IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

# IChemE webinar – Sustainability SIG

## The urban food-energy-water-waste nexus: where urban agriculture meets organic waste management

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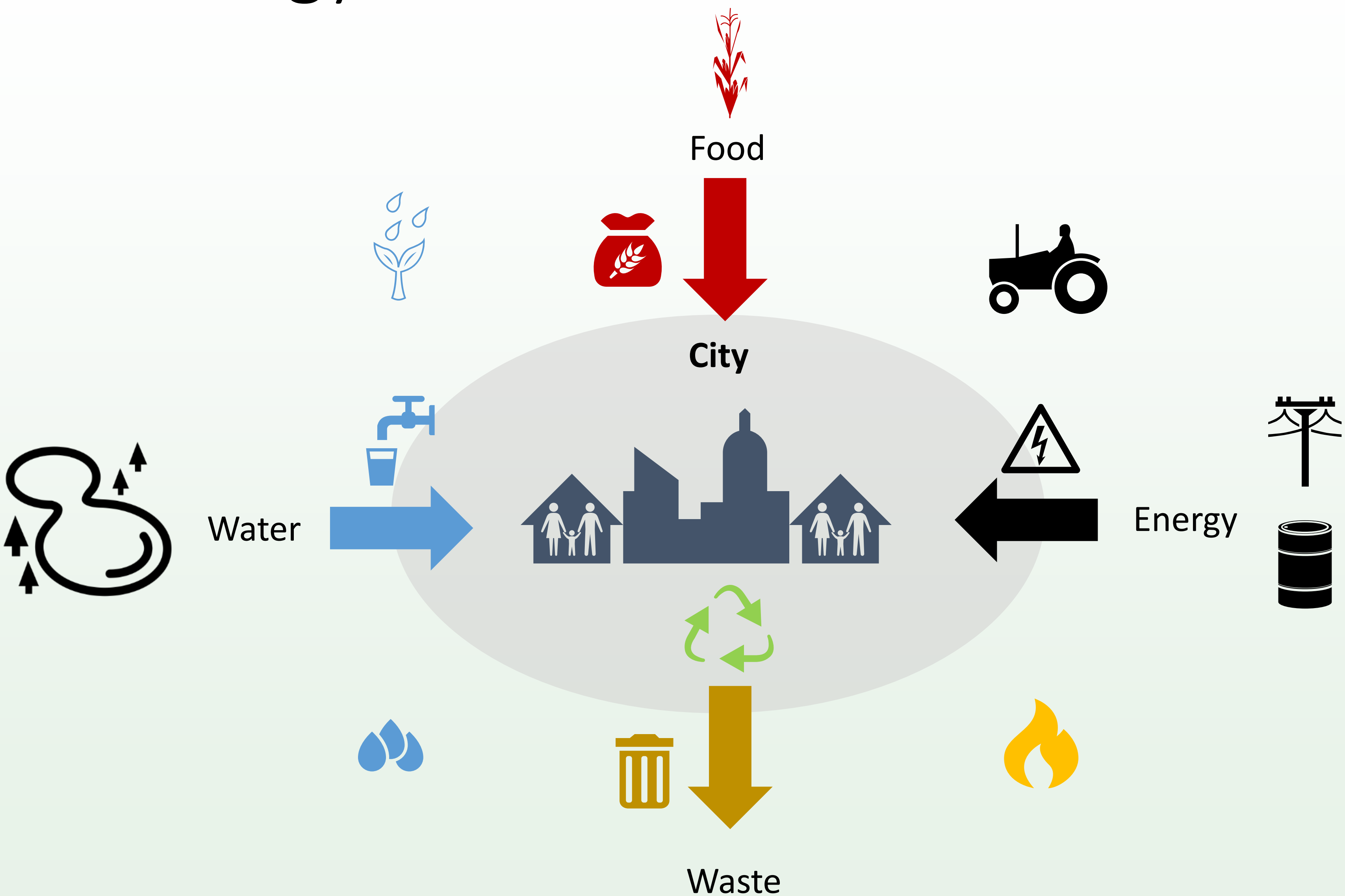
# Content overview

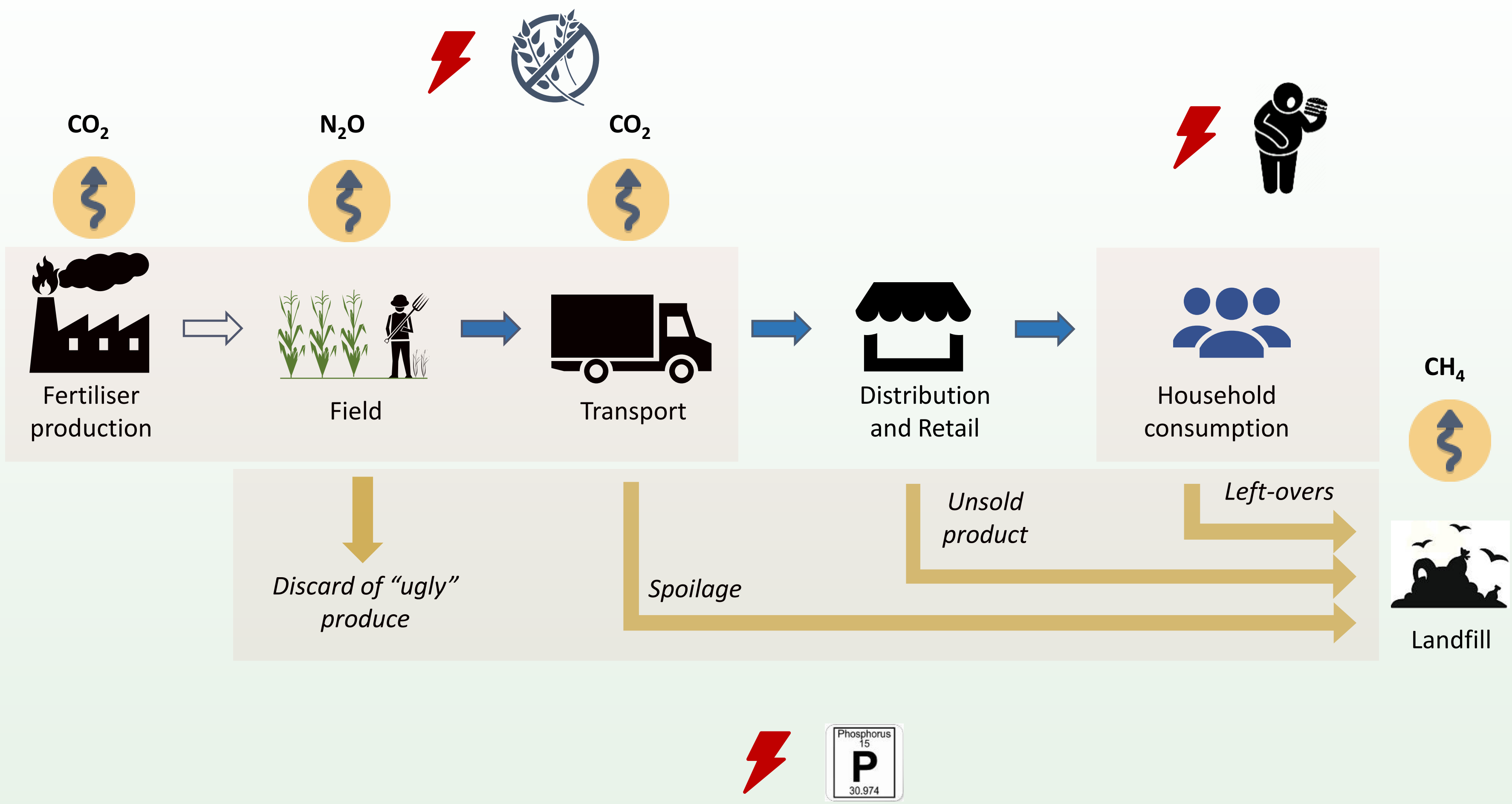
- Motivation
- 1st project – Urban FEWW nexus optimization
  (urban agriculture with organic waste)
- 2nd project – Design and evaluation of fully decentralised waste system
  (organic waste to agriculture)
- Future work
- Key messages

# MOTIVATION

# Introduction: Urban metabolism and the food-energy-water-waste nexus



# Issue 1: The current linear food system is inefficient, unsustainable and fragile



# Issue 2: Organic waste is usually treated centrally with low resource recovery

Degree of centralization

| Pathway |  Landfill |  Incineration |  Industrial composting |  Anaerobic digestion |  Home composting |
|---|---|---|---|---|---|
| Scale | | | | | |
| Climate impact | • Landfill gas | • Energy recovery | • Fertilizer | • Biogas and fertilizer | • Fertilizer |
| Resource recovery | | | • Nutrients & organic matter | • Biogas & nutrients | • Nutrients & organic matter |
| Throughput in Europe[1] (Mt) | 20 | 18 | 14 / 14 | 3 | • No figures |

1 Bio-waste recycling in Europe against the backdrop of the circular economy package, European Compost Network, 2017

# Proposed approaches have limitations when considered in isolation

**Technology**

**Urban agriculture**

- On rooftops and greenspaces
- Open-air and greenhouses

Benefits

- Nutritious food produce with short transport
- Community cohesion and connection to food
- Job creation in urban environments

**Separate decentral biological organic waste conversion**

- Primary: Community scale composting, anaerobic digestion and insect rearing
- Secondary: CHPs, biogas upgrading plants and larvae processing facilities


Benefits

- Local production of fertilizer and soil amendments
- Scale-independent
- Provision of energy, heat and animal feed

**Obstacles**

Urban agriculture:

- Reliance on synthetic fertiliser and fossil fuel heating
- Weak policy support (e.g. land access)
- Uncertainty about sustainability and profitability

Separate decentral biological organic waste conversion:

- Complex governance and logistics of (semi-) decentralised systems
- Public perception of waste
- Limited or no end use or sink for waste products in cities

**Current issues limiting development**

- Projects typically planned individually
- Utopian ambitions
- Uncertainty about impact

# Changing the narrative for urban food and waste systems by combining approaches

**A potential solution…**

**Circular urban agriculture**

Locally combined with

**Decentralized organic waste valorization**

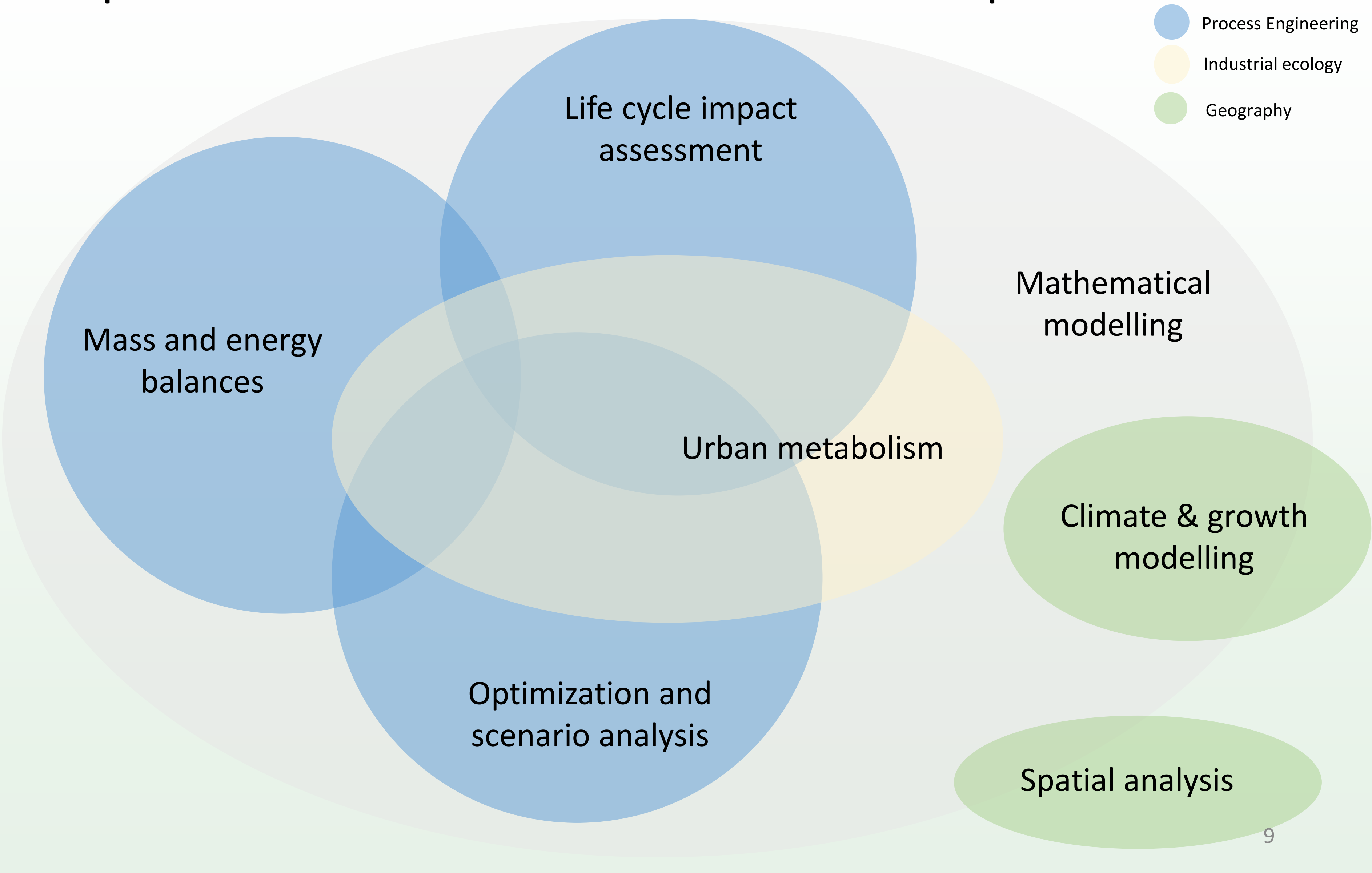
**What we know**

- Organic waste will have to be treated separately from other waste in the future (EU regulation from 2024)
- Interest from cities, citizens and business in UA and increased food self-sufficiency
- Technical feasibility demonstrated of individual projects integrating both approaches

**What we don't now:**

- How do location (e.g. climate), city characteristics (e.g. population density) and intensity of growing practices affect <u>self-sufficiency, waste assimilation (i.e. sink) potential and resource requirements of UA?</u>
- How to <u>best utilize organic waste flows</u> to sustainably meet resource requirements of UA?
- How does the proposed combination <u>compare to the current food/waste system</u> in terms of GHG emissions, cost and operatability?

# Process and systems engineering tools can help answer techno-economic questions



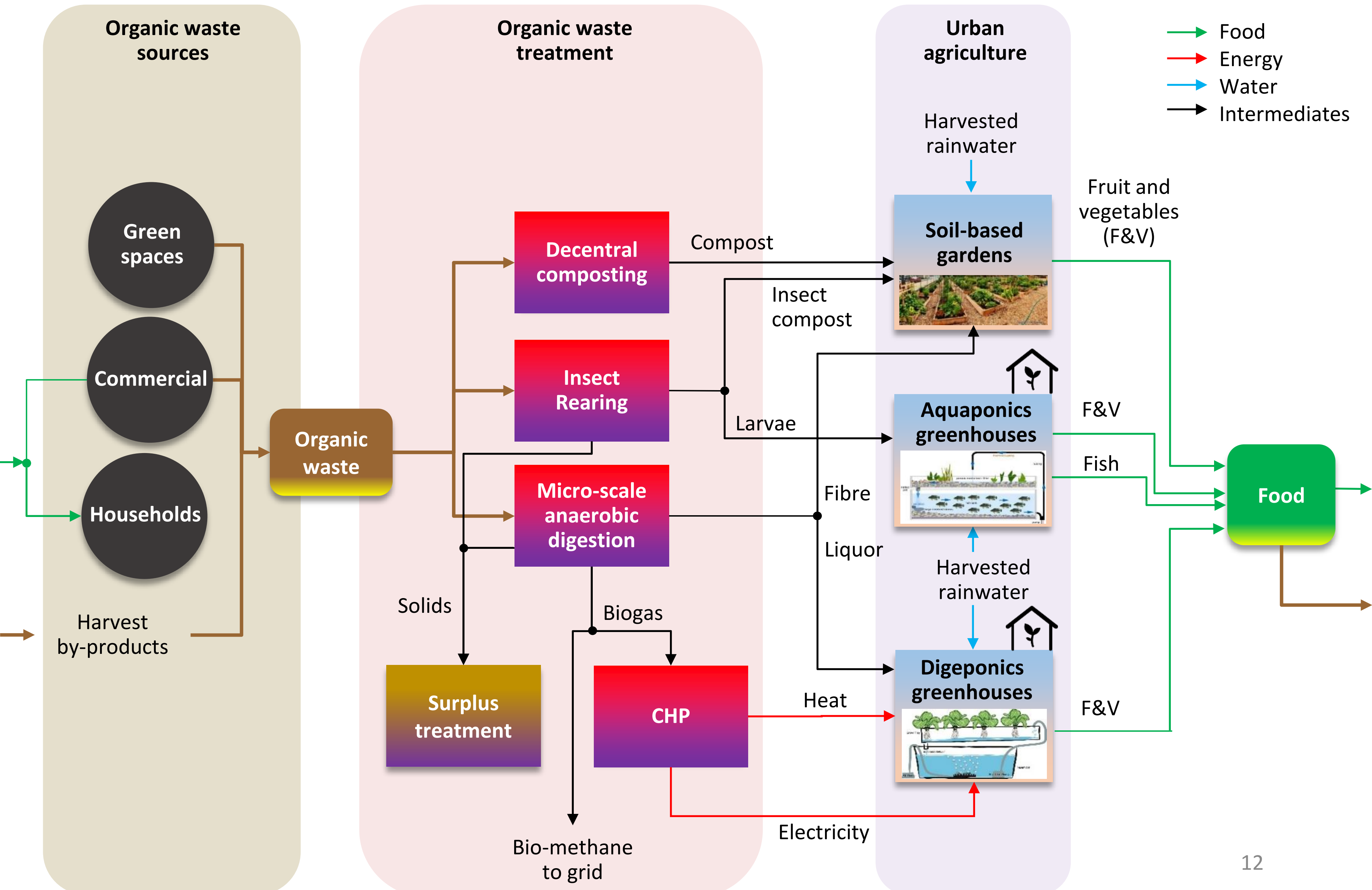
# Two projects have been carried out to shed light on some of the open questions

| | Urban FEWW nexus optimization | Design and evaluation of fully decentralised waste system |
|---|---|---|
| Scale or system boundary | City-wide (urban center) | District level and metropolitan area |
| Location | Glasgow, Lyon | Porto |
| Overview research questions | Influence of location, city layout and growing practices<br>Optimum waste pathways<br>Carbon footprint comparison | Design of localized compost system<br>Local waste logistic and use<br>Economic and environmental comparison |
| Focus | • UA + waste valorization | • Organic waste management + (peri-) UA as sinks |
| Set of tools | • ArcGIS (spatial analysis)<br>• Excel<br>• What's Best (optimization) | • ArcGIS (spatial analysis)<br>• Google Distance API (distances)<br>• Excel<br>• EASETECH (LCA component) |

# 1ST PROJECT

Optimizing the urban food-energy-water nexus by combining urban agriculture and organic waste management

# A novel urban resource nexus design



# Digeponic and aquaponics as novel intensive greenhouse growing methods

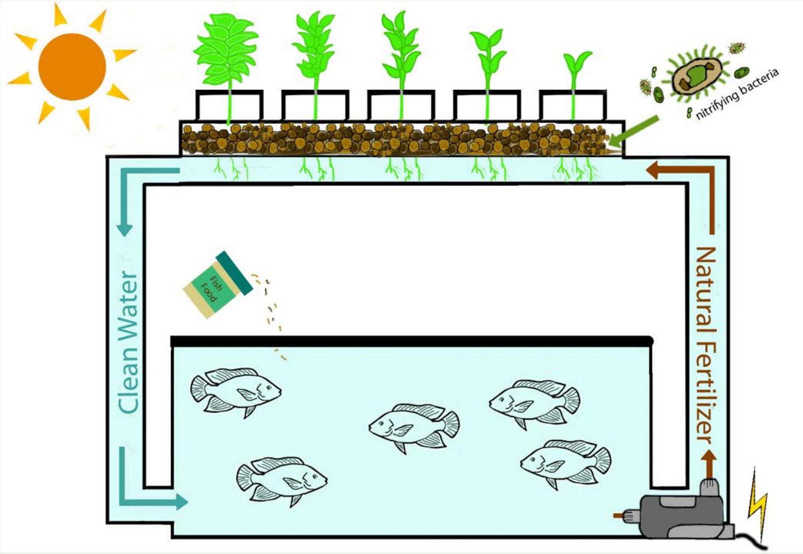
**Digeponic and hydroponic**

- No soil
- Circular nutrient-water system
- Controlled evironment

**Aquaponics**

- Input = fish feed (e.g. fish meal or larvae)
- Biofilm converts fish sewage to natural fertilizer

$$NH_3 \rightarrow NO_2^- \rightarrow NO_3^-$$



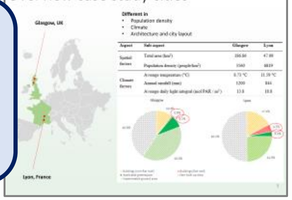
# Insect rearing and micro-scale anaerobic digestion for waste treatment

| Insect rearing | Micro-scale anaerobic digestion |
|---|---|
| • Black soldier fly larvae is fed on food scraps<br>• Larvae can be fed alive<br>• Limited hatching | • Digester tank volumes between 2 and 100 $m^3$<br>• Energy efficient within greenhouses<br>• Comparable biogas yield to large scale |


# Methodology

Obtain data from case cities (Glasgow, Lyon)

Overview case study cities



Climate modelling (energy, water)

Seasonal yield assessments

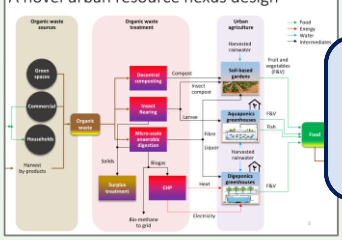
Spatial analysis

Spatial analysis and growing practices

**Simulate food growing process**

Self-sufficiency and net resource requirements

A novel urban resource nexus design



Resource nexus and waste processes

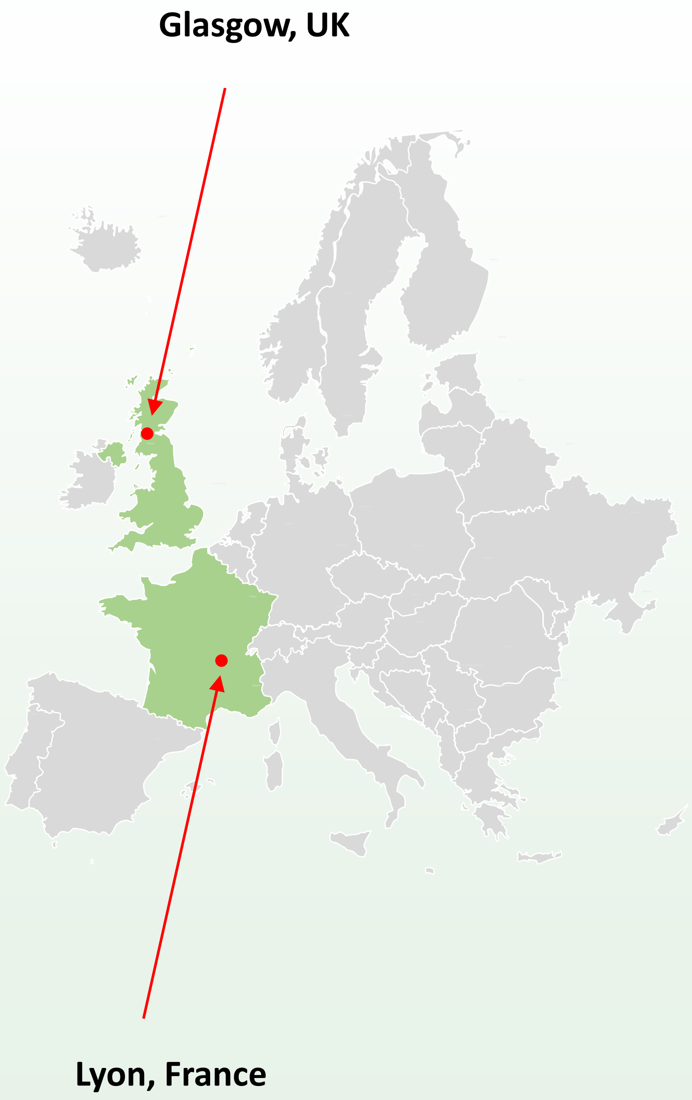
System boundaries and carbon footprints

**Optimize waste integration**

Material flows of system

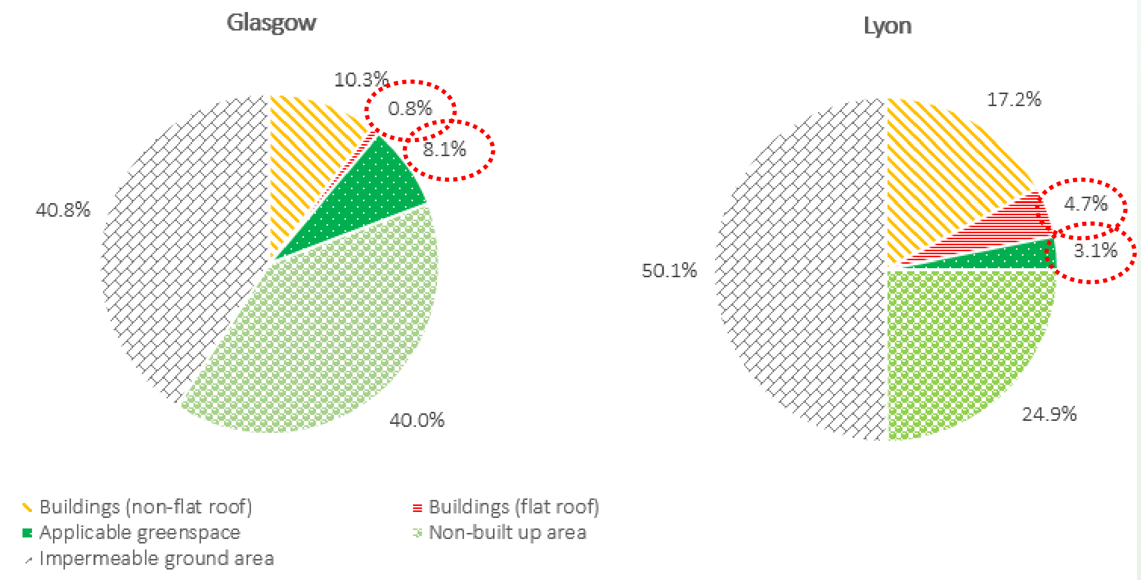
Carbon footprint of overall system

# Overview case study cities




**Different in**
- Population density
- Climate
- Architecture and city layout

| Aspect | Sub-aspect | Glasgow | Lyon |
|---|---|---|---|
| Spatial factors | Total area ($km^2$) | 186.86 | 47.09 |
| | Population density (people/$km^2$) | 3560 | 6819 |
| Climate factors | Average temperature (°C) | 8.73 °C | 11.59 °C |
| | Annual rainfall (mm) | 1200 | 844 |
| | Average daily light integral (mol PAR / $m^2$) | 13.8 | 18.8 |



# Spatial analysis and growing practices

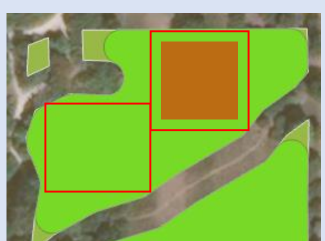
**Spatial analysis**

1 Merging of different data sources

2 Removal infeasible spaces

3 Removal narrow patches

4 Realistic space utilization



**Growing practices**

Open-air gardens

Polytunnels

+

**20%**

**greenhouse adoption level**
on large ground plots….

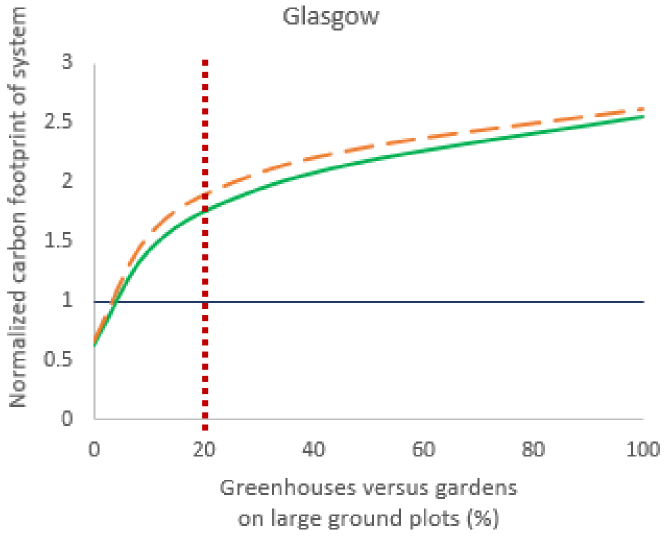
Digeponics greenhouses

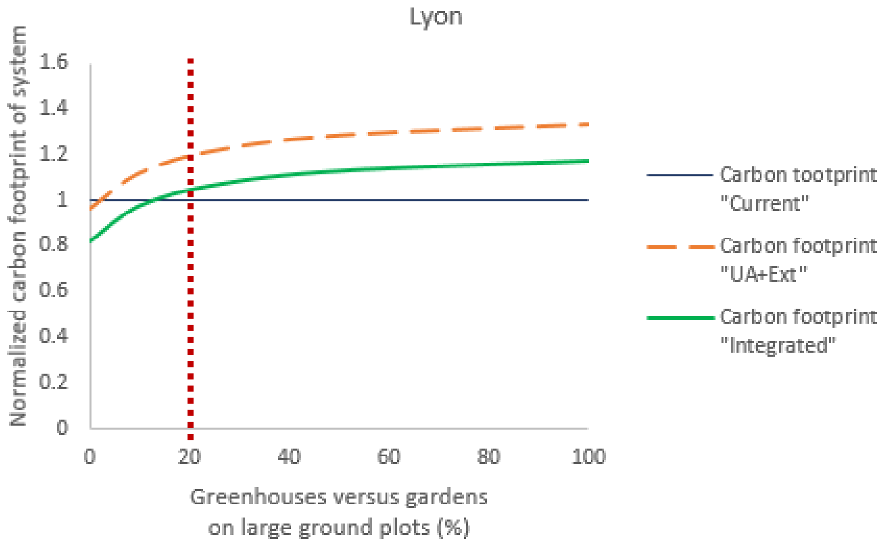
Aquaponics greenhouses

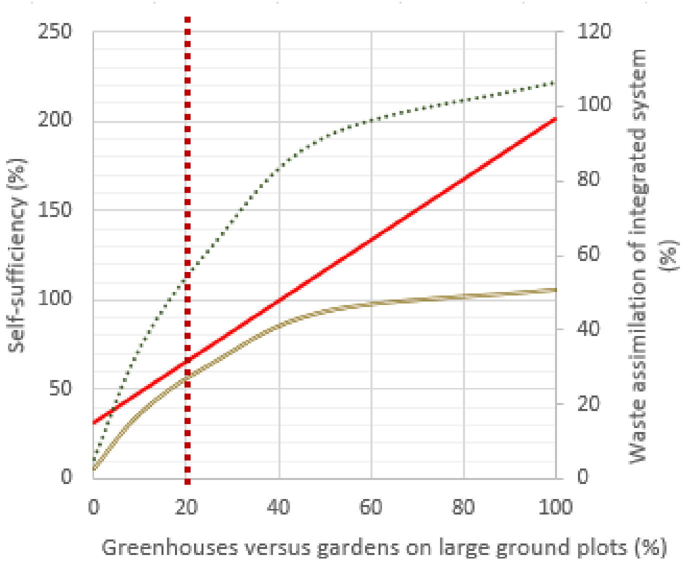
# Results

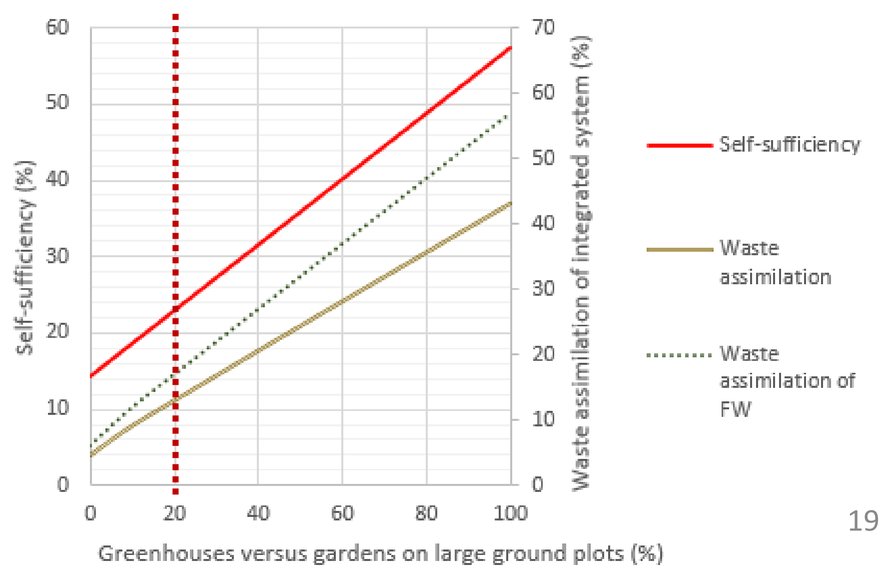
# Impact of greenhouse adoption level

Fix ground greenhouse adaption level at 20%

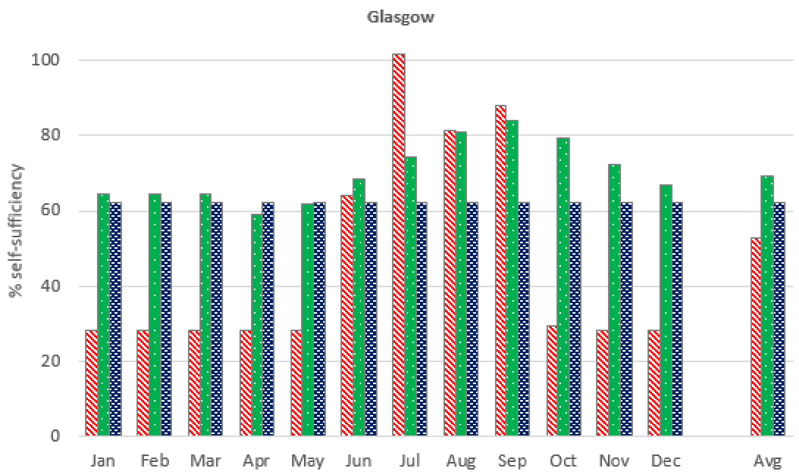


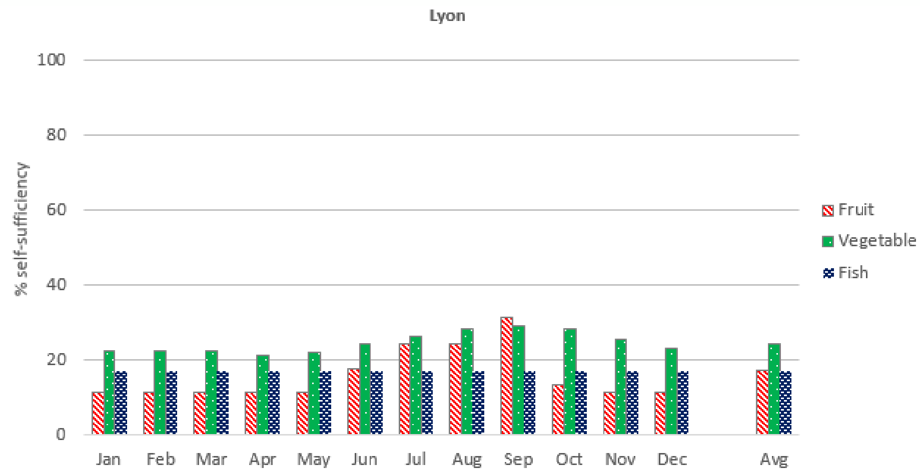



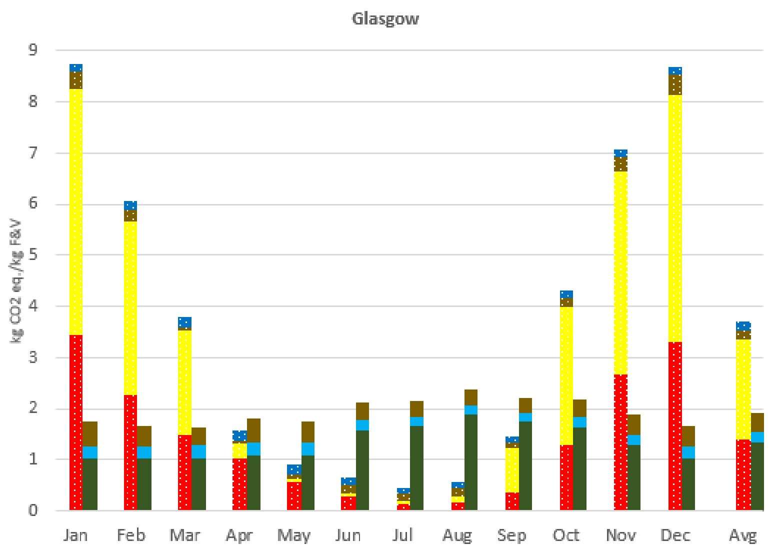



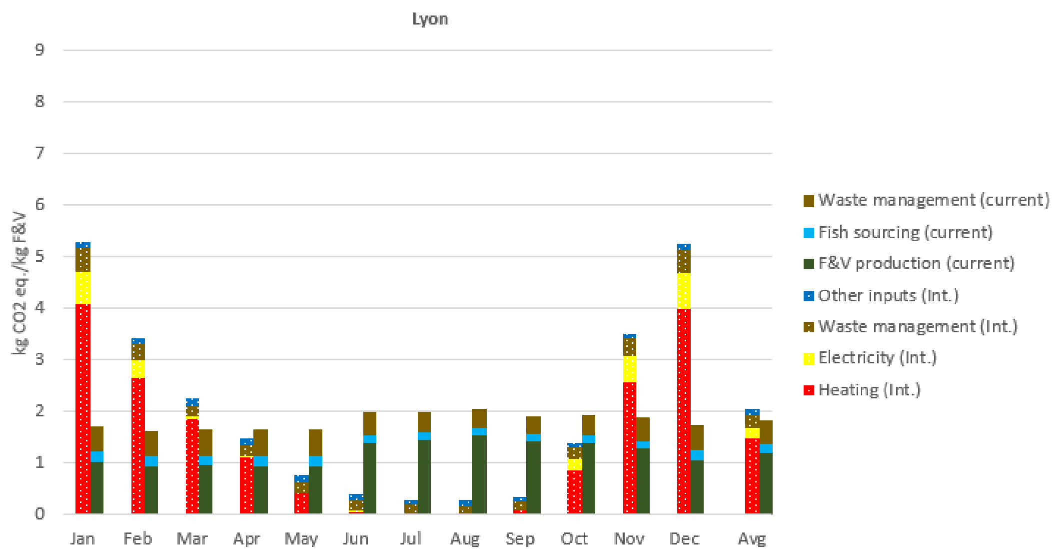



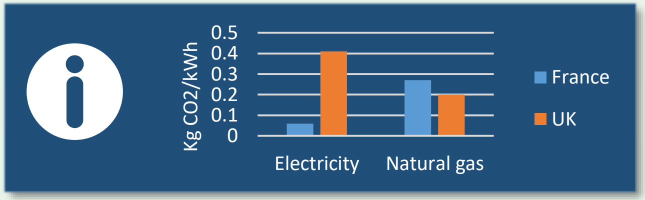
# Self-sufficiency and carbon footprint



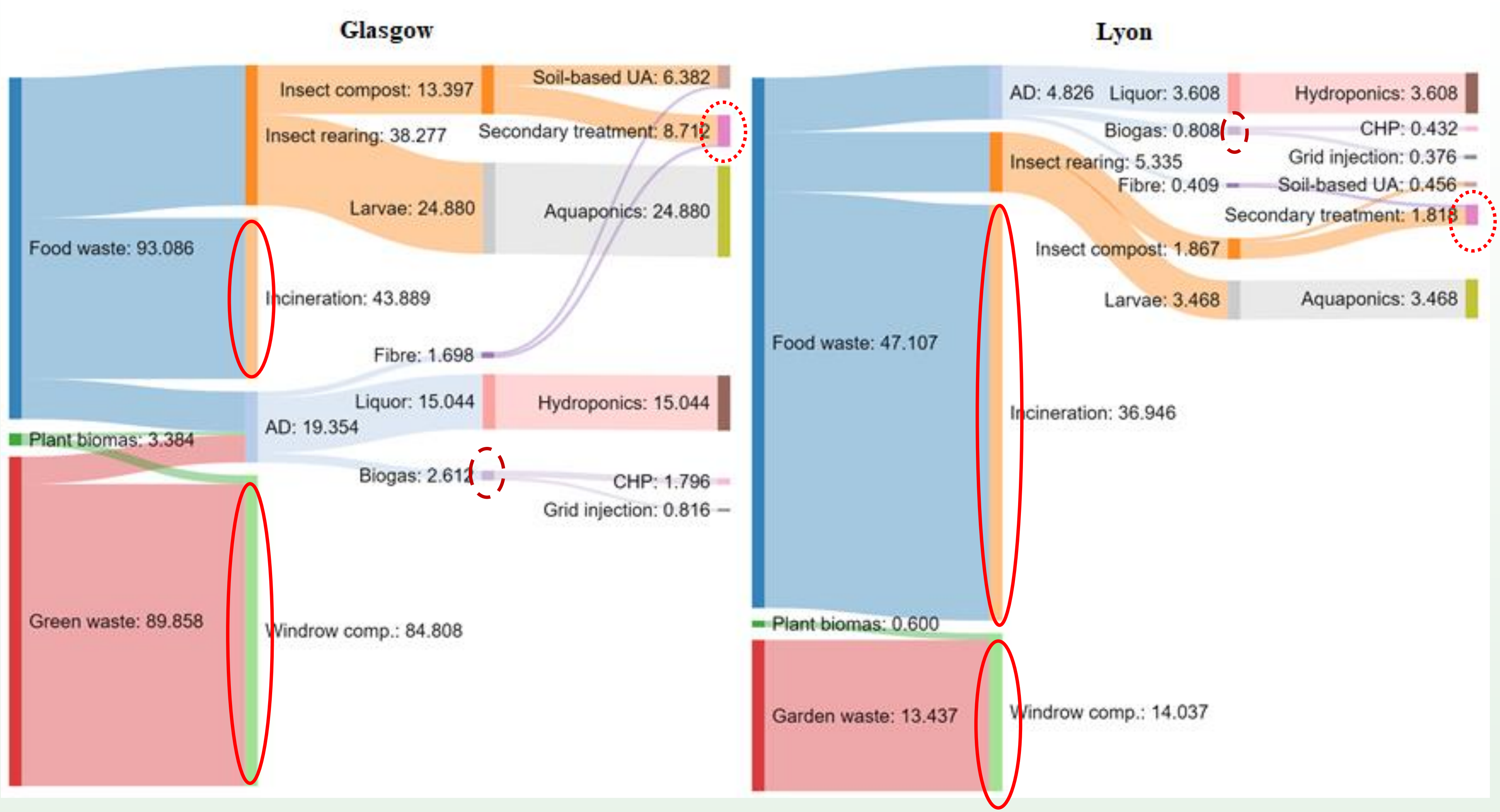



# Optimized material flows



# Water use for different harvesting scenarios

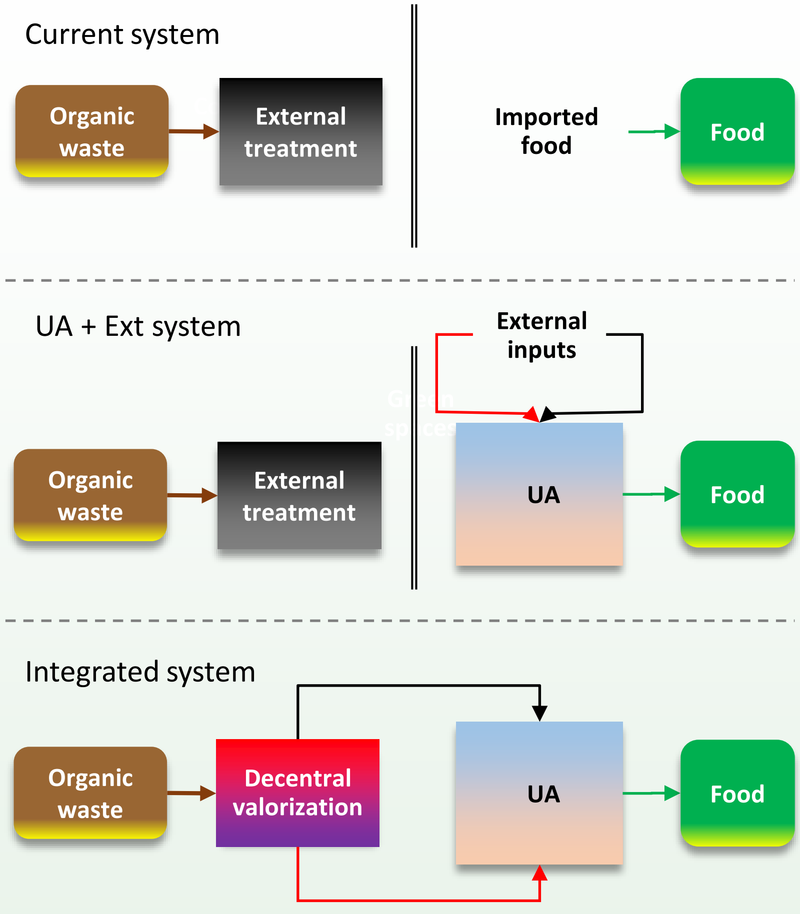
**Table** **Resource metrics for both cities**

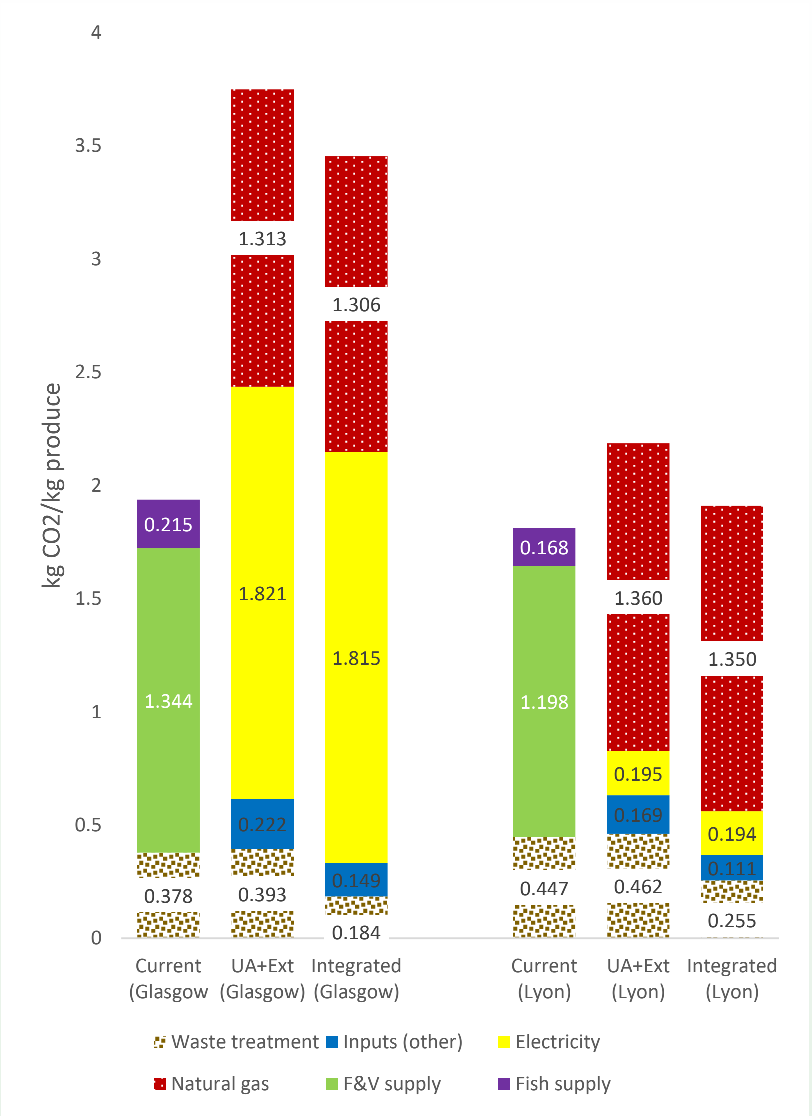
| Aspect | Sub-aspect | Feature | City | | Value |
|---|---|---|---|---|---|
| Water use (l/kg) | Soil-based gardening | No harvesting | Glasgow | | **191.4** |
| | | | Lyon | | **224.1** |
| | | Short-term storage | Glasgow | | **108.9** |
| | | | Lyon | | **144.7** |
| | | Shared reservoir | Glasgow | | **18.8** |
| | | | Lyon | | **69.6** |
| | Hydroponics greenhouses | No harvesting | Glasgow | | **23.3** |
| | | | Lyon | | **28.3** |
| | | Short-term storage | Glasgow | | **1.1** |
| | | | Lyon | | **5.3** |
| | | Shared reservoir | Glasgow | - | **19.3** |
| | | | Lyon | - | **0.3** |

| | | | | |
|---|---|---|---|---|
| Waste integration (%) | Resource recovery | P-recovery | Glasgow | **13.5%** |
| | | | Lyon | **5.5%** |

# Benefit of organic waste valorization #1

UA perspective



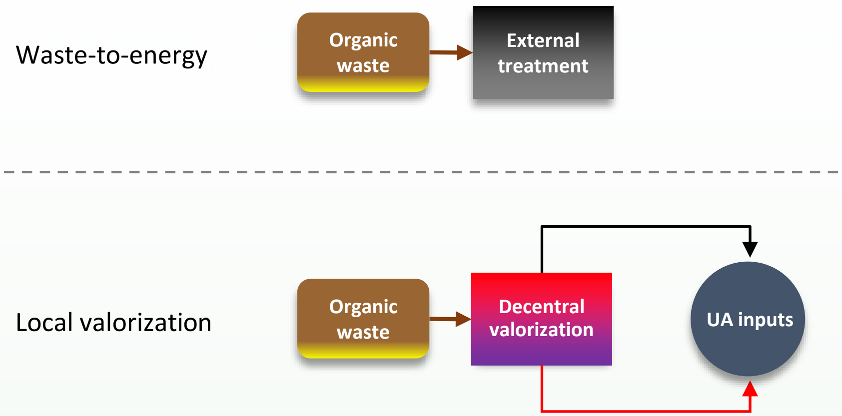




***Question:***
***Does waste integration justify the deployment of UA?***

- Benefit of waste product use small compared to impact of energy inputs

# Benefit of organic waste valorization #2

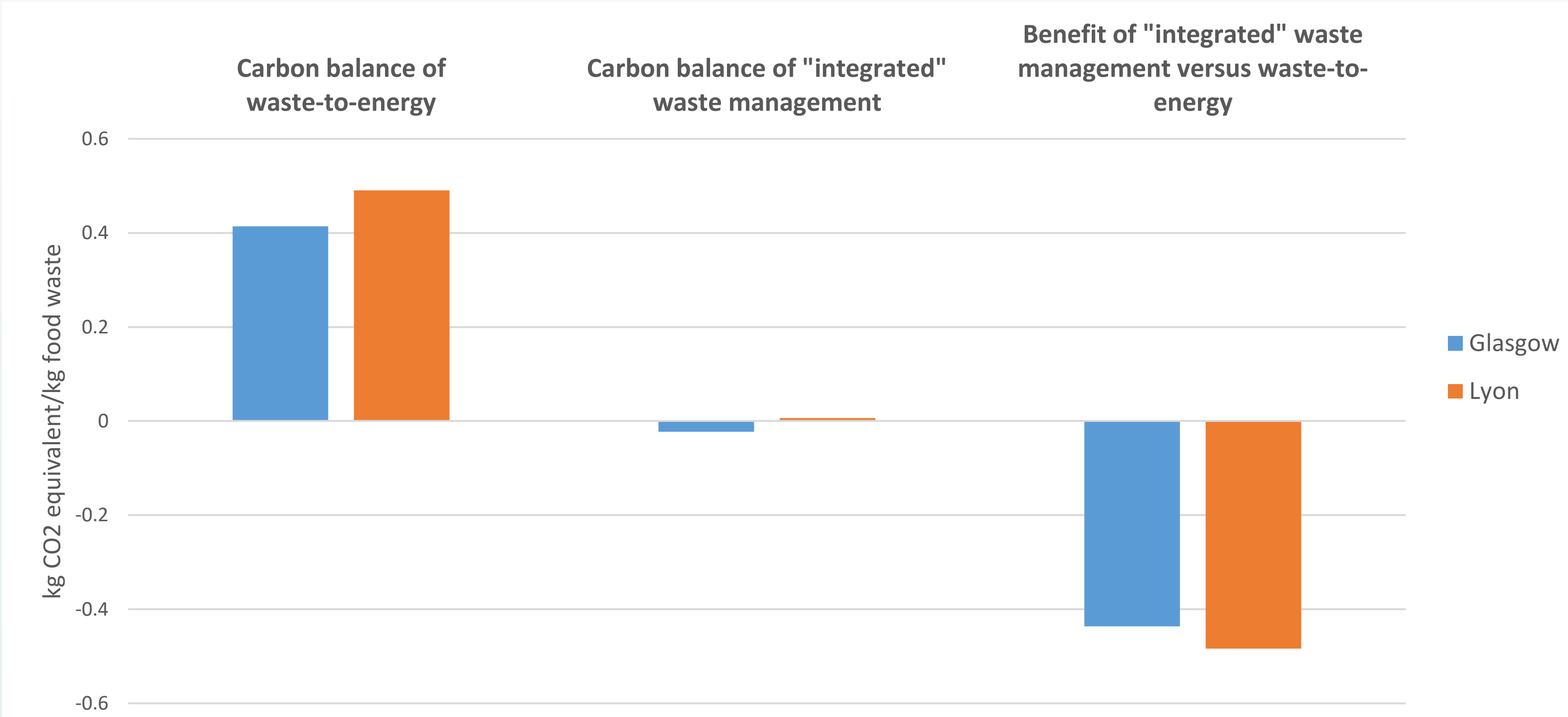
**Waste**
perspective




*Question: If there is a UA-system in place, does it make sense to integrate waste products?*

- Assumption: all waste products assimilated
- Ratio Insect rearing vs. AD higher in Glasgow

> ➢ Significant benefits over waste-to-energy



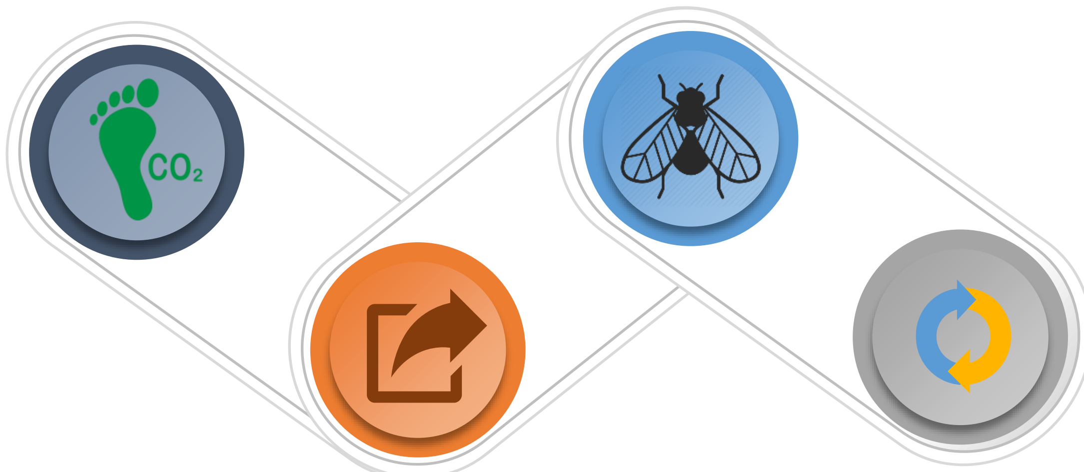
# Key learnings

**System carbon footprint**
Mainly influenced by
I. Greenhouse production level
II. Carbon intensity of electricity grid
III. Climate conditions

➢ Take all into account for decision making

**Live feeding of insect larvae**
for fish production most
promising treatment option

➢ Explore and develop further




**Limited organic waste assimilation**

➢ Explore integration of organic waste with broader scope (e.g. other sinks)
➢ Best to match throughput of local treatment system with local UA input requirements

**No additional resource burden**
- Nutrient, fish feed and water requirements could be fully met
- Similar carbon footprint for limited high-intensity growing and low carbon grid

➢ Increased self-sufficiency possible
➢ Explore policy for scaling up

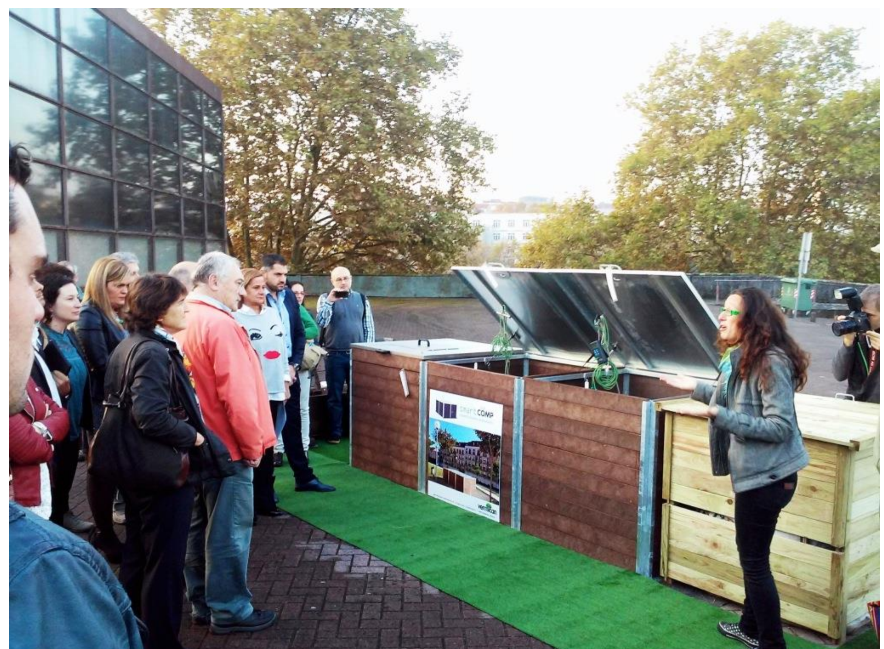
# 2ND PROJECT

Evaluating a fully localised organic waste management system with land application

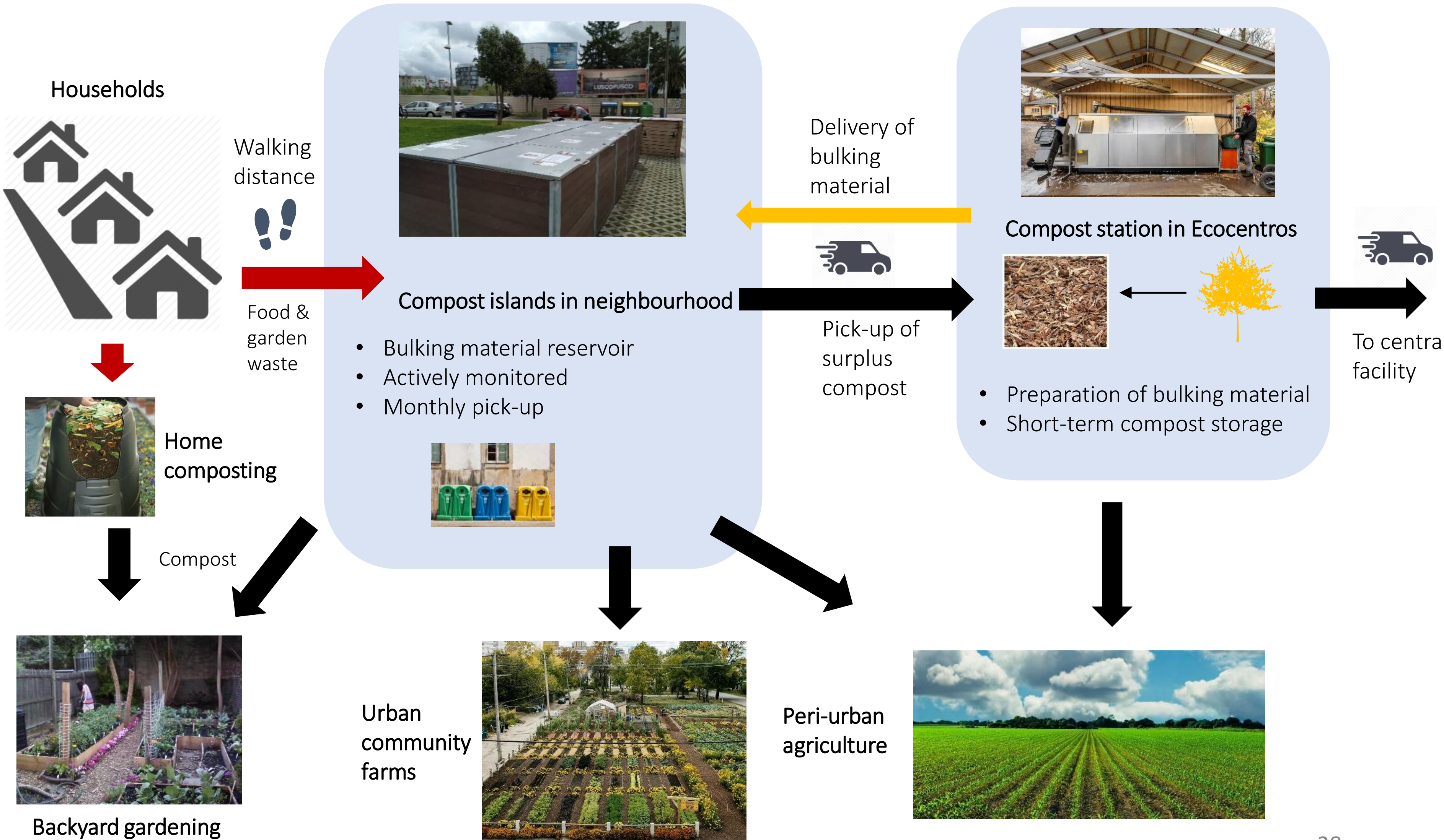
# Inspired by Pontevedra in Galicia, Spain

Europe's first car-free city, 20 year history of policies aiming to reduce car use

Pioneered monitored community composting



# Decentralized composting operations within a municipality



# Overview of different scenarios with collection and land application

| | | | | |
|---|---|---|---|---|
| Scenario |  Basecase |  Centralized anaerobic digestion |  Fully decentralized |  Fully decentralized + urban agriculture |
| Treatment | • Centralized via energy recovery of mixed waste | • Centralized via anaerobic digestion<br>• Biogas to biomethane | • Localized via compost islands or home composting | • Localized via compost islands or home composting |
| Collection and logistics | • Mixed waste (3x week) | • Non-organic mixed waste (1x week) and separate organic (3x week) | • Structure material (weekly)<br>• Surplus compost (monthly) | • Structure material (weekly)<br>• Surplus compost (monthly) |
| Land application | • Ash landfilled | • (Productive) land application, distance 45 km | • Local (*existing* farms and peri-urban fields, home use)<br>• (Produtive) land application, distance 45 km | • Local (*potential* farms and peri-urban fields, home use)<br>• (Produtive) land application, distance 45 km |

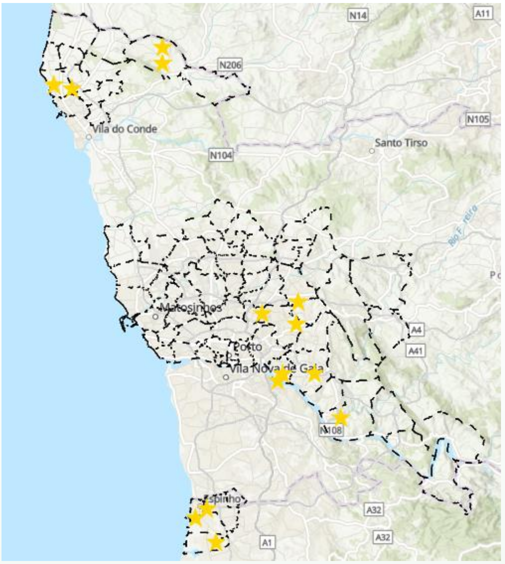
# Initial hypothesis about expected outcomes

**Hypothesis 1:** A fully decentralized model may be more costly but reduces environmental impacts

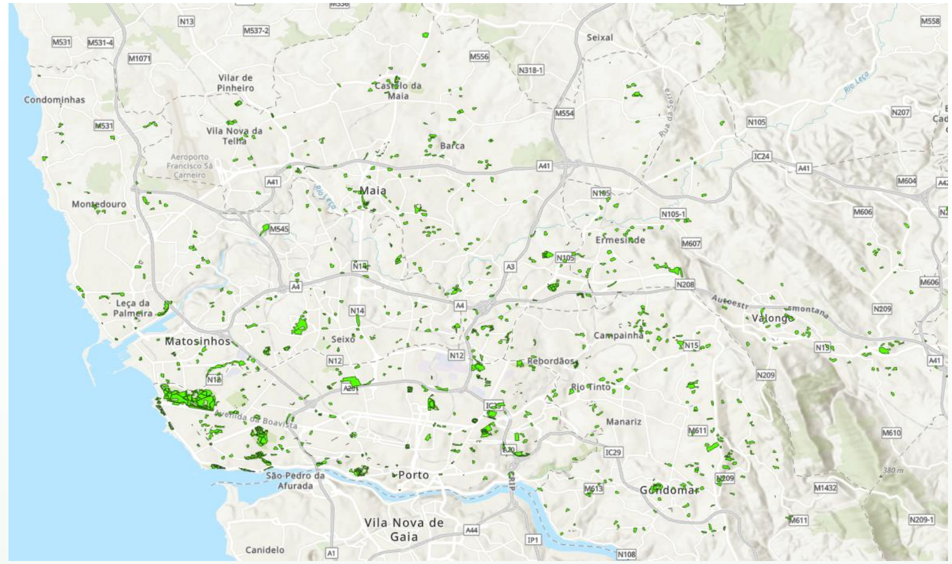
**Hypothesis 2:** Given a limited sink capacity, surplus compost produced incurs high cost when it has to be brought out of town

**Hypothesis 3:** Creating additional urban farms reduces the cost incurred by compost logistics significantly

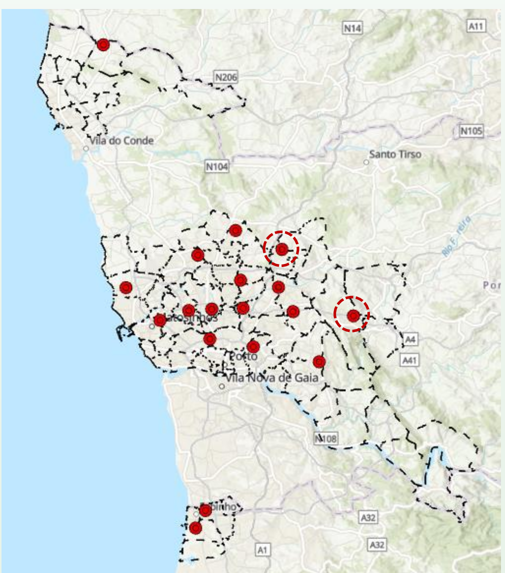
# Spatial analysis inputs



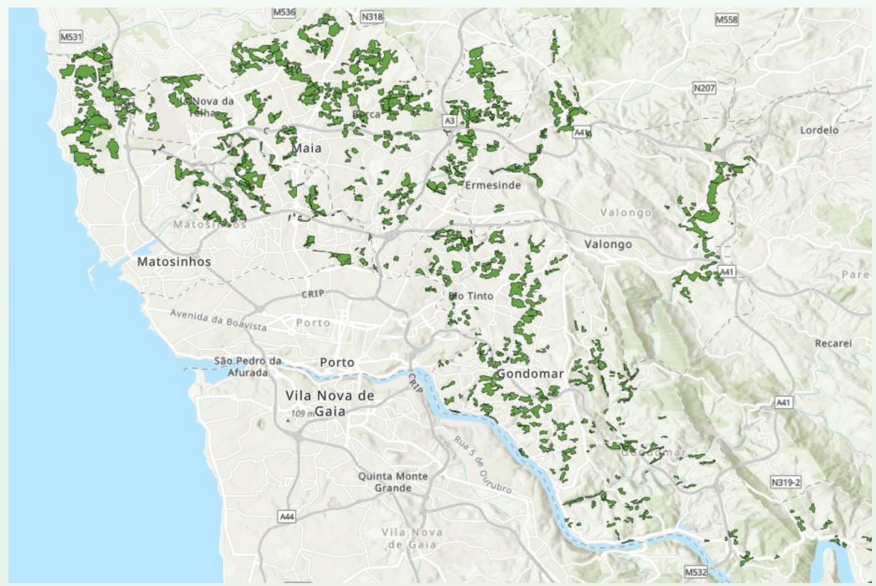

Existing urban farms[1]




Land potentially convertible to urban organic farms




Existing ecocentros serving municipalities

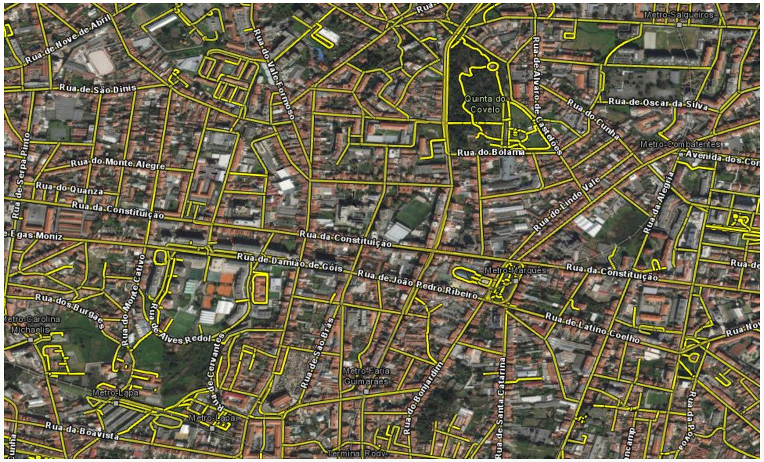



Peri-urban farmland



1 Assessment excludes Vila do Conde in the North-West due to lack of data

# Spatial analysis: location-allocation




**Road network**
To determine walking distances


**Waste generation points**
Each block one point
Generation according to CENSUS and seasons
(around 835,000 inhabitants)

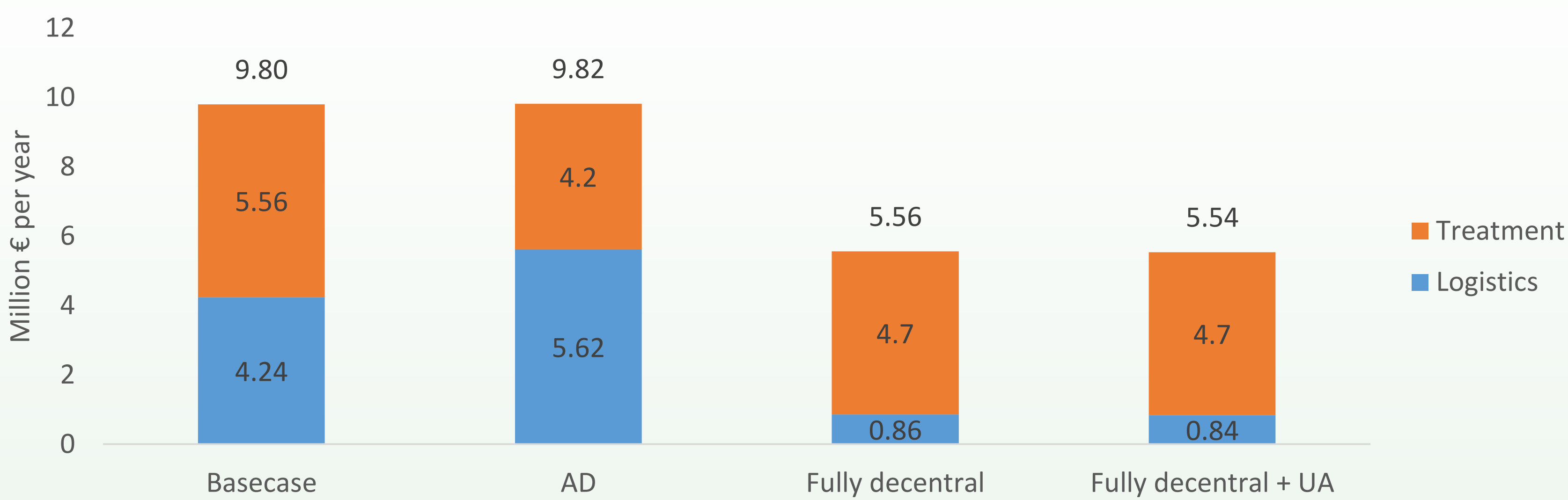

**Locations of compost islands**
Star: chosen as location
Grey: potential site

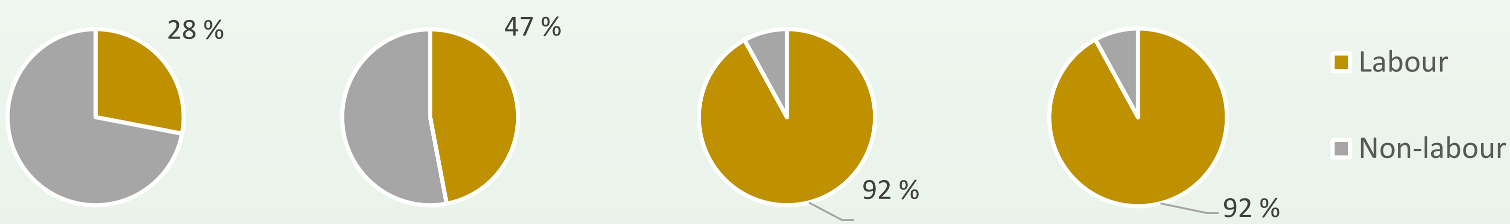
# Results

# Economic assessment – metropolitan area of Porto

**TENTATIVE RESULTS**

Annual cost for each scenario[1]




| | | | |
|---|---|---|---|
| **TBC** | **1.19 M € (21.4% of cost)** | **1.31 M € (23.6% of cost)** | Economic potential through value of compost |

1 Includes kitchen, household and compost bin provision and annualised investment cost

# Environmental assessment – metropolitan area of Porto


**Assumptions for basecase:**

- Electricity grid with 80% renewables (2030 pledge)
- Home composting process 10% optimized vs literature
- Surplus without productive use, i.e. only land application
- Households >200m from island do home composting

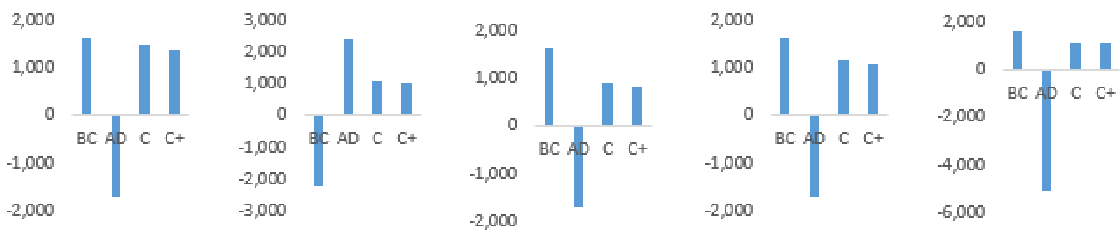
*Note: Further benefits of compost not considered*

**TENTATIVE RESULTS**

# Influence of assumptions on emissions

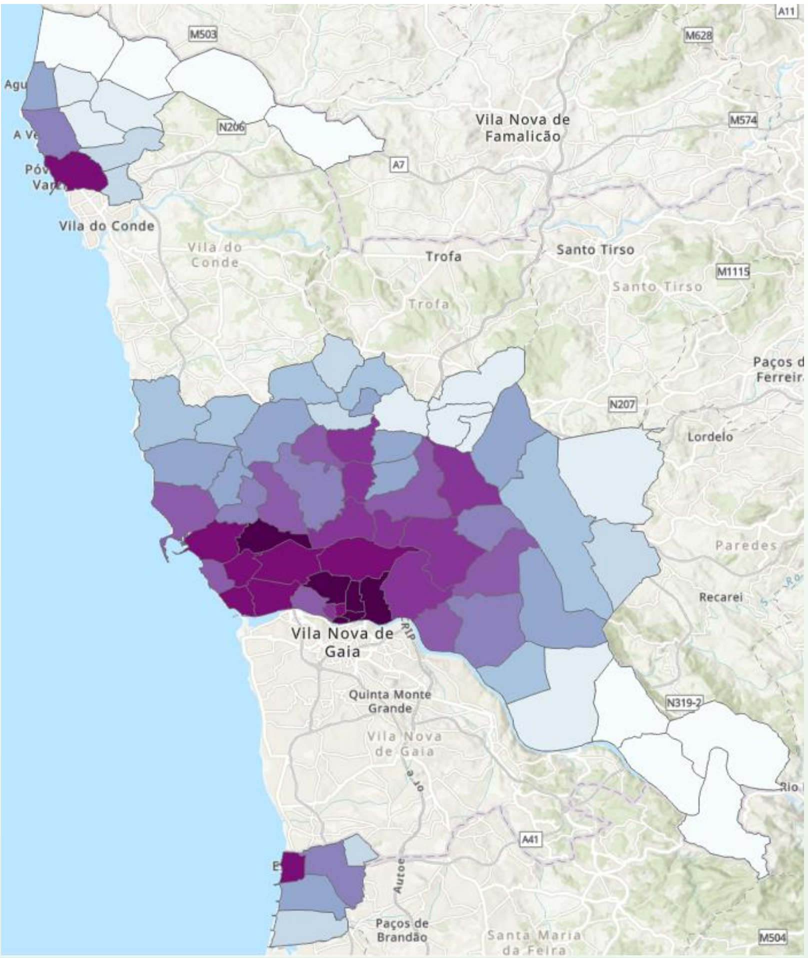
| Scenario | Aspect | Basecase[1] | No increased renewables | Optimized home composting 50% | >200m compost island distance | 100% productive surplus use |
|---|---|---|---|---|---|---|
| Incineration (basecase) | Waste collection | | | | | |
| | Waste treatment | | | | | |
| | **Total** | **1,609** | **-2,196** | **1,609** | **1,609** | **1,609** |
| Anaerobic digestion | Waste collection | | | | | |
| | Waste treatment | | | | | |
| | Biomethane credits | | | | | |
| | Digestate (application, fertilizer, transport) | | | | | |
| | **Total** | **-1,681** | **2,406** | **-1,681** | **-1,681** | **-5,083** |
| Compost scenario | Compost surplus logistics | | | | | |
| | Structure material logistics | | | | | |
| | Compost process emissions | | | | | |
| | Fertilizer replacement benefits | | | | | |
| | Compost application emissions | | | | | |
| | **Total** | **1,465** | **1,065** | **912** | **1,144** | **1,129** |
| Compost scenario (+UA) | Compost surplus logistics | | | | | |
| | Structure material logistics | | | | | |
| | Compost process emissions | | | | | |
| | Fertilizer replacement benefits | | | | | |
| | Compost application emissions | | | | | |
| | **Total** | **1,386** | **985** | **833** | **1,061** | **1,125** |

Unit: tonne CO2 / year

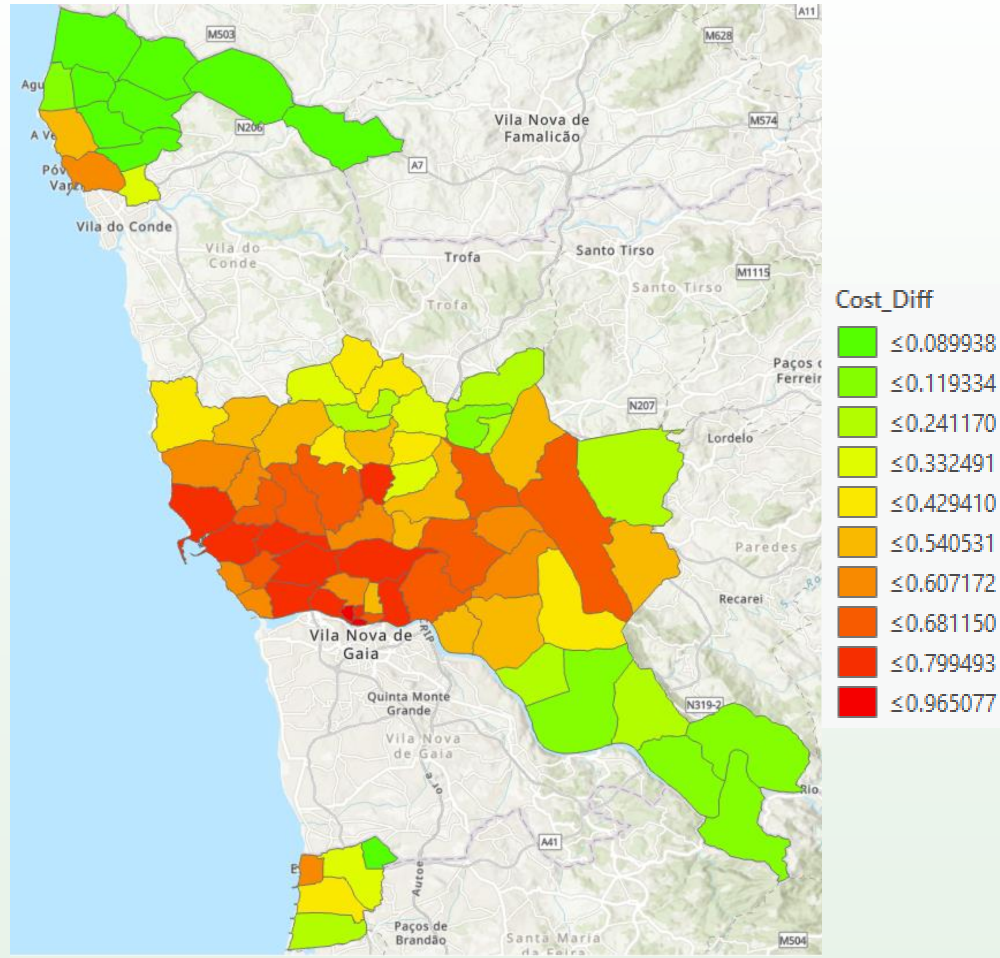



**TENTATIVE RESULTS**

# Spatially sensitive results by district – cost difference to basecase



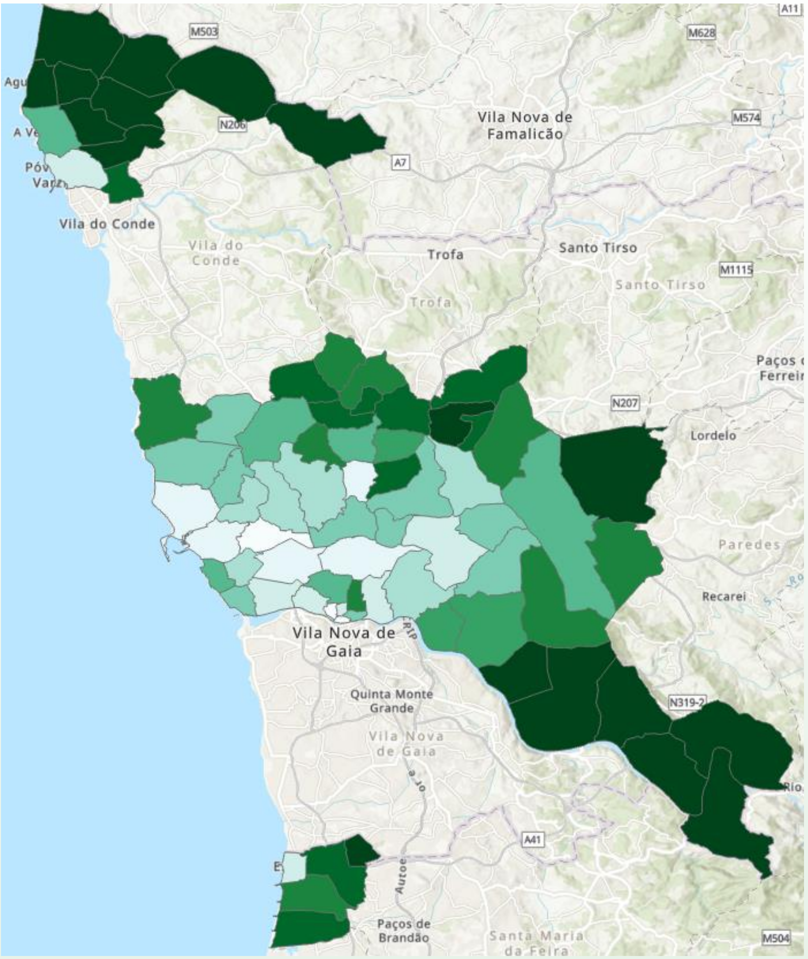

Population density
(darker equals higher)



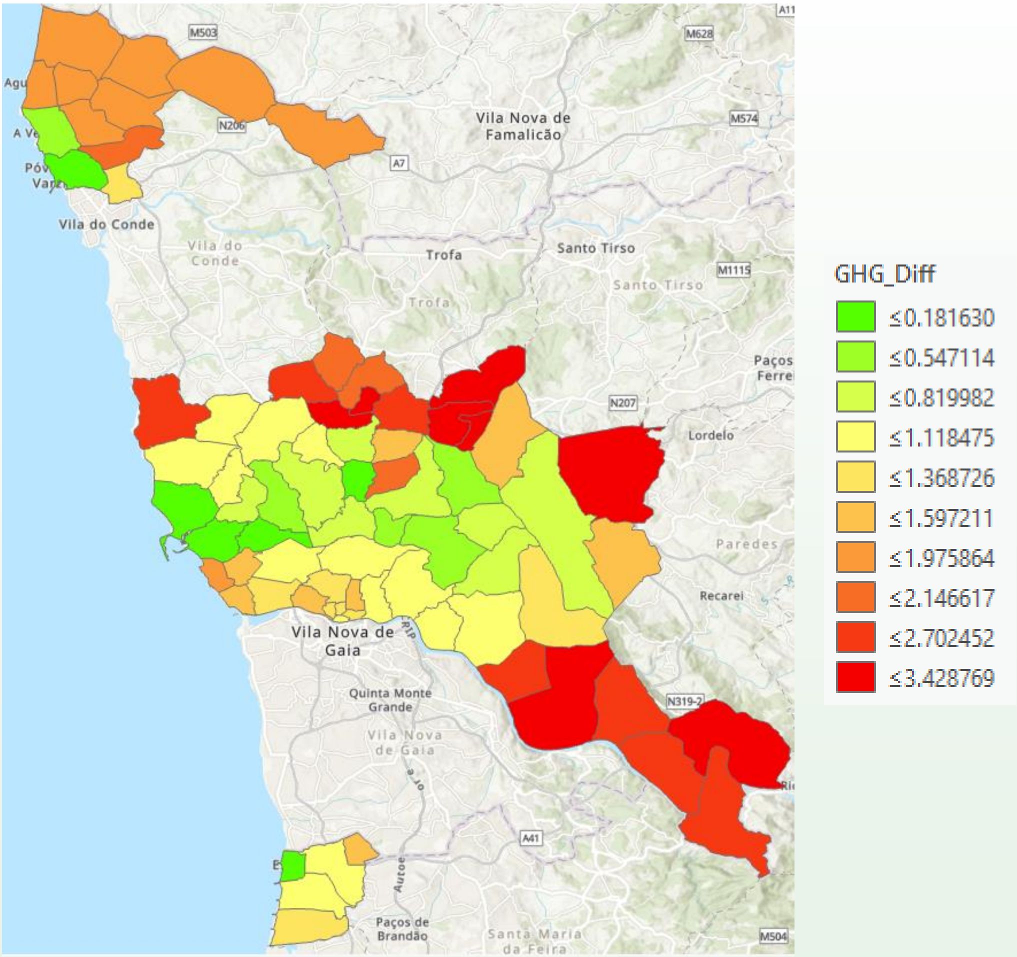

Percentage cost difference to basecase

**TENTATIVE RESULTS**

# Spatially sensitive results by district – GHG emissions difference to basecase[1]




Rate of home composting
(darker = higher)




Percentage GHG emissions difference to basecase

**TENTATIVE RESULTS**

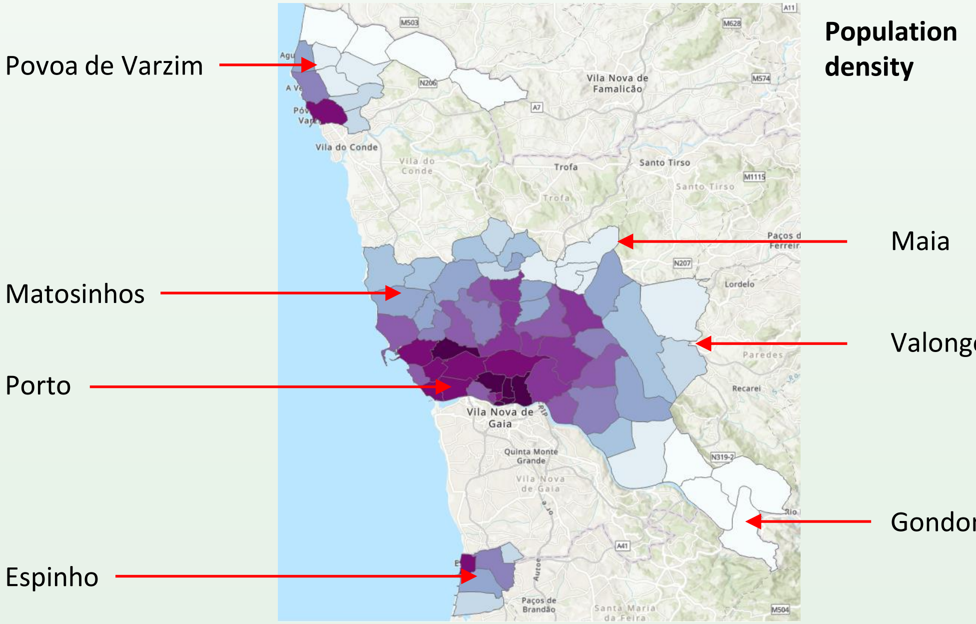


1 Excludes compost use outside city boundaries to show spatial differences, total emissions lower than basecase

# Local compost use and generated surplus

**TENTATIVE RESULTS**

| **Municipality** | Item / Unit | compost surplus (current) % | compost surplus (UA+) % | Land to UA conversion required to assimilate all compost | Land to UA conversion possible | Sink gap |
|---|---|---|---|---|---|---|
| Espinho | | 50.6% | 28.4% | 0.5% | 2.4% | -1.8% |
| Gondomar | | 11.3% | 9.2% | 0.5% | 0.2% | 0.3% |
| Maia | | 14.8% | 10.5% | 0.7% | 0.3% | 0.4% |
| Matosinhos | | 54.7% | 48.2% | 1.6% | 0.3% | 1.3% |
| Porto | | 89.5% | 73.1% | 3.3% | 0.6% | 2.7% |
| Povoa de Varzim | | 74.0% | 62.6% | 0.3% | 0.2% | 0.1% |
| Valongo | | 40.8% | 29.5% | 0.5% | 0.2% | 0.3% |



# Key learnings

**Increased urban farming does not change outcome substantially**

The collection of surplus compost and its distribution only contribute a small amount to the overall cost

**GHG emissions dependency on compost practices and use**

Home composting with poor monitoring and non-productive land application make composting less sensible

**Centralized treatment more costly**

Non-labour expenses much lower for decentralized small-scale technology

**Limited sink potential in metropolitan area**

Even with peri-urban agriculture too much waste would be generated for productive use within the wider wide area (for studied region)

**TENTATIVE RESULTS**

# FUTURE WORK

# Global and facility scale assessments

**Global assessment**

**Questions:**
- For which regions is circular UA particular interesting?
- Depending on location, which growing and waste practices should be implemented for an optimum balance between productivity and carbon footprint?

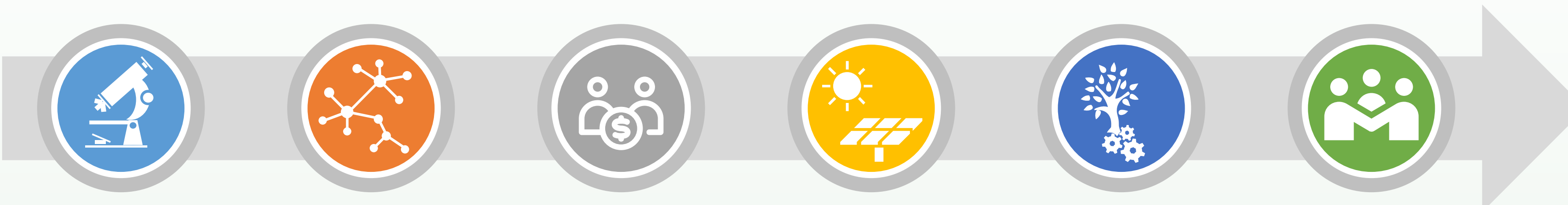
**Facility scale assessment**

**Questions:**
- Which symbiotic waste integration pathways are the most promising?
- What can a city expect if they scale up a specific approach?

Sharing of ideas and collaboration desired

# KEY MESSAGES

# How to make the most of combining UA and localized OW valorization



**Evaluate trade-off**
High monthly self-sufficiency <> resource intensive growing practices

→ seasonal crops and reduced winter intensity

**Mind the gap**
Limited sink potential

→ decentralization schemes in combination with local UA projects

**Support practitioners**
Novel combinations promising (e.g. Insect rearing + aquaponics)

→ need to be further developed

**Be aware of grid developments**
Renewable grids favor UA and localized waste management

**Ensure productive sink access**
Productive land application is imperative
= resilient and nutrient-rich soils

**Work with the community**
Good composting and waste sortation practices
= more environmental benefits

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