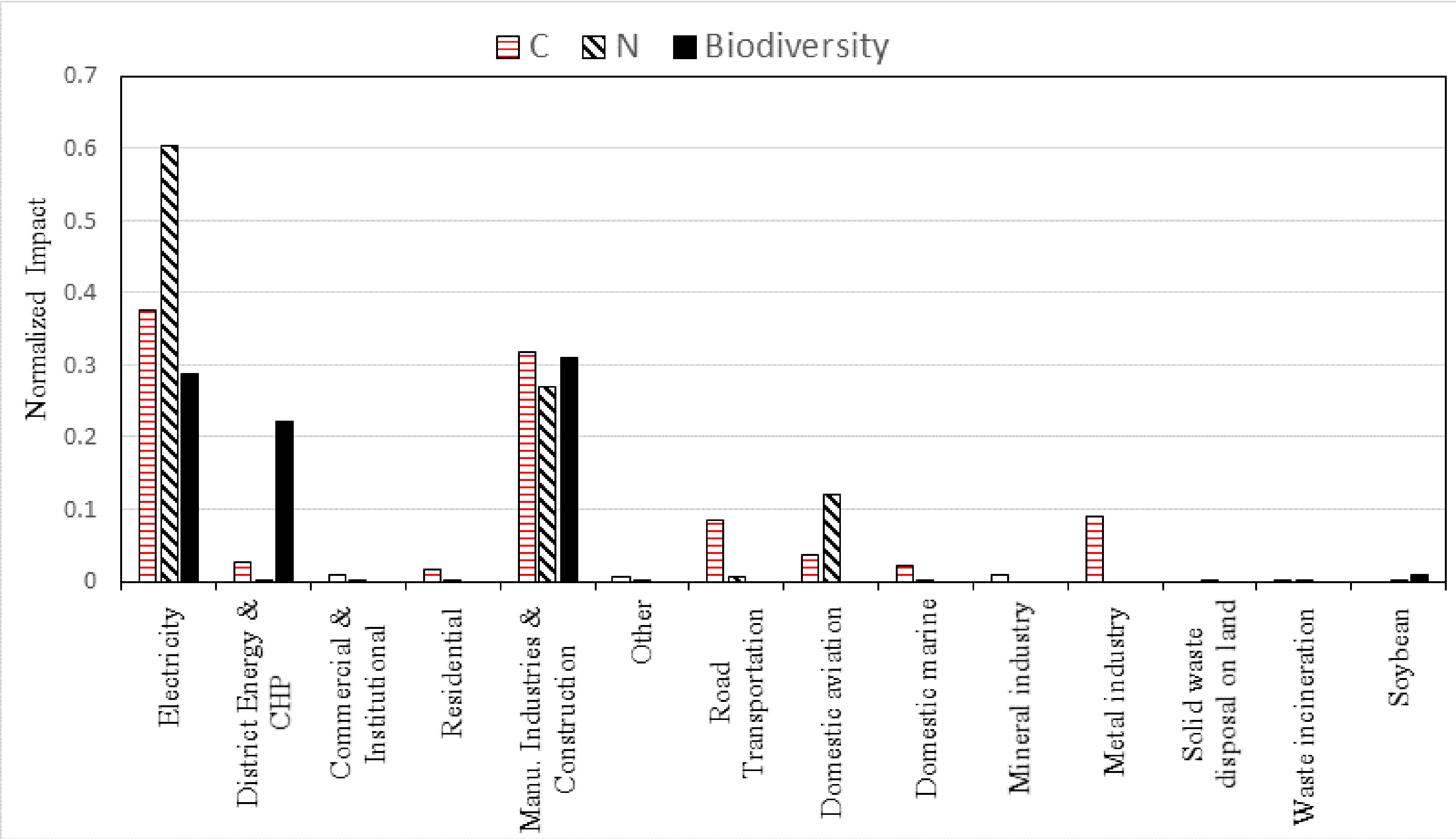
Metabolism of Neighbourhoods
Natalia Codoban (2008)

UM and biodiversity loss drivers



(Singh & Kennedy, 2018)

C, N and biodiversity impacts for Shanghai (with limited categories)



(Singh & Kennedy, 2018)

Energy Stored in Cities as a Measure of Resilience

Resiliency is associated with the time it takes for a system to return to operation after a shock.

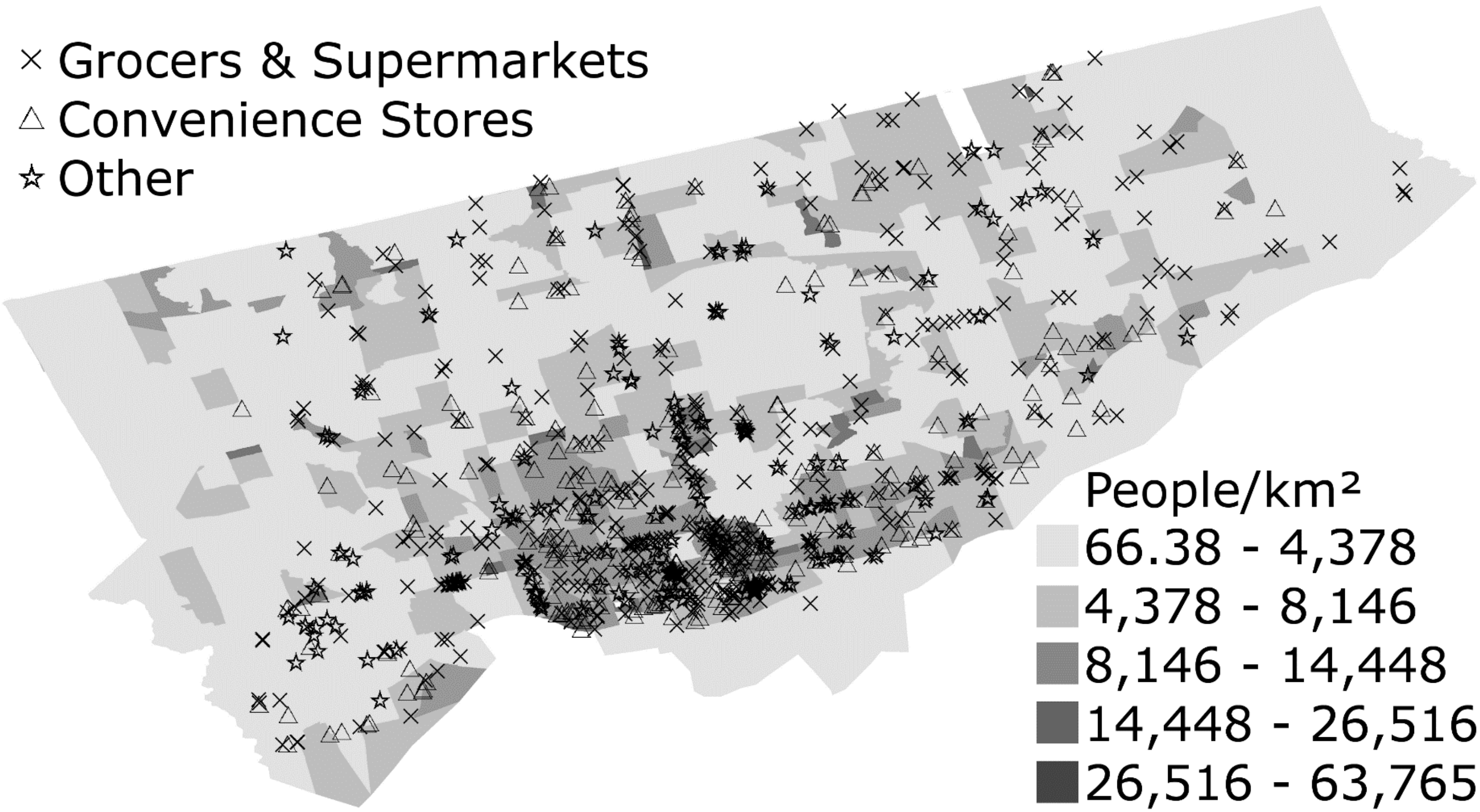
When supply fails, internal buffer capacity becomes vital to meeting demand and hence is an important factor in resilience.

Toronto energy stocks and residence times

Stock	Energy Content (TJ)	Days
Gasoline (total)	1,732	5.9
- Gas in Vehicle Tanks	1,190	4.1
- Gas at Stations	543	1.9
Diesel (total)	973	12
Food (total)	770	20
- Food in Residential Kitchens*	117	3
- Food in Grocery Stores	653	17
Local biomass for heating homes†	49,800	64

(Bristow & Kennedy, 2013)

Location of retail food outlets relative to population



(Bristow & Kennedy, 2013)

Global Cities Institute

Civil Engineering
UNIVERSITY OF TORONTO

Enel Foundation
Energy for Knowledge

Metabolism of Megacities

(Kennedy et al. Energy and Material Flows of Megacities, PNAS, 112 (19) 5985-5990, 2015)

Objectives

Conduct UM studies for the world's 27 megacities, collecting data on:

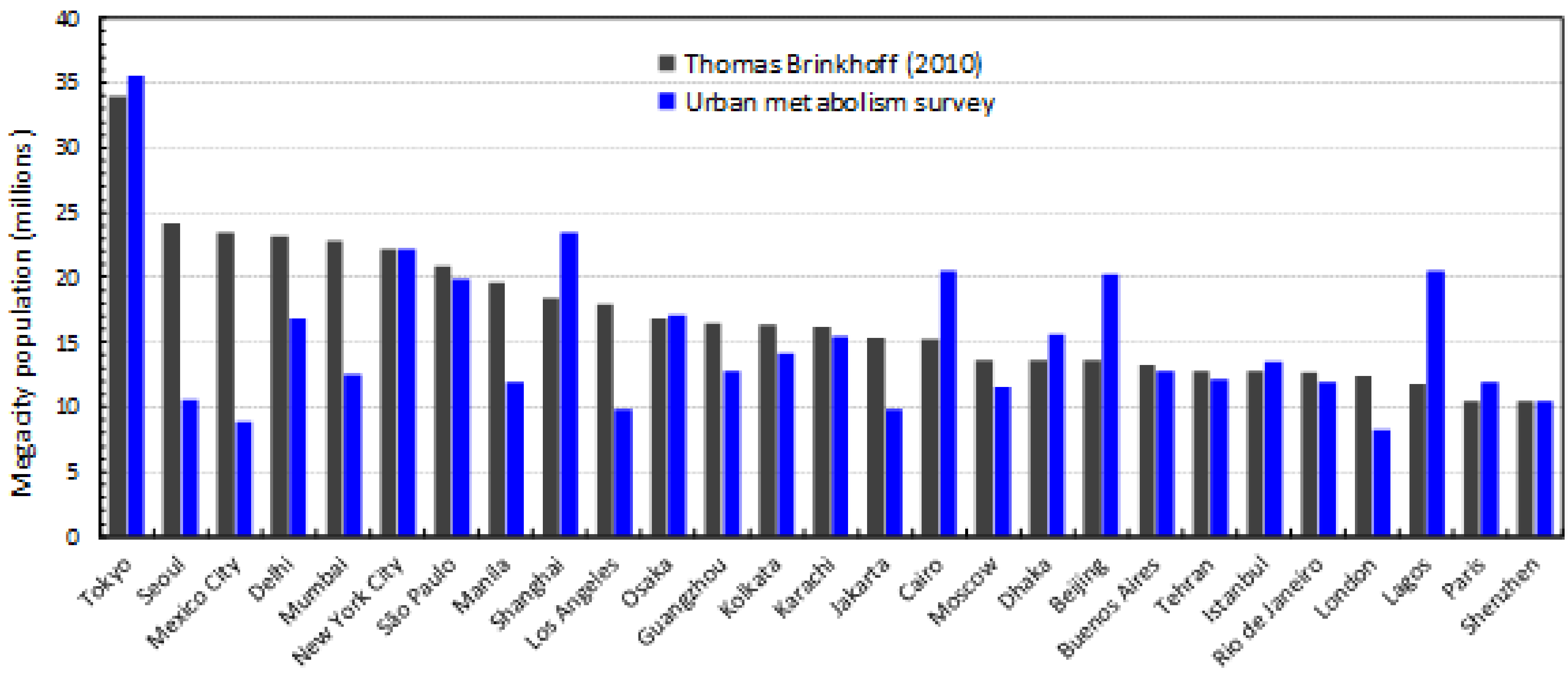
- resources: energy, water, food and materials
- rates of change of resource use
- access to resources / services
- market structure of resource suppliers
- adoption of potentially low carbon technologies

Objectives

Identify biophysical and economic factors that underlie the UM of megacities.

Growth of Megacities

Megacity Populations



(Kennedy et al. 2015)

Metabolism of Megacities - Data collection

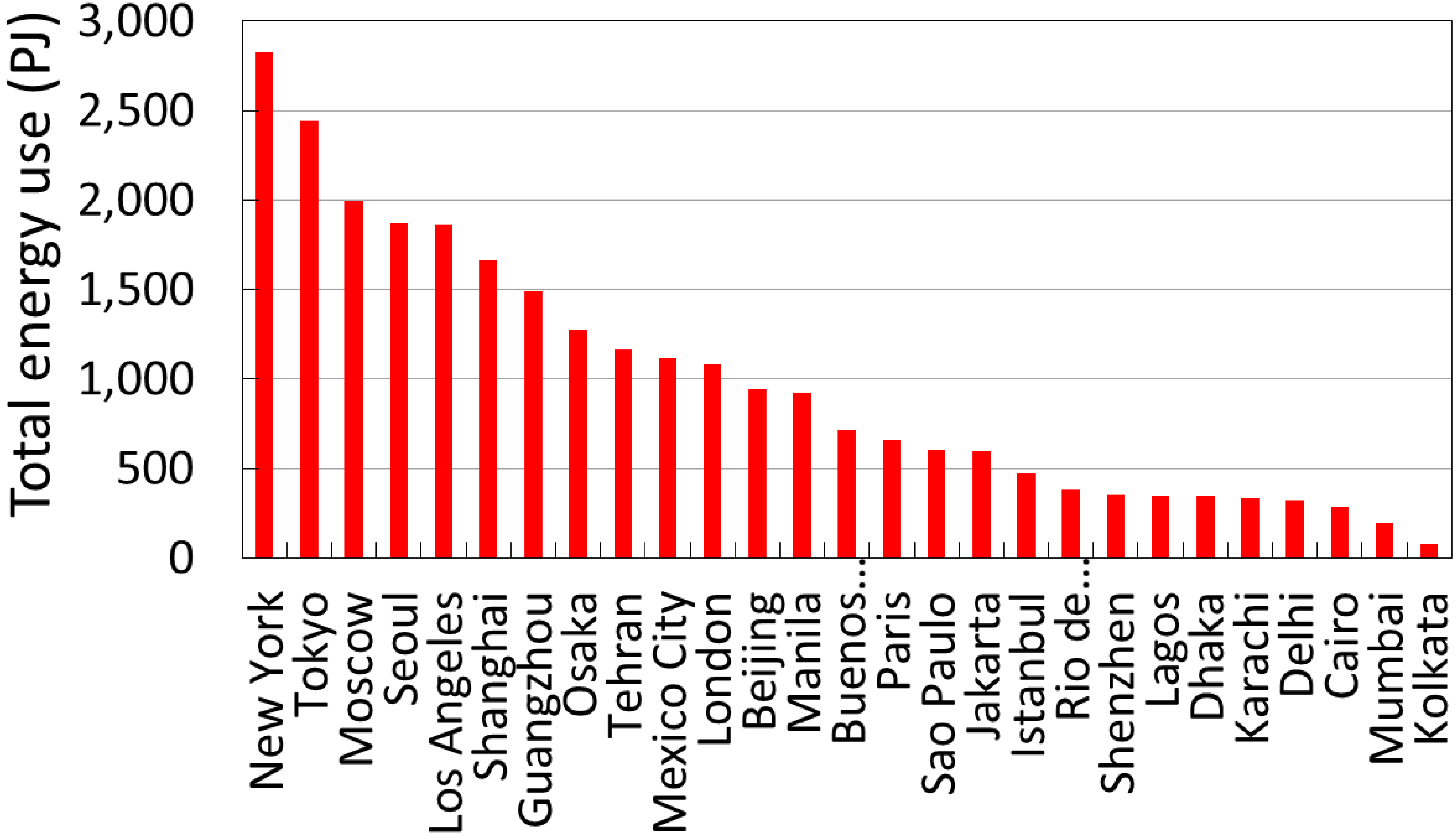
1. Definition of megacity
   - spatial boundaries
   - constituent cities
   - population
   - economy

2. Biophysical descriptors
   - climate
   - latitude
   - population density
   - building stock

3. Urban metabolism
   - energy (all types)
   - water
   - materials
   - waste

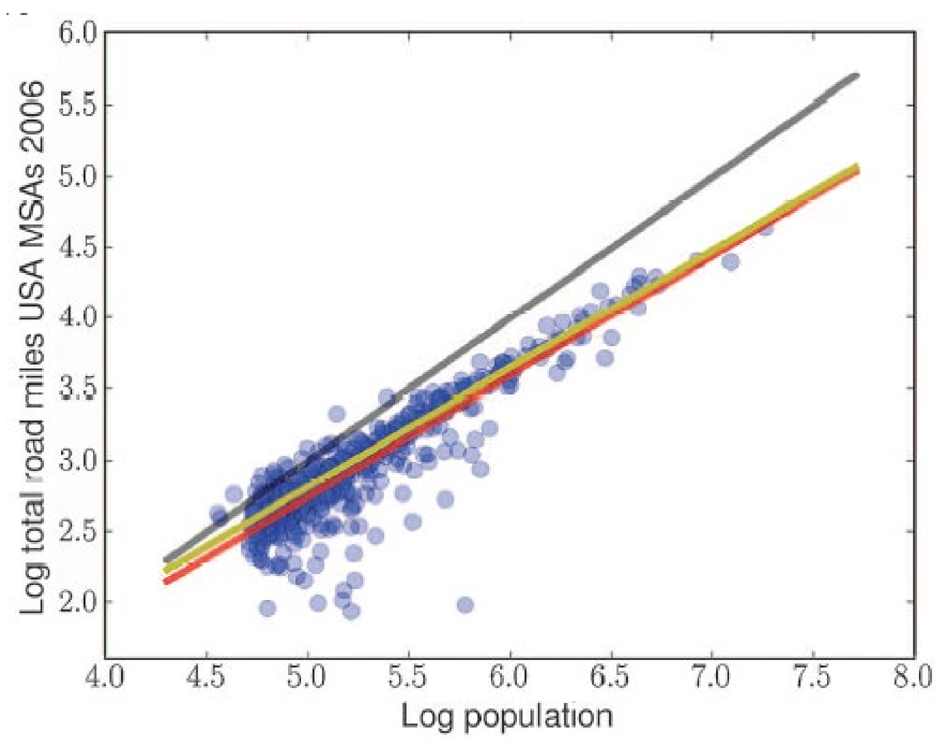
4. Role of utilities
   - access of households to basic services;
   - potential to provide new services

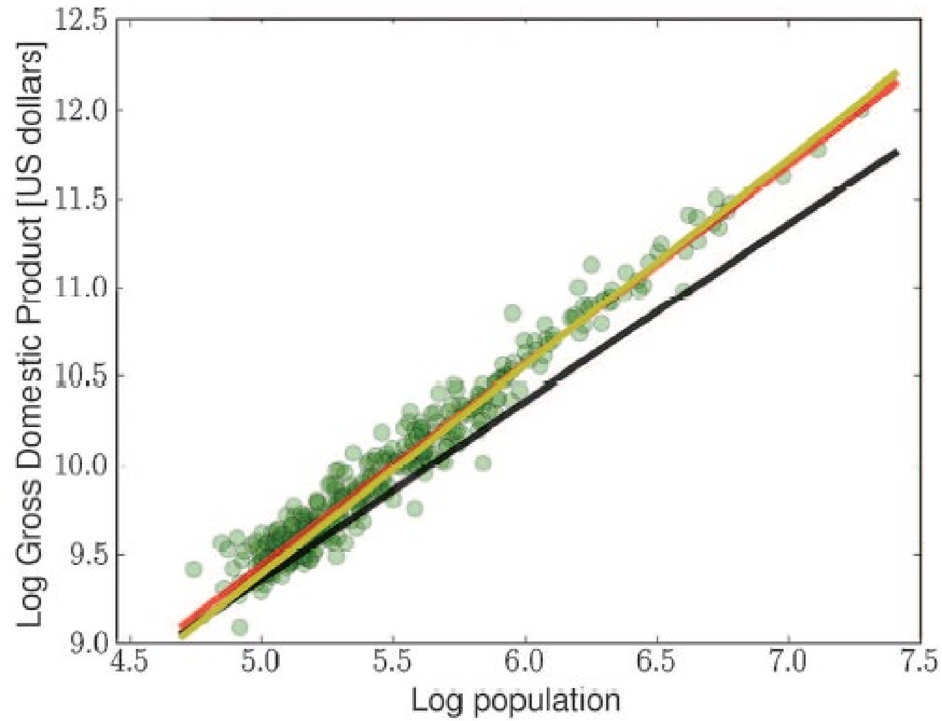
Total Energy Use in Megacities



(Kennedy et al. 2015)

City Scaling Laws



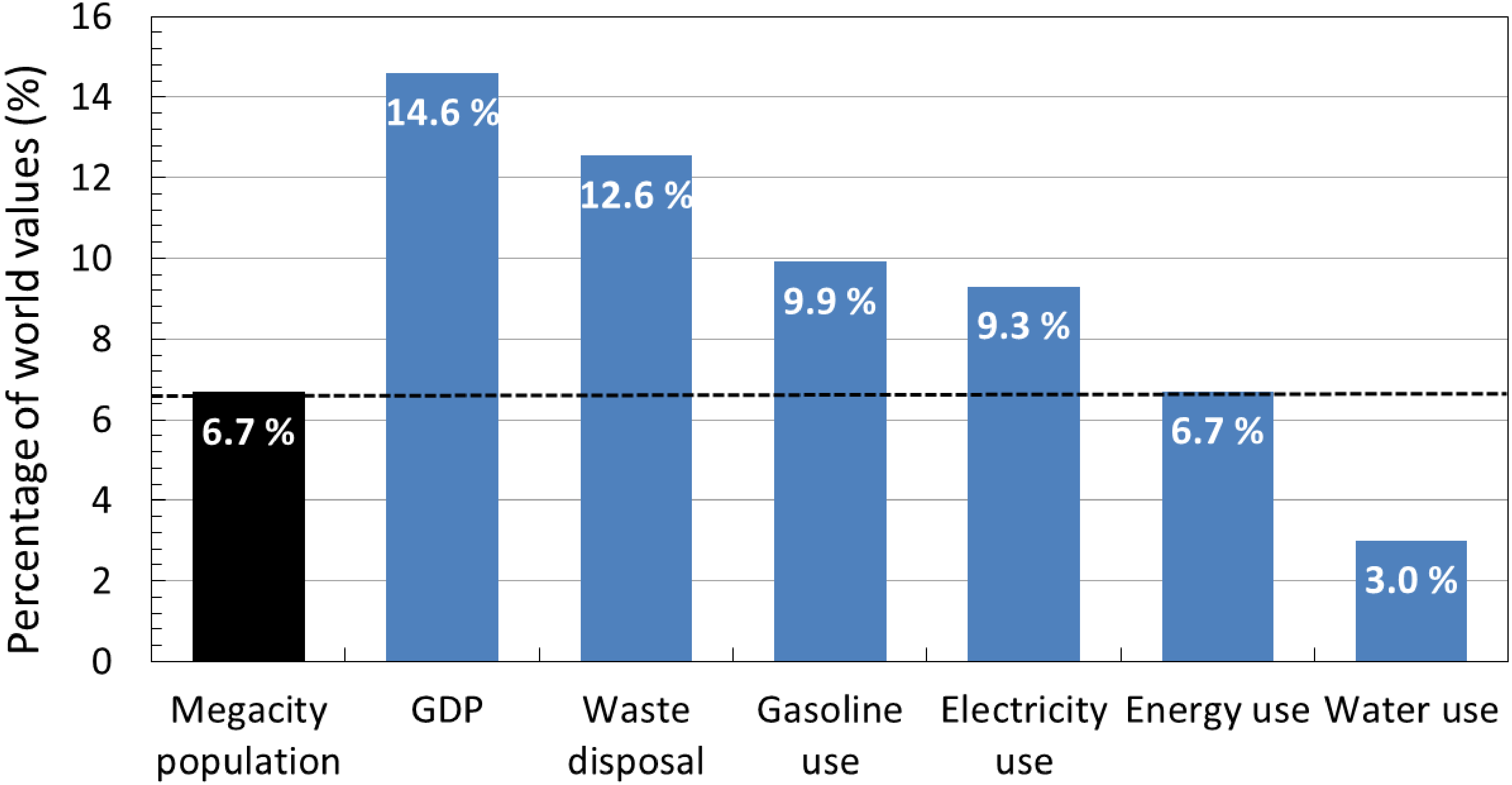


Length of urban roads (USA) Sub-linear

Metro GDP (USA) Super-linear

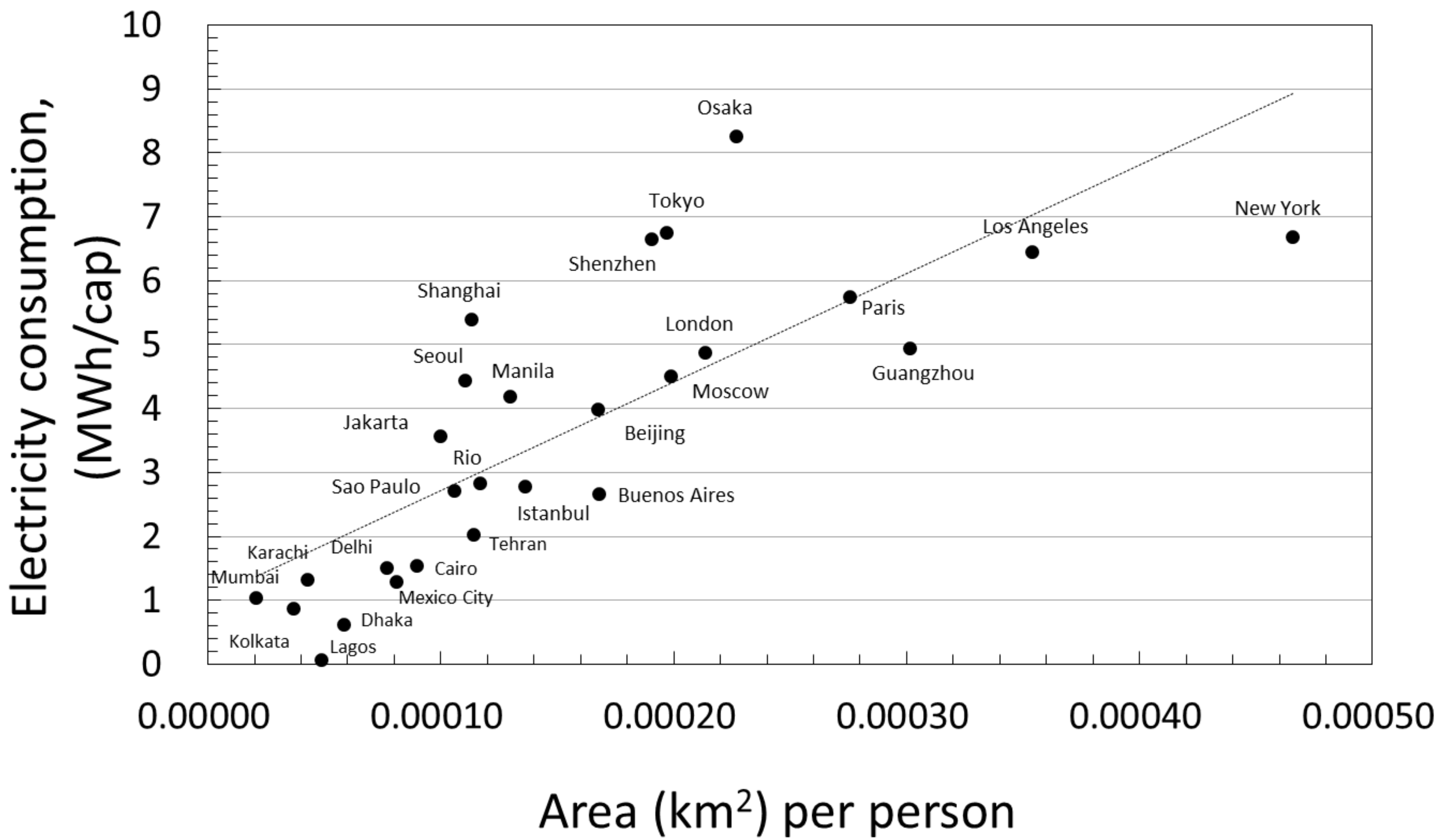
(Adapted from Fig. 1 of Bettencourt, 2013)

Megacity resource & waste flows as a percentage of world values



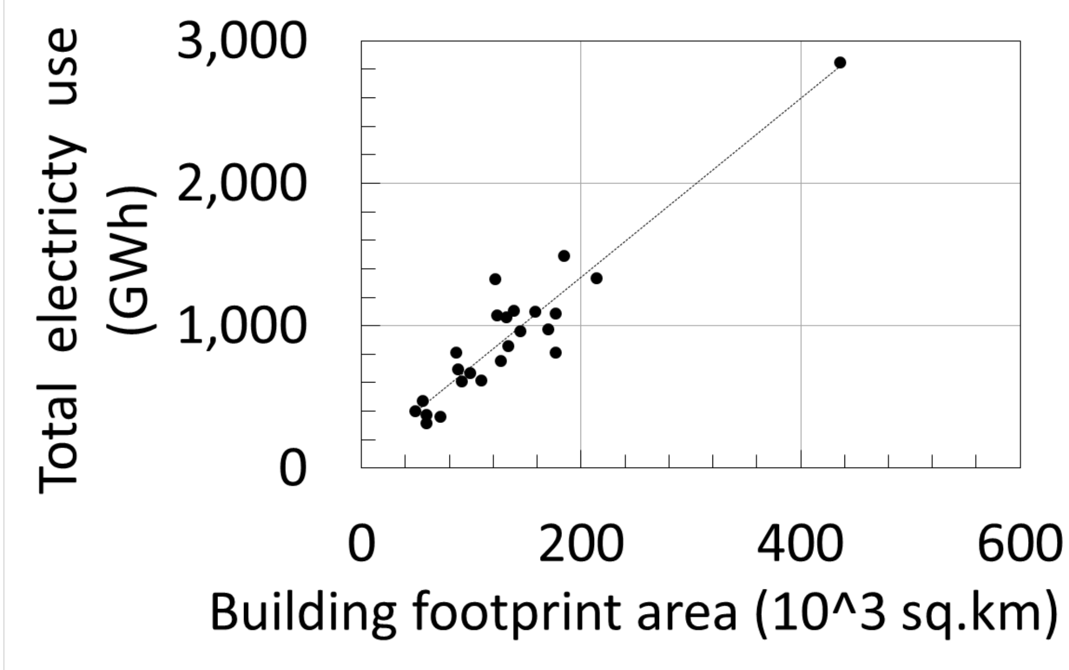
(Kennedy et al. 2015)

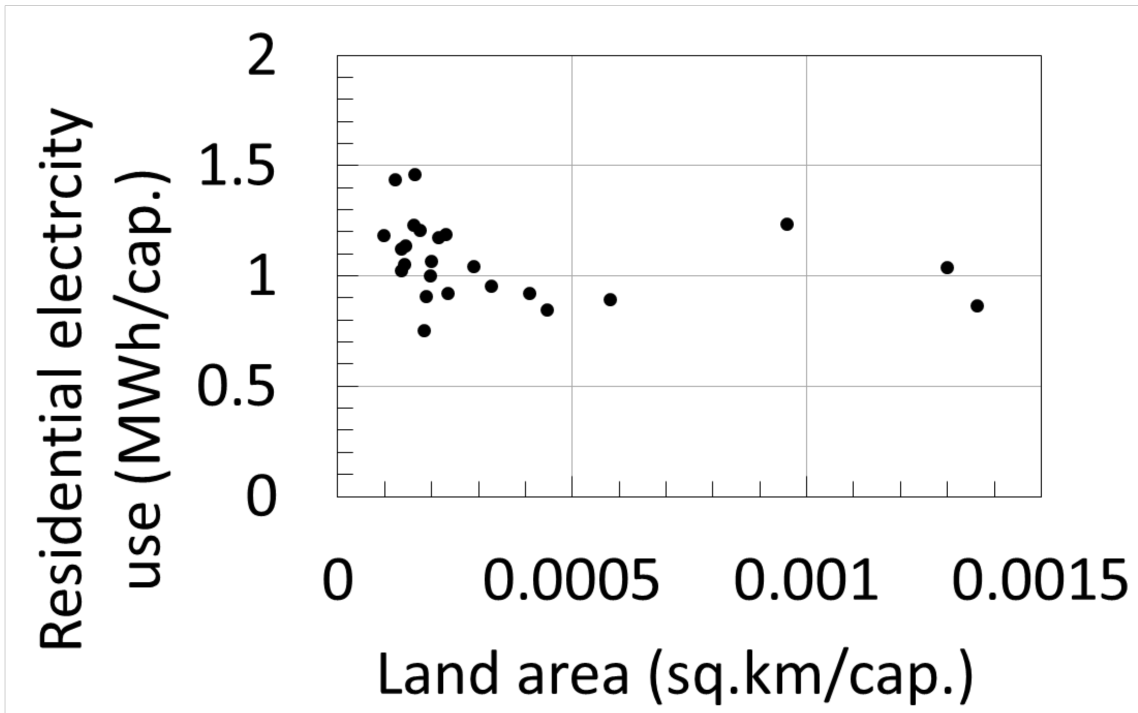
Electricity Use vs. Urbanized Area per capita



(Kennedy et al. 2015)

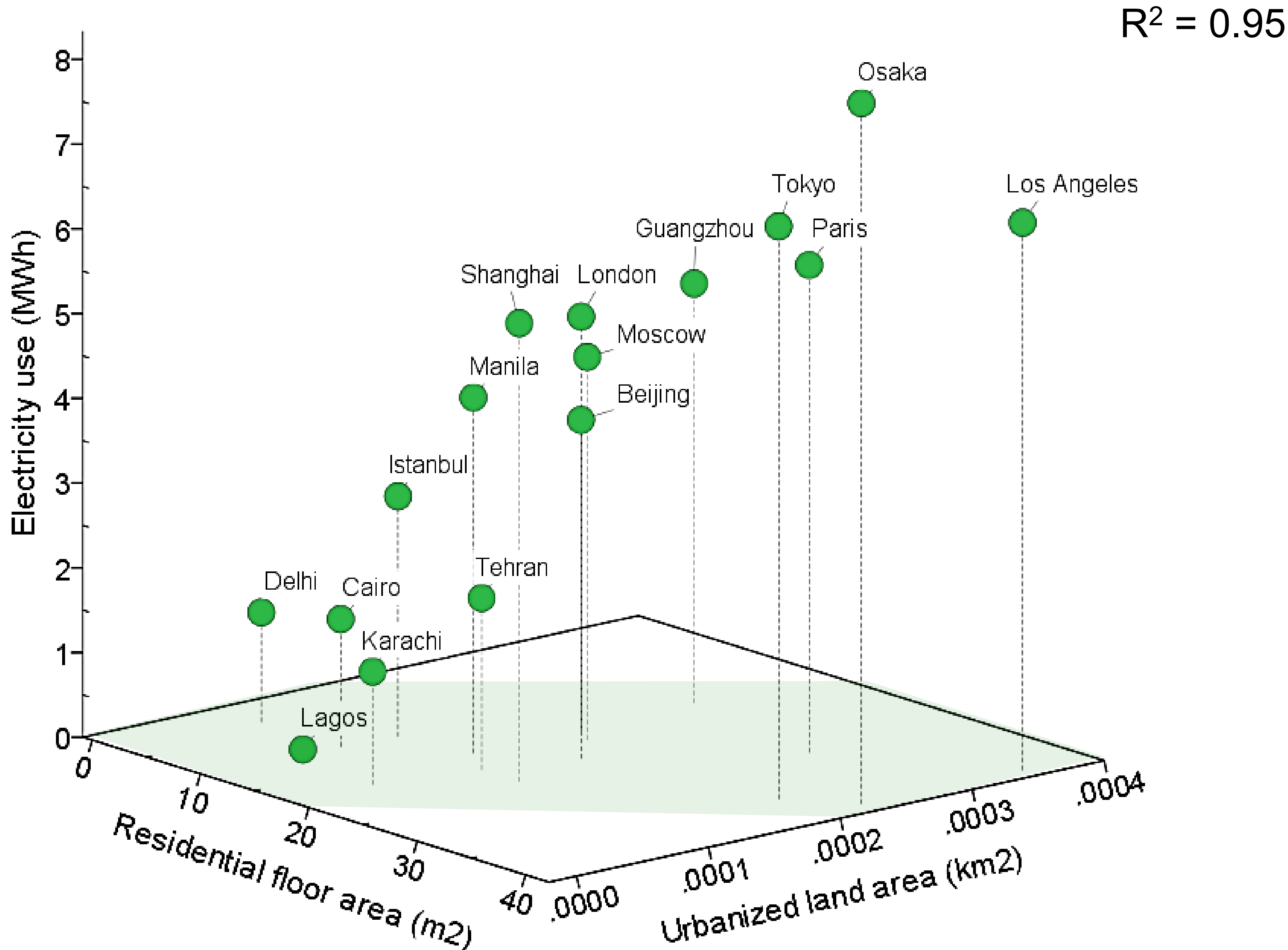
Electricity use in districts of Buenos Aires megacity





(Kennedy et al. 2015)

Electricity use and urban form



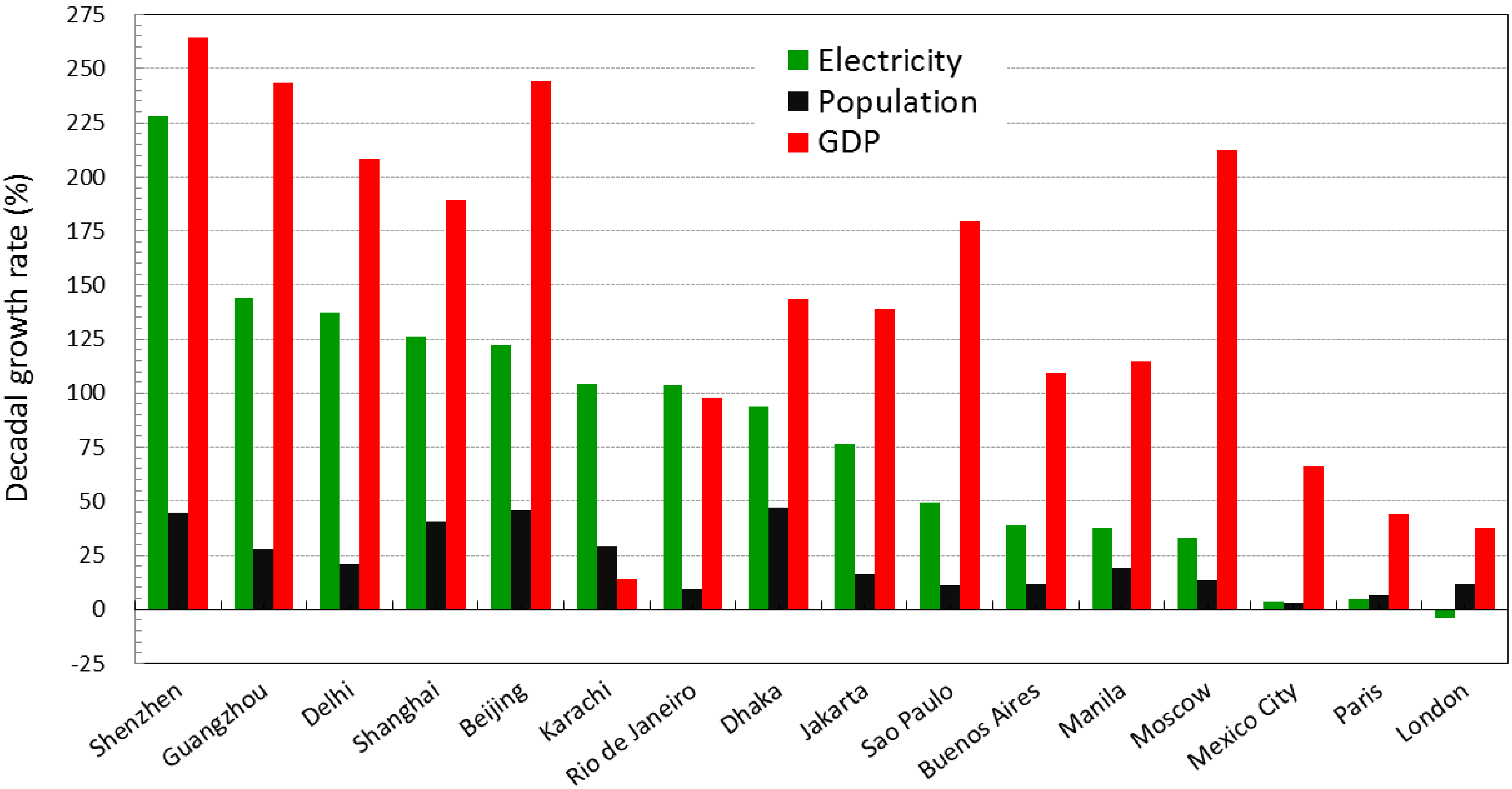
* All values per capita, 2011

Correlation

	Electricity use	Heating/ industrial fuel	Transport fuel	Water consumption	Solid waste production	Heating degree-days	Area (km^2) per person	GDP
Electricity use (MWh)	---							
Heating/industrial fuel (GJ)	0.36	---						
Transportation fuel (GJ)	0.58	0.56	---					
Water consumption (kL)	0.52	0.33	0.67	---				
Solid waste production (t)	0.37	0.03	0.30	0.04	---			
Heating degree-days	0.46	0.80	0.54	0.17	0.25	---		
Area (km^2) per person	0.78	0.46	0.75	0.72	0.39	0.42	---	
GDP ($)	0.69	0.52	0.71	0.46	0.47	0.58	0.80	---

(Kennedy et al. 2015)

Growth in Electricity Use (2001-2011)



(Kennedy et al. 2015)

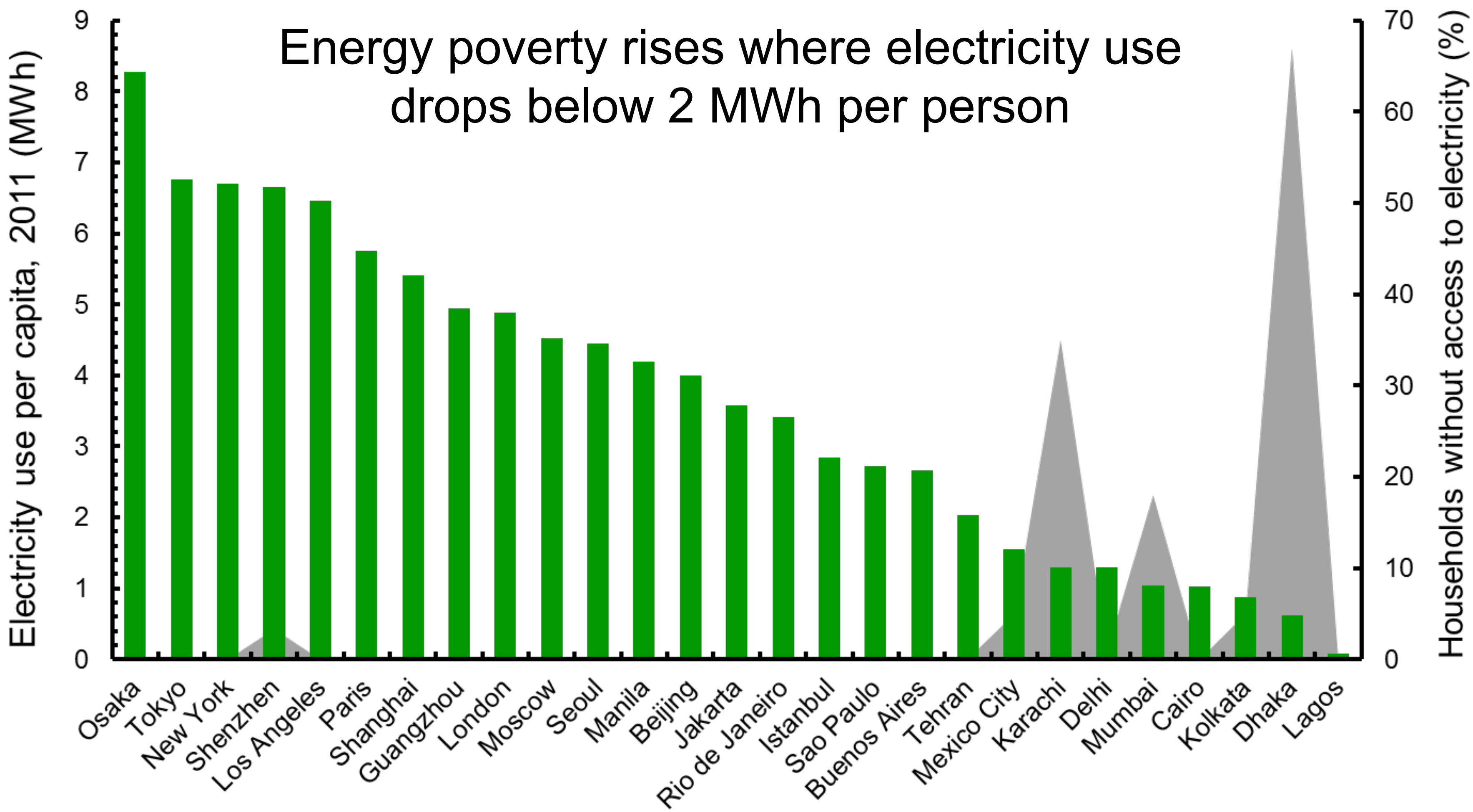
Access to Services (%)

Megacity	Households without direct access to water	Households without direct access to drinkable water	Water line losses as a share of total water use	Households without sewerage	Households without public waste collection	Households without grid electricity connection
Mumbai	21	21	3.7	64	48	18
Delhi	20	22	40	64	n.d.	0.9
Dhaka	7	31	33.1	65	10	67
Kolkata	n.d.	39	22	37	n.d.	5
Karachi	40	60	40	43	40	35
Jakarta	8	24	n.d.	12	n.d.	0.3
Cairo	8	19	6.1	23	n.d.	n.d.
Tehran	0	0	33.3	55	0	0.1
Rio de Janeiro	1	11	54.2	26	9	0
São Paulo	2	2	71.4	8	5	0
Buenos Aires	11	11	76.1	14	5	0
Mexico City	4	n.d.	n.d.	0.5	n.d.	5
Guangzhou	0.3	2	n.d.	15	1	15
Shenzhen	5	6	n.d.	30	1	15
Shanghai	0	0.6	15	10	1	0
Beijing	0	0.3	15.3	5	0	0
Lagos	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

(Kennedy et al. 2015)

* n.d. = no data

Electricity use



Summary

1. Wealth effects dominating efficiency.
2. Building floor area explains correlation between electricity and urban area per capita.
3. High correlation of area/cap., GDP and energy.
4. Rapid growth in electricity and transport fuels linked with GDP.
5. Wide variations in UM and in access to services.

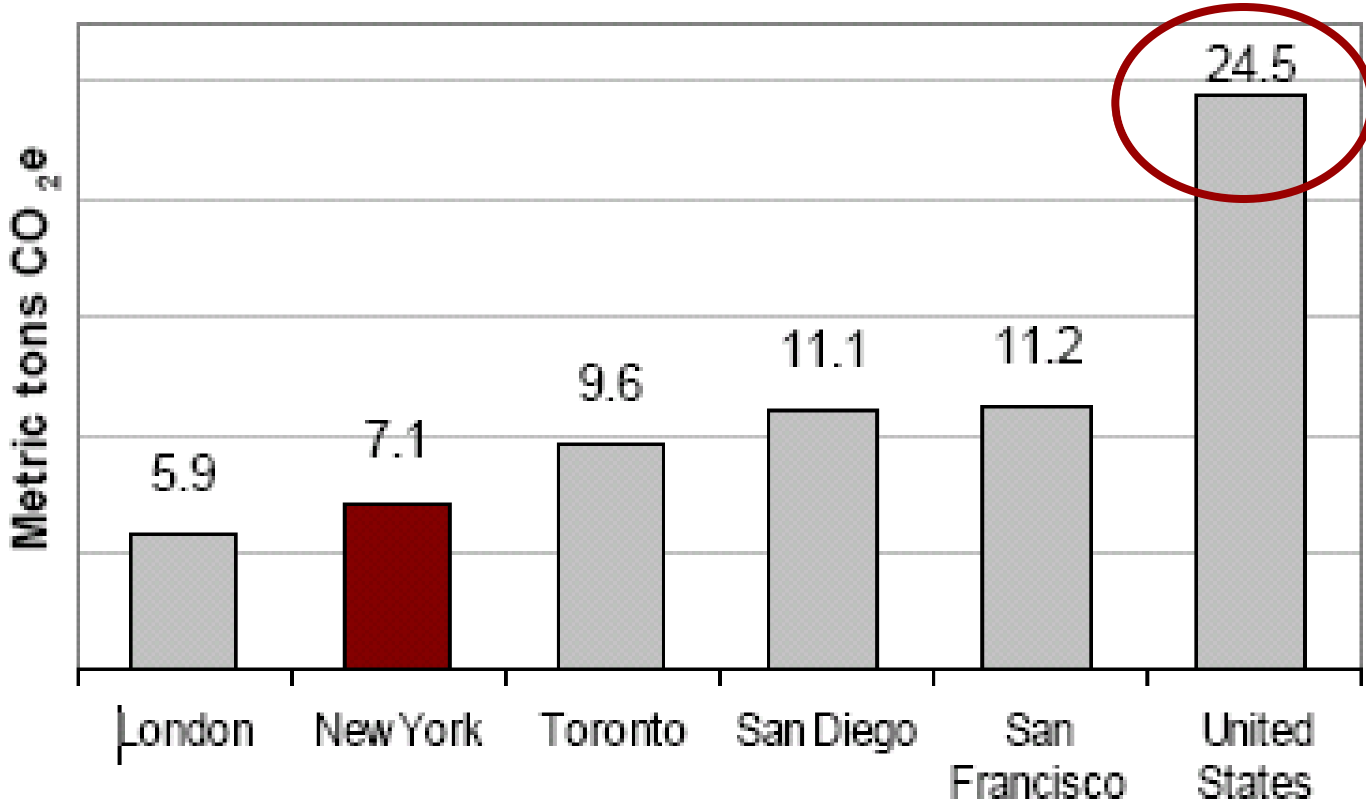
4. City Greenhouse Gas Accounting

4.1 Protocol for city GHG inventories

4.2 Towards Low Carbon Electric Cities

(Kennedy, et al. Methodology for Inventorying Greenhouse Gas Emissions from Global Cities, Energy Policy, 37(9), 4828-4837, 2010.)

e.g., New York City (2007):



National Average w/ all sources included

Figure i. Per capita CO_2e emissions of select cities and the United States. Calculations are based on reported greenhouse gas inventories with the understanding that differing methodologies and emissions sources exist.


HOLLYWOOD

IPCC Guidelines

- Include emissions that occur within the territory under each nation's jurisdiction

IPCC: National Scale

- Energy
- Non-Energy Emissions from Industrial Processes and Product Use
- Agriculture, Forestry and Other Land Use (AFOLU)
- Waste

WRI Protocol For Corporations

Scope 1: Owned / controlled sources operating within corporate boundary

Scope 2: Electricity consumed by the company, generated "outside"

Scope 3 (optional): Consequence of the *activities* of the company

WRI recommends a small set of most relevant Scope 3 items to create win-win GHG mitigation strategies.

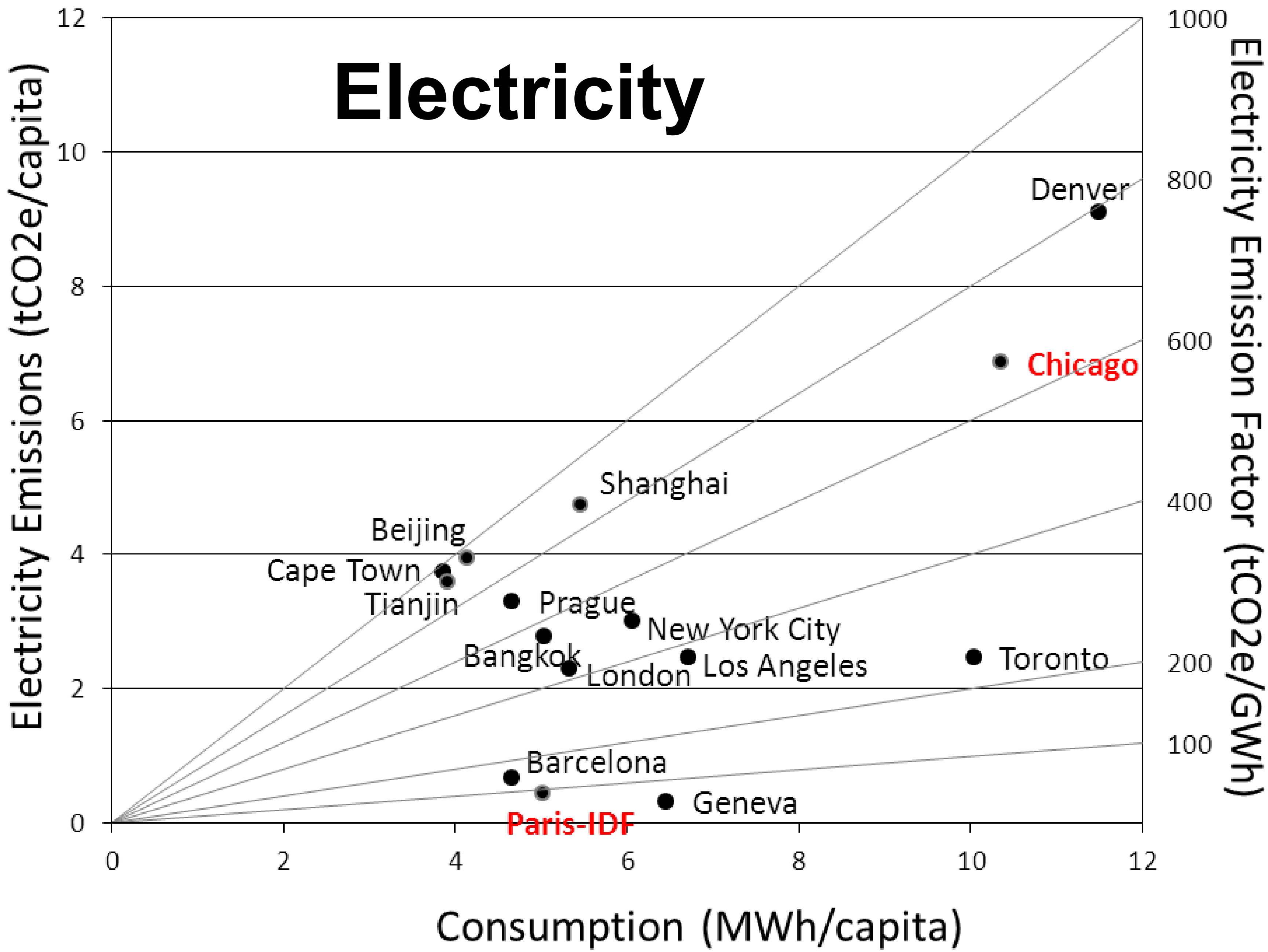
Heating and Industrial Fuels

$$GHG_{fuel} = C_{fuel} * I_{fuel}$$

where

C_{fuel} is total fuel consumed (TJ);

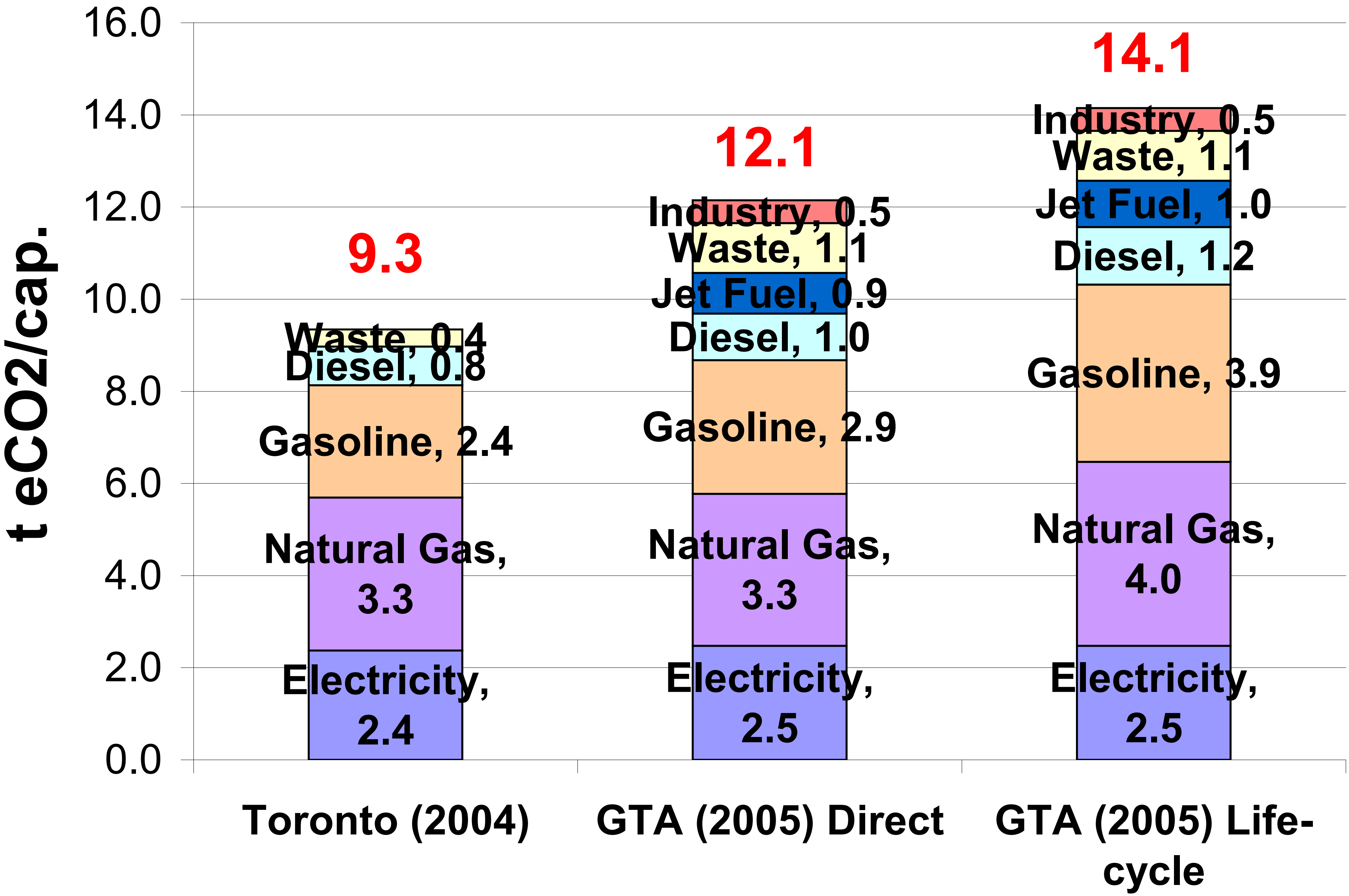
I_{fuel} is the GHG emissions factor (t CO_2 e / TJ)


Electricity
Electricity Emissions (tCO2e/capita)
Electricity Emission Factor (tCO2e/GWh)
Consumption (MWh/capita)
0
2
4
6
8
10
12
100
200
400
600
800
1000
Denver
Chicago
Shanghai
Beijing
Cape Town
Tianjin
Prague
New York City
Bangkok
London
Los Angeles
Toronto
Barcelona
Geneva
Paris-IDF

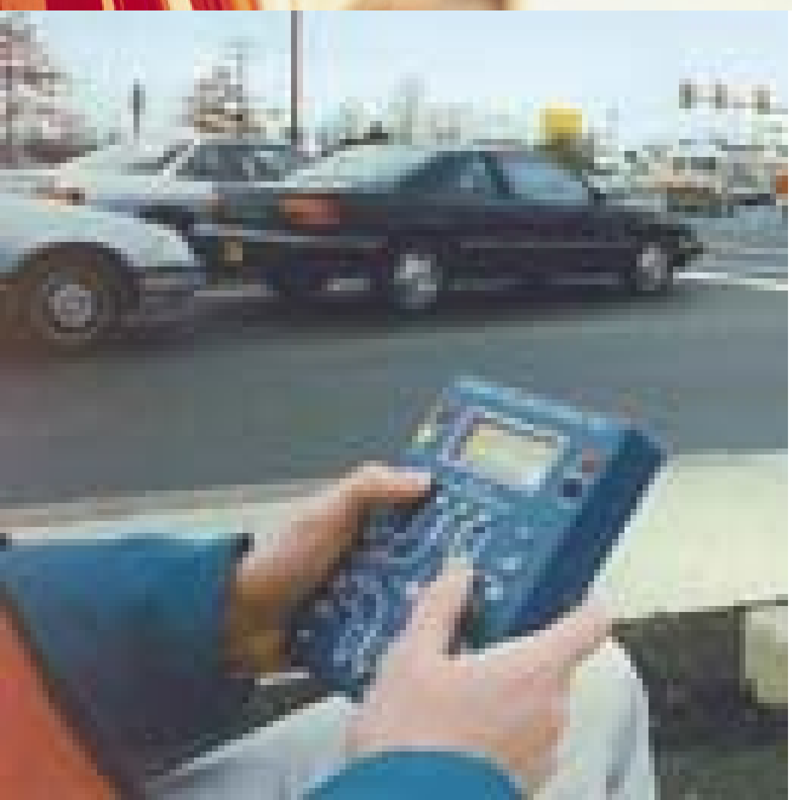
GHG Emission Intensity
(t eCO_2 /TJ)

·	**Direct Emissions** (IPCC)	**Life-cycle Canada** (GHGenius)	**Life-cycle Europe** (Ecoinvent)
Gasoline	69.2	91.9	82.9
Diesel	73.9	91.0	84.1
Natural Gas	56.1	67.9*	61.6
……etc.			

(* GaBi4 & TransCanada Pipelines)



t eCO2/cap.
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
9.3
12.1
14.1
Waste, 0.4
Diesel, 0.8
Gasoline, 2.4
Natural Gas, 3.3
Electricity, 2.4
Industry, 0.5
Waste, 1.1
Jet Fuel, 0.9
Diesel, 1.0
Gasoline, 2.9
Natural Gas, 3.3
Electricity, 2.5
Industry, 0.5
Waste, 1.1
Jet Fuel, 1.0
Diesel, 1.2
Gasoline, 3.9
Natural Gas, 4.0
Electricity, 2.5
Toronto (2004)
GTA (2005) Direct
GTA (2005) Life-cycle



Gasoline

- Fuel sales
- Traffic counts / surveys / models
- Scaling

Gasoline: Consumption (ML)

	Fuel sales	Modeled VKT	Scaled
Bangkok	2,741	2,662	
New York City		4,179	4,107
Toronto	6,691		6,988

Aviation

1. Exclude (beyond local. gov.)
2. Include domestic (UNFCCC)
3. Include international (reflect urban economy)

Le Bilan Carbon™ de Paris

Includes embodied GHGs in:

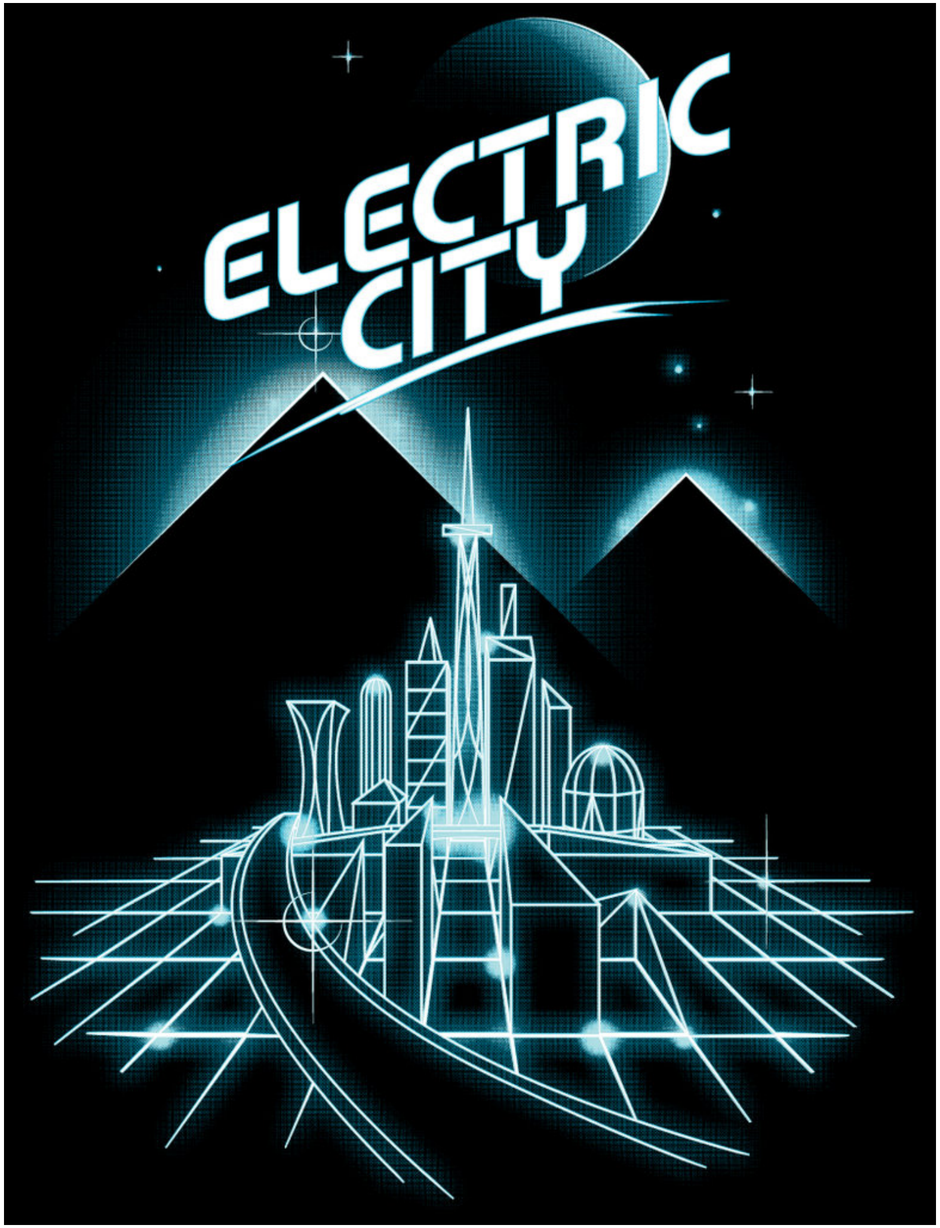
- **building materials**
- **maintenance of vehicles**
- **refining of fuels**
- **transport of merchandise to the city**
- **food**

Cities Get Common Standard for Measuring Greenhouse Gas Emissions

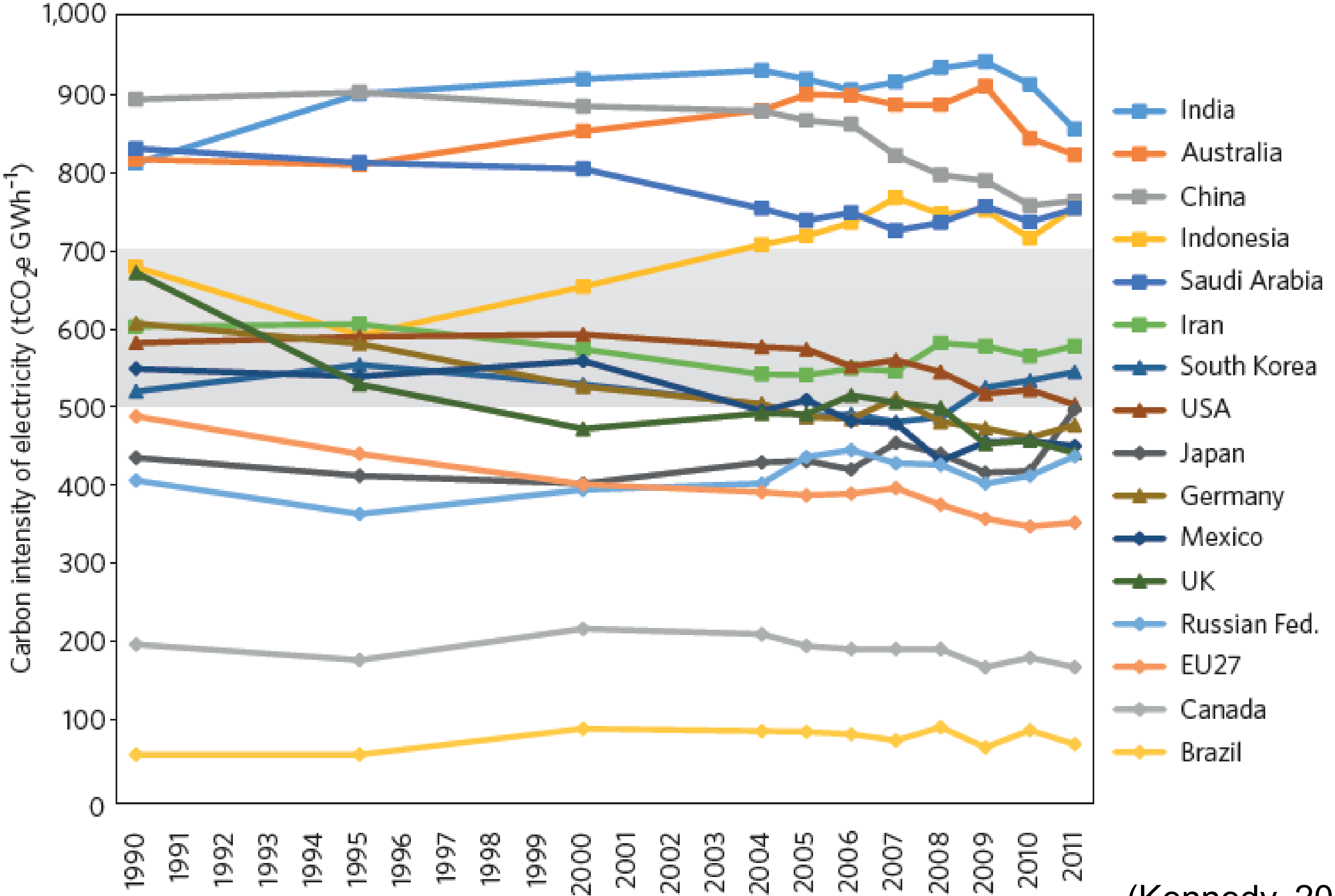
UNEP
United Nations Environment Programme

THE WORLD BANK

UN HABITAT
FOR A BETTER URBAN FUTURE

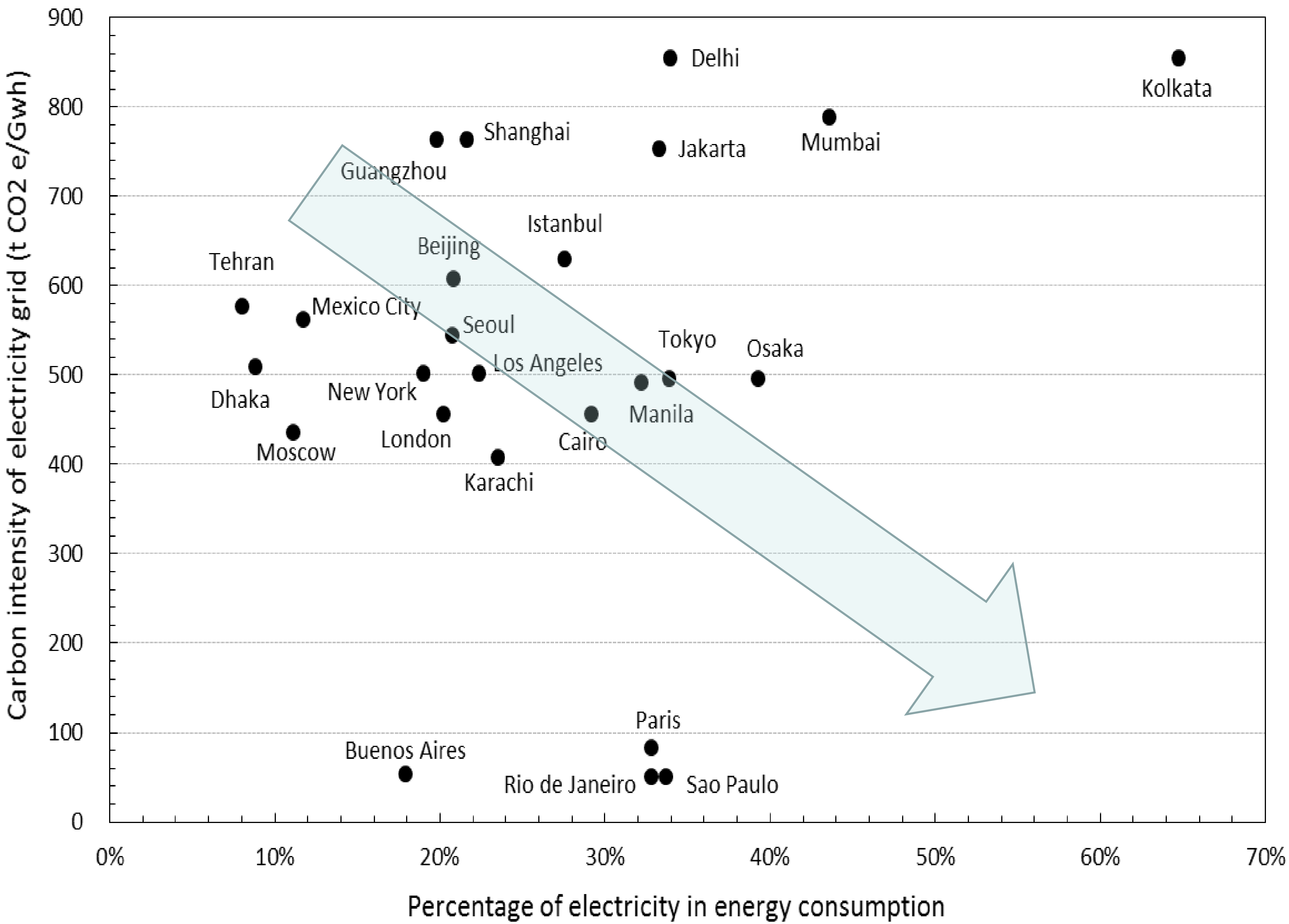

ELECTRIC
CITY

Key Threshold for Electrification



(Kennedy, 2015)

Transforming to low carbon electric cities



(Kennedy et al., 2017)