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.”

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)
Oxygen Gas 50
(Atmosphere)
Goods 140
(Transportation)
Raw Water 2100
(Water Way)
Human Bodies 30
(Traffic)

Deposits

Goods Wastes

Carbon Dioxide (50)
Water Vapor (20)
(Atmosphere)

Goods 110
(Transportation)
Waste Water 2100
(Rivers, Sewers)
Ocean Dumping 1
(Ship)

Human Bodies 30
(Traffic)

10^9 tons/year

Hanya & Ambe (1976)
ECOSYSTÈME BRUXELLES (16.178 ha)

PLANTES
1500.10^3 t frais
750.10^3 t sec

HOMMES (1075000)
59.10^3 t frais
19.10^3 t sec

ENERGIE NATURELLE

ENERGIE DE SUPPLEMENT
IMPORTATION (10^{12} kcal)

- Aliments
- Electricité
- Charbon + Pétrole + Essence
- Gaz

CO_2

BILAN D'EAU (10^6 t)

Eaux usées

Immondices : 237
Egouts : 40
Déchets : 277

Exportations (10^3 t)

- Imm. fines : 41
- Papier + Bois : 33
- Plastiques : 10
- Déchets végétaux : 3
- Déchets animaux : 2
- Verre + Fer : 51
- Déchets solides : 195
- Produits manufacturés : 226

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
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)

Per Capita GHG Emissions
(tCO₂e/capita)

(Kennedy et al., 2014)
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?
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

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

(Bristow & Kennedy, 2013)
Location of retail food outlets relative to population

- Grocers & Supermarkets
- Convenience Stores
- Other

(Bristow & Kennedy, 2013)
Metabolism of Megacities

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

- 1960: 5
- 1970: 6
- 1980: 7
- 1990: 10
- 2000: 20
- 2010: 25
- 2020: 35
Megacity Populations

(Kennedy et al. 2015)
### Metabolism of Megacities - Data collection

<table>
<thead>
<tr>
<th>1. Definition of megacity</th>
<th>2. Biophysical descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>spatial boundaries</td>
<td>climate</td>
</tr>
<tr>
<td>constituent cities</td>
<td>latitude</td>
</tr>
<tr>
<td>population</td>
<td>population density</td>
</tr>
<tr>
<td>economy</td>
<td>building stock</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Urban metabolism</th>
<th>4. Role of utilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy (all types)</td>
<td>access of households to</td>
</tr>
<tr>
<td>water</td>
<td>basic services;</td>
</tr>
<tr>
<td>materials</td>
<td>potential to provide new</td>
</tr>
<tr>
<td>waste</td>
<td>services</td>
</tr>
</tbody>
</table>
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

R² = 0.95

* All values per capita, 2011
## Correlation

<table>
<thead>
<tr>
<th></th>
<th>Electricity use (MWh)</th>
<th>Heating/industrial fuel (GJ)</th>
<th>Transportation fuel (GJ)</th>
<th>Water consumption (kL)</th>
<th>Solid waste production (t)</th>
<th>Heating degree-days</th>
<th>Area (km²) per person</th>
<th>GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity use (MWh)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Heating/industrial fuel (GJ)</td>
<td>0.36</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
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</tr>
<tr>
<td>Transportation fuel (GJ)</td>
<td>0.58</td>
<td>0.56</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Water consumption (kL)</td>
<td>0.52</td>
<td>0.33</td>
<td>0.67</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Solid waste production (t)</td>
<td>0.37</td>
<td>0.03</td>
<td>0.30</td>
<td>0.04</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Heating degree-days</td>
<td>0.46</td>
<td>0.80</td>
<td>0.54</td>
<td>0.17</td>
<td>0.25</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Area (km²) per person</td>
<td>0.78</td>
<td>0.46</td>
<td>0.75</td>
<td>0.72</td>
<td>0.39</td>
<td>0.42</td>
<td>---</td>
<td>0.80</td>
</tr>
<tr>
<td>GDP ($)</td>
<td>0.69</td>
<td>0.52</td>
<td>0.71</td>
<td>0.46</td>
<td>0.47</td>
<td>0.58</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

(Kennedy et al. 2015)
Growth in Electricity Use (2001-2011)

(Kennedy et al. 2015)
## Access to Services (%)

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

*(n.d. = no data)*

(Kennedy et al. 2015)
Energy poverty rises where electricity use drops below 2 MWh per person.
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

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

**Figure 1.** Per capita CO$_2$e 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.
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

\[ \text{GHG}_{\text{fuel}} = C_{\text{fuel}} \times I_{\text{fuel}} \]

where

- \( C_{\text{fuel}} \) is total fuel consumed (TJ);
- \( I_{\text{fuel}} \) is the GHG emissions factor (t CO₂ e / TJ)
### GHG Emission Intensity (t eCO₂ /TJ)

<table>
<thead>
<tr>
<th></th>
<th>Direct Emissions (IPCC)</th>
<th>Life-cycle Canada (GHGenius)</th>
<th>Life-cycle Europe (Ecoinvent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>69.2</td>
<td>91.9</td>
<td>82.9</td>
</tr>
<tr>
<td>Diesel</td>
<td>73.9</td>
<td>91.0</td>
<td>84.1</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>56.1</td>
<td>67.9*</td>
<td>61.6</td>
</tr>
</tbody>
</table>

……etc.

(* GaBi4 & TransCanada Pipelines)
Electricity, 2.4
Natural Gas, 3.3
Gasoline, 2.4
Diesel, 0.8
Waste, 0.4
Industry, 0.5
Jet Fuel, 1.0

Toronto (2004)

GTA (2005) Direct
tCO2/cap.

GTA (2005) Life-cycle

14.1
12.1
9.3

Industry, 0.5
Waste, 1.1
Jet Fuel, 0.9
Diesel, 1.2
Gasoline, 3.9
Natural Gas, 4.0
Electricity, 2.5

0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Gasoline

- Fuel sales
- Traffic counts / surveys / models
- Scaling
# Gasoline: Consumption (ML)

<table>
<thead>
<tr>
<th></th>
<th>Fuel sales</th>
<th>Modeled VKT</th>
<th>Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangkok</td>
<td>2,741</td>
<td>2,662</td>
<td></td>
</tr>
<tr>
<td>New York City</td>
<td>6,691</td>
<td>4,179</td>
<td>4,107</td>
</tr>
<tr>
<td>Toronto</td>
<td>6,691</td>
<td></td>
<td>6,988</td>
</tr>
</tbody>
</table>
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
Key Threshold for Electrification

(Kennedy, 2015)
Transforming to low carbon electric cities

(Kennedy et al., 2017)