Laboratory on Human-Environment Relations in Urban Systems
Swiss Mobiliar Chair in Urban Ecology and Sustainable Living

ENV 370 (GR A332 – GRB001)
Environmental system analysis and assessment – Evaluation et analyse environnementale systémique

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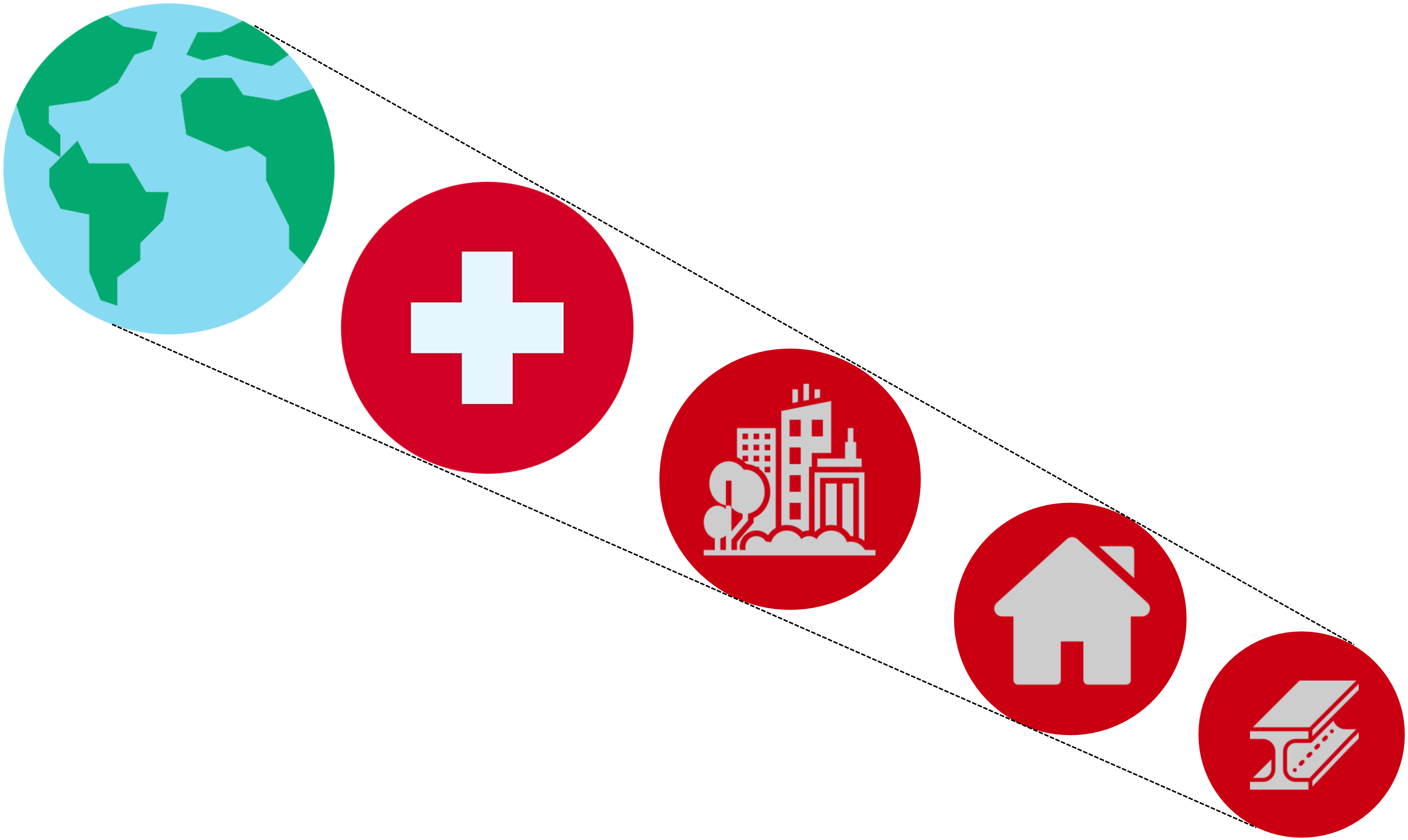
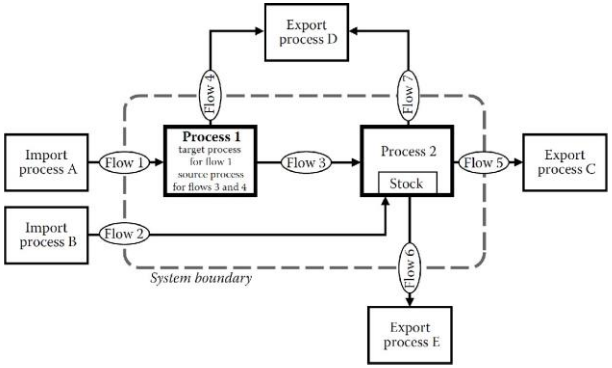
RECAP



Definition of MFA



Brunner & Rechberger, 2016

Material Flow Analysis (MFA) is a systematic assessment of the **flows and stocks of materials** within a system defined in **space** and **time** .

- MFA connects the **sources, pathways and sinks** of a material.
- MFA results can be controlled by a **mass balance** comparing all inputs, stocks, and outputs of a process/system measured in kg (principle of mass conservation).

Steps of MFA

Step I: System definition
Problem definition, definition of system boundaries, selection of processes and flows of materials/substances (qualitative model)

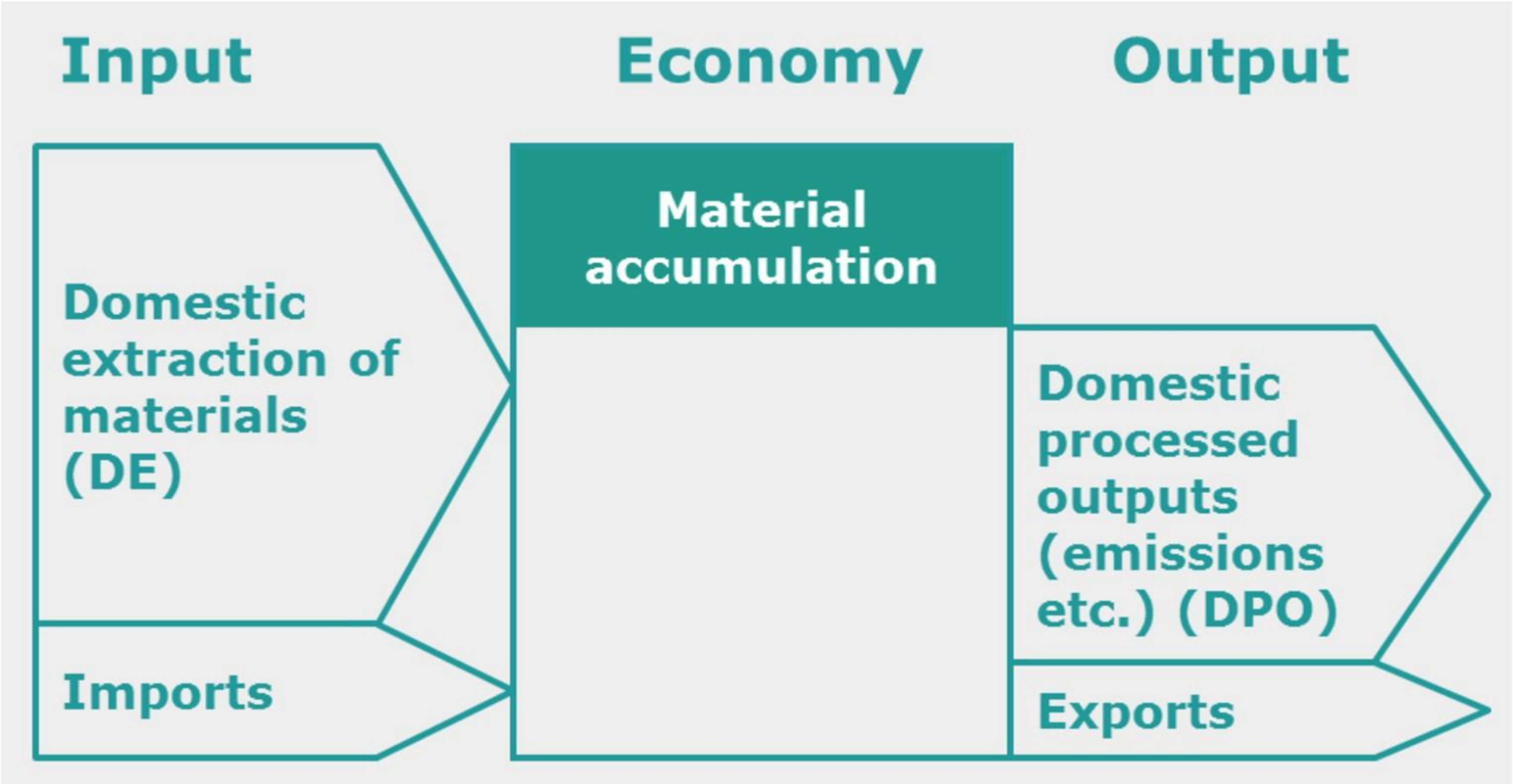
Step II: Measurement
Data collection of flows and stocks of materials/substances and characterization of uncertainties (measurements, literature data, estimations)

Step III: Calculation
Calculation of unknown quantities by balancing of materials based on the principle of mass conservation (MFA software)

Step IV: Illustration and interpretation
Sources, stocks, flows and sinks

Step V: Recommendations
How can the system be optimized?

EW-MFA (in Europe): detailed method

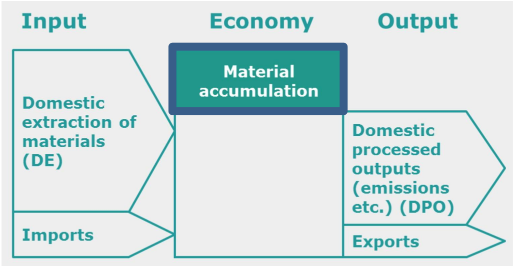


Material flows within the economy, Water flows and electricity flows are not represented in EW-MFA

Questions ?

Material Flow Analysis

MFA (Eurostat): material accumulation



- **Material accumulation or net additions to stock (NAS):** measure of physical growth in an economy.
- New materials in form of **buildings, infrastructures, durable goods** such as e.g. cars, industry machinery, or household appliances are added to the economy's material stock each year **(gross additions).**
- Old materials are removed from stock as buildings are demolished, and durable goods disposed of **(removals).**

MFA (Eurostat): indicators

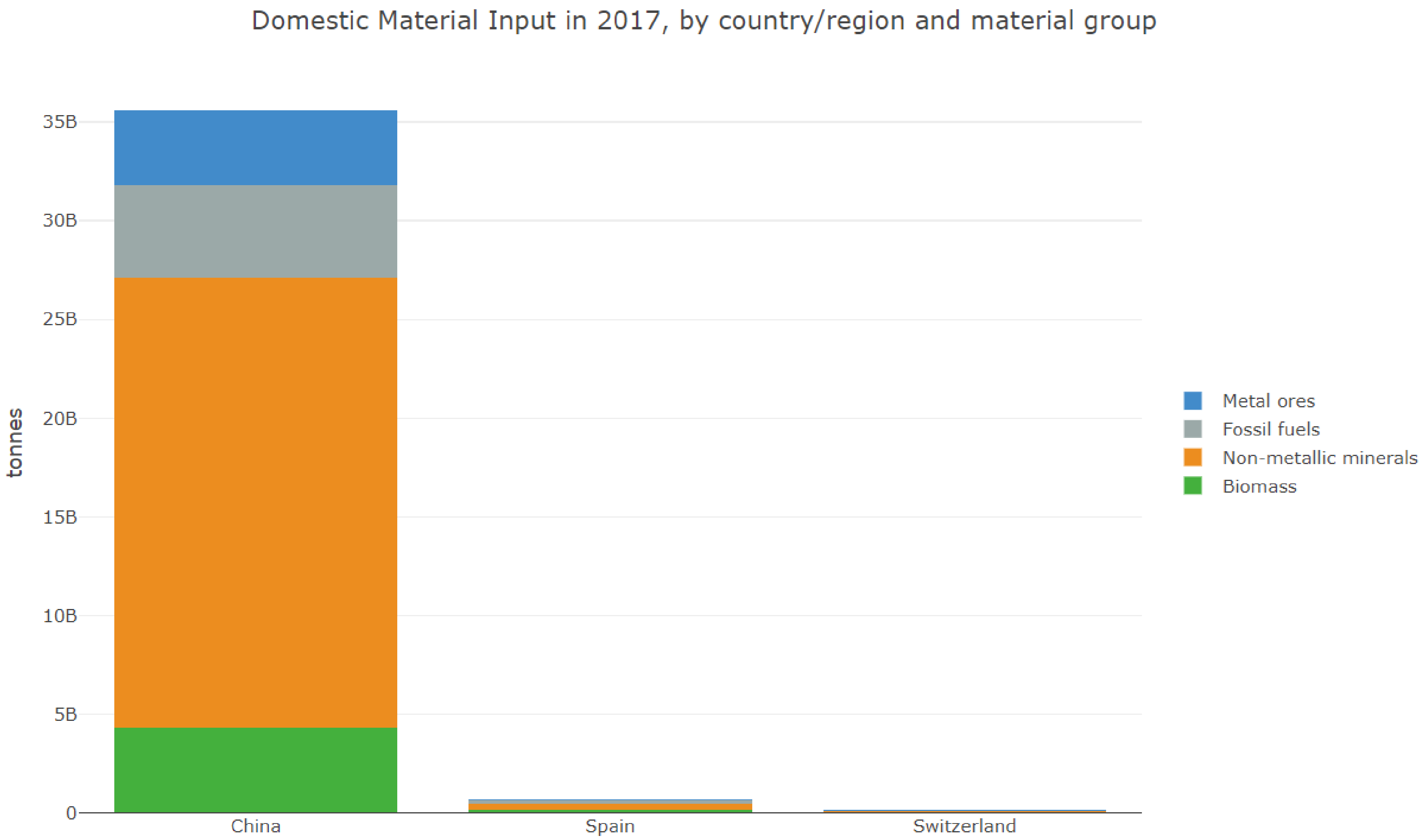
Basic flow types

- Domestic extraction (DE)
- Domestic processed output (DPO)
- Imports (IMP)
- Exports (EXP)

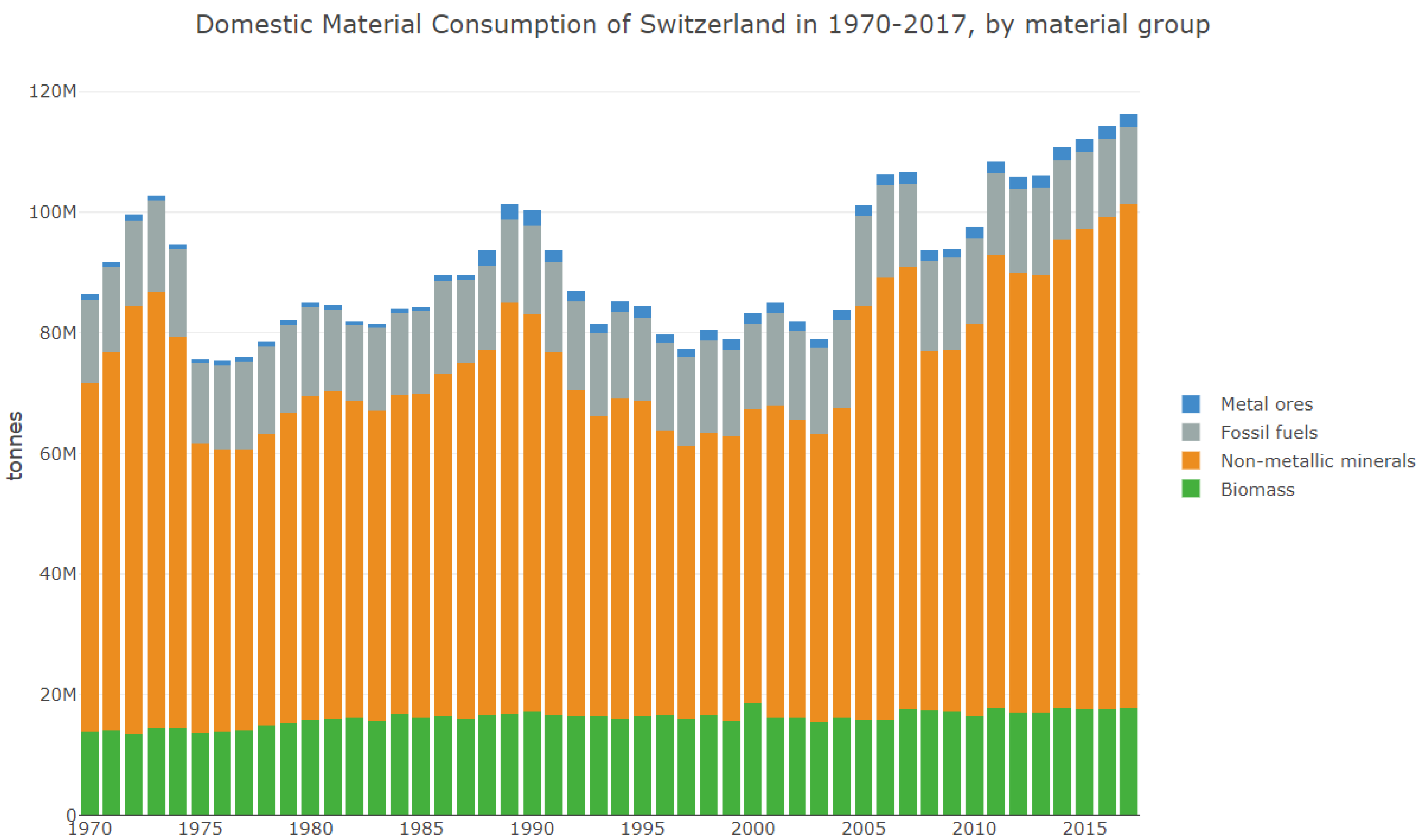
Flows types are basis for indicators

- Domestic material input (DMI) = DE + IMP
- Domestic material consumption (DMC) = DE + IMP – EXP
- Physical trade balance (PTB) = IMP – EXP
- Net additions to stock = DMI – DPO – EXP

MFA (Eurostat): indicators DMI

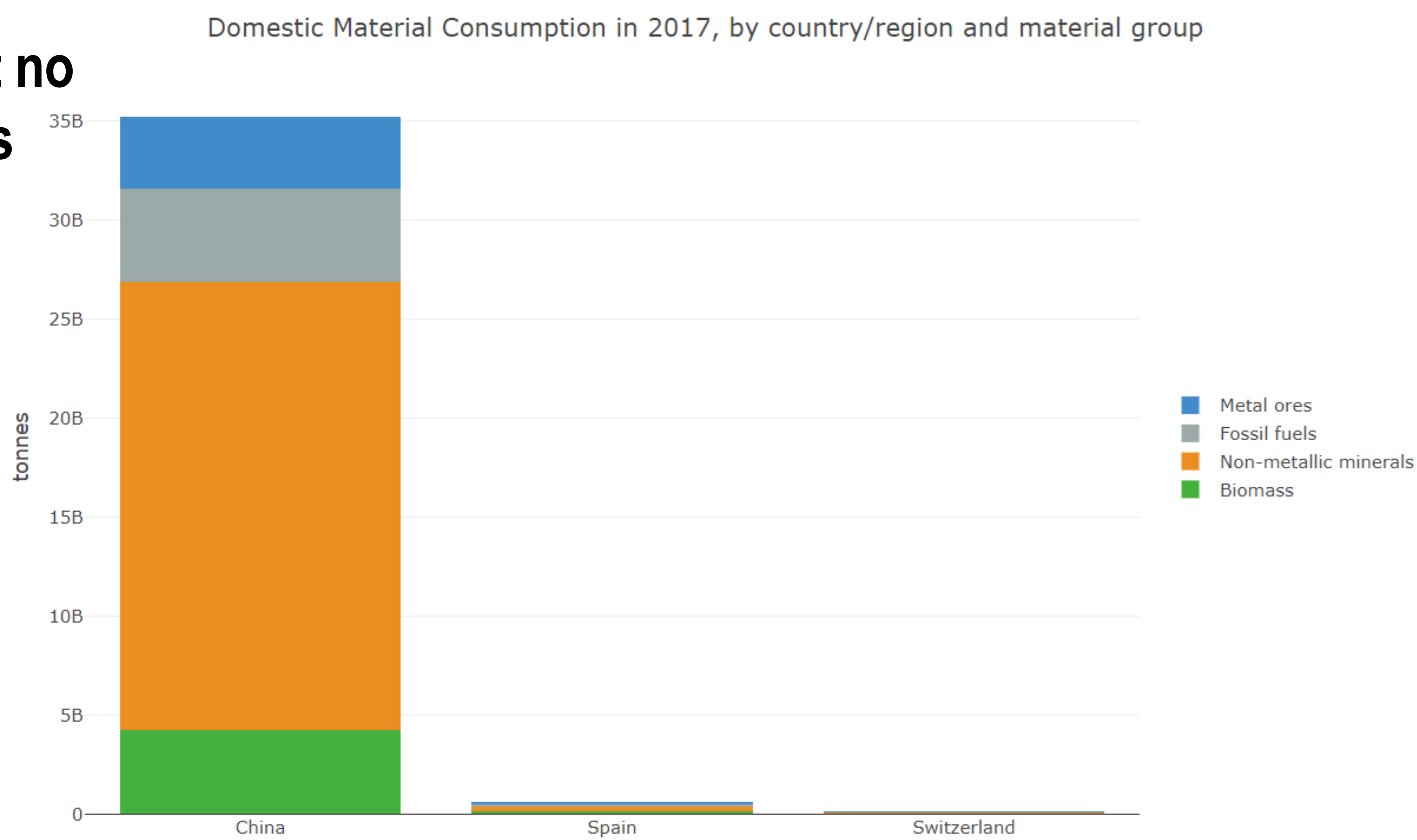


Domestic material consumption in CH



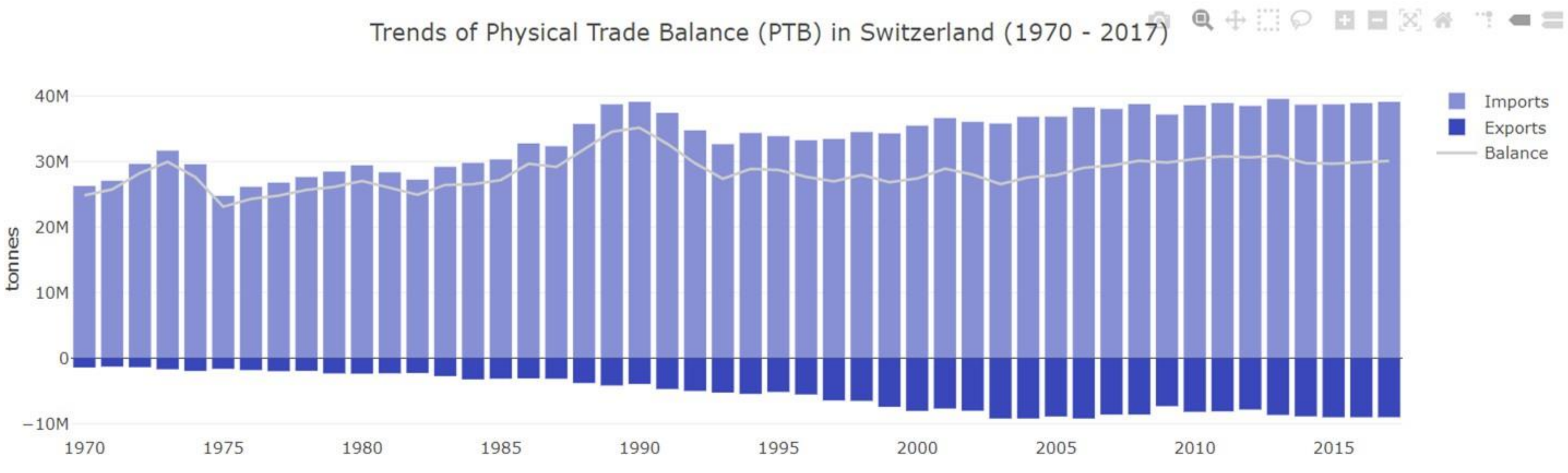
Domestic material consumption

Almost no imports



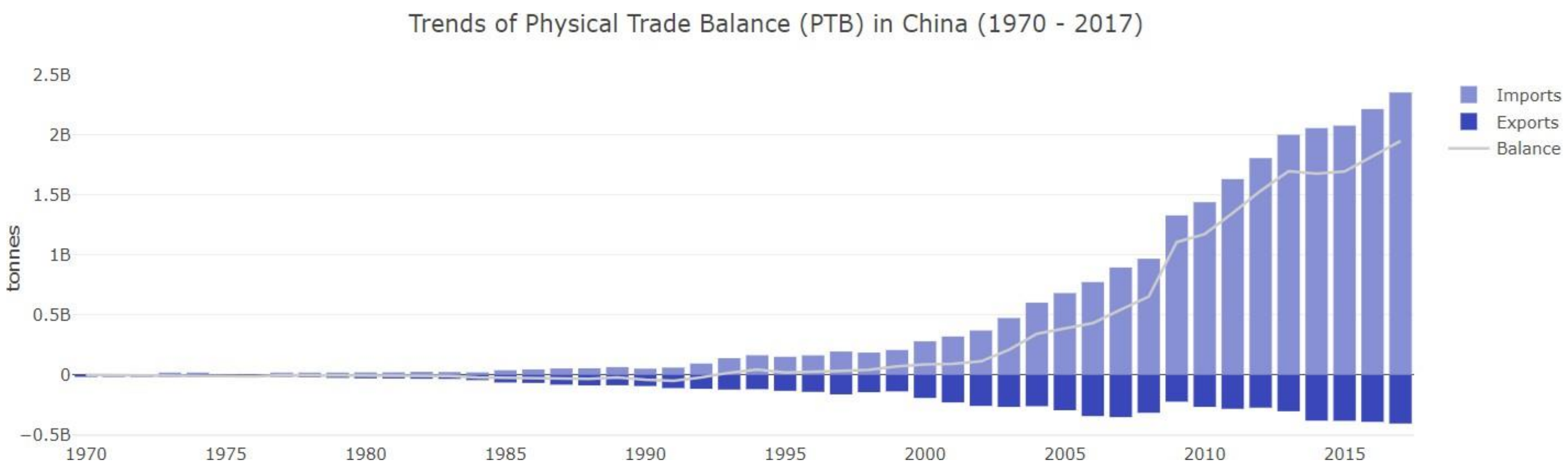
PTB in CH

Is a country a physical net-importer or net-exporter of raw materials?



PTB in China

Is a country a physical net-importer or net-exporter of raw materials?



MFA (Eurostat): additional “monetary” indicators

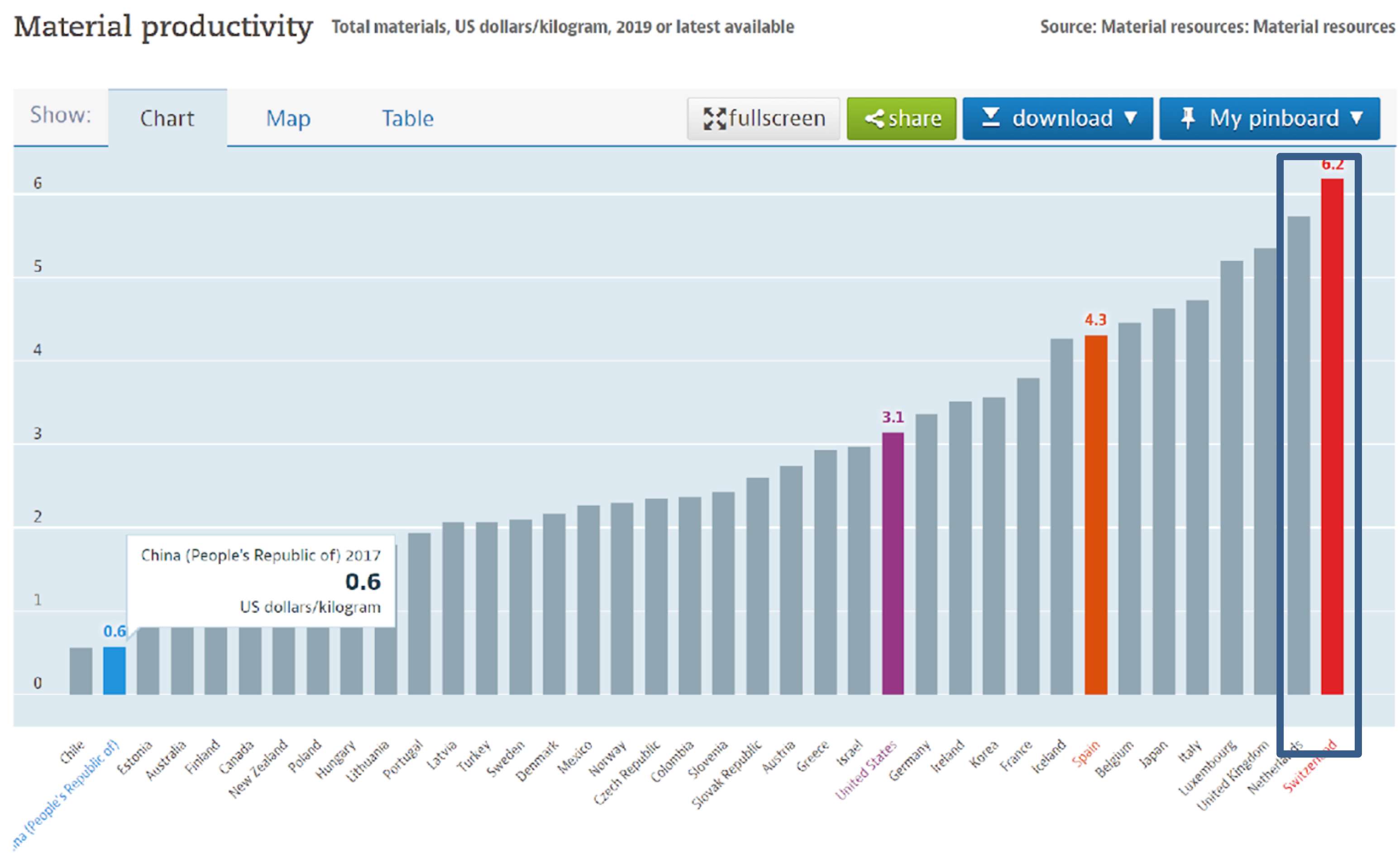
Material productivity = GDP $_{\text{[€ of added value]}}$ **/ DMC** $_{\text{[t of material input]}}$

- **Material productivity:** measure of economic output (goods or services) per unit of material input.
- Increase in material productivity = decoupling material use and economic performance.

Material intensity = DMC $_{\text{[t of material input]}}$ **/ GDP** $_{\text{[€ of added value]}}$

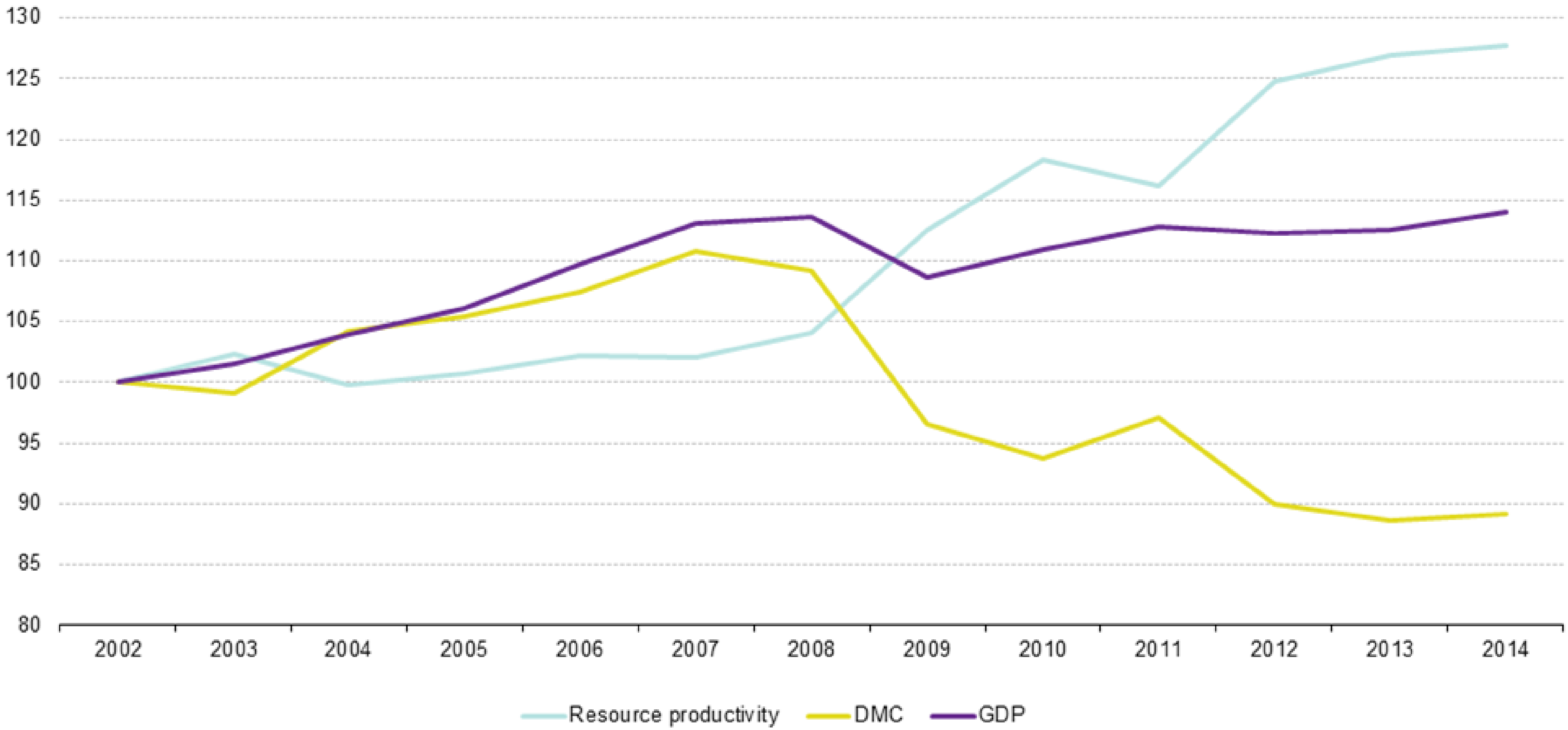
- **Material intensity:** measure of material input used per economic output (good or service)
- Decrease in material intensity = more efficient material use.

Material productivity OECD-37



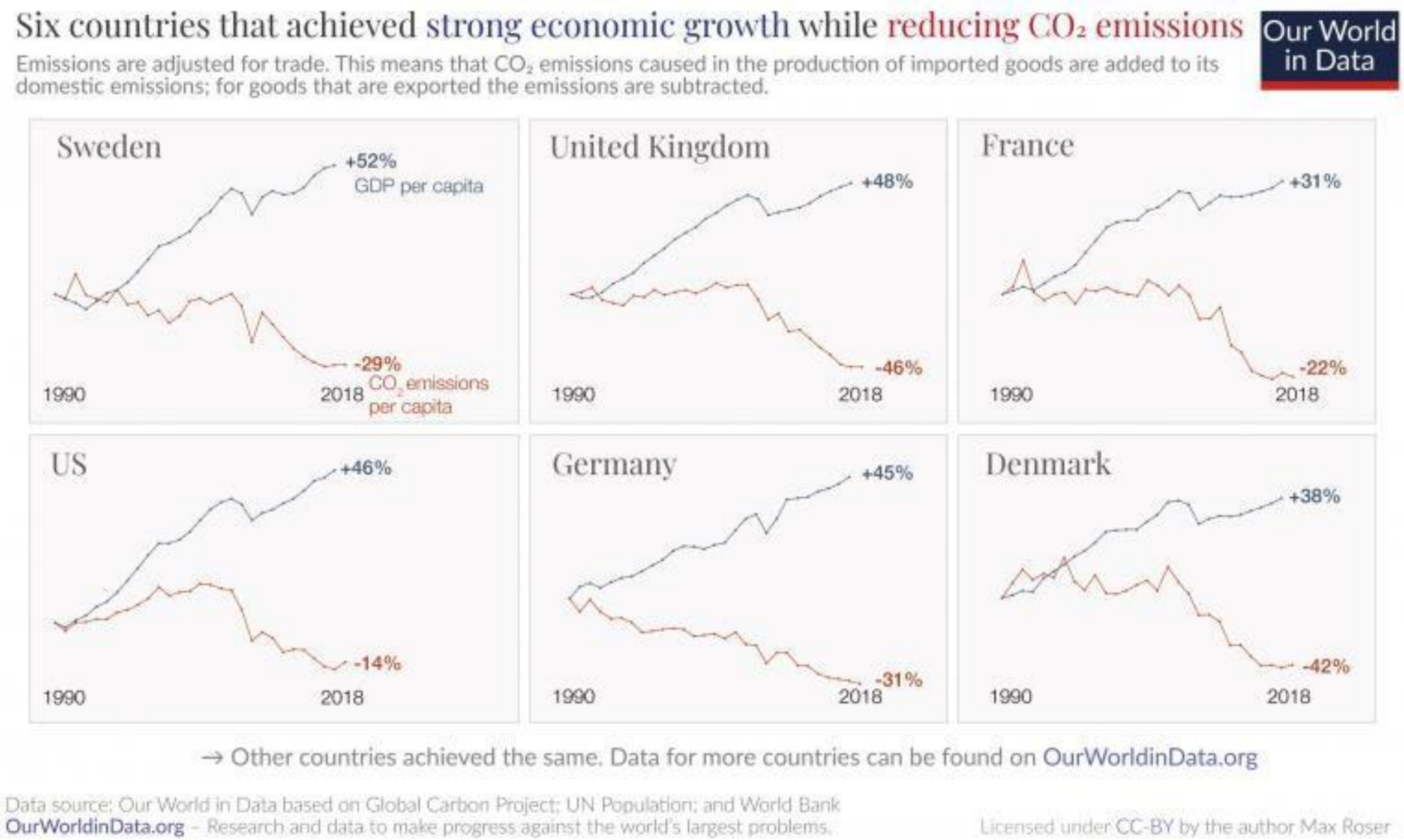
Why?

Let's talk about decoupling (absolute, relative, sufficient)



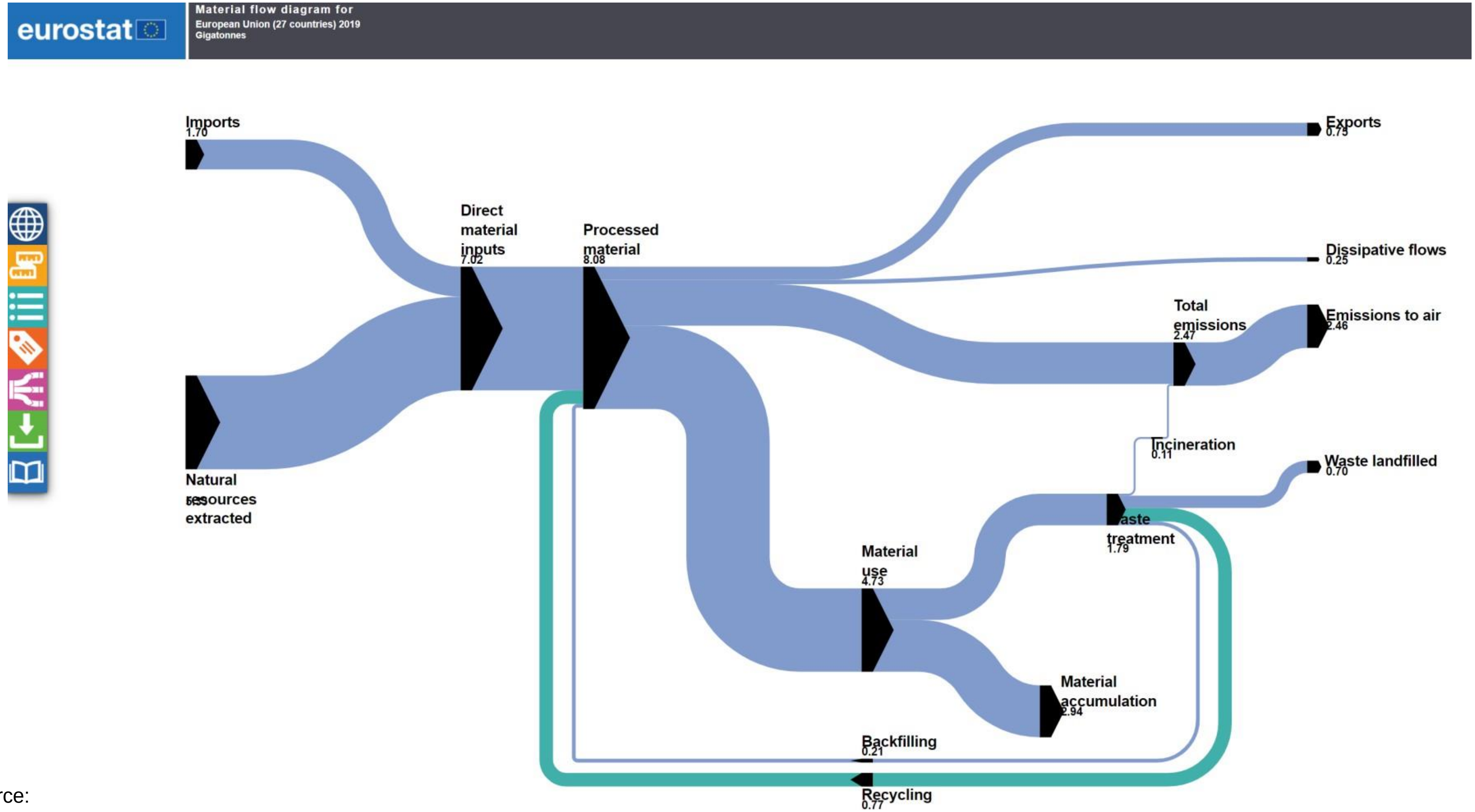
https://data.oecd.org/materials/material-productivity.htm#indicator-chart

Let's talk about decoupling (absolute, relative, sufficient)



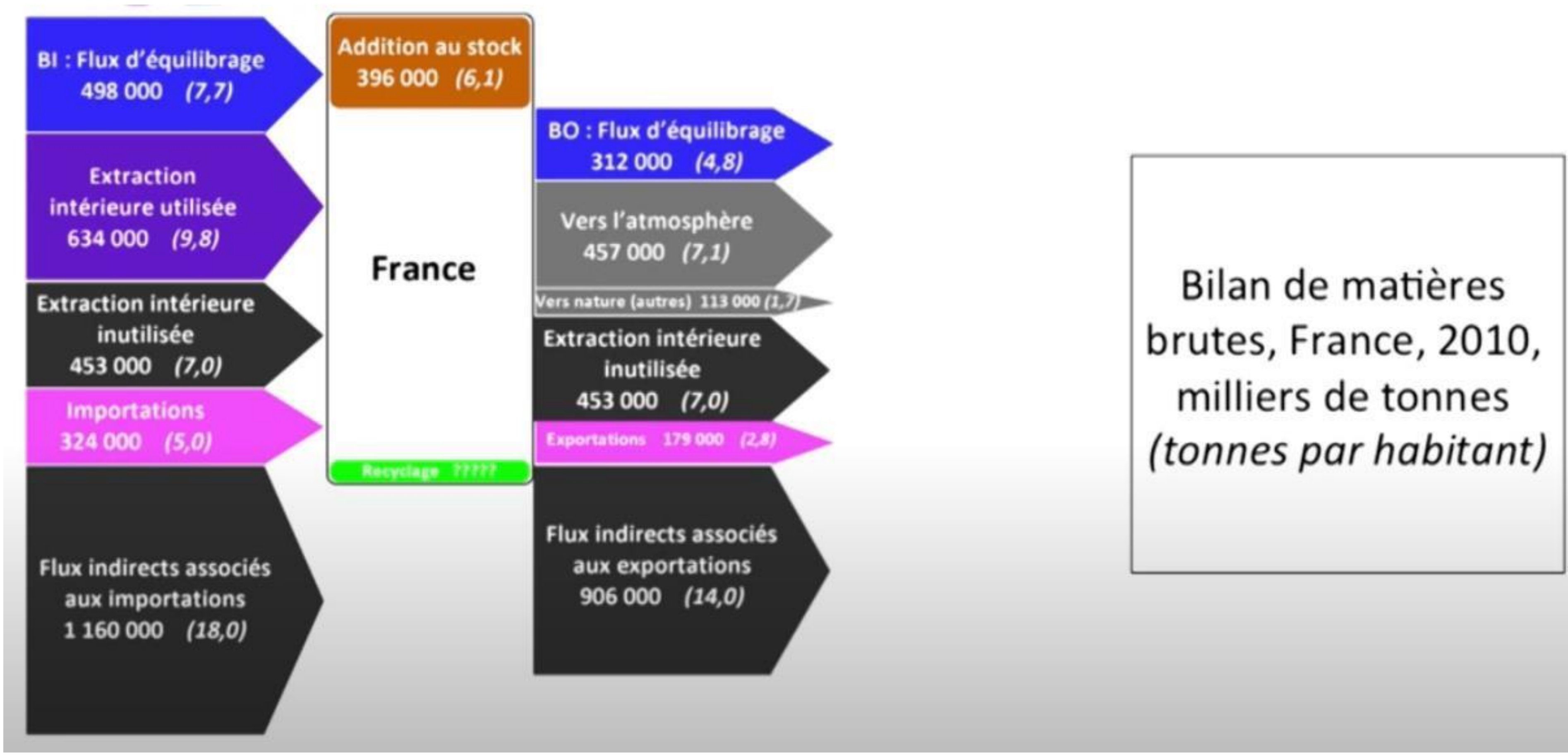
https://ourworldindata.org/carbon-price

Circular Economy at a EU level



Source:
https://ec.europa.eu/eurostat/cache/sankey/circular_economy/sankey.html?geos=EU27&year=2019&unit=G_T&materials=TOTAL&highlight=0&nodeDisagg=0101100100&flowDisagg=false&translateX=200&translateY=70&scale=0.6&language=EN&xyz=89&material=TOTAL

EW-MFA: Use at a territorial level (French case study)



Source: https://www.youtube.com/watch?v=W1Fgqh1xlaM&list=PLeU78T5dtVW6wH7xsbDc2KdU3QmnlT8RC

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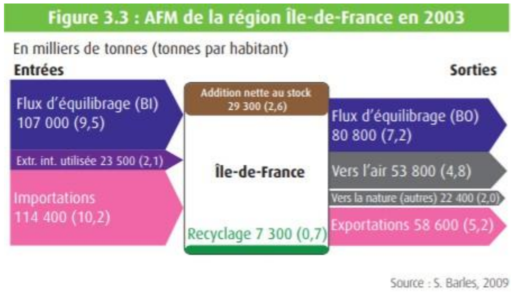
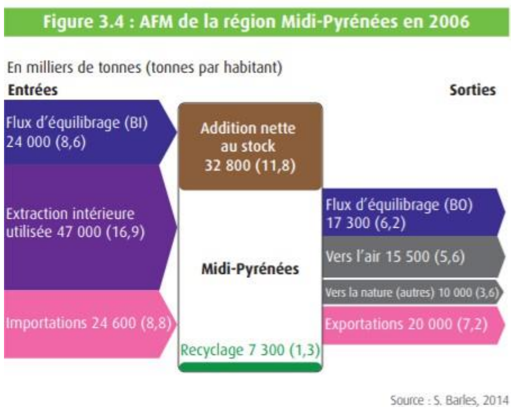
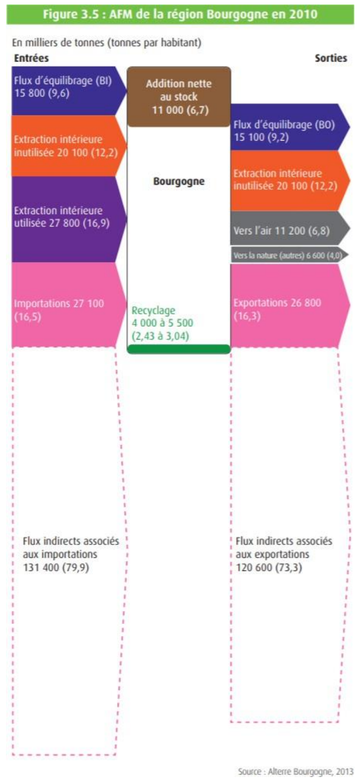






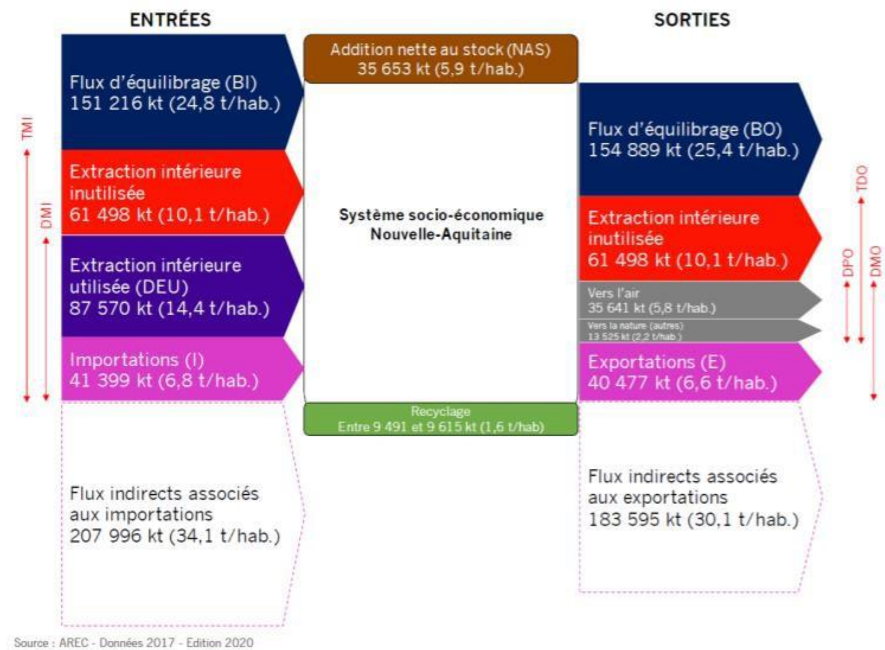
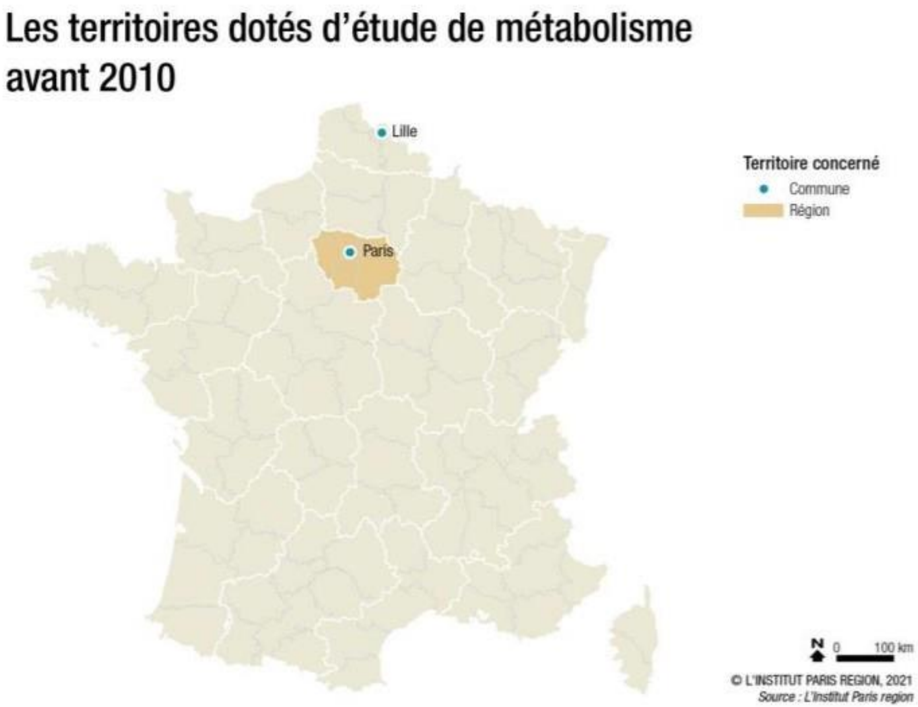
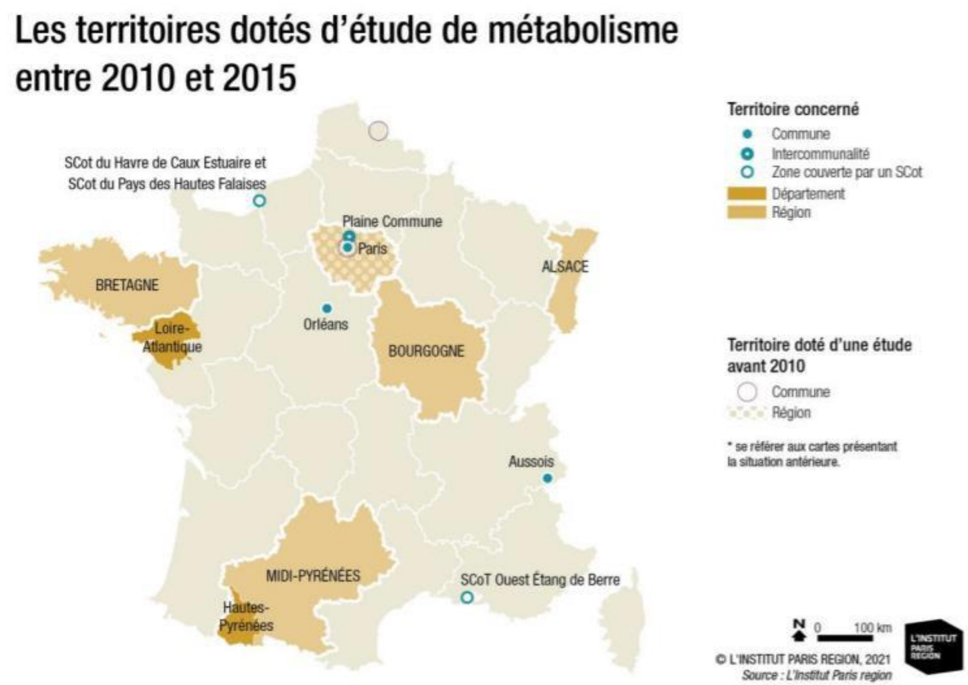


Figure 6. Schéma de principe et principaux indicateurs de l'analyse de flux de matières de la Nouvelle-Aquitaine en 2017. Sources : « Analyse de flux de matières de la Nouvelle-Aquitaine ». Les synthèses de l'AREC - ORDEC Edition 2020 – année 2017.

Source: https://www.ecologie.gouv.fr/sites/default/files/EIT%20-%20comptabilite%20des%20flux%20de%20matieres.pdf / https://www.institutparisregion.fr/fileadmin/NewEtudes/000pack2/Etude_2625/EtudesMetabolisme_Recensement_VF.pdf

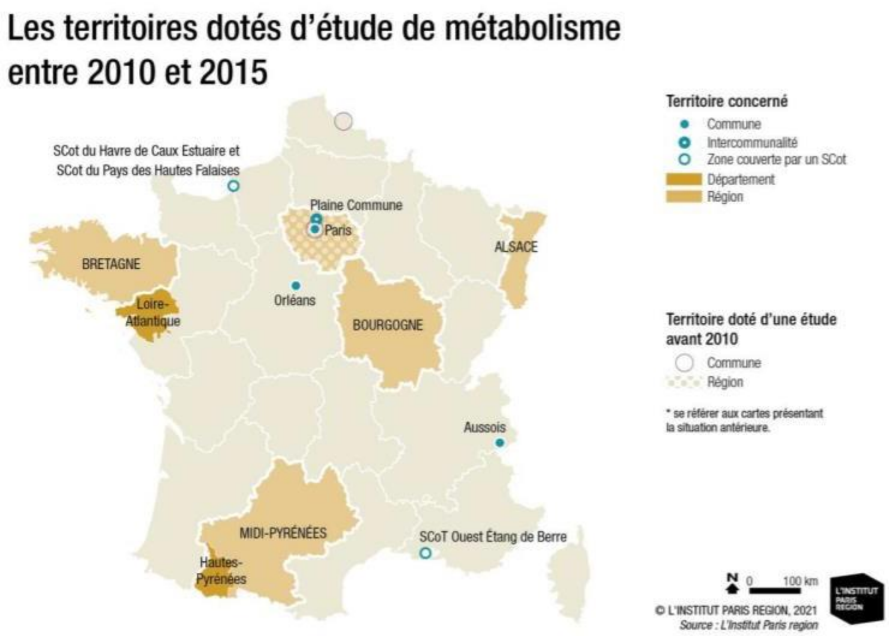
EW-MFA: Use at a territorial level (French case study)

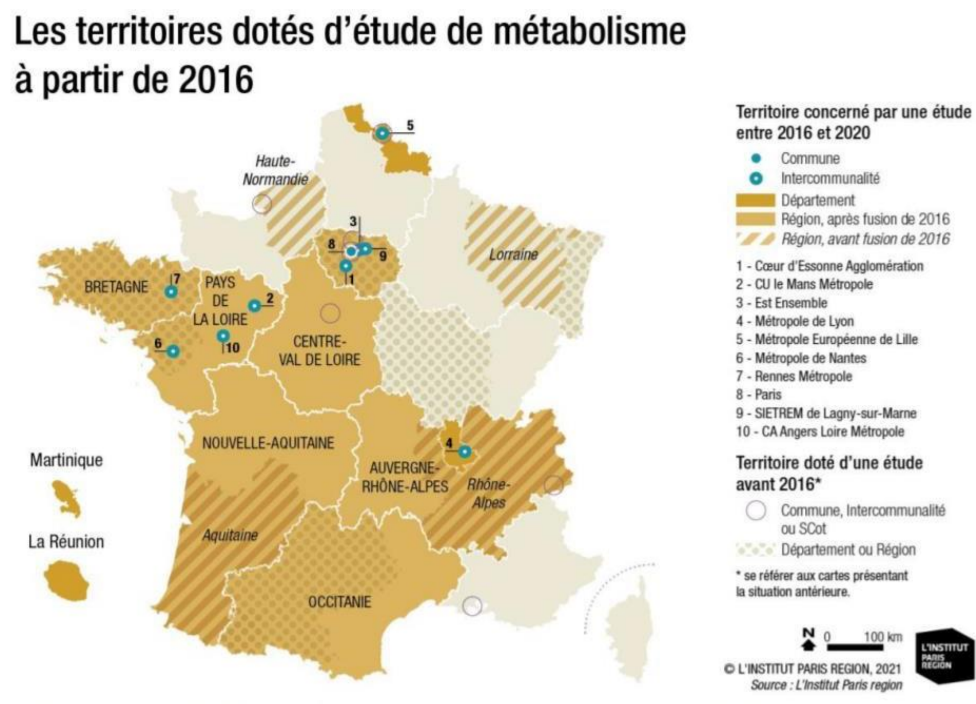




Source:https://www.institutparisregion.fr/fileadmin/NewEtudes/000pack2/Etude_2625/EtudesMetabolisme_Recensement_VF.pdf

EW-MFA: Use at a territorial level (French case study)





Carte n°3 : Etudes de métabolisme territorial en France métropolitaine en 2020

Source:https://www.institutparisregion.fr/fileadmin/NewEtudes/000pack2/Etude_2625/EtudesMetabolisme_Recensement_VF.pdf

EW-MFA: advantages vs. disadvantages

Advantages

- Trend representation within countries
- Identification of proportions and hotpots
- Comparative analysis across countries/regions
- Development of physical indicators which can be set in relation to economic indicators
- Monitoring and assessment of overarching policy goals (e.g. SDGs)
- Circular Economy monitoring

Disadvantages

- Black-box approach
- Difficulties in explaining trends
- Difficulties in deriving causalities
- None of the indicators show the full picture

EW-MFA: source

- **Eurostat**
  https://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity
- **International Resource Panel (IRP)**
  https://www.resourcepanel.org/global-material-flows-database
- **OECD Statistics**
  https://stats.oecd.org/
- **World Resource Institute**
  http://www.wri.org/
- **WU Vienna / CSIRO**
  http://www.materialflows.net/
- **Material flows of Switzerland**
  https://www.bfs.admin.ch

Method 2:
Material Flow Analysis

Baccini/Brunner/
Rechberger method

EPFL

Steps of MFA

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Problem definition, definition of system boundaries, selection of processes and flows of materials/substances (qualitative model)

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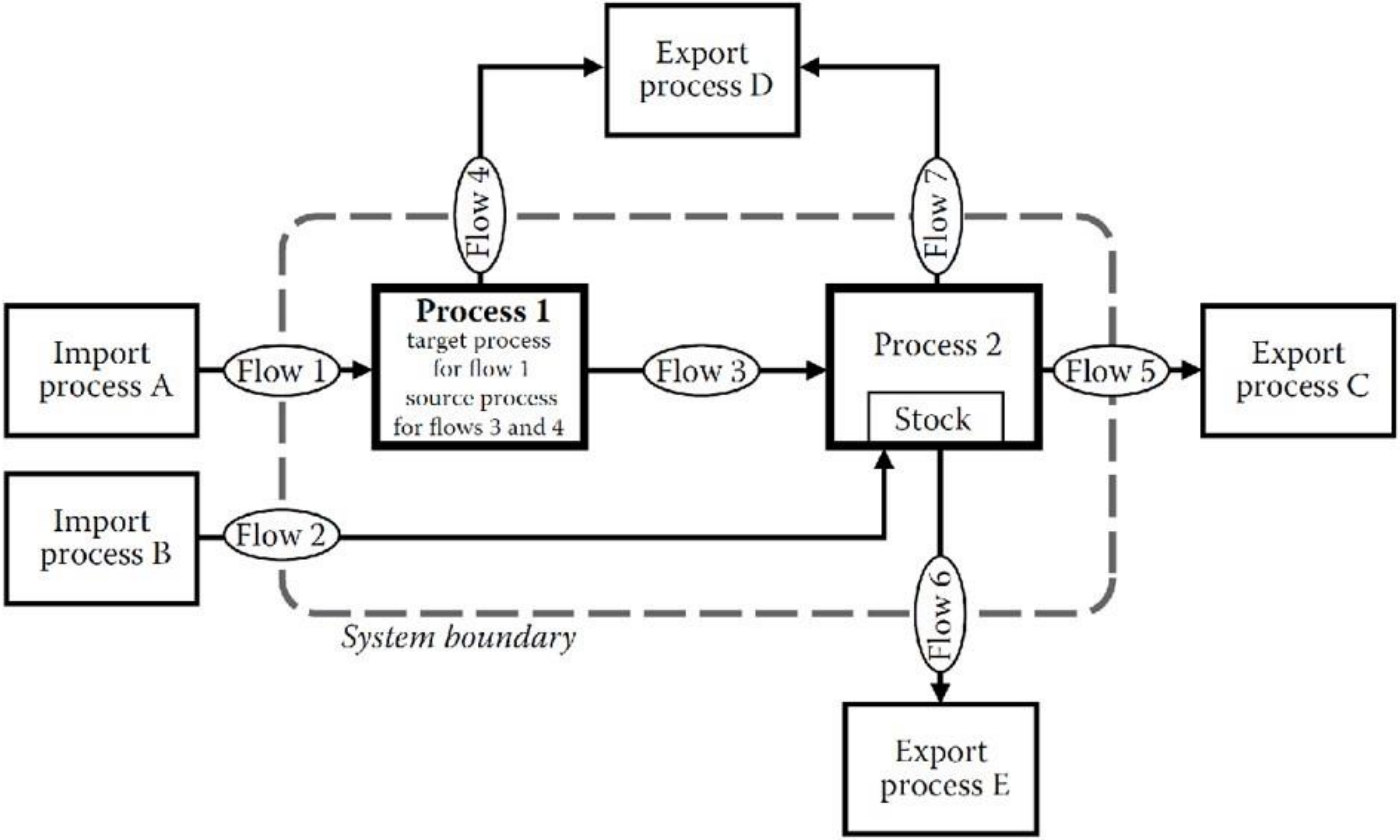
Steps of MFA



Brunner & Rechberger, 2016

Definitions: MFA system

MFA system: comprises a set of material flows, stocks, and processes within a defined boundary.

- **System boundary** is defined in space and time.
- **Temporal boundary:** time period over which the material balance is calculated (e.g. 1 hour for waste incineration process, 1000 years for landfills, 1 year for a city).
- **Spatial boundary:** geographical area (e.g. municipality, region, city)
  or virtual limits (e.g. private households, company).

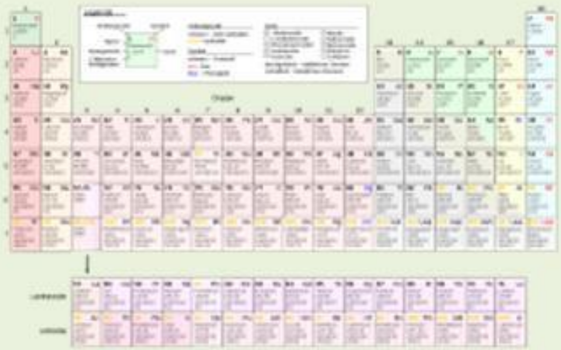
Definitions: MFA system

Materials: substances and goods.

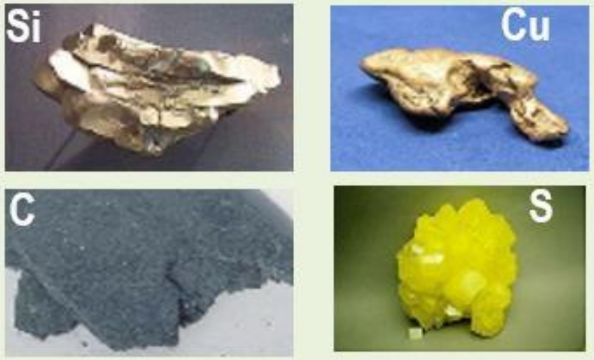
Definitions: MFA system

Substances: chemical elements (e.g. carbon, iron) or a chemical compound (e.g. carbon dioxide) composed of uniform units.

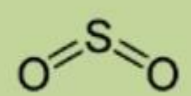
Chemical elements



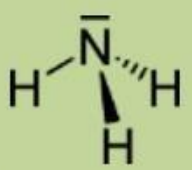
e.g.



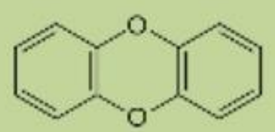
Chemical compounds



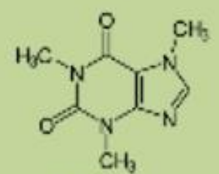
Sulfur dioxide



Ammonia



Dibenzodioxin

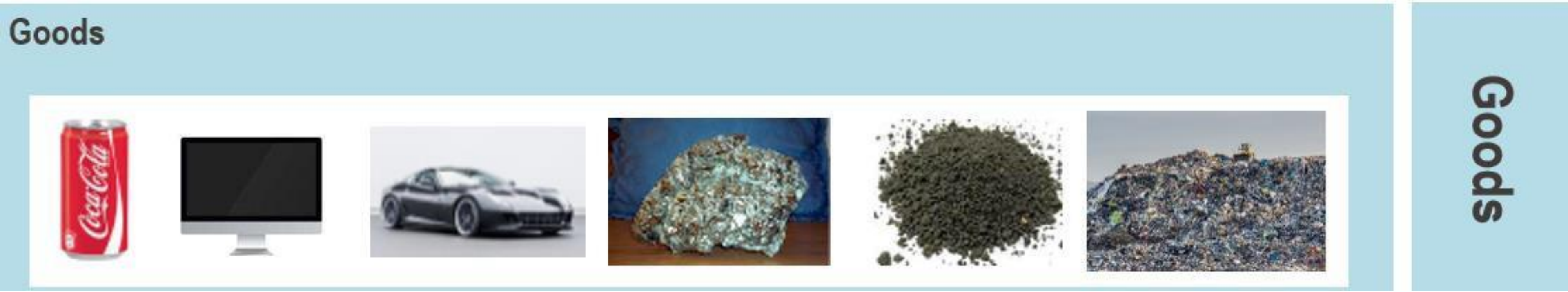


Caffeine

Substance

Definitions: MFA system

Goods: substances or mixtures of substances with positive (e.g. car, fuel) or negative (e.g. waste, sewage sludge) economic values.



Definitions: process

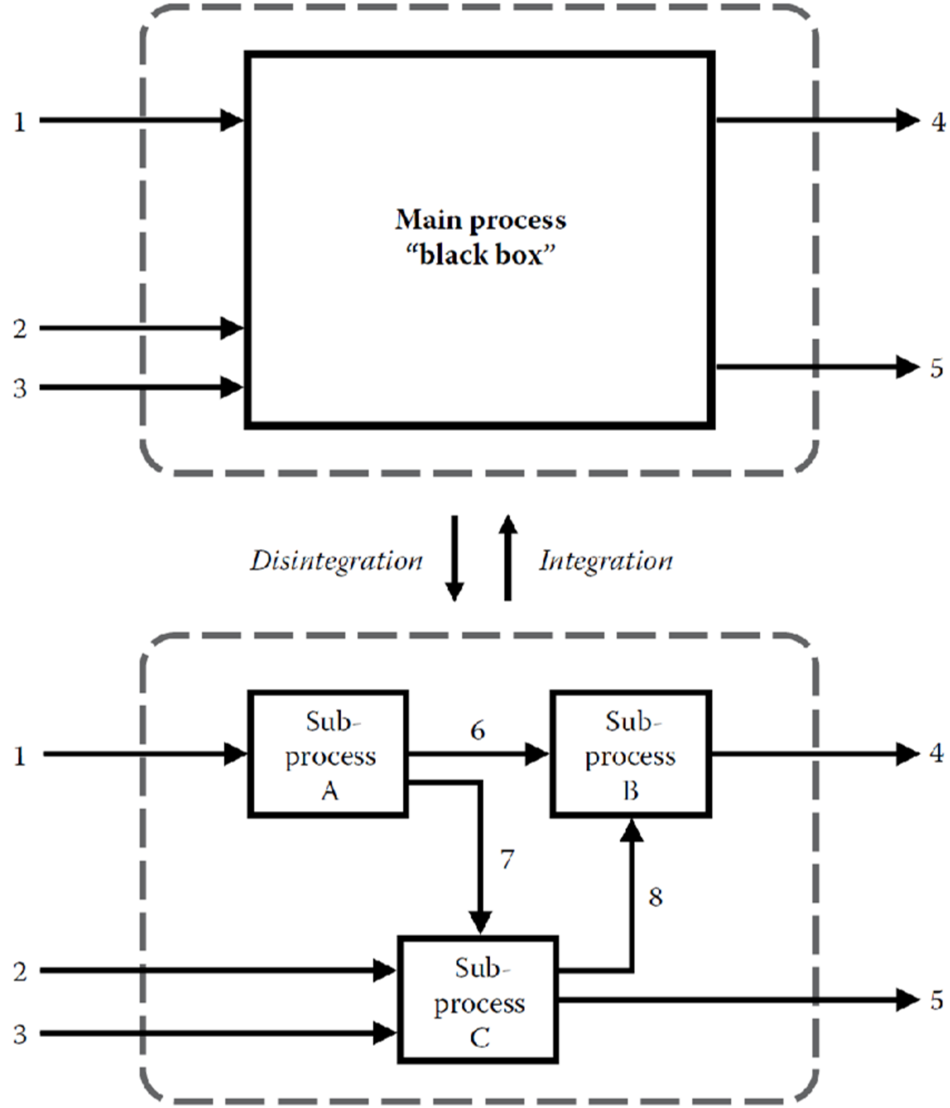
Process: any kind of transformation, transport or storage of a material that is characterized by input and output flows.

- Waste incineration process
- Wastewater treatment plant
- Energy production process
- Recycling process
- Human physiological process
- Landfill
- Gas tank farm






Subdividing black box into subprocesses



Brunner & Rechberger, 2016

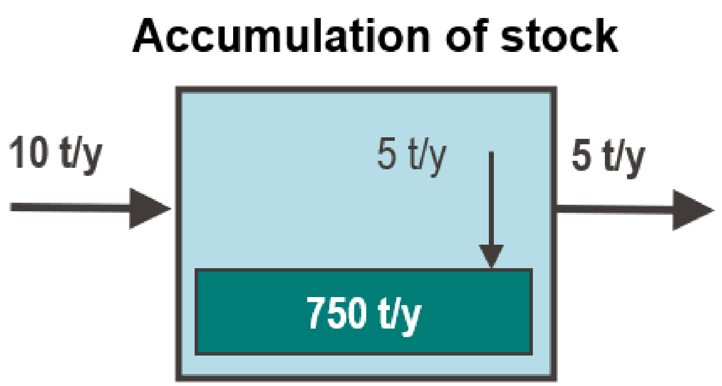
Can you give some examples of subprocesses

Water use

Definitions: stocks

Stocks: material reservoirs or material quantity within a process.

- Stocks can stay constant, increase or decrease in size.
- Accumulation/depletion of stock: difference between process inputs and outputs between two time steps.



Definitions: geogenic and anthropogenic stocks

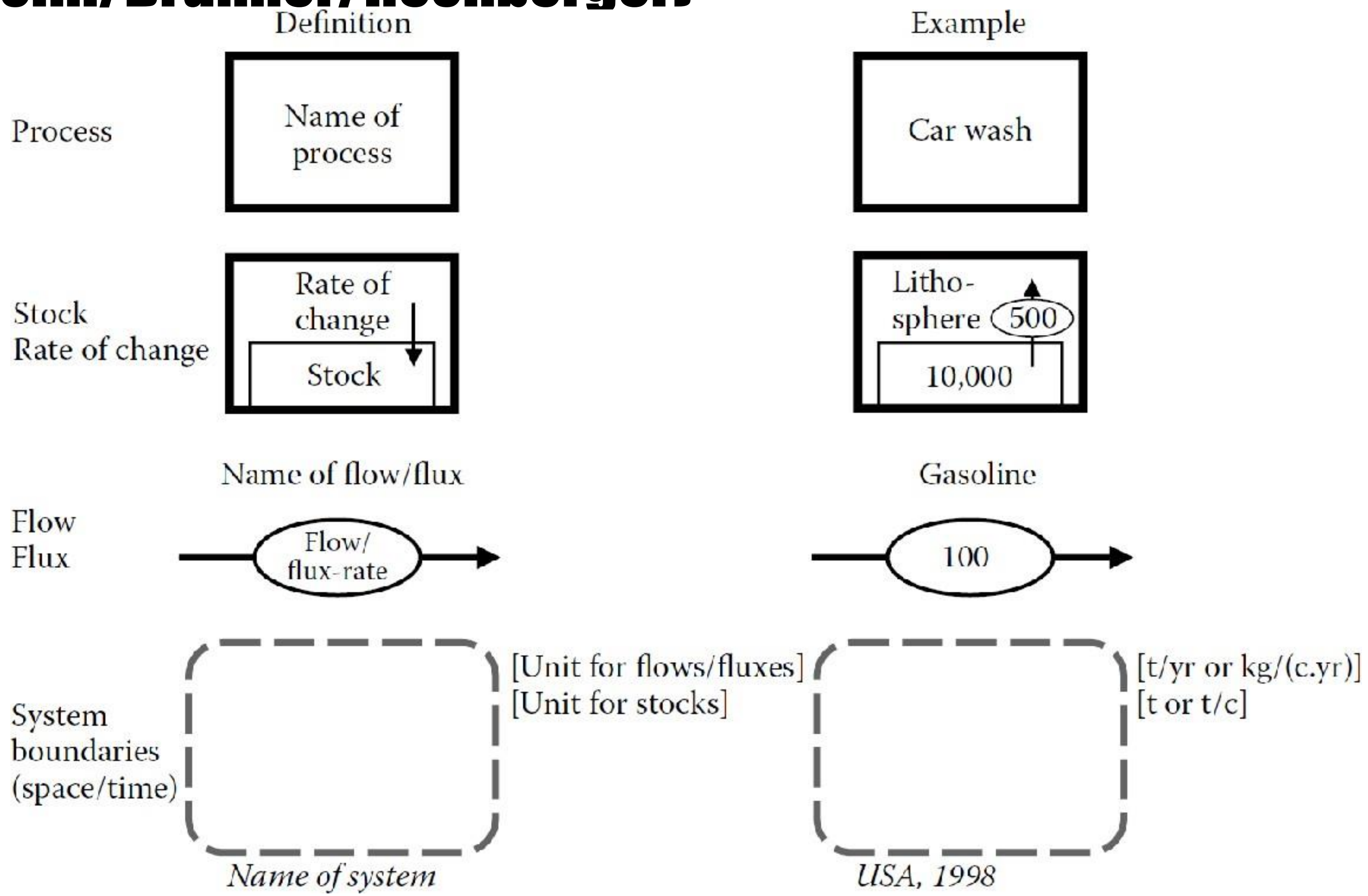
Geogenic stocks

- Surface and ground water
- Quarries (e.g. granit, limestone)
- Metal ores
- Oil and gas fields
- etc.

Anthropogenic stocks

- Concrete and steel in buildings
- Copper wires in buildings and goods
- Urban mines (e.g. landfills)
- etc.

Symbols used in MFA diagrams (Baccini/Brunner/Rechberger)



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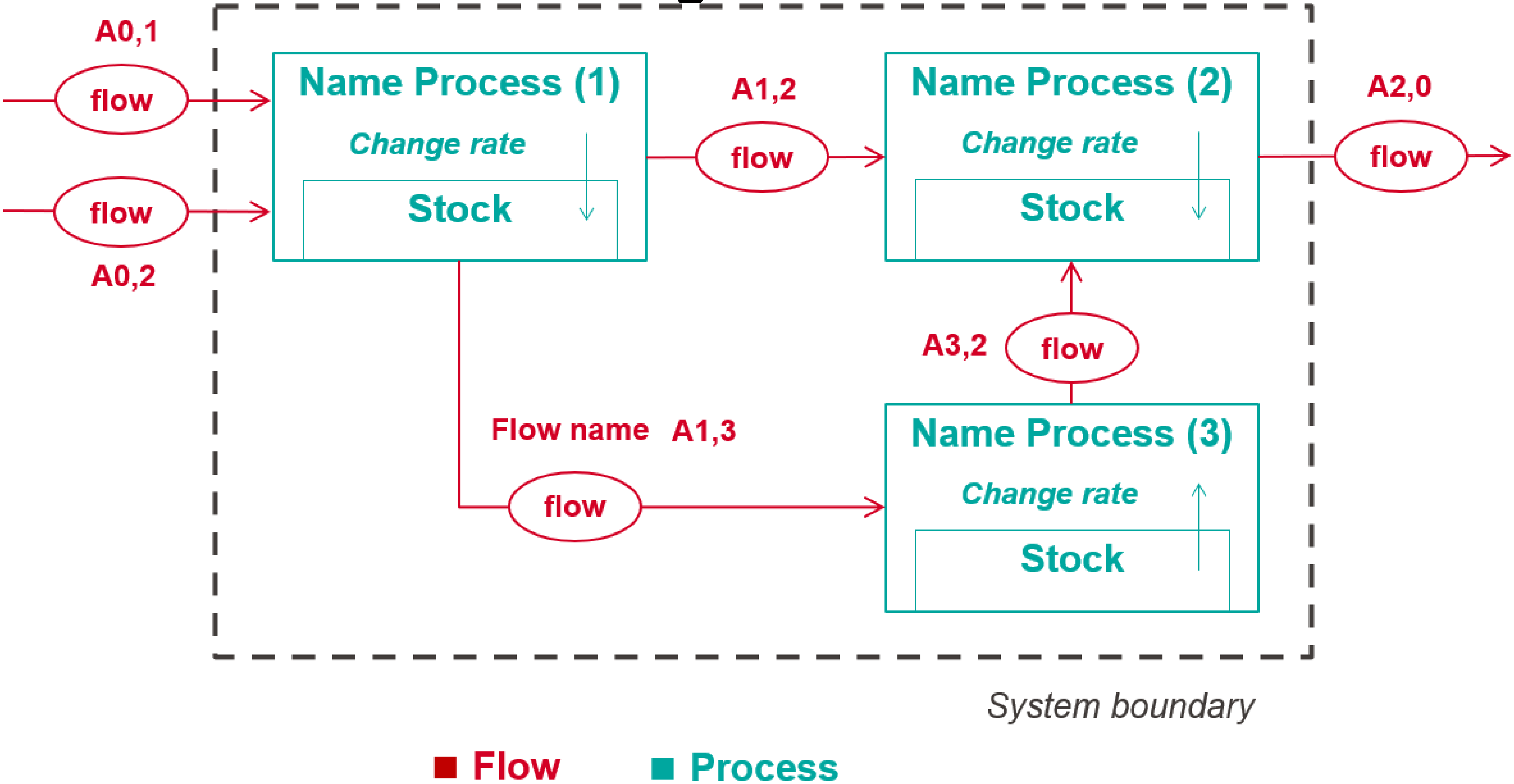


Time in MFA

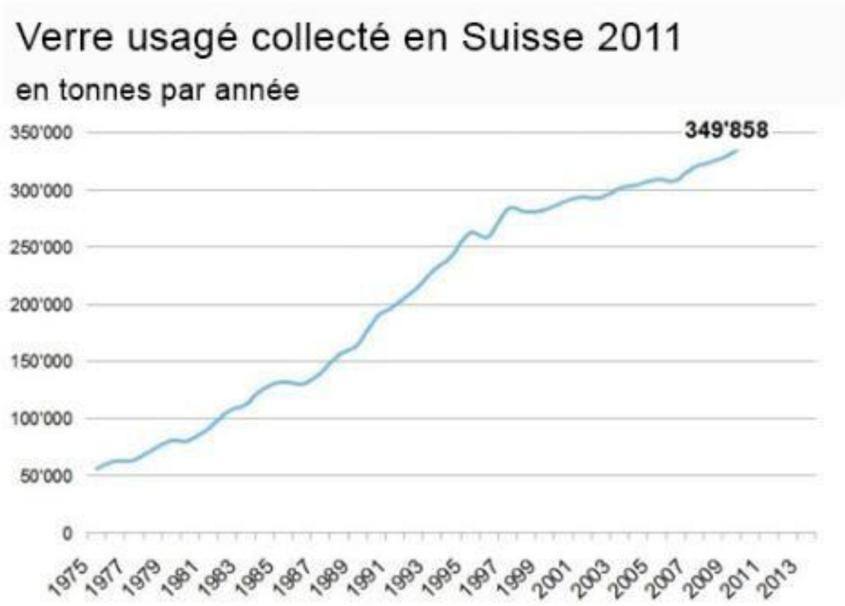
- **Steady state**: constant flows and stocks

  $dM_{stock}/dt = 0$ and $M_{stock}(0) = M_{stock}(t)$
- **Quasi stationary**: constant flows and linear (de)growth of stocks: $dM_{stock}/dt = c$ and

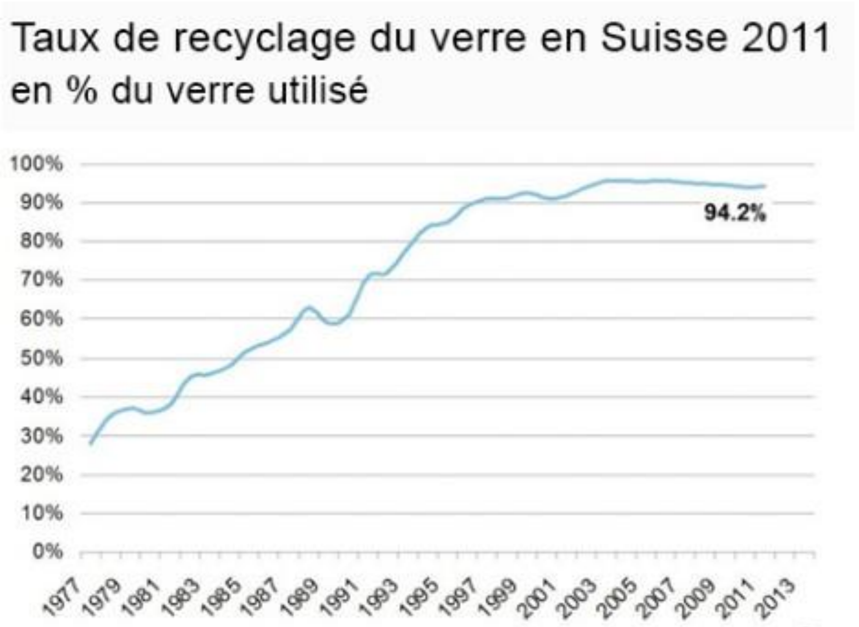
  $M_{stock}(0) \neq M_{stock}(t)$
- **Time dependent**: parameters external to the model are function of time (e.g. extraction or disposal costs).
- **Dynamic**: System state at t is a function of the state a t-1.

Example – Recycling glass

... pour un recyclage efficace du verre ...



Evolution du verre usagé collecté dans toute la Suisse (Source : www.vetrorecycling.ch)



Evolution du taux de recyclage du verre en Suisse (Source : www.vetrorecycling.ch)

Example – Recycling glass

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Example – Recycling glass

Formulate a precise question.
What problem should be tackled with the material flow analysis?

Define the system in space and time.
Determining the spatial and temporal boundary for material flow modelling.

Characterize the material balance system.
Which processes and material flows are relevant to the question formulated and have to be taken into account in the model?

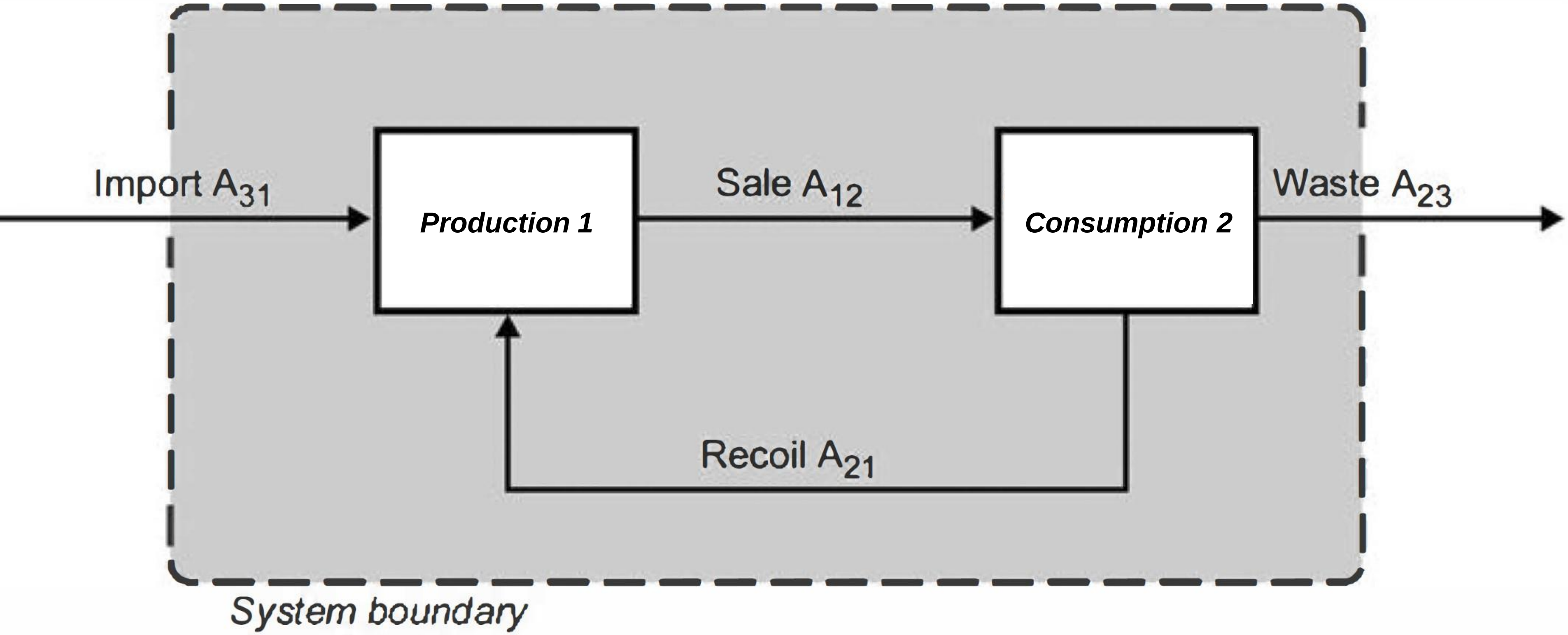
Select material flow indicators.
Which material flow indicators are relevant for answering the question?

Example – Recycling glass

- **Research question for glass bottle management in CH:**
  How does glass recycling change the system?
  a. How much glass needs to be imported?
- **System boundary:** Switzerland, 1 year
  Unit for flows/fluxes: kg/c,yr
  Unit for stocks: kg/c
- **Processes:** glass production, glass consumption
- **Material flows/fluxes:** glass, waste glass
- **Indicators:** glass import rate, energy use

Example – Recycling glass

Material flow/flux: glass, waste glass



Simplified material system for glass bottle management in Switzerland.

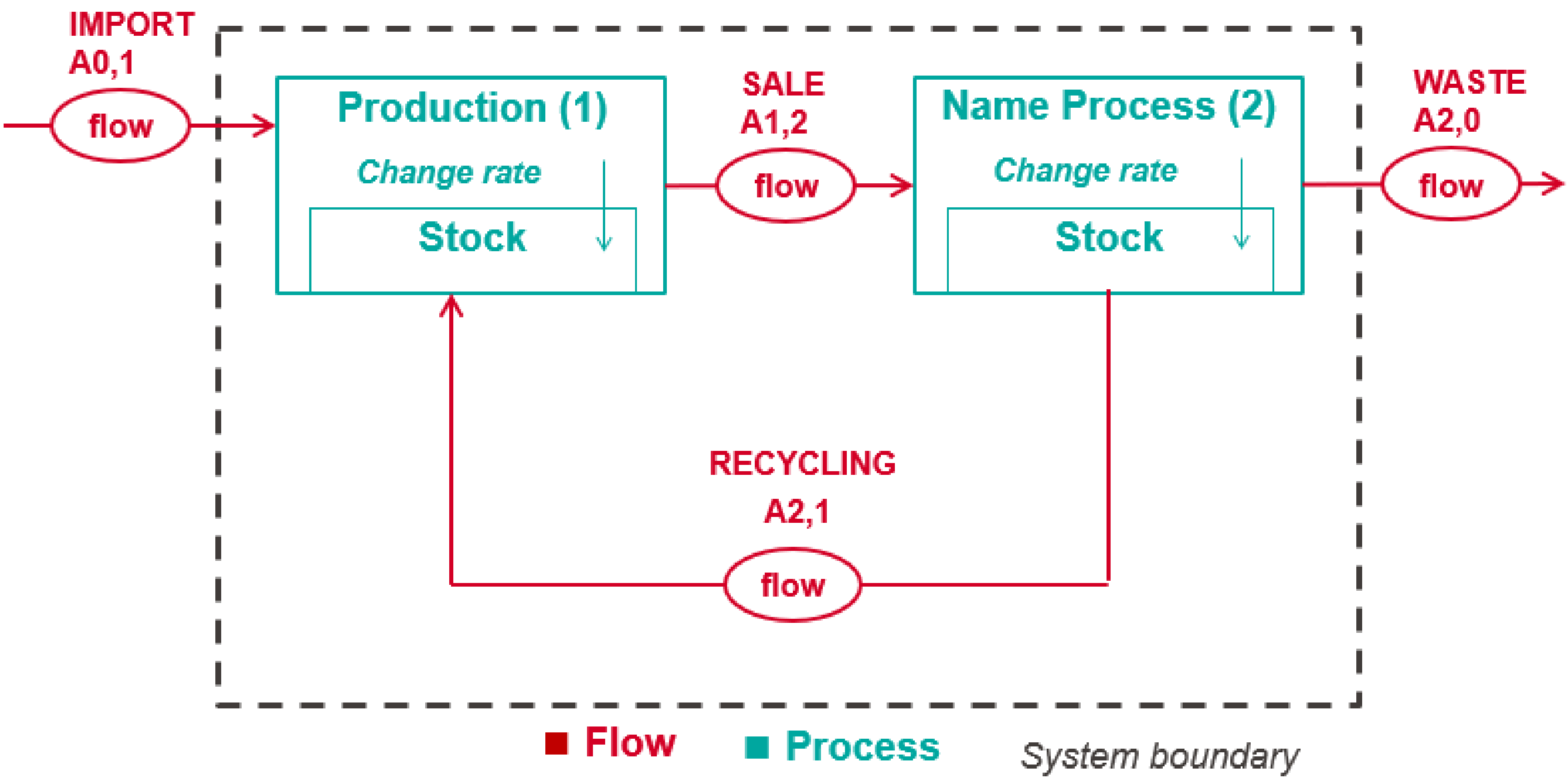
Baccini & Brunner, 2012

Example – Recycling glass

Procedure for mathematical system definition:

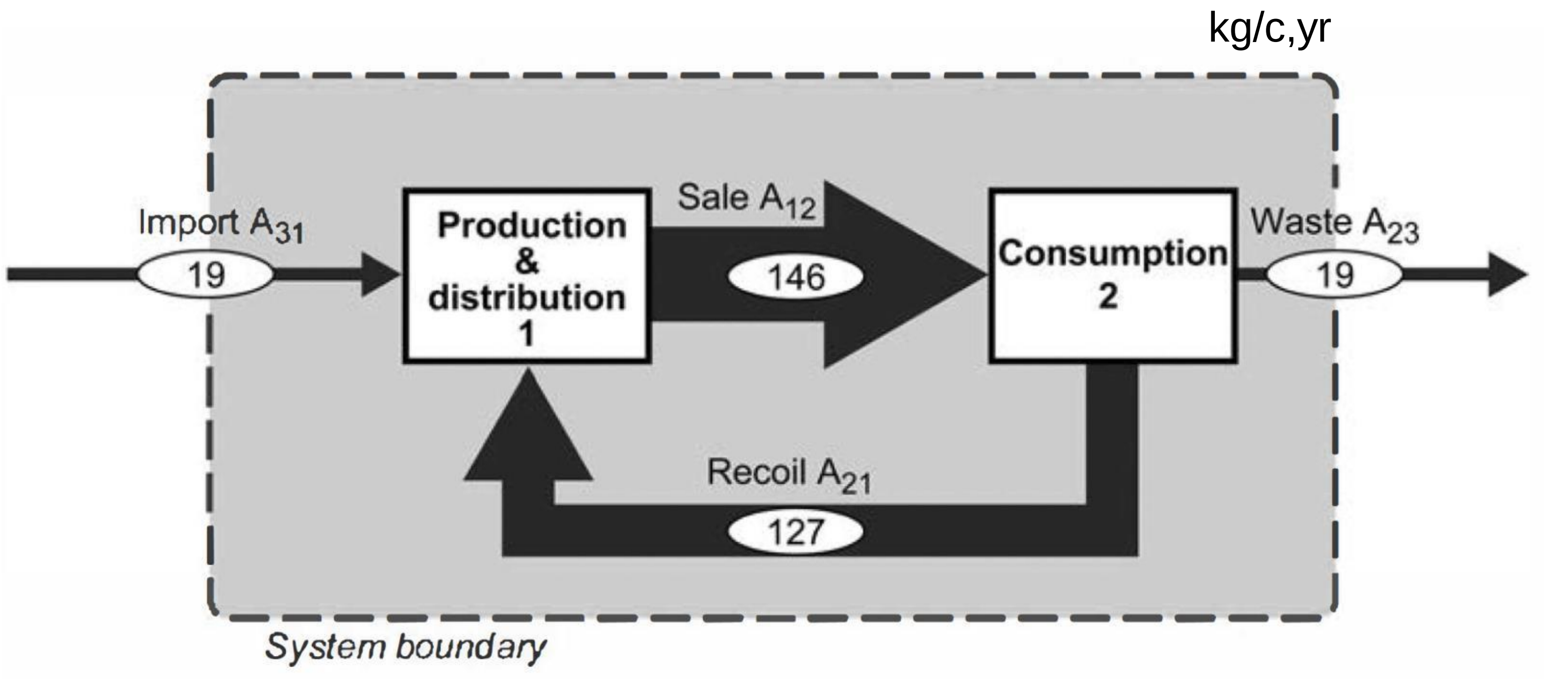
- Define the system unknowns.
- Setup the system of equations.
- Complete the system of equations with specific relationships.
- Solve the system of equations.
- Analyze the results and check for errors.

Example – Recycling glass



General case: 8 system unknowns (stocks, stock changes, flows)
Steady state: 6 system unknowns (stocks, flows)

Example – Recycling glass



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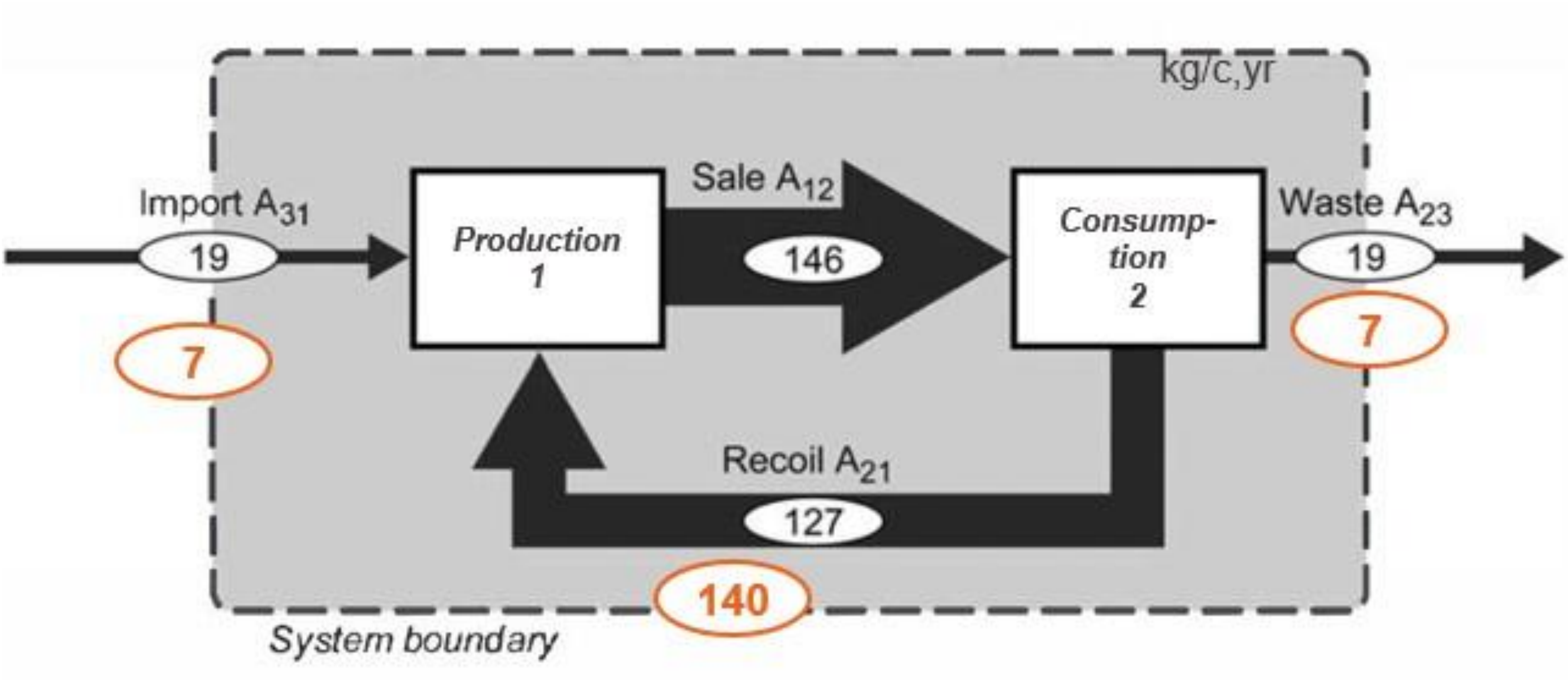
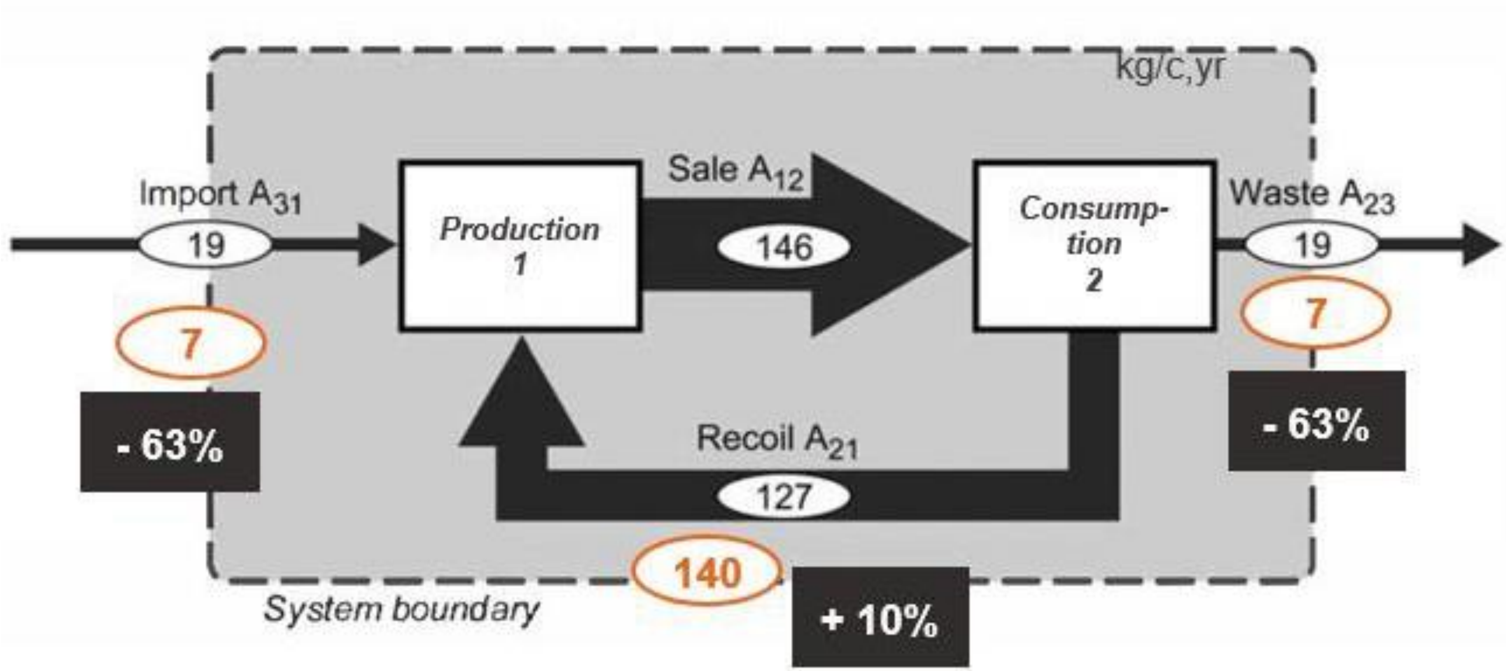
Example – Recycling glass



What if recycling rate increases by 10%
assuming that glass imports and exports stay constant

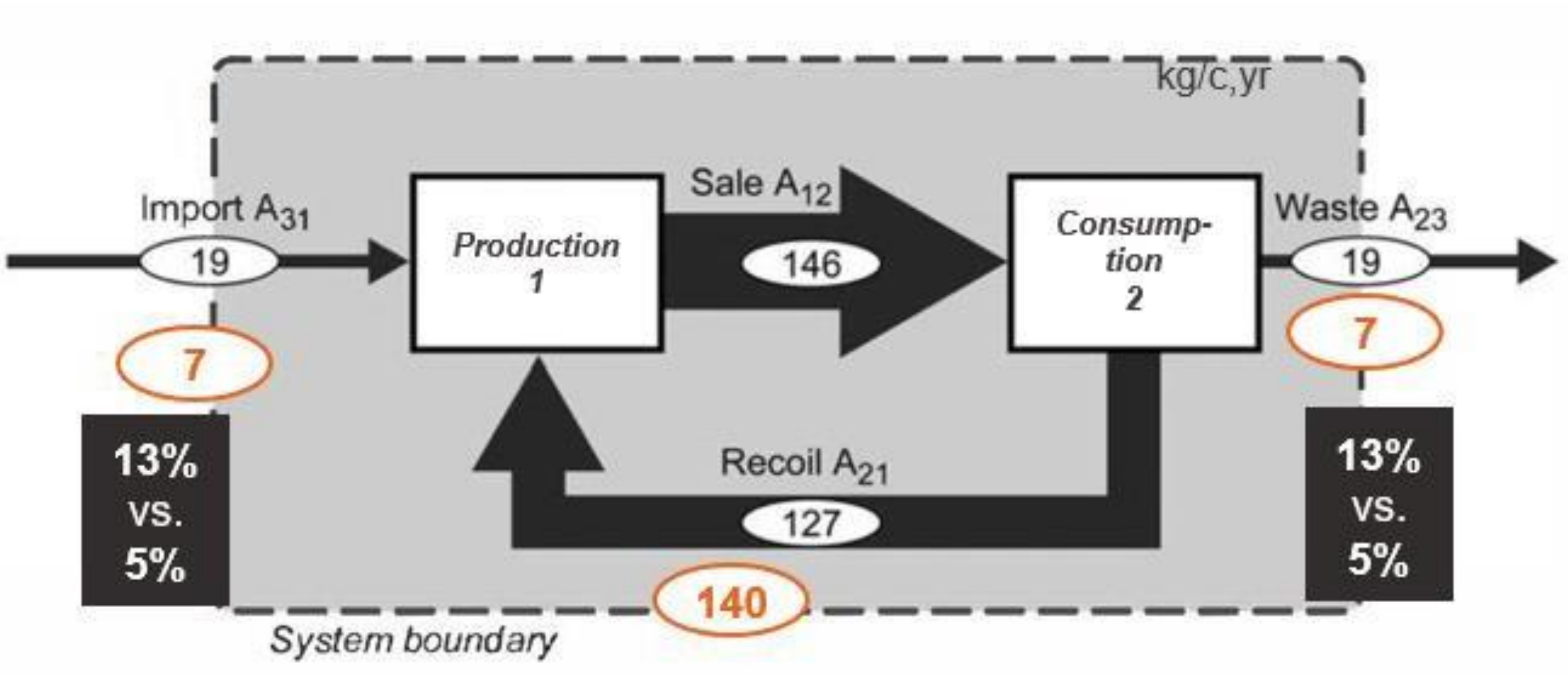
Example – Recycling glass



How to check the results?

a. Compare with statistical data
b. Compare with literature data
c. Get feedback from field experts

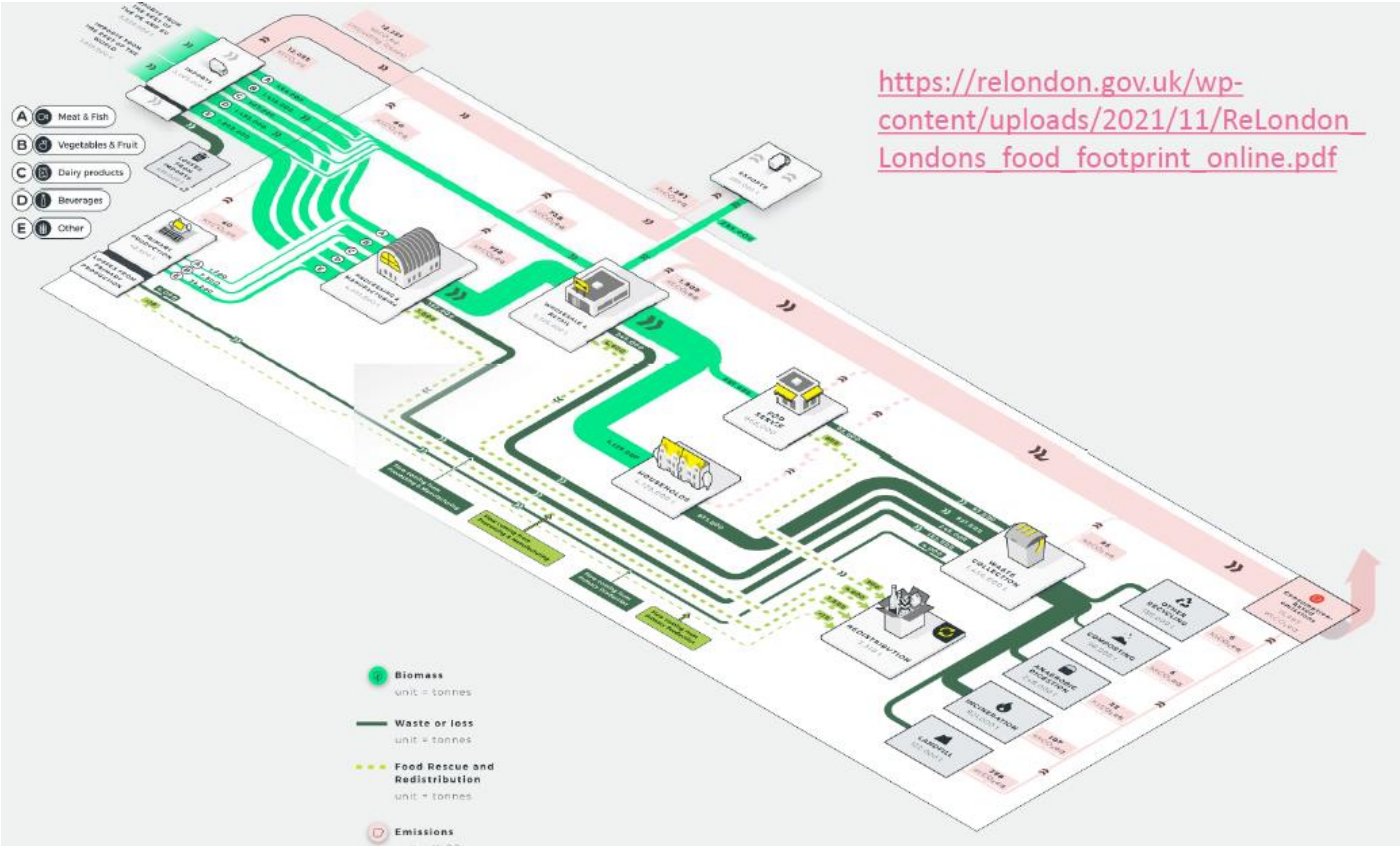
Example – Recycling glass



Indicators (as defined earlier)

a. Import rate

Example – Biomass flows



https://relondon.gov.uk/wp-content/uploads/2021/11/ReLondon_Londons_food_footprint_online.pdf

Method 3: Combining top-down & bottom-up

Complete

Accurate

Monitoring

Operational

Sector-wide MFA – main process - define

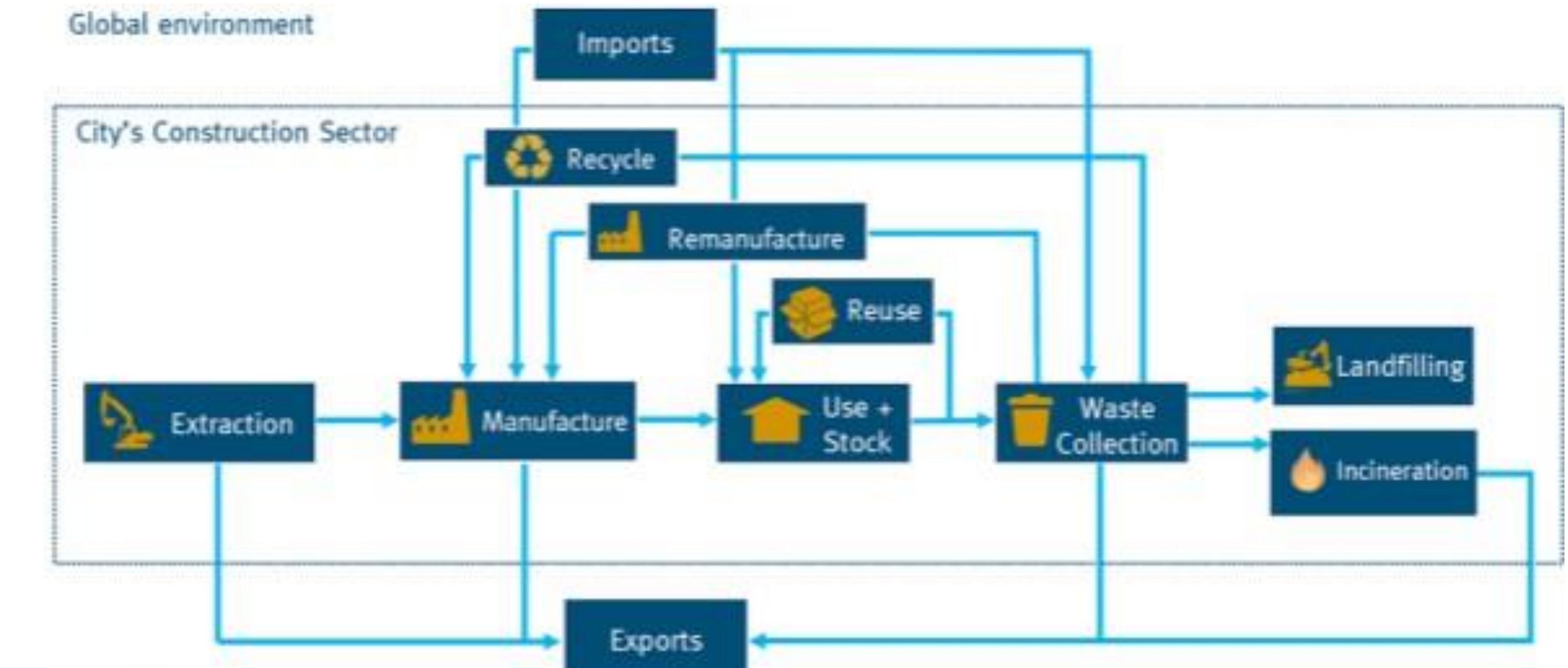
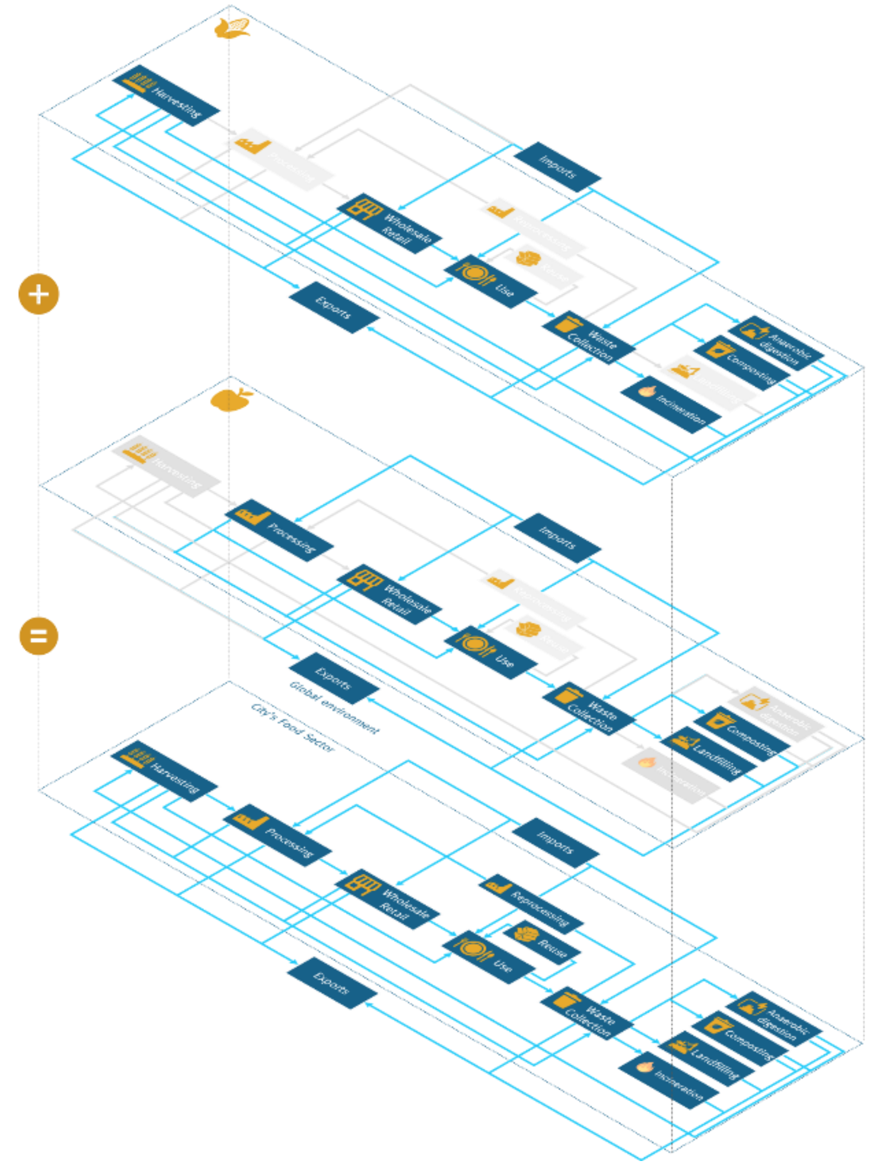


Figure 21: Generic value chain of construction materials

[Source: https://cityloops.metabolismofcities.org/media/uploads/libraryitem/report/CityLoops_WP4_D4.3_Sector-Wide_Circularity_Assessment_Method.pdf](https://cityloops.metabolismofcities.org/media/uploads/libraryitem/report/CityLoops_WP4_D4.3_Sector-Wide_Circularity_Assessment_Method.pdf)

Sector-wide MFA – per material



[Source: https://cityloops.metabolismofcities.org/media/uploads/libraryitem/report/CityLoops_WP4_D4.3_Sector-Wide_Circularity_Assessment_Method.pdf](https://cityloops.metabolismofcities.org/media/uploads/libraryitem/report/CityLoops_WP4_D4.3_Sector-Wide_Circularity_Assessment_Method.pdf)

From national to urban

What is urban metabolism?

What is urban metabolism?

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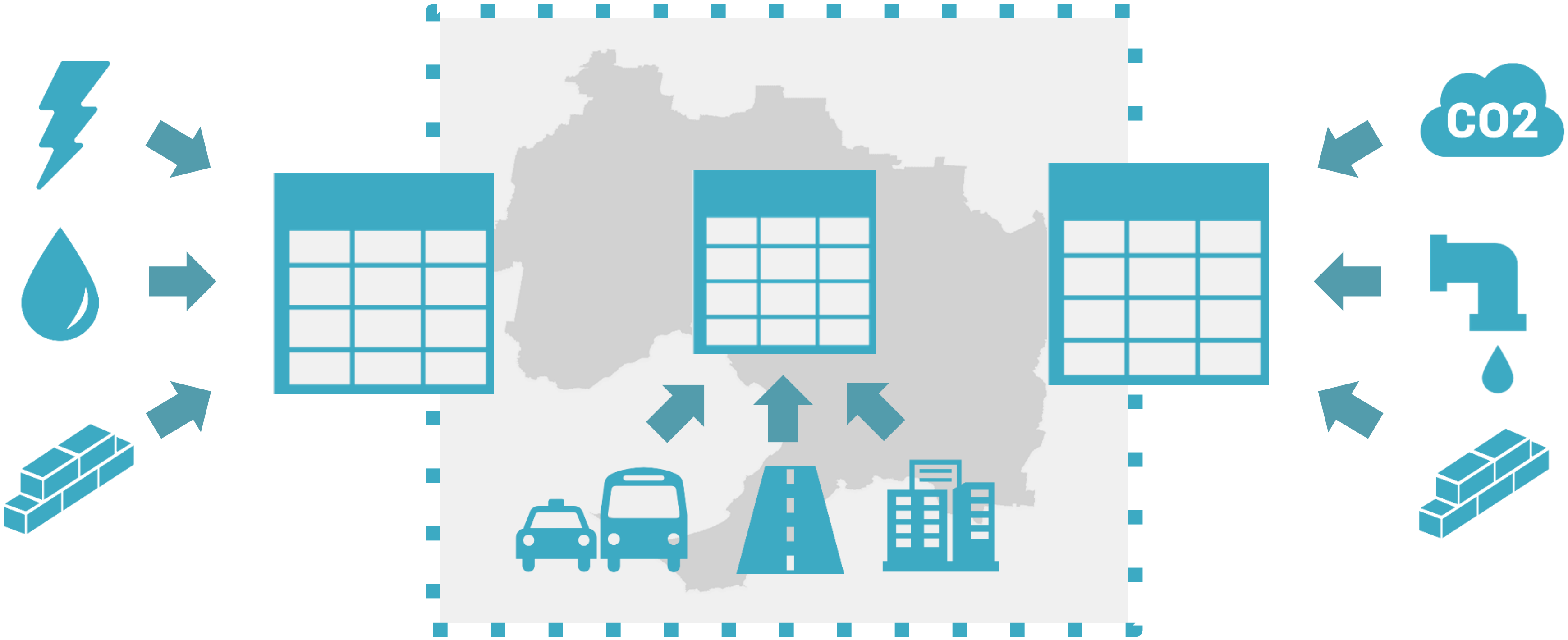
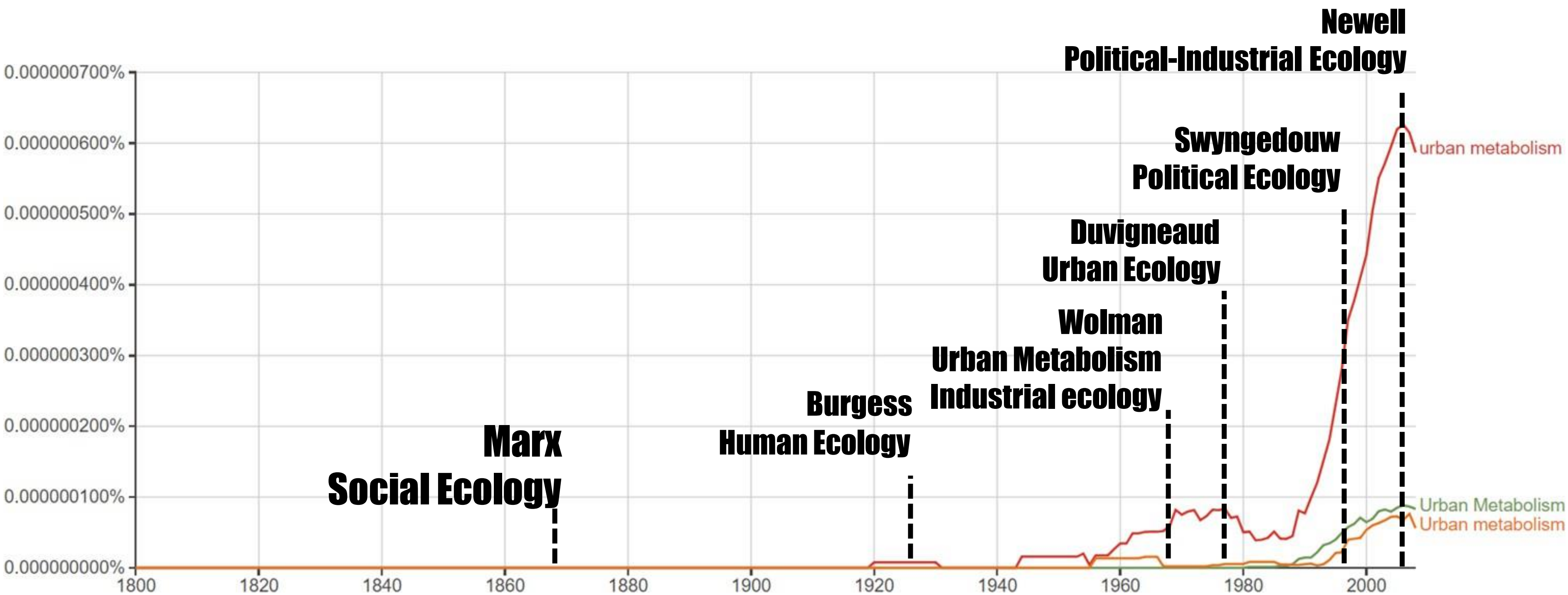
What is urban metabolism?



An (unconsolidated) field studying urban flow/stocks and actors from a systemic perspective

What is urban metabolism?

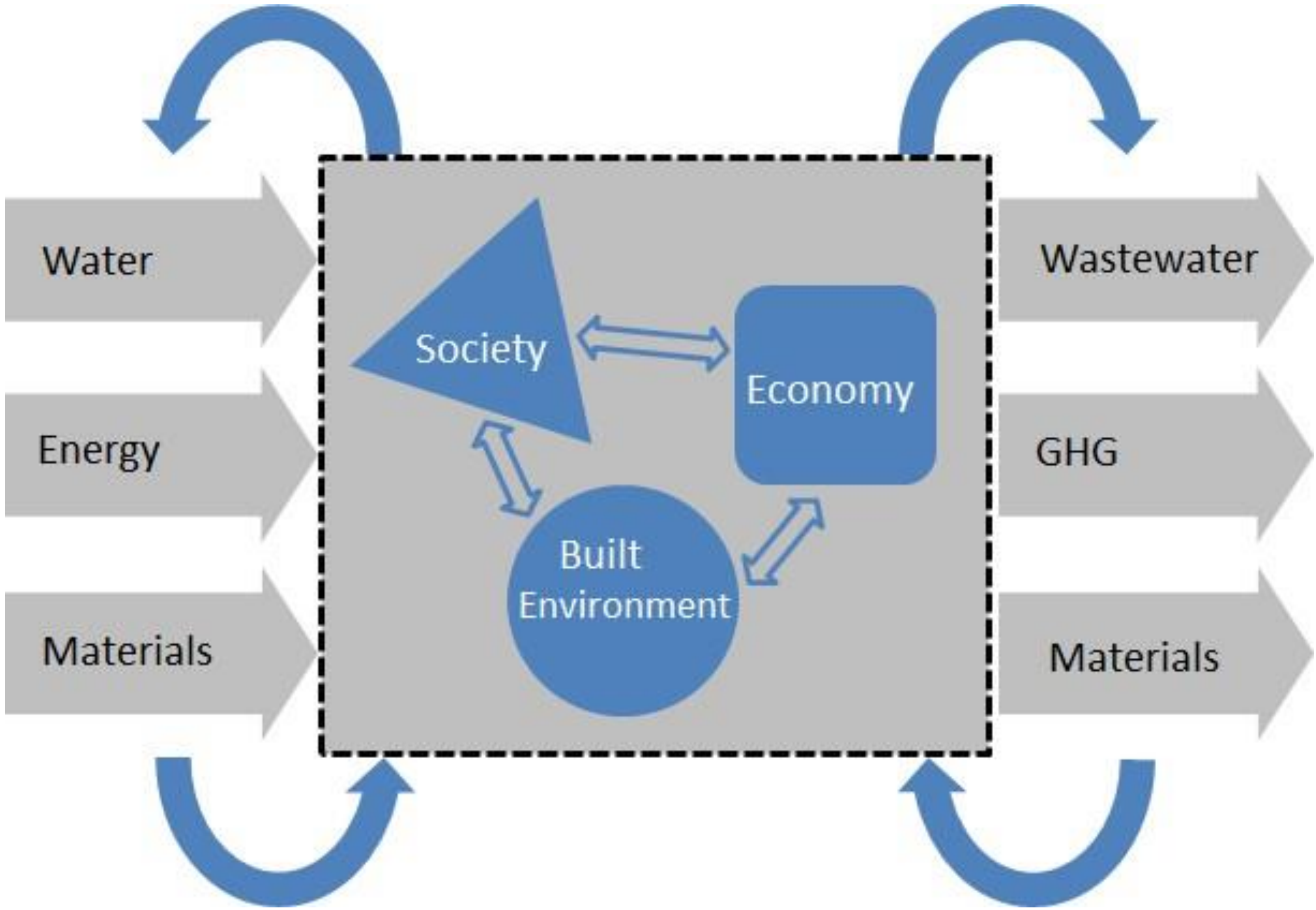


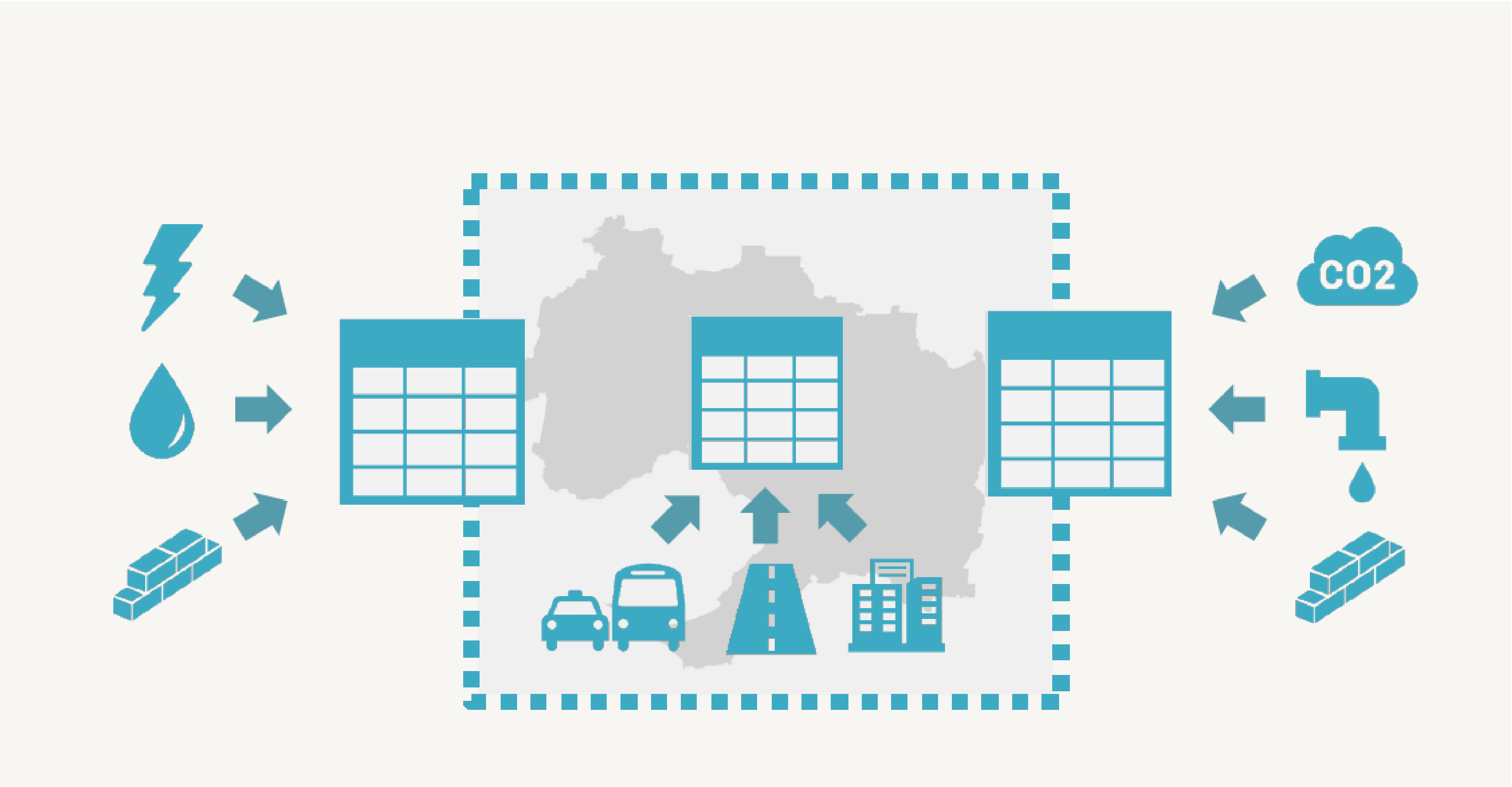
Industrial Ecology, Political Ecology, Urban Ecology

Main insights

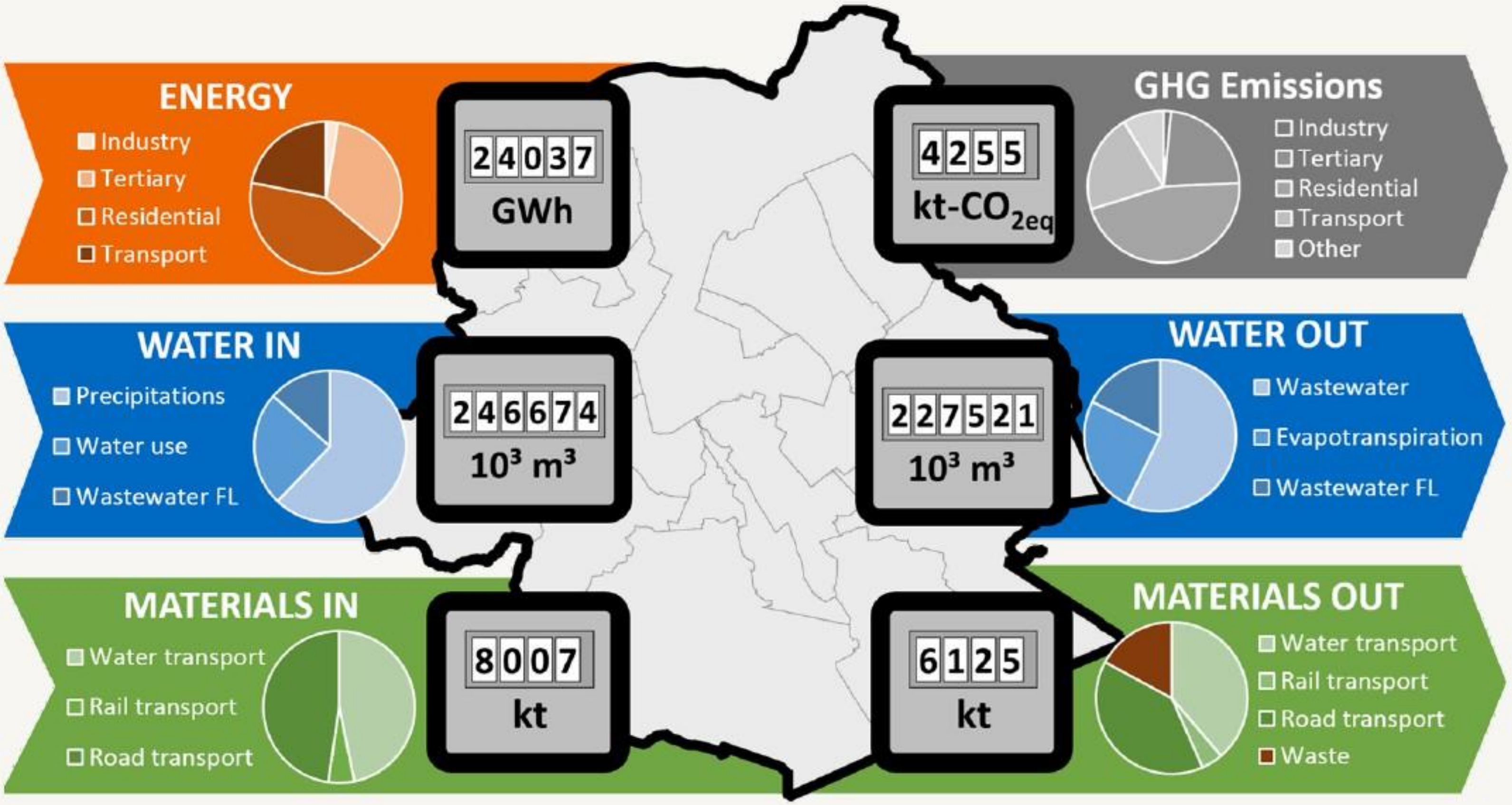
Why is Urban Metabolism relevant?

Interrelationship between urban activities and flows



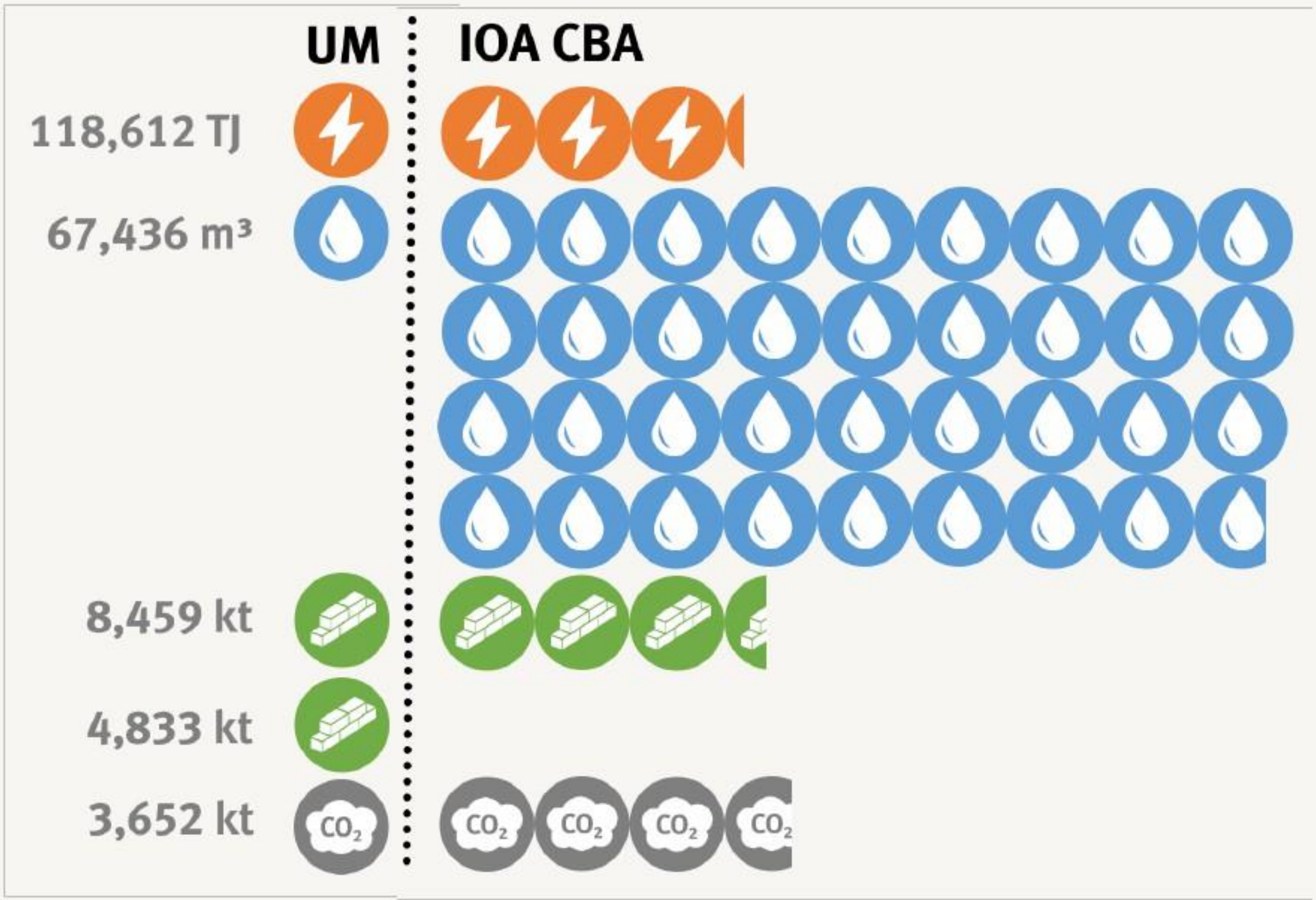


Monitoring urban resource use and pollution emissions



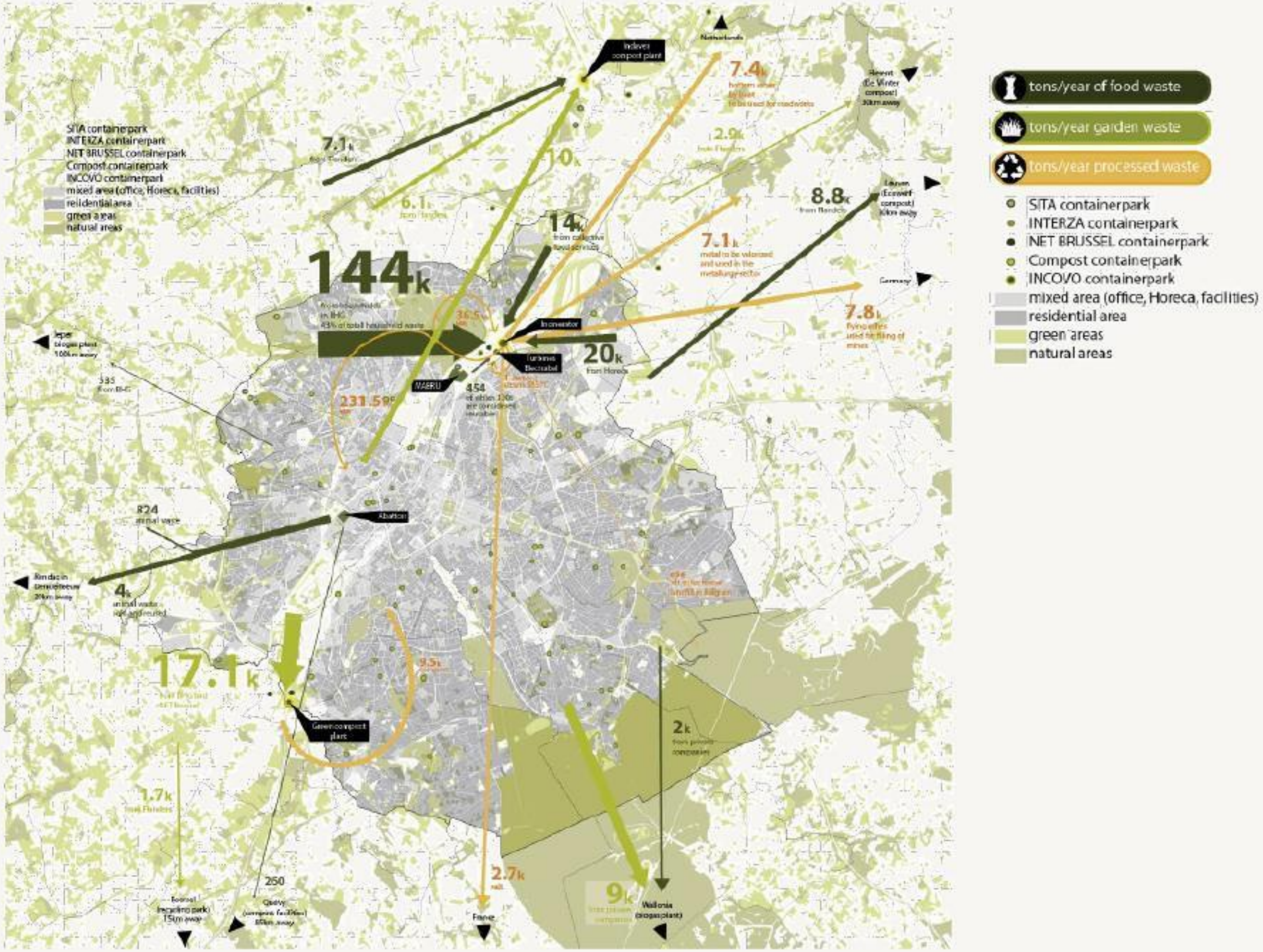
Athanassiadis, A., P. Bouillard, R. H. Crawford, and A. Z. Khan. 2017. Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010. *Journal of Industrial Ecology* 21(2): 307-319.

Example - Brussels' metabolism in 2010

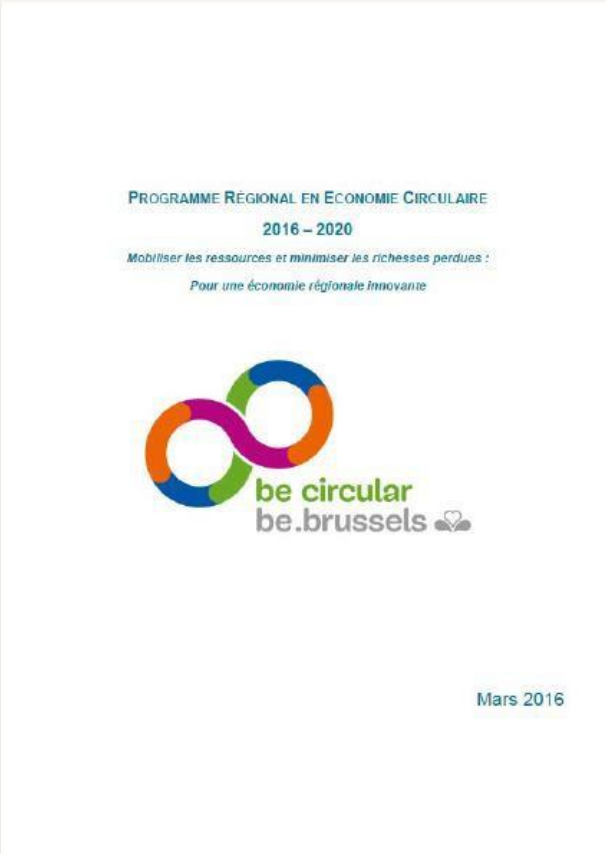


Athanassiadis, A., M. Christis, P. Bouillard, A. Vercalsteren, R. H. Crawford, and A. Z. Khan. 2018. Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. *Journal of Cleaner Production* 173: 112-123.

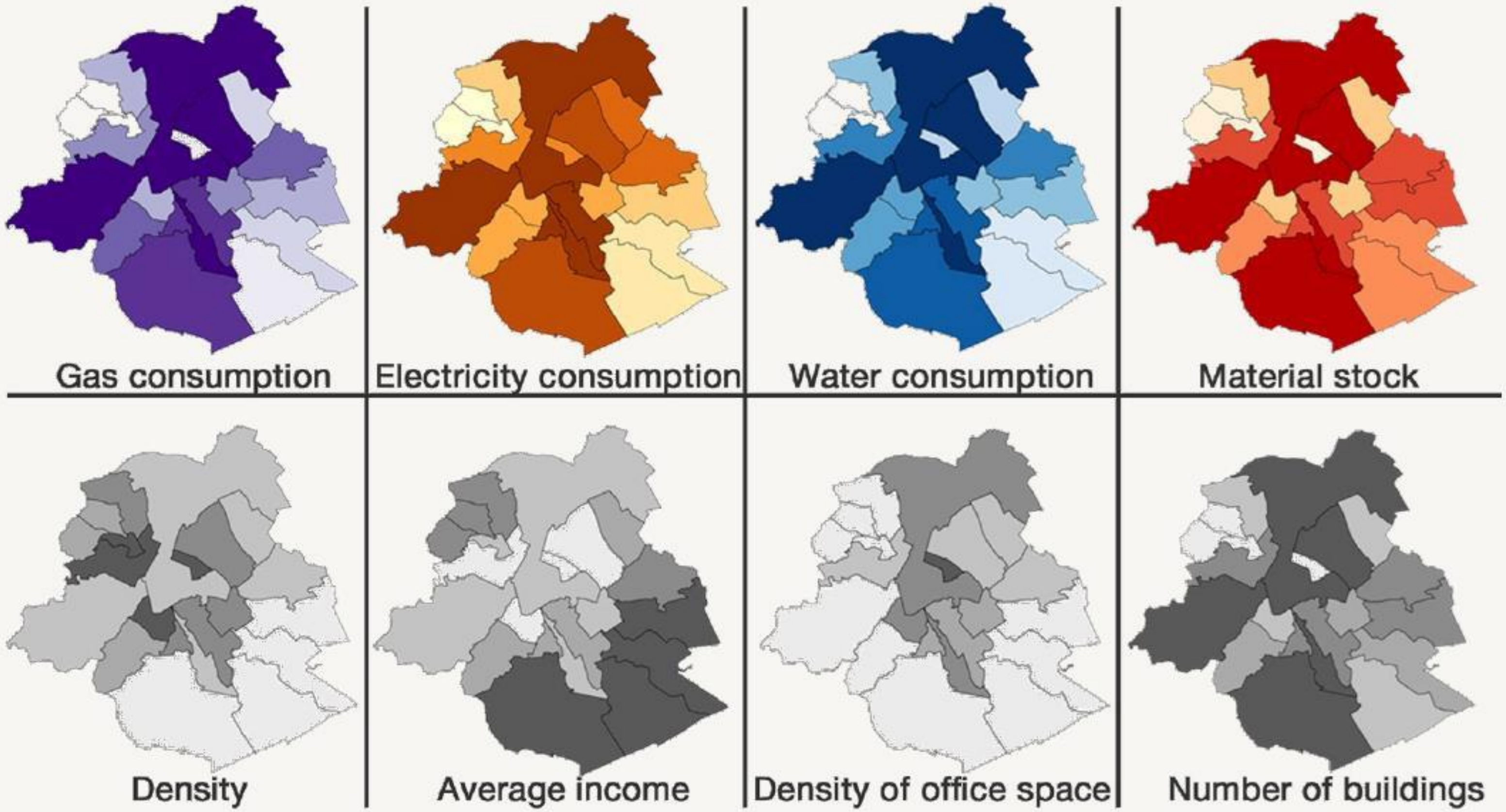
Example - Indirect effects/impacts of cities



Example - Mapping flows & manifesting actors/infrastructure

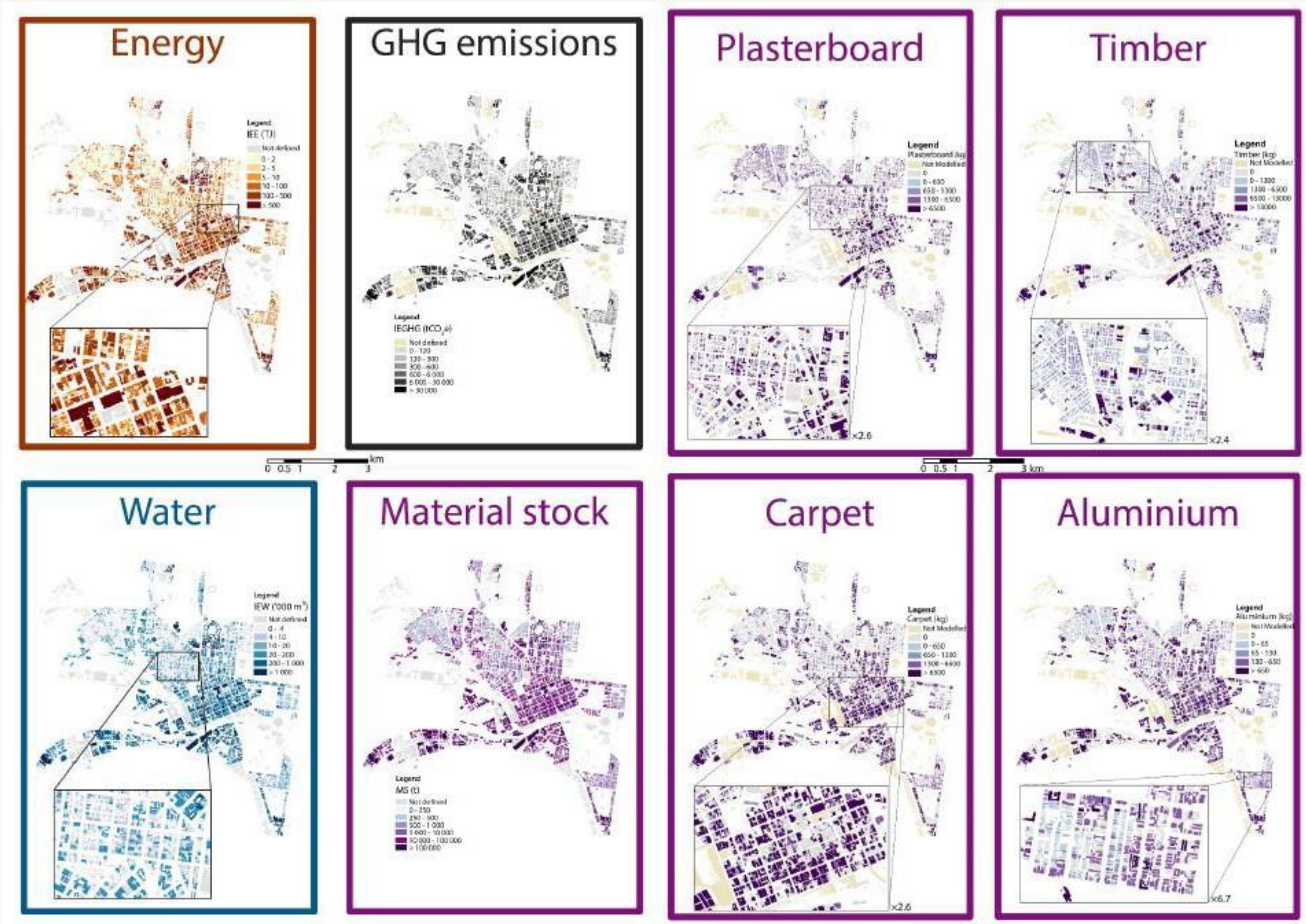


Developing policies



Athanassiadis, A. and P. Bouillard 2013. Contextualizing the Urban Metabolism of Brussels: Correlation of resource use with local factors. In *Proceedings of CISBAT 2013, International Conference, Cleantech for Smart Cities & Building from Nano to Urban Scale*. Lausanne: EPFL-Lausanne.

Identifying drivers



Mapping the urban mine

Stephan, A. and A. Athanassiadis. 2017. Quantifying and mapping embodied environmental requirements of urban building stocks. *Building and Environment* 114: 187-202.

Stephan, A. and A. Athanassiadis. 2018. Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. *Resources, Conservation and Recycling* 129: 248-262.

System boundary definition (city)

Steps of MFA

Step I: System definition
Problem definition, definition of system boundaries, selection of processes and flows of materials/substances (qualitative model)

Step II: Measurement
Data collection of flows and stocks of materials/substances and characterization of uncertainties (measurements, literature data, estimations)

Step III: Calculation
Calculation of unknown quantities by balancing of materials based on the principle of mass conservation (MFA software)

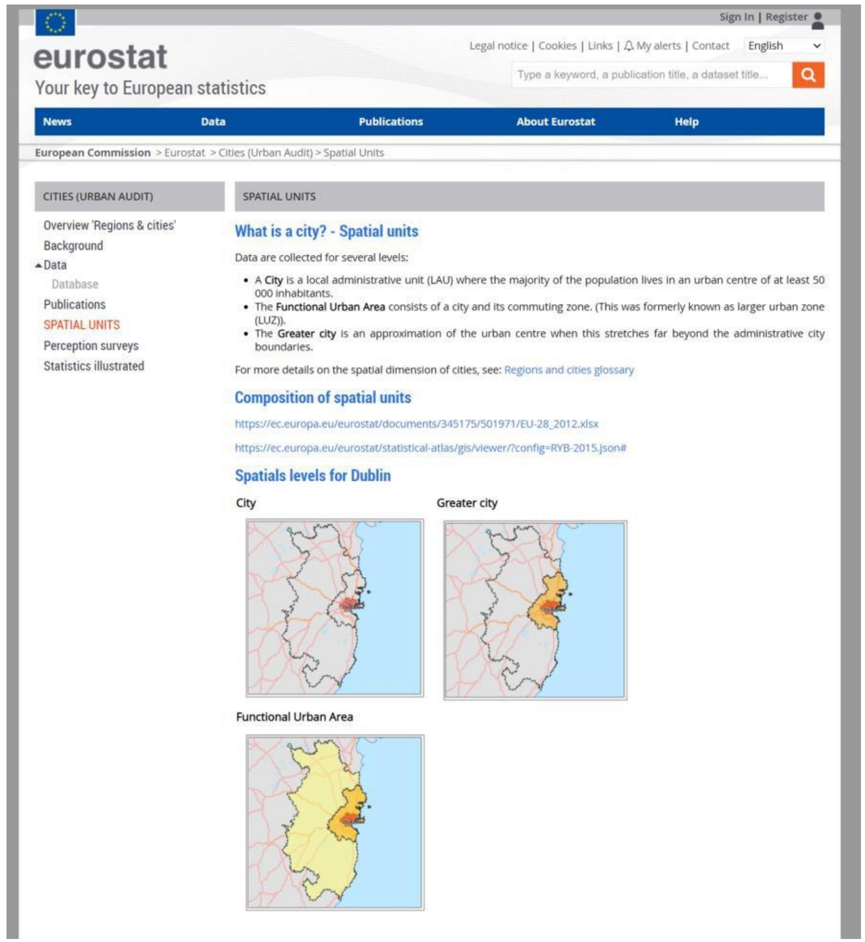
Step IV: Illustration and interpretation
Sources, stocks, flows and sinks

Step V: Recommendations
How can the system be optimized?

How do you define a city ?

How do you define a city ?

A **City** is a local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50 000 inhabitants.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CITIES (URBAN AUDIT)
Overview 'Regions & cities'
Background
Data
Database
Publications
SPATIAL UNITS
Perception surveys
Statistics illustrated

SPATIAL UNITS

What is a city? - Spatial units

Data are collected for several levels:

- A **City** is a local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50 000 inhabitants.
- The **Functional Urban Area** consists of a city and its commuting zone. (This was formerly known as larger urban zone (LUZ)).
- The **Greater city** is an approximation of the urban centre when this stretches far beyond the administrative city boundaries.

For more details on the spatial dimension of cities, see: Regions and cities glossary

Composition of spatial units

https://ec.europa.eu/eurostat/documents/345175/501971/EU-28_2012.xlsx

https://ec.europa.eu/eurostat/statistical-atlas/gis/viewer/?config=RYB-2015.json#

Spatials levels for Dublin

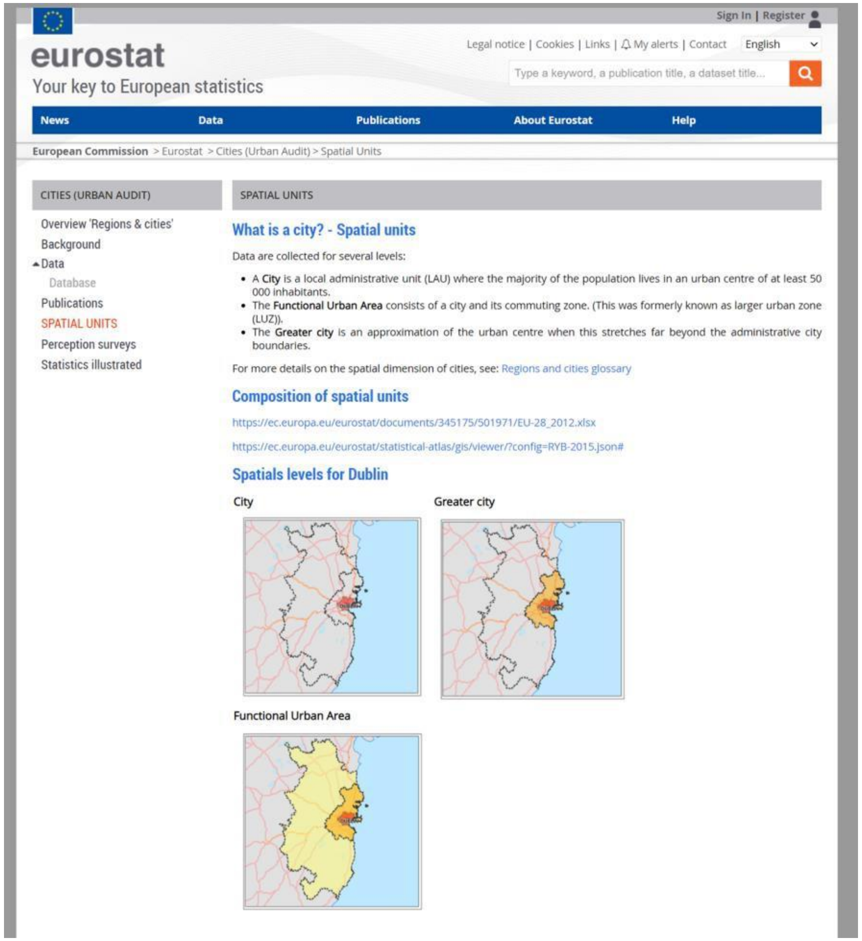
City Greater city

Functional Urban Area

https://ec.europa.eu/eurostat/web/cities/spatial-units

What boundary to choose? And for what? (Q&A)

A **City** is a local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50 000 inhabitants.



https://ec.europa.eu/eurostat/web/cities/spatial-units

In practice

- Find an administrative scale closest to the city you focus
- Find a scale where there is data (and also a perhaps a statistical office)
- Look at existing studies (either existing MFA or related studies)

Main methods

Main accounting methods

Data layers	Urban EW-MFA	Urban MFA (balanced)
• Structured data collection • Flexible • Not standard • Easy to compare?	• Structured data collection • Balanced • Indicators • Comparable to countries • Black box	• Topic specific • Very analytic • Data heavy • Great for modelling and forecast • Difficult to compare?

Data Layers (Kennedy et al. 2014)

Table 3: Parameters for a basic urban metabolism

Layer	Description
Layer 1: Context	Examine context of the city: spatial boundaries; constituent cities; population; economy
Layer 2: Biophysical characteristics	Examine the biophysical characteristics: land area; urbanized area; climate; building gross floor area
Layer 3: Urban energy metabolism parameters	Examine urban metabolism parameters: consumption of materials, water, food, energy – all types; electricity sources; and sectors related to energy consumption (water; waste water; food; transport; housing), waste generated from consumption
Layer 4: Role of utilities	Number and ownership of distributors and suppliers of resources: water, energy (electricity; natural gas; access to basic services), food, waste
Layer 5: Policy frameworks	Existing policies that shape the direction of resource flows

Adapted from Kennedy et al. (2014) and Musango et al. (Forthcoming)

Musango, J.K., Currie, P. & Robinson, B. (2017) Urban metabolism for resource efficient cities: from theory to implementation. Paris: UN Environment.

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Data Layers (Kennedy et al. 2014)

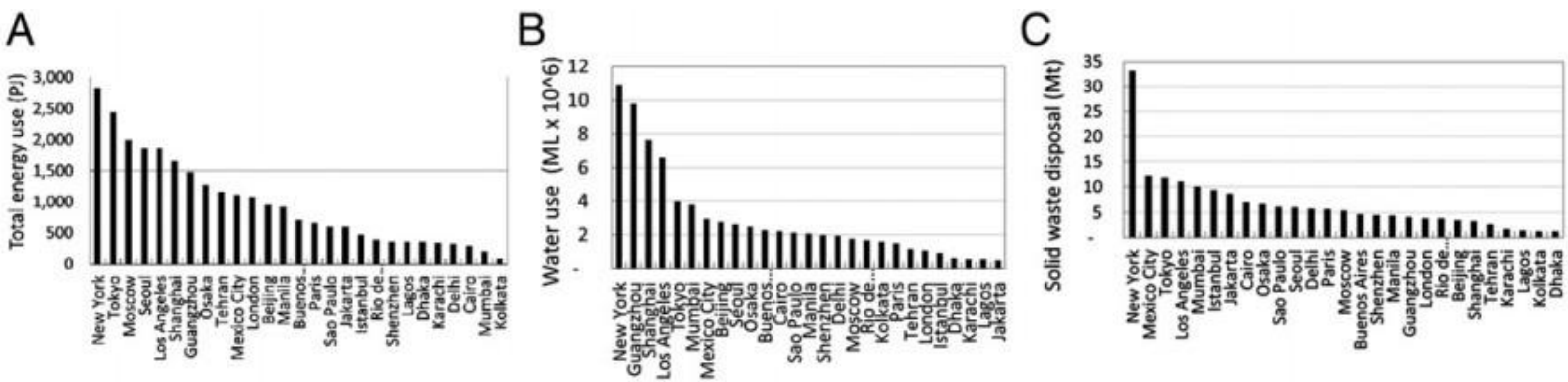
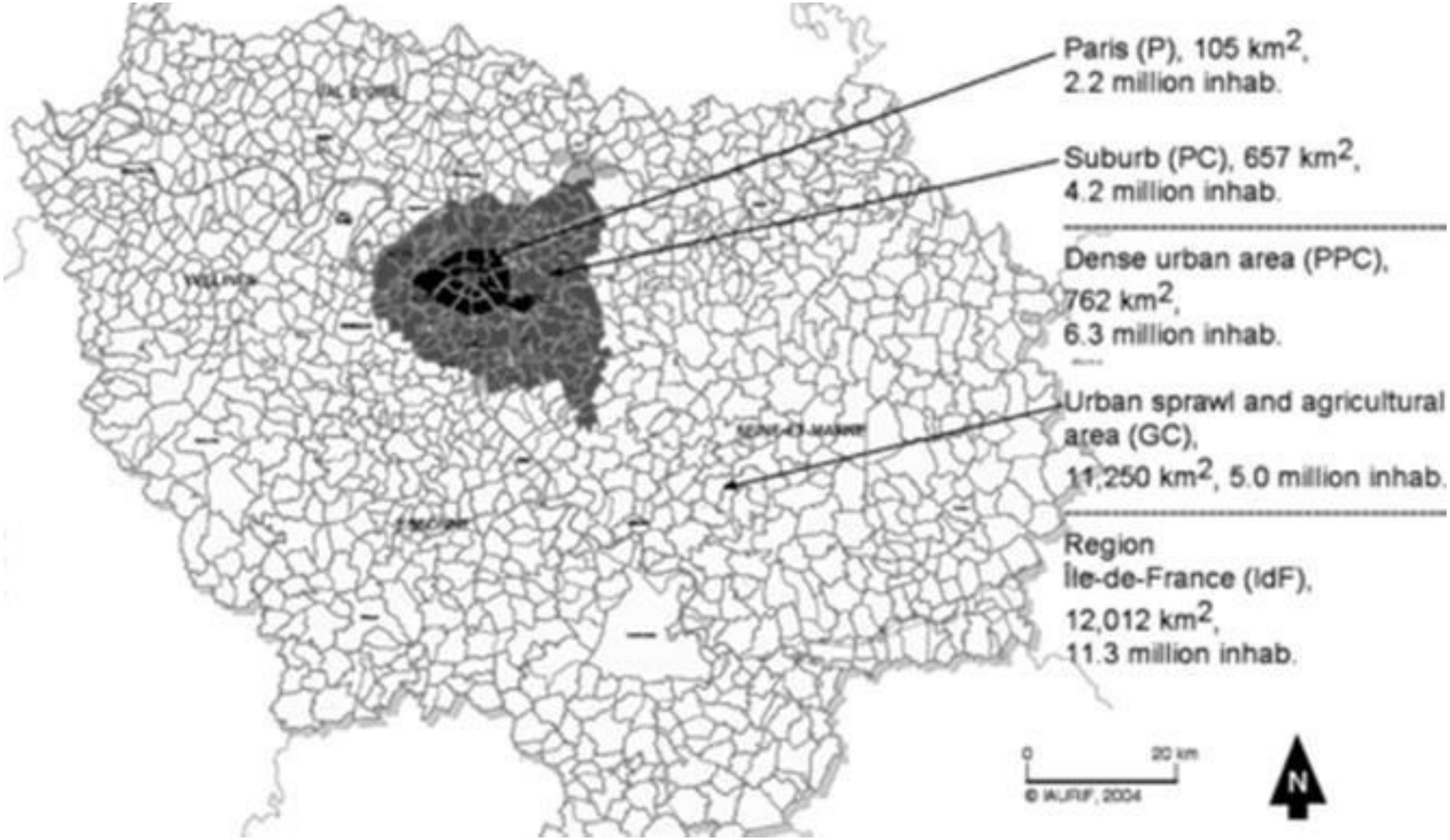


Fig. 1. Resource flows for megacities in 2011. (*A*) Energy use. (*B*) Water use including line losses. (*C*) Municipal solid waste production. Values shown are for the megacity populations scaled on a per capita basis from recorded data for the study area population (*Methods*).

Kennedy, C. A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., ... & Sahin, A. D. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences*, *112*(19), 5985-5990.

Urban EW-MFA



Barles, S. 2009. Urban metabolism of Paris and its region. Journal of Industrial Ecology 13(6): 898-913.

Urban EW-MFA

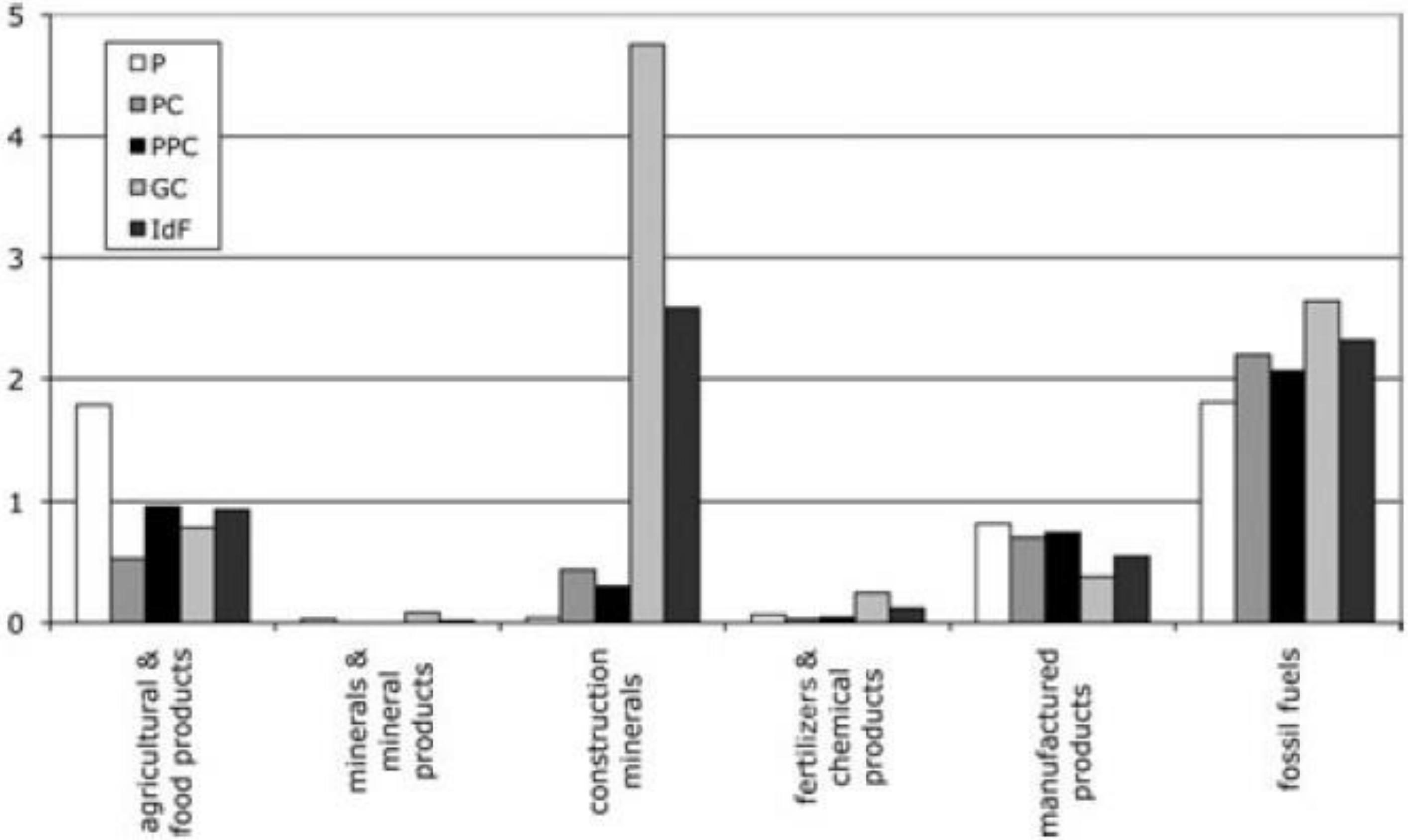
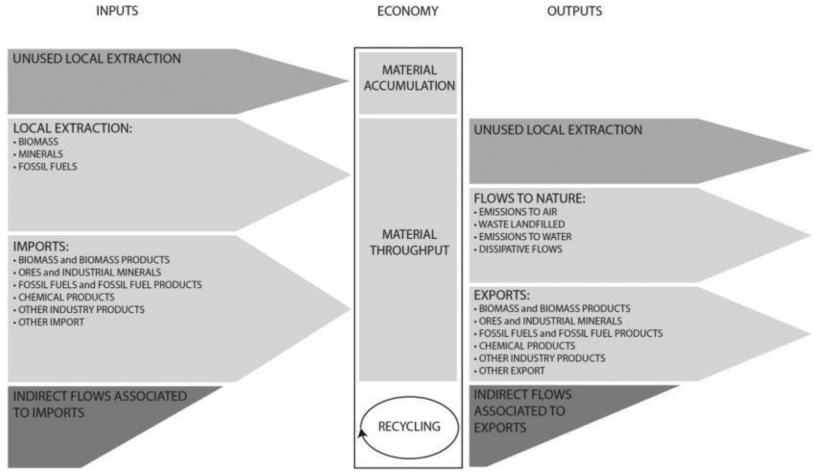
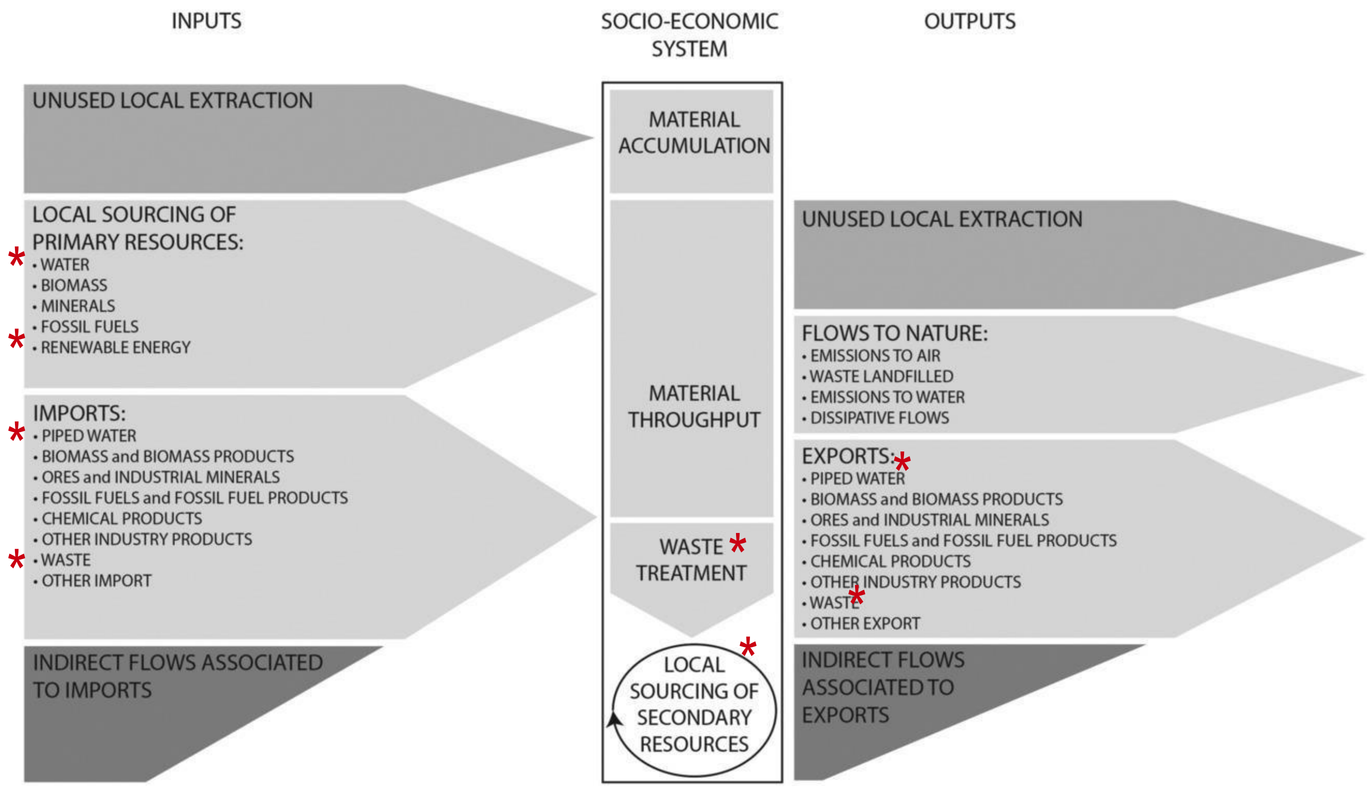


Figure 4 Domestic material consumption (DMC), 2003 (tonnes per capita). P = Paris; PC = dense suburb of Paris; PPC = dense urban area (PPC = P + PC); GC = urban sprawl and agricultural area; IdF = Île-de-France region.

Barles, S. 2009. Urban metabolism of Paris and its region. Journal of Industrial Ecology 13(6): 898-913.

Urban EW-MFA





Voskamp, I. M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J. P., & Rijnaarts, H. H. (2017). Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: A material flow analysis of Amsterdam. *Journal of Industrial Ecology*, *21*(4), 887-902.

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Course organisation

Aim of the course (I)

- Analyser un produit ou nu service avec l'ACV
- Calculer les impacts environnementaux d'un produit
- Anticiper les évolutions réglementaires en environnement
- Optimiser les performances environnementales des produits
- Critiquer une étude existante
- Elaborer des stratégies holistiques pour boucler les flux de matière
- Critiquer les stratégies et plans environnementaux des villes et pays
- Analyser les flux de ressources et de déchets

Aim of the course (II)

- Planifier des actions et les mener à bien de façon à faire un usage optimal du temps et des ressources à disposition.
- Recevoir du feedback (une critique) et y répondre de manière appropriée.
- Ecrire un rapport scientifique ou technique.
- Utiliser les outils informatiques courants ainsi que ceux spécifiques à leur discipline.
- Etre responsable des impacts environnementaux de ses actions et décisions.