Environomic optimal design and synthesis of energy conversion systems in urban areas

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ÉCOLE POLYTECHNIQUE
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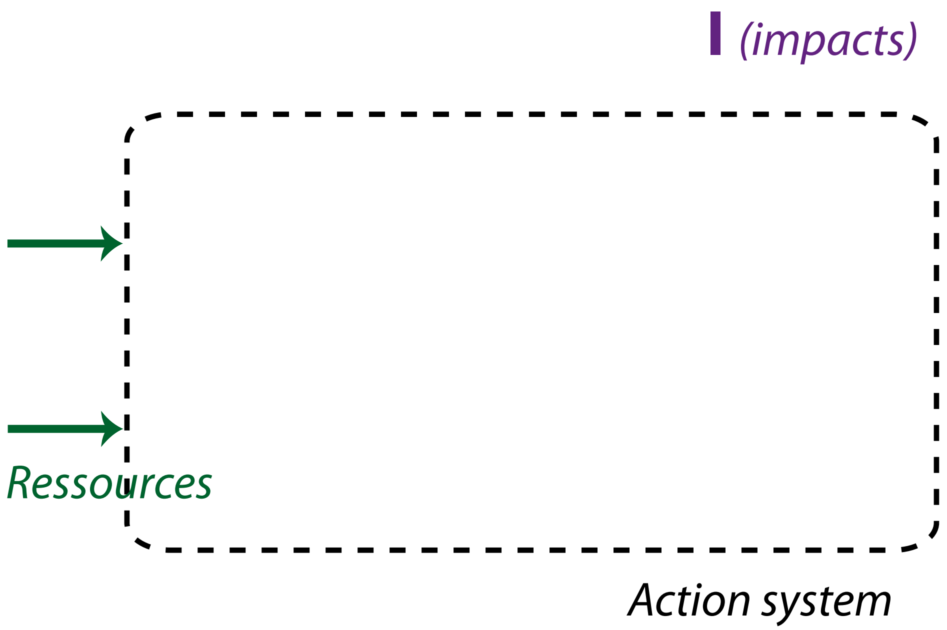
Context

- Industrial ecology
  - Mitigate environmental impacts and resource usage



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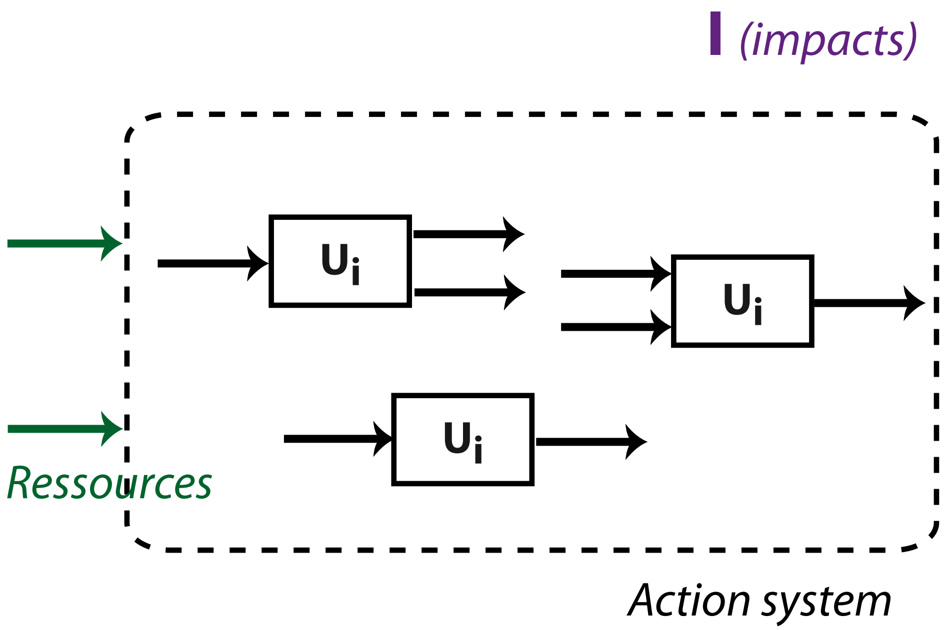
  - Process design techniques for industrial symbioses
    - Extended flowsheet considering action system[1]



1: Gerber L., et al., Computer Aided Chemical Engineering 29, 2011

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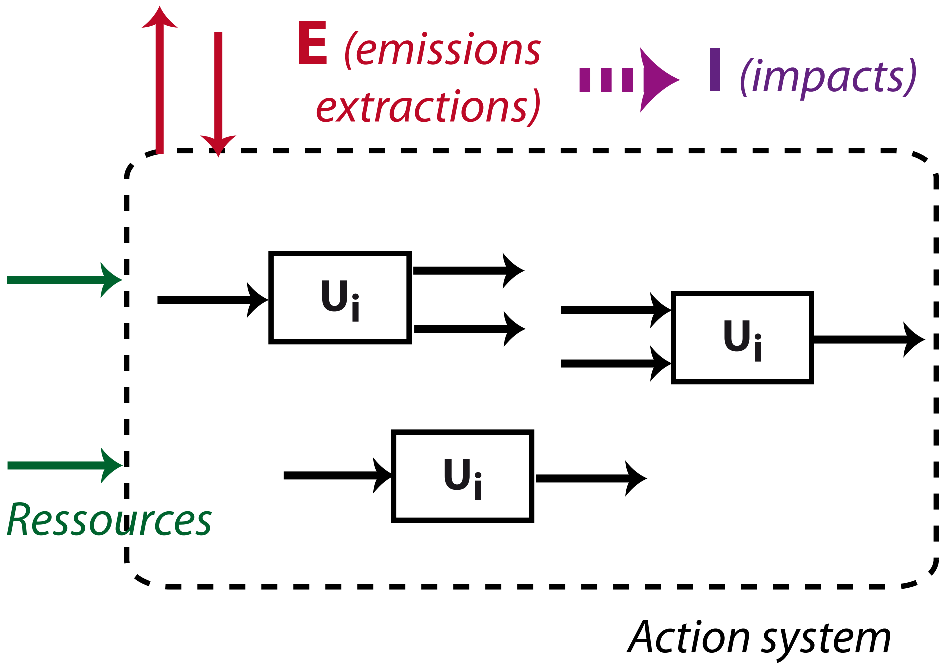
- Integration of LCA in process systems design
  - LCI linked with process flowsheet[2]



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Context

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  - Mitigate environmental impacts and resource usage
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    - Extended flowsheet considering action system[1]
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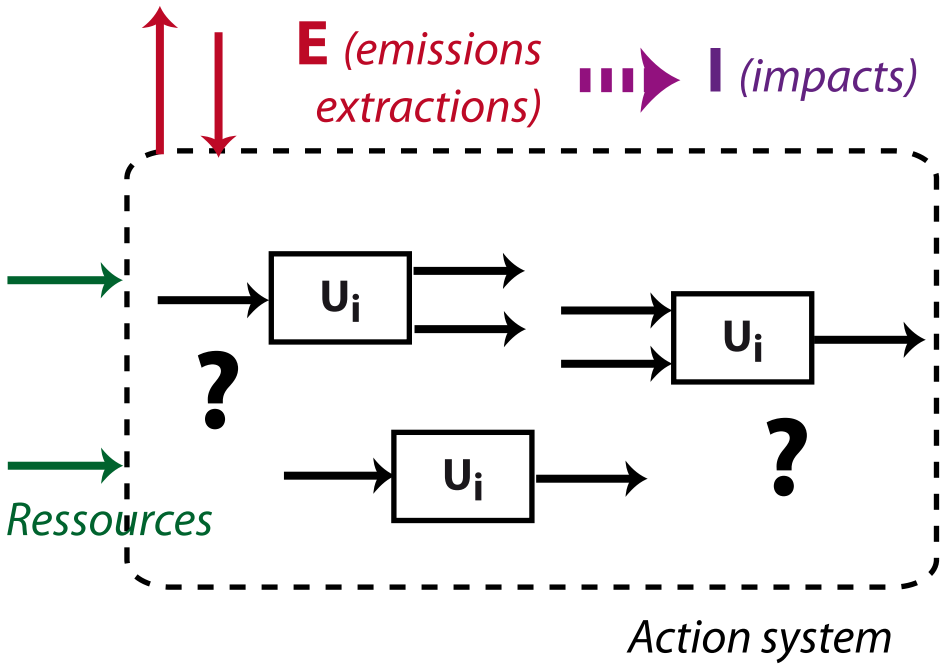
  - LCI linked with process flowsheet[2]
- Environomic design and synthesis of conversion chains combining 2 approaches
  - Eco-Industrial parks, Urban systems



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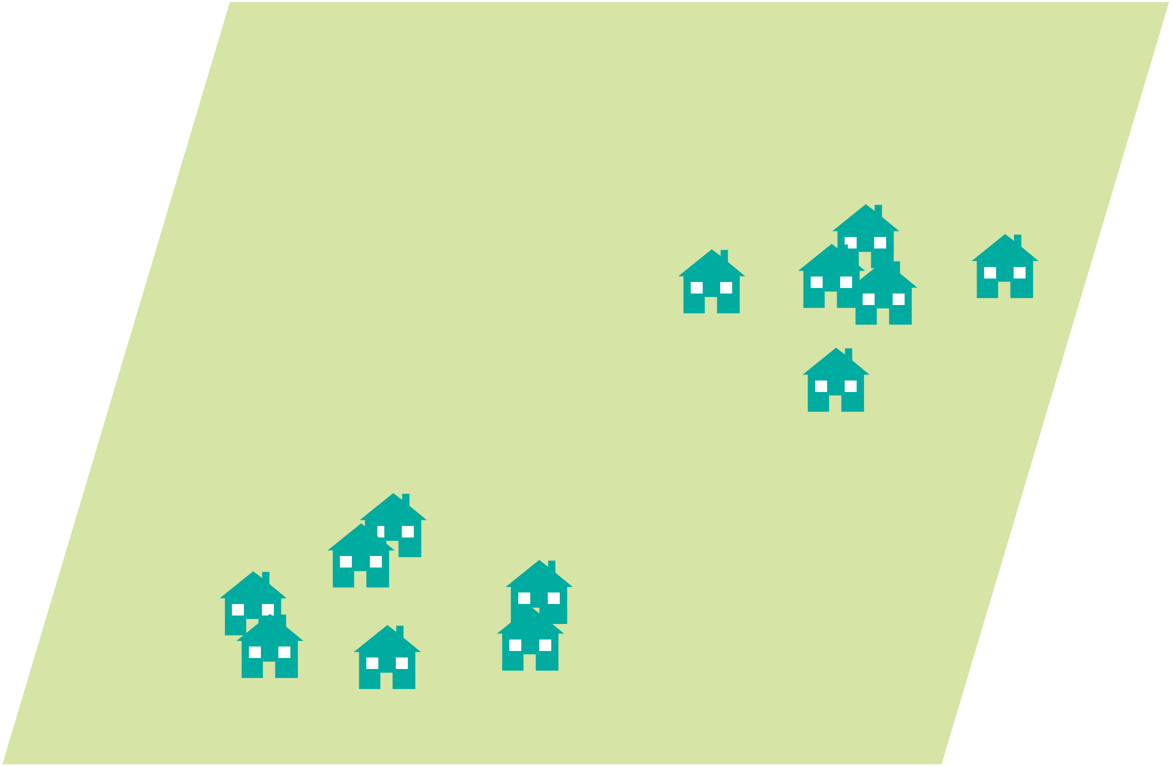

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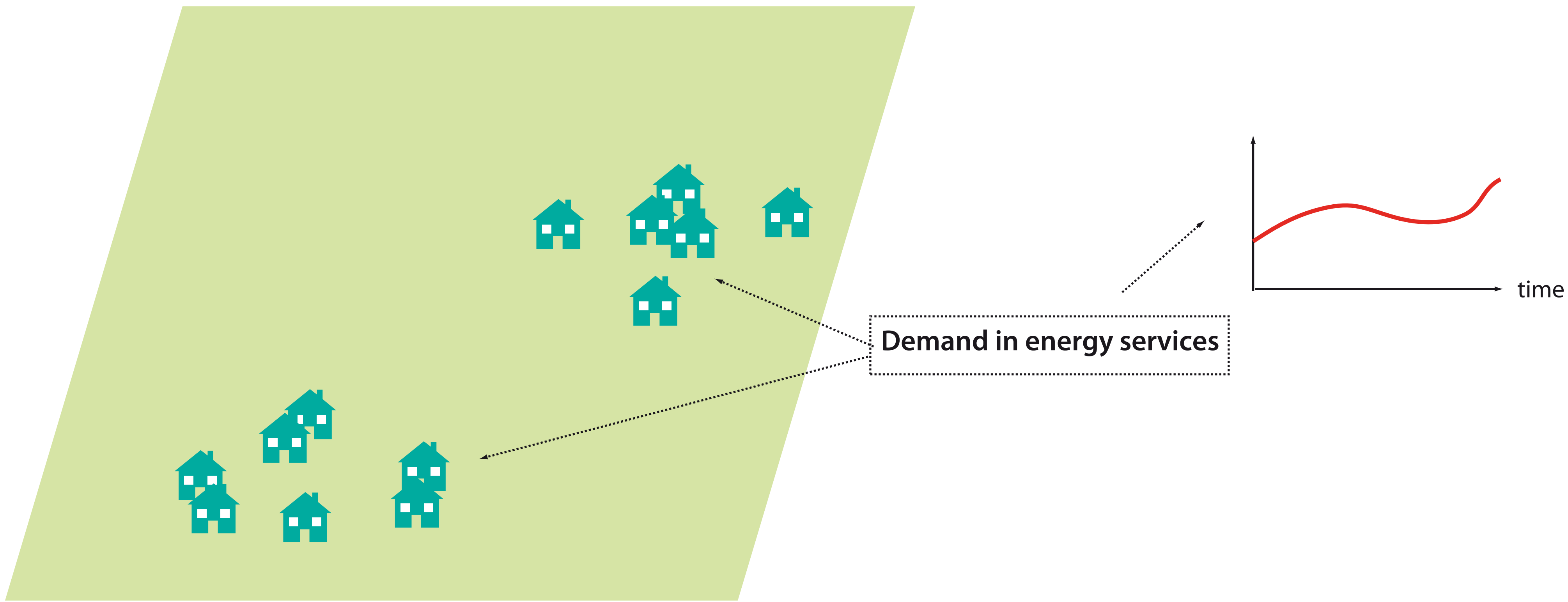

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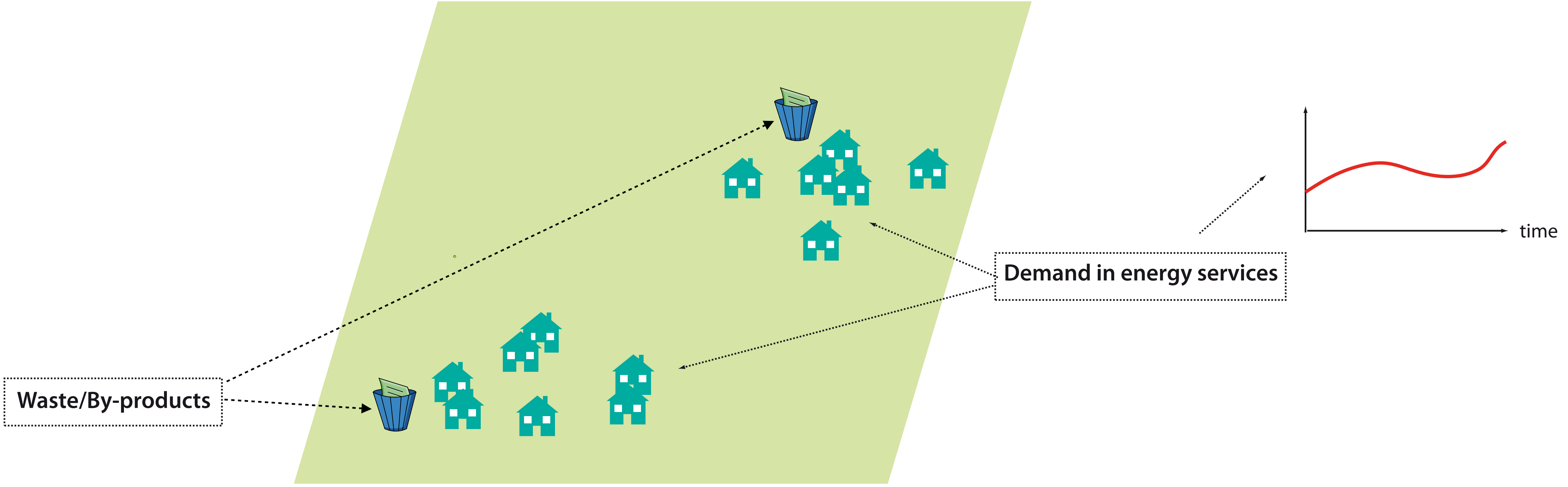

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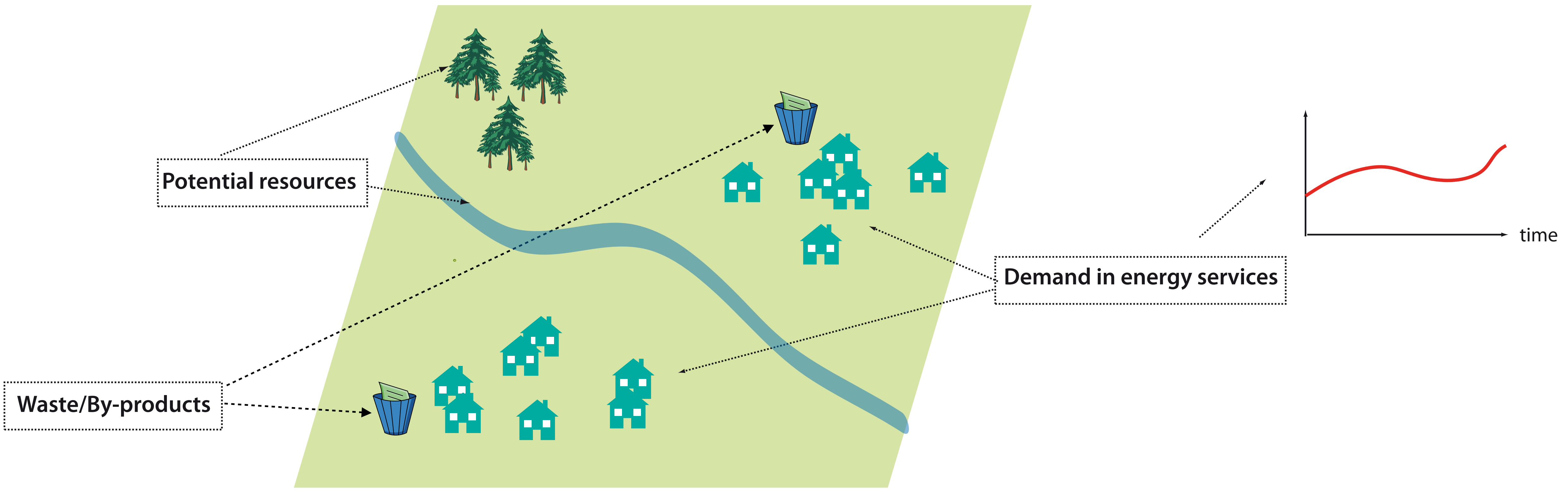

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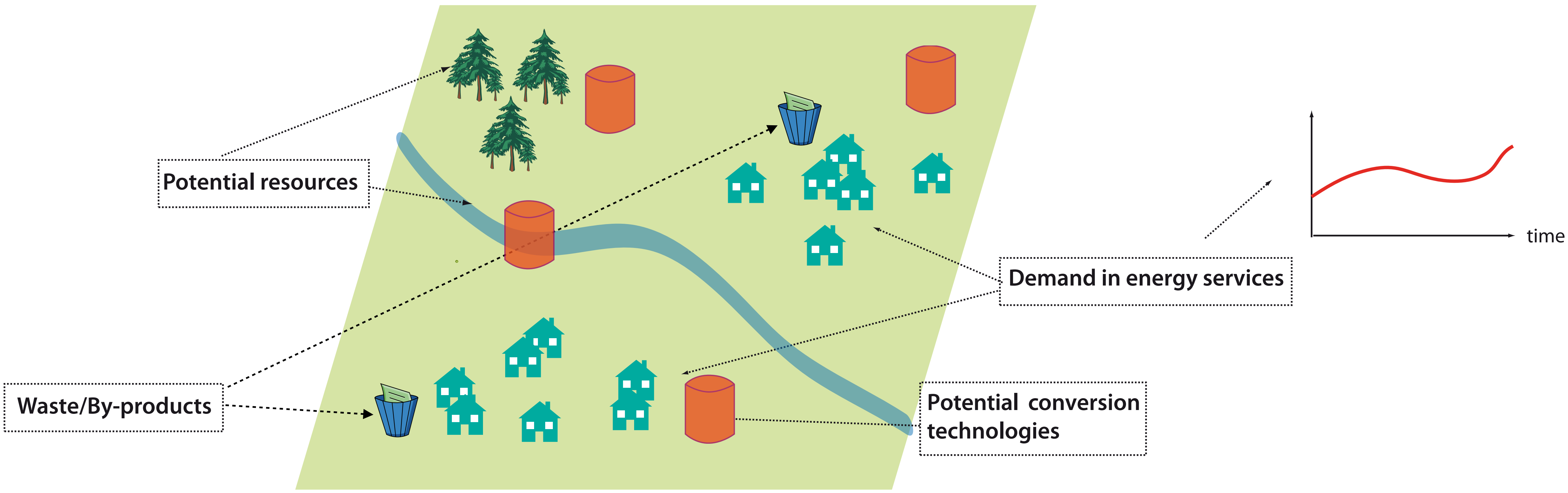

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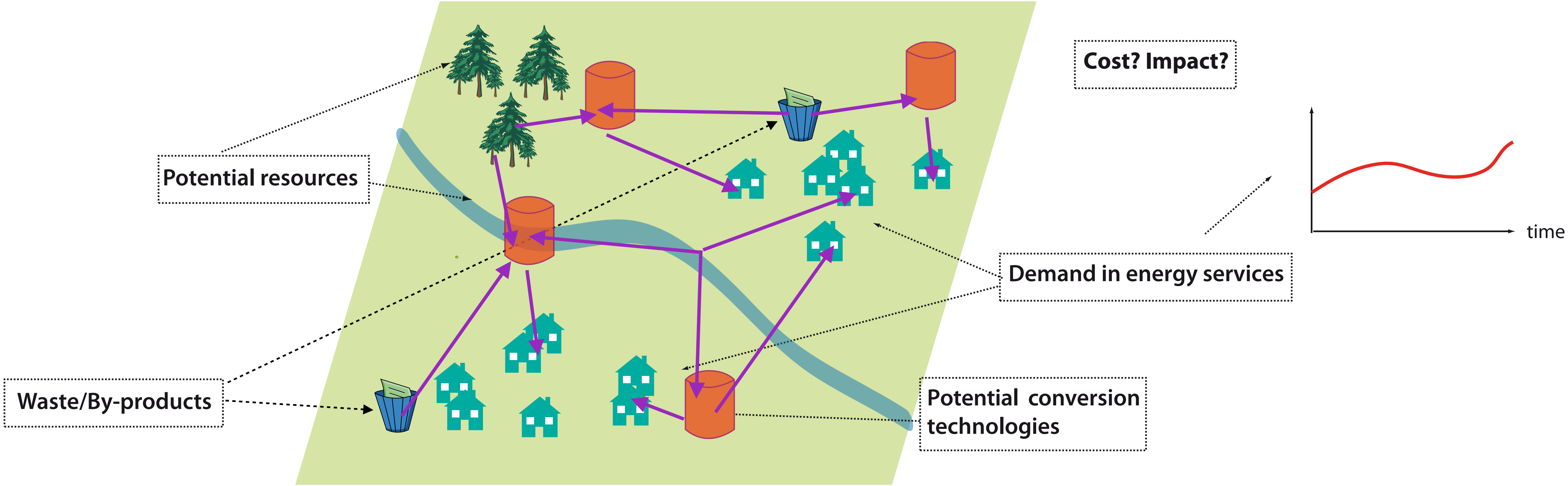
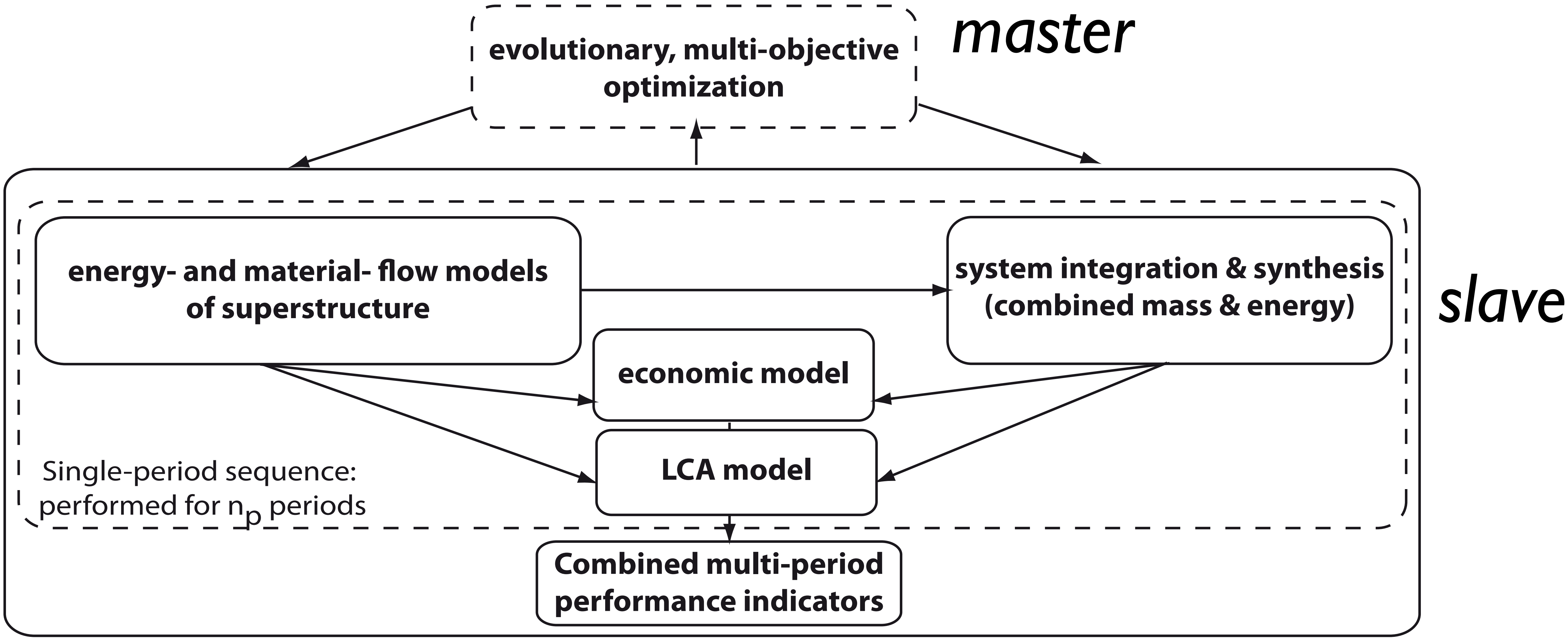


  - Environomic optimal synthesis of conversion chains
    - Superstructure generation
    - Optimization problem formulation

Computational framework

- 2-step decomposition of optimization problem



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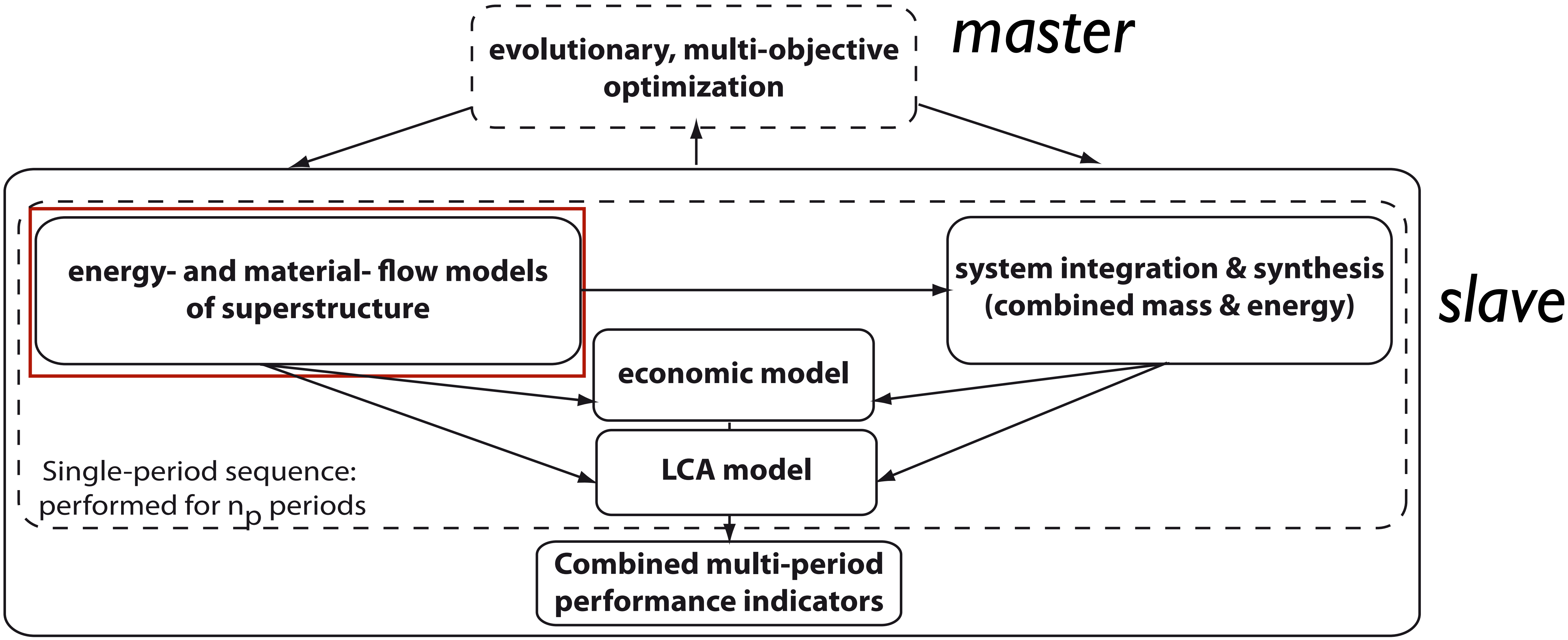

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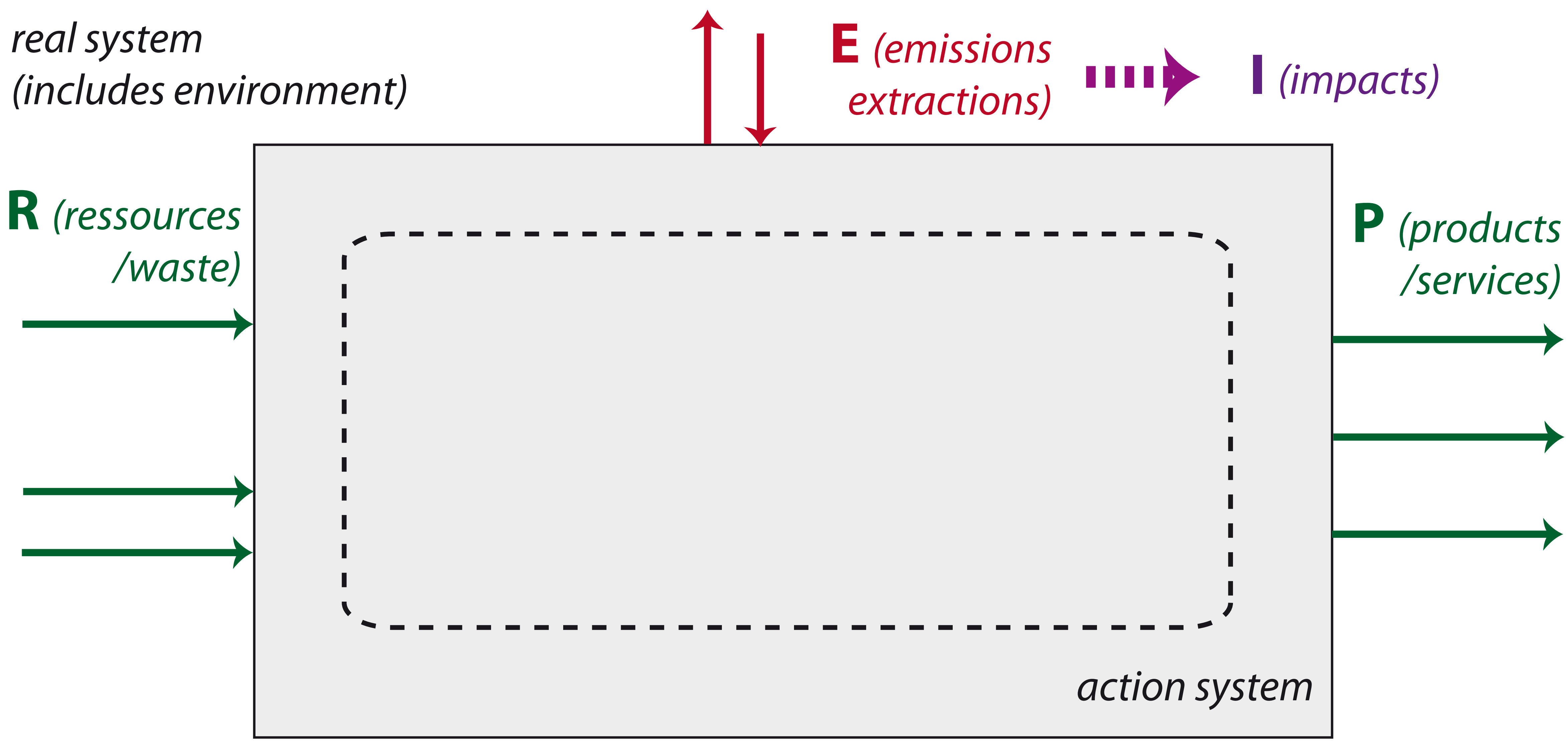

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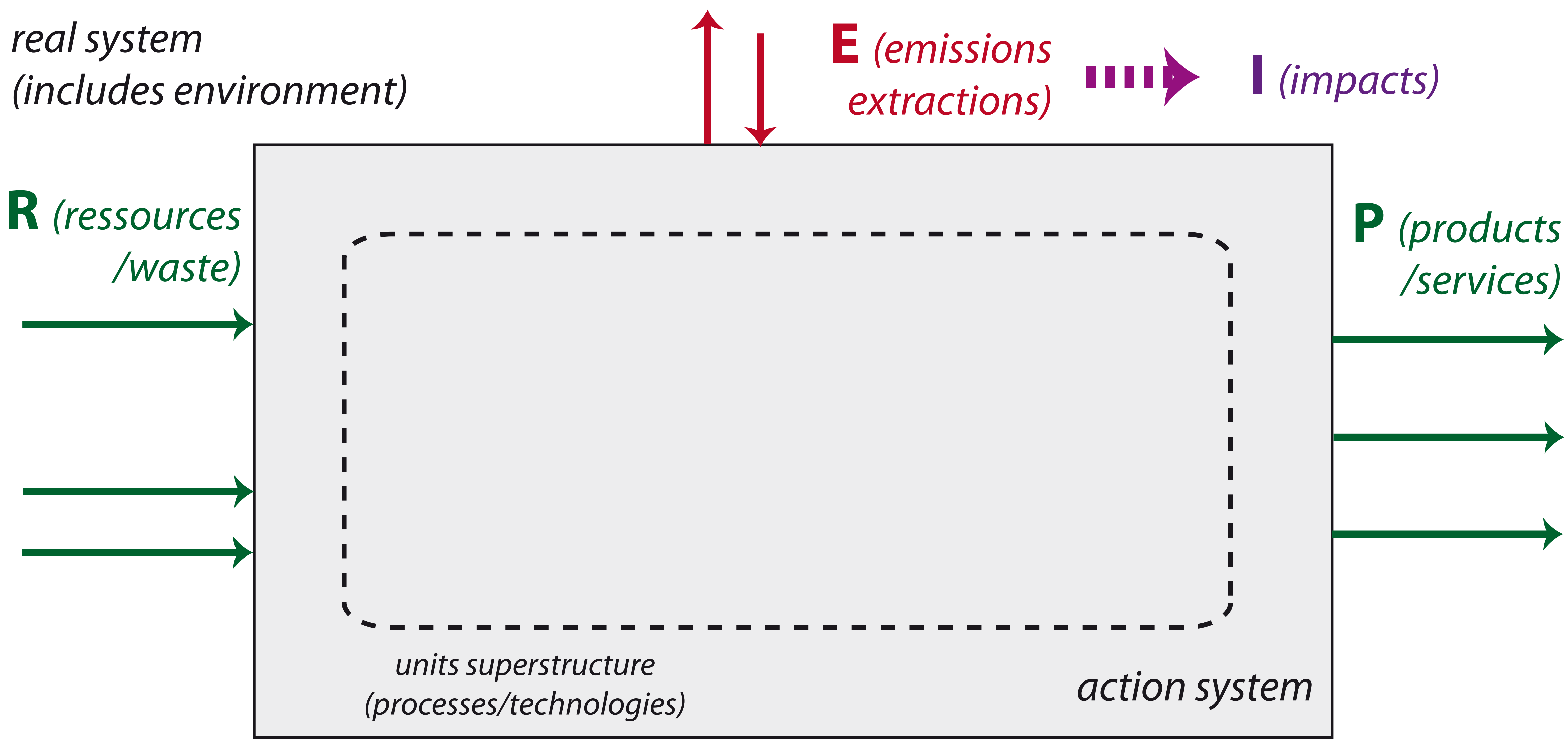
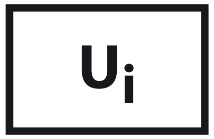
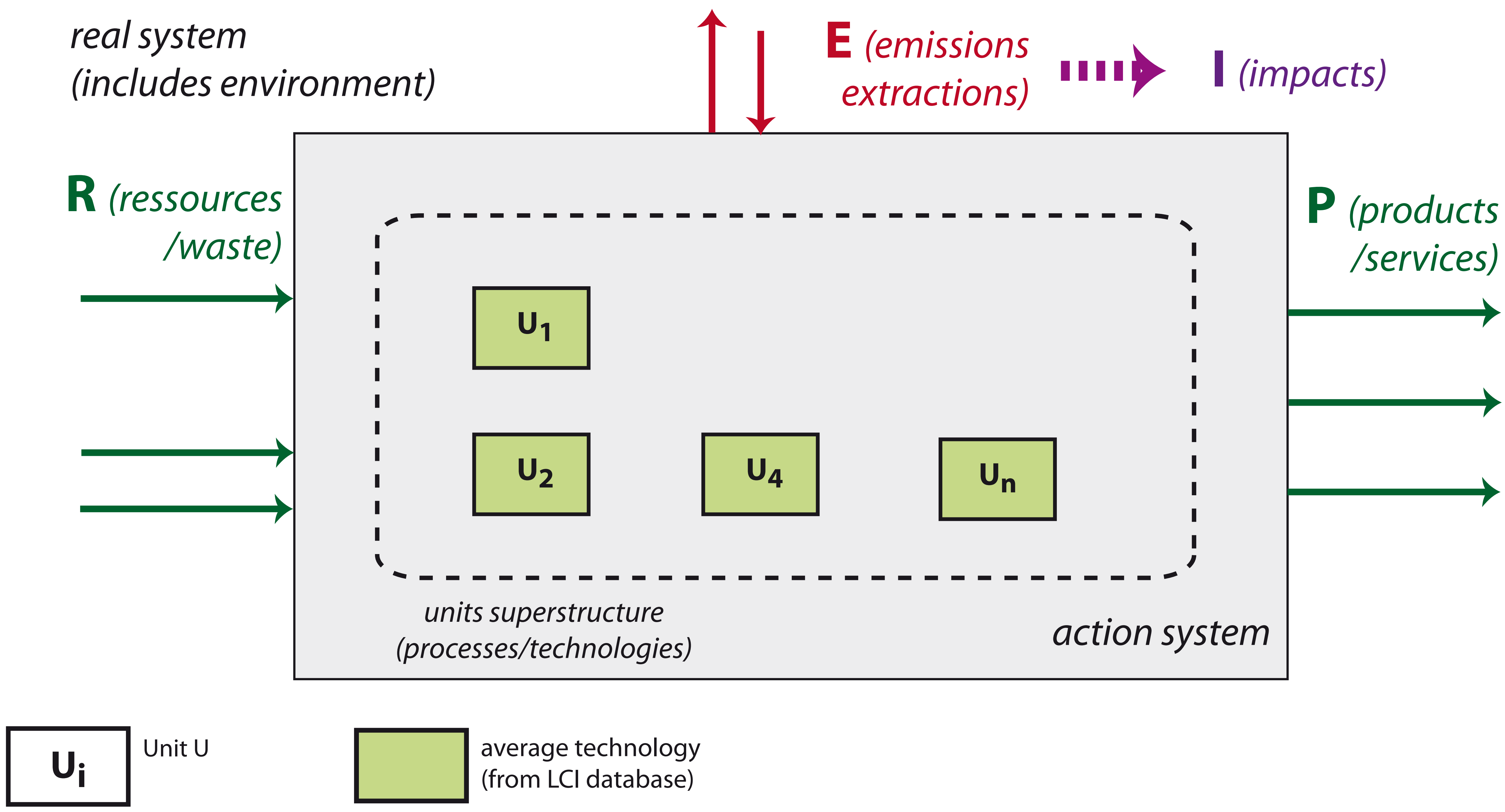




Unit U

Superstructure generation



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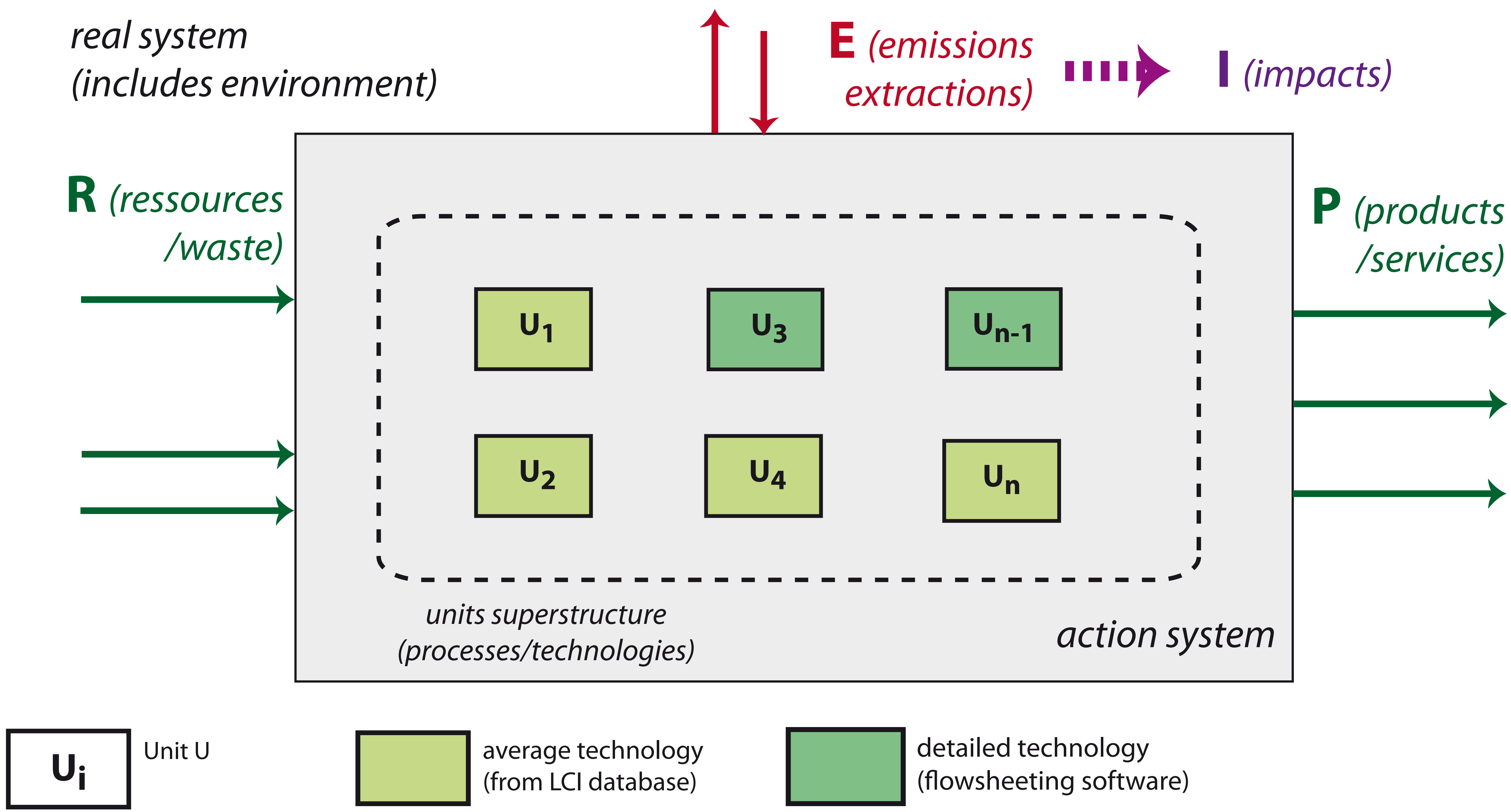

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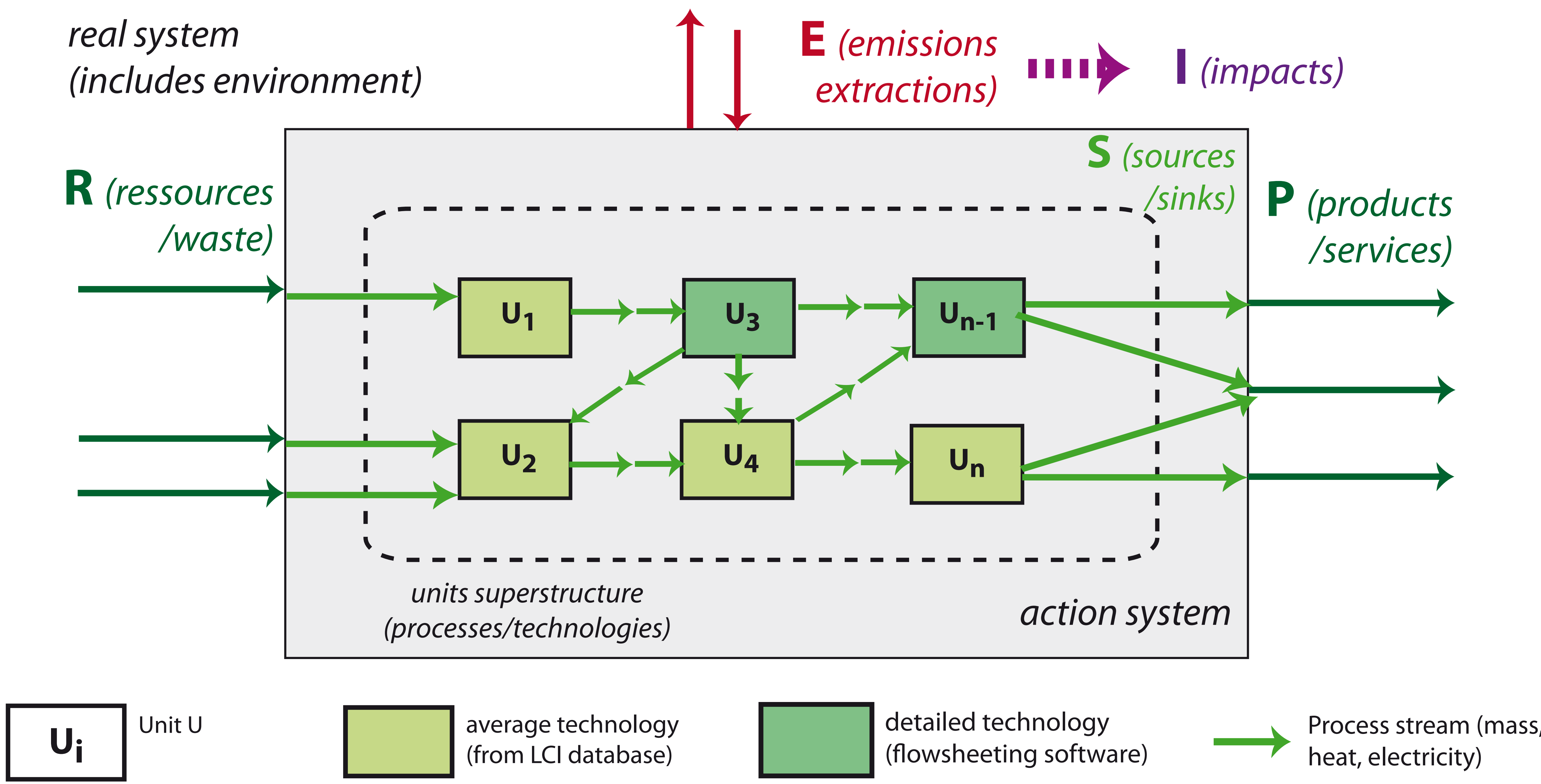

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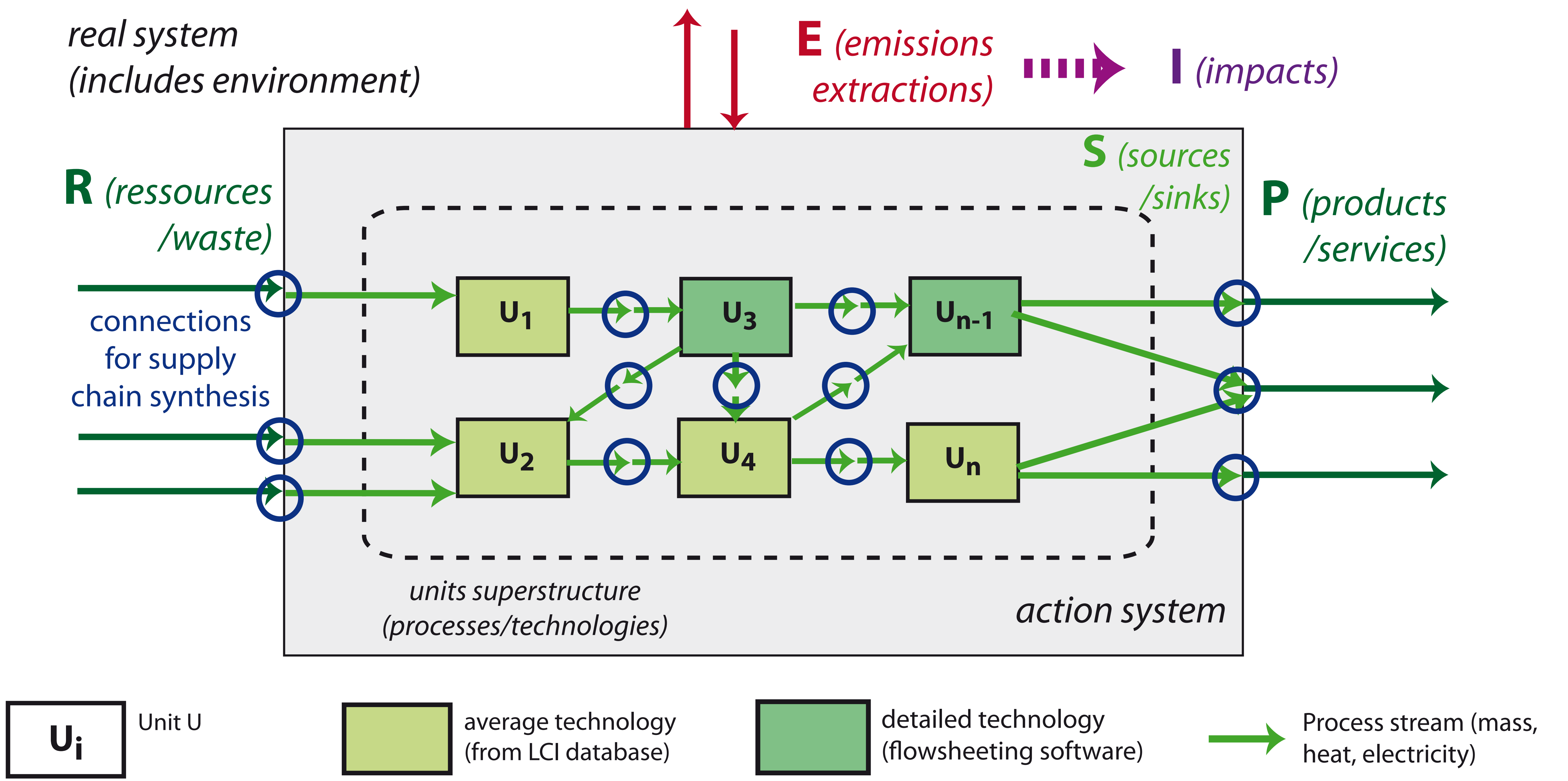

Optimization problem formulation

- 2-step decomposition
  - slave (MILP for each independent period):

x_d : decision variables of MINLP problem

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$$min\ C_{O,p} = \sum_{u=1}^{n_u} \mathbf{f_{u,p}} \cdot (C_{O,u,p} + \dot{I}_{CO2,u,p} \cdot \mathrm{c_{co2}}) + \sum_{r=1}^{n_r} (\dot{R}_{r,p} \cdot c_{r^+} + \dot{I}_{CO2,r} \cdot \mathrm{c_{co2}}) + \dot{E}_p^+ \cdot c_{e^+} - \dot{E}_p^- \cdot c_{e^-} (\mathrm{x_d})$$

$\mathrm{x_d}$: decision variables of MINLP problem

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Utilization factor of unit u, for period p

$\mathrm{x_d}$: decision variables of MINLP problem

Optimization problem formulation

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Utilization factor of unit u, for period p

Operating cost

$\mathrm{x_d}$: decision variables of MINLP problem

Optimization problem formulation

- 2-step decomposition
  - slave (MILP for each independent period):

environmental tax

$$min\ C_{O,p} = \sum_{u=1}^{n_u} \mathbf{f_{u,p}} \cdot (C_{O,u,p} + \dot{I}_{CO2,u,p} \cdot \mathrm{c_{co2}}) + \sum_{r=1}^{n_r} (\dot{R}_{r,p} \cdot c_{r+} + \dot{I}_{CO2,r} \cdot \mathrm{c_{co2}}) + \dot{E}_p^{+} \cdot c_{e+} - \dot{E}_p^{-} \cdot c_{e-} (\mathrm{x_d})$$

Utilization factor of unit u, for period p

Operating cost

Impact

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Optimization problem formulation

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environmental tax

buying price of resource r

$$min\ C_{O,p} = \sum_{u=1}^{n_u} \mathbf{f_{u,p}} \cdot (C_{O,u,p} + \dot{I}_{CO2,u,p} \cdot \mathrm{c_{co2}}) + \sum_{r=1}^{n_r} (\dot{R}_{r,p} \cdot c_{r+} + \dot{I}_{CO2,r} \cdot \mathrm{c_{co2}}) + \dot{E}_p^+ \cdot c_{e+} - \dot{E}_p^- \cdot c_{e-} (\mathrm{x_d})$$

Utilization factor of unit u, for period p

Operating cost

Impact

Consumption of resource r, for period p

$\mathrm{x_d}$: decision variables of MINLP problem

Optimization problem formulation

- 2-step decomposition
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environmental tax

buying price of resource r

electricity buying price

$$min\ C_{O,p} = \sum_{u=1}^{n_u} \mathbf{f_{u,p}} \cdot (C_{O,u,p} + \dot{I}_{CO2,u,p} \cdot \mathrm{c_{co2}}) + \sum_{r=1}^{n_r} (\dot{R}_{r,p} \cdot c_{r+} + \dot{I}_{CO2,r} \cdot \mathrm{c_{co2}}) + \dot{E}_p^{+} \cdot c_{e+} - \dot{E}_p^{-} \cdot c_{e-} (\mathrm{x_d})$$

Utilization factor of unit u, for period p

Operating cost

Impact

Consumption of resource r, for period p

Electricity import

$\mathrm{x_d}$: decision variables of MINLP problem

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environmental tax

buying price of resource r

electricity buying price

electricity selling price

Utilization factor of unit u, for period p

Operating cost

Impact

Consumption of resource r, for period p

Electricity import

Electricity export

$\mathrm{x_d}$: decision variables of MINLP problem

Optimization problem formulation

- 2-step decomposition
  - slave (MILP for each independent period):

environmental tax — buying price of resource r — electricity buying price — electricity selling price

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Utilization factor of unit u, for period p — Operating cost — Impact — Consumption of resource r, for period p — Electricity import — Electricity export

- submitted to
  - heat cascade constraints
  - mass balance for each layer

$\mathrm{x_d}$: decision variables of MINLP problem

Optimization problem formulation

- 2-step decomposition
  - master (MOO MINLP):

$\mathrm{x_d}$: decision variables of MINLP problem

$\mathrm{f_u}$: utilization factor of unit u

$\mathrm{c_{co2}}$: environmental tax

Optimization problem formulation

- 2-step decomposition
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$$min\ C_{inv} = \sum_{u=1}^{n_u} max\ \left(C_{inv,u,p}(\mathrm{x_d}, \mathbf{f_{u,p}}, \mathrm{c_{co2}})\right)$$

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Investment cost of unit u

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$$min\ C_O = \sum_{p=1}^{n_p} C_{O,p}(\mathrm{x_d}, \mathbf{f_{u,p}}, \mathrm{c_{co2}})$$

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Optimization problem formulation

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$$min\ I_{tot} = \sum_{u=1}^{n_u}(max\ (I_{C,u,p}) + max\ (I_{E,u,p}) + \sum_{p=1}^{n_p} I_{O,u,p})(\mathrm{x_d}, \mathbf{f_{u,p}}, \mathrm{c_{co2}})$$

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Construction impact of unit u

End-of-life impact of unit u

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Construction impact of unit u — End-of-life impact of unit u — Operation impact of unit u

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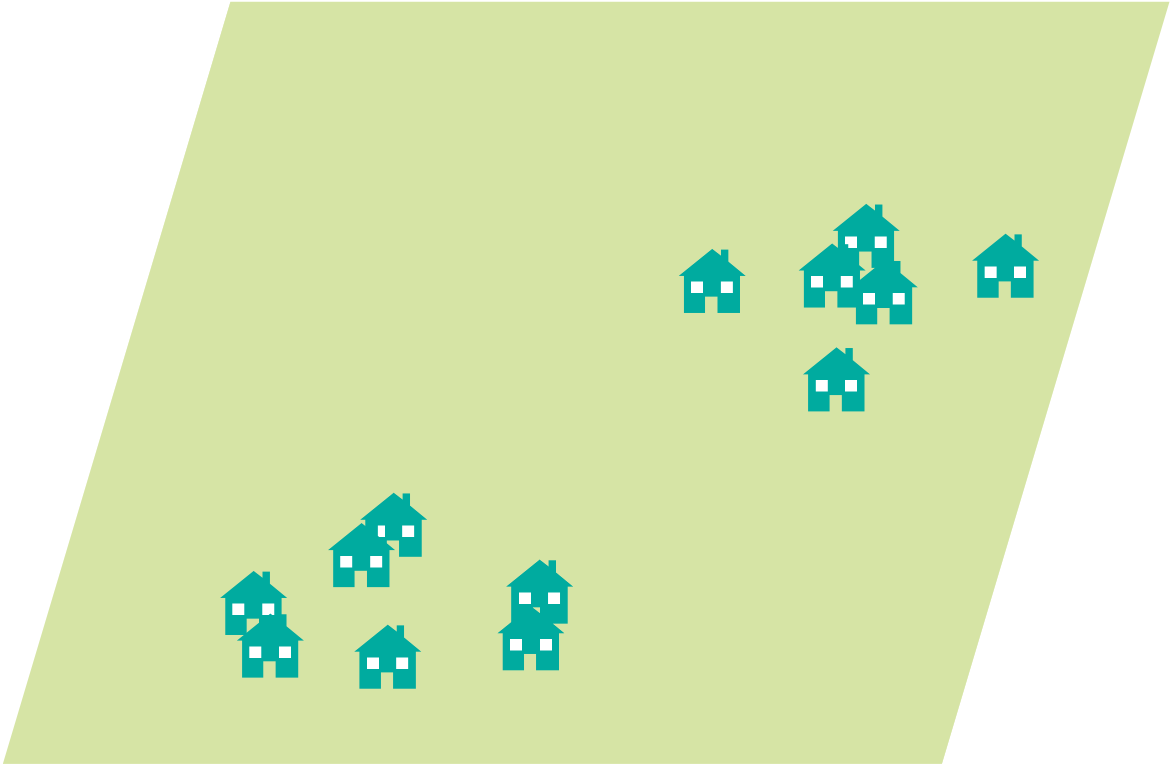
Application case study

- 40‘000 inhabitants city in Switzerland (La Chaux-de-Fonds, 1000m alt.)



Application case study

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Energy services to be supplied:

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- Heat using existing district heating network (seasonal variation in T and load): **3357 kWh$_{th}$/yr/cap**

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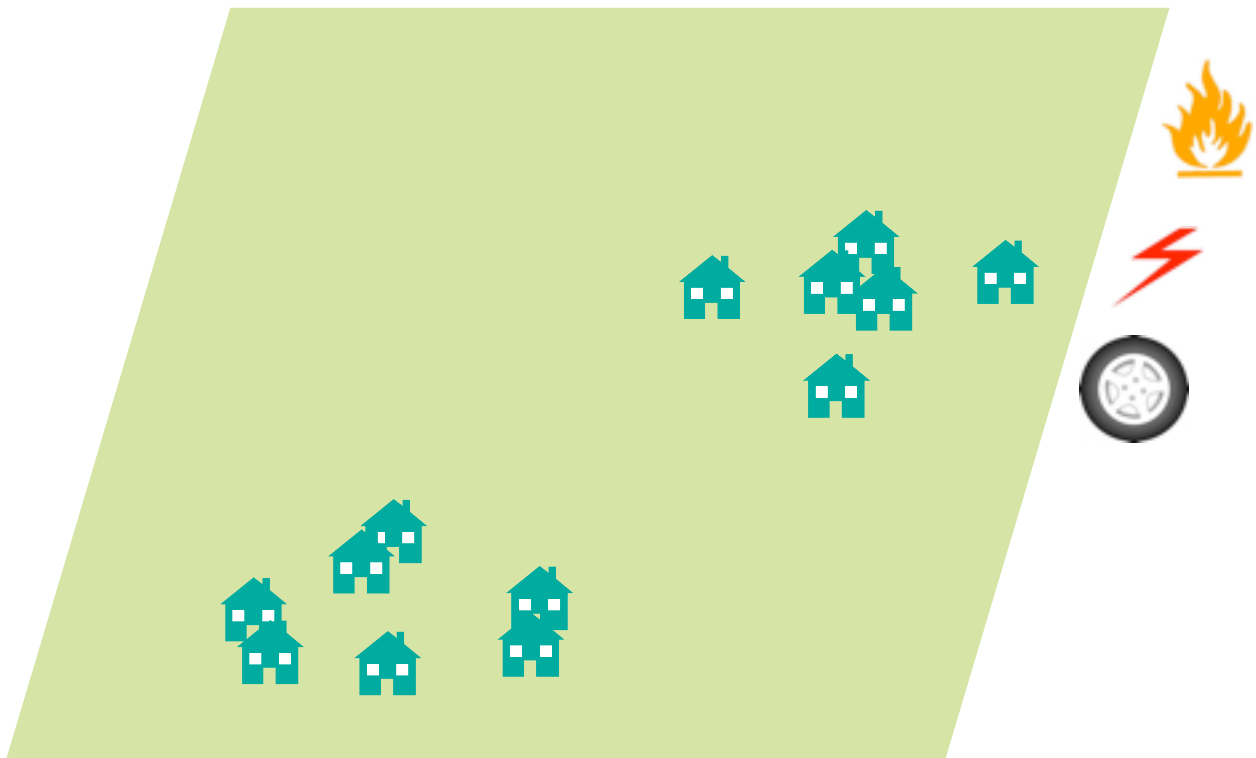

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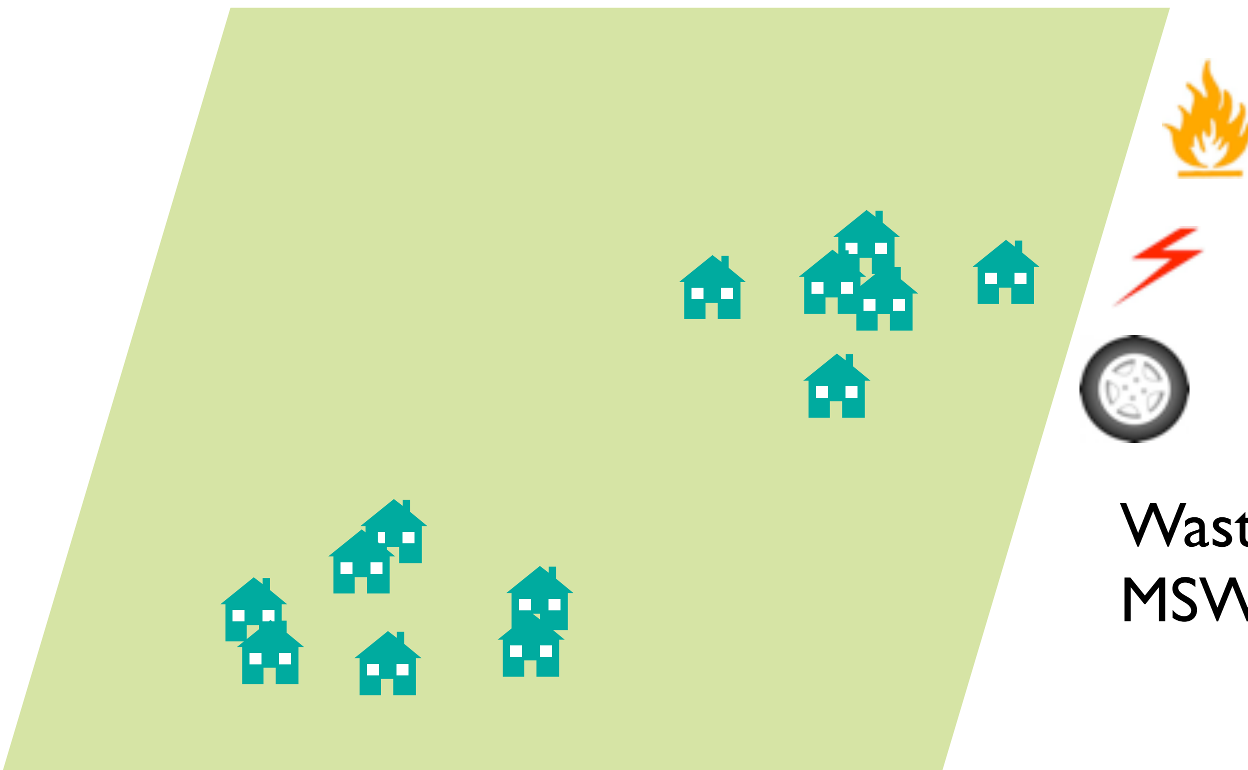

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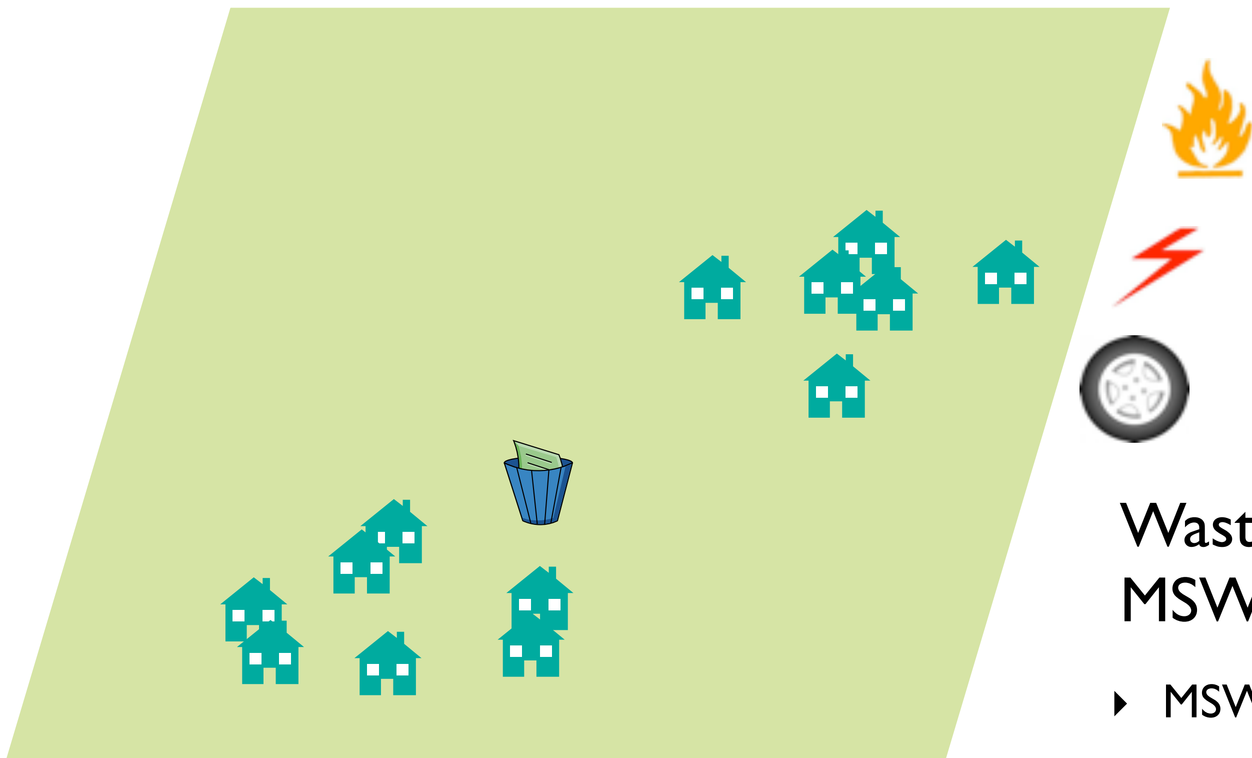

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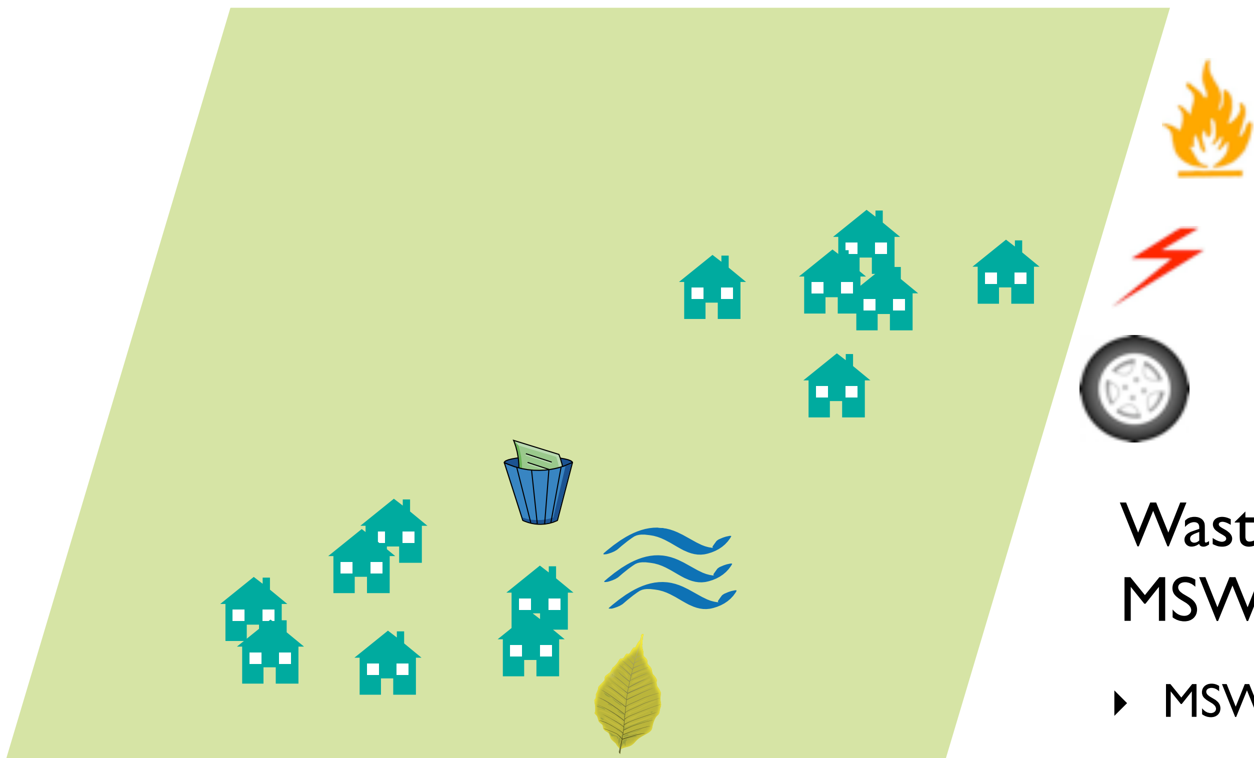

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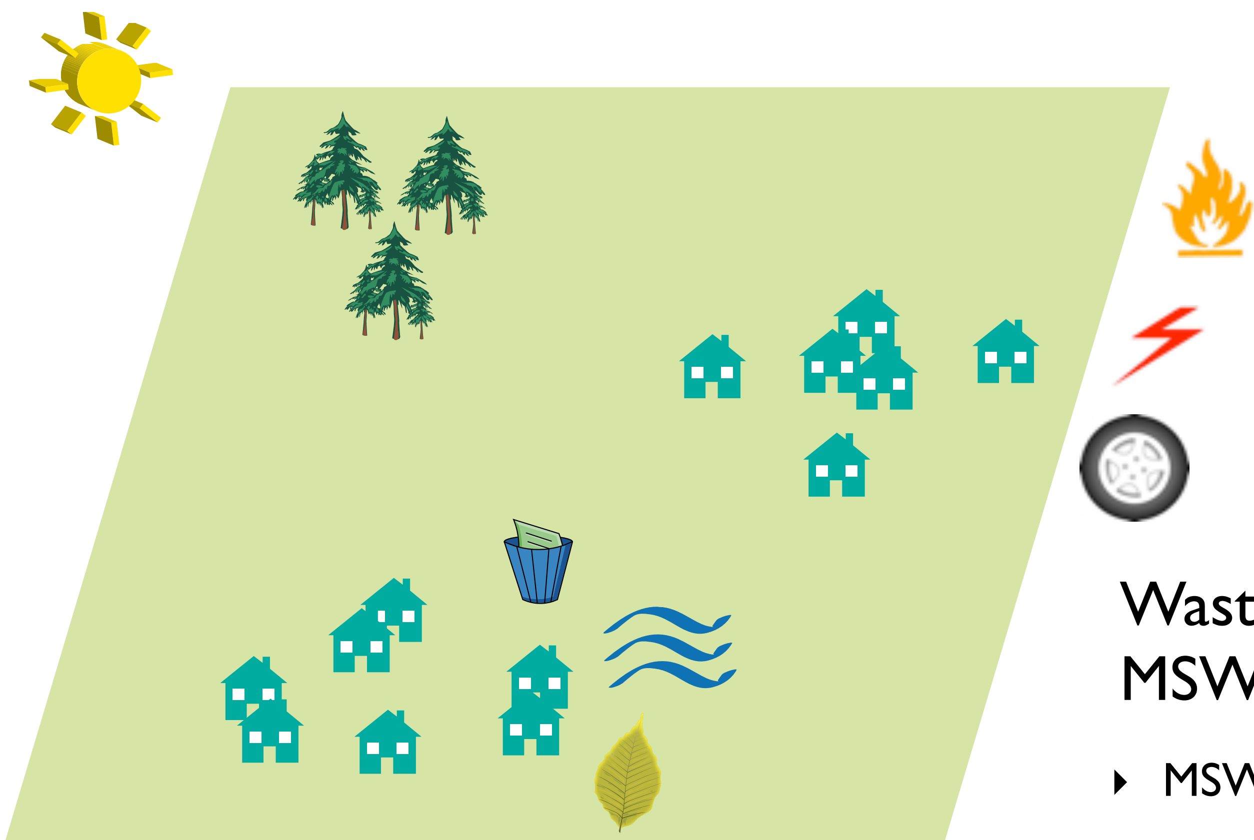

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Application case study

- 40‘000 inhabitants city in Switzerland (La Chaux-de-Fonds, 1000m alt.)

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Waste to be treated (existing facilities for MSW and WWTP):

- MSW: **1375 kg/yr/cap**
- Wastewater: **300 m3/yr/cap**
- Biowaste: **87.5 kg/yr/cap**

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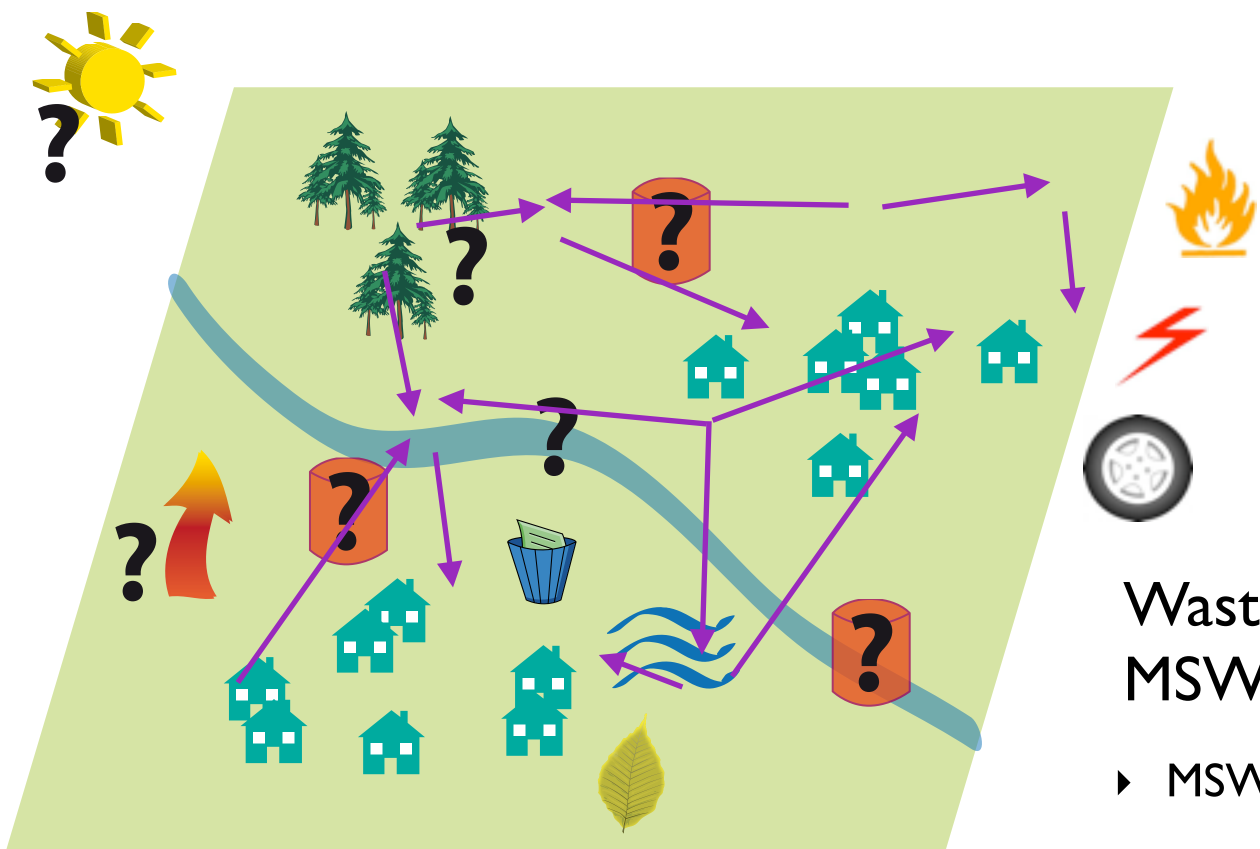

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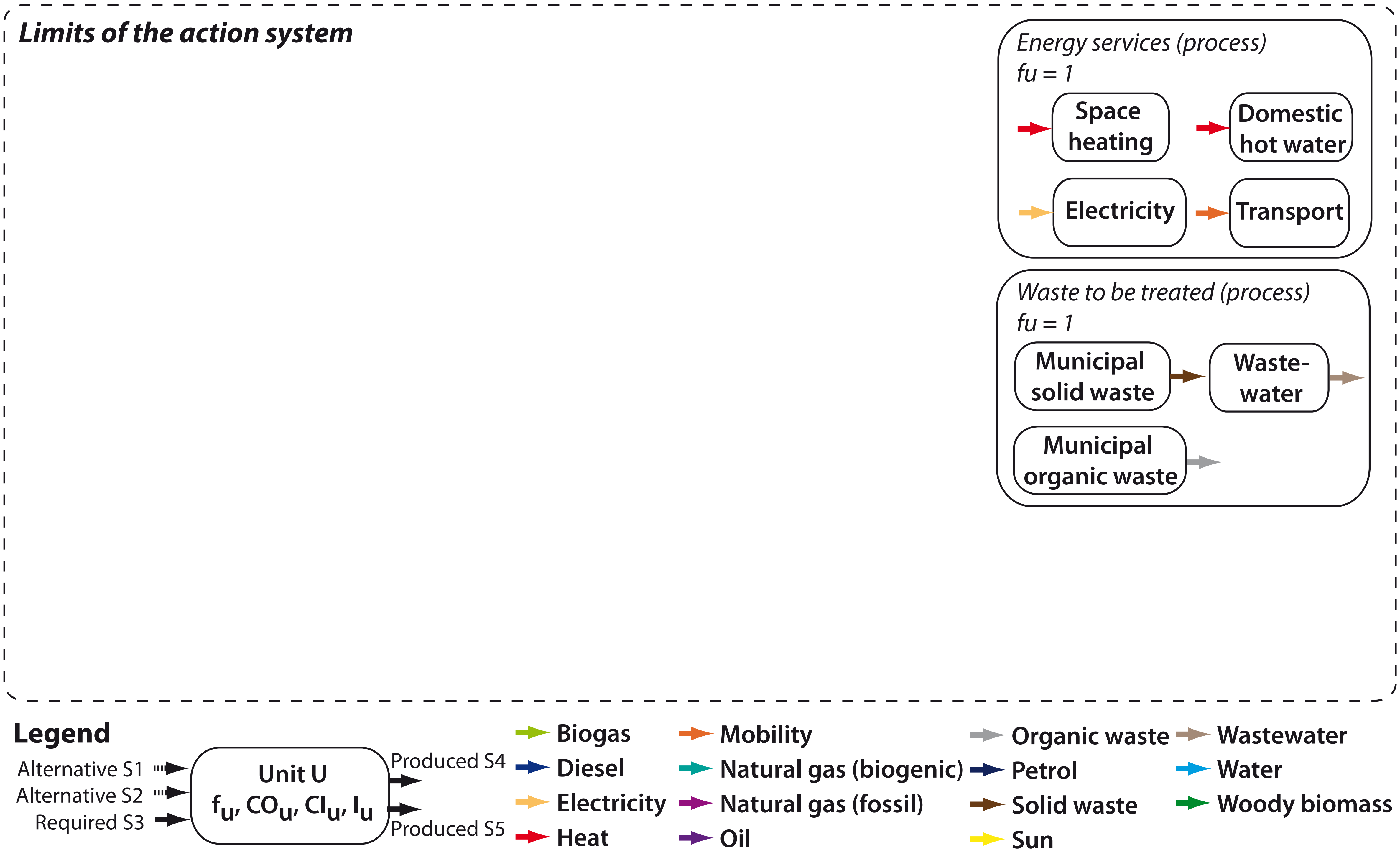
- Which resources with which technologies for which services?
- Min. Costs and CO2 emissions

Urban System Superstructure



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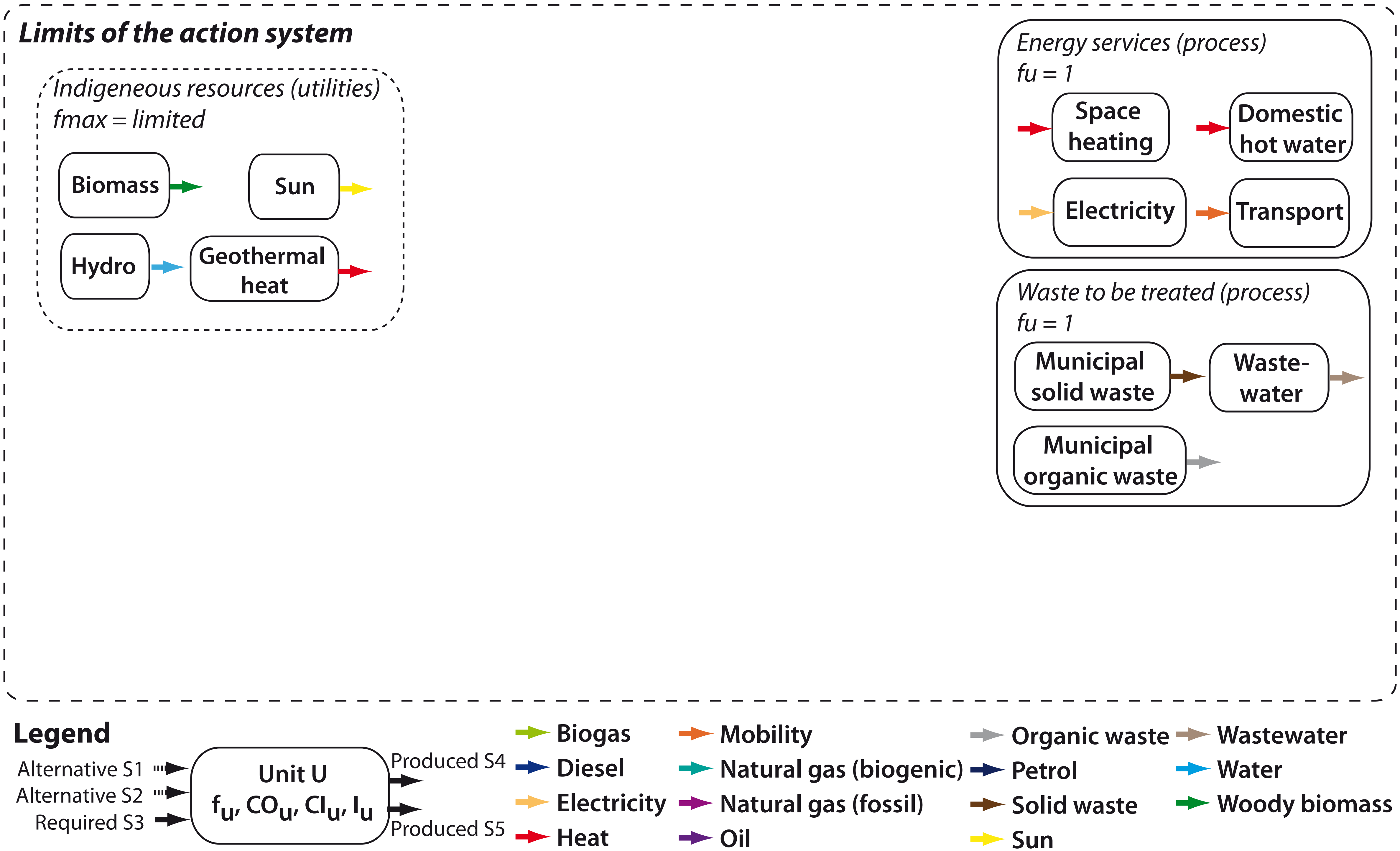

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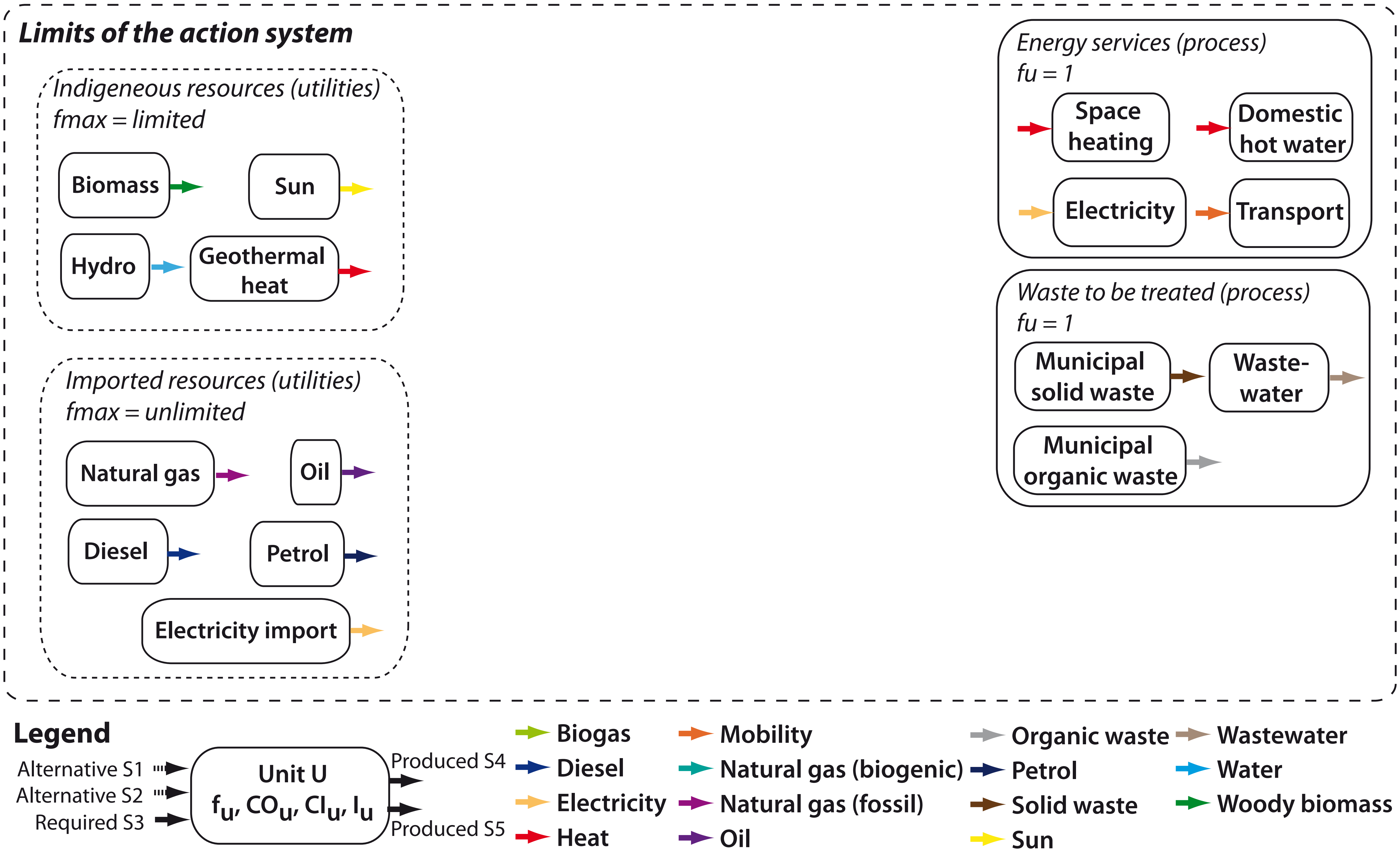

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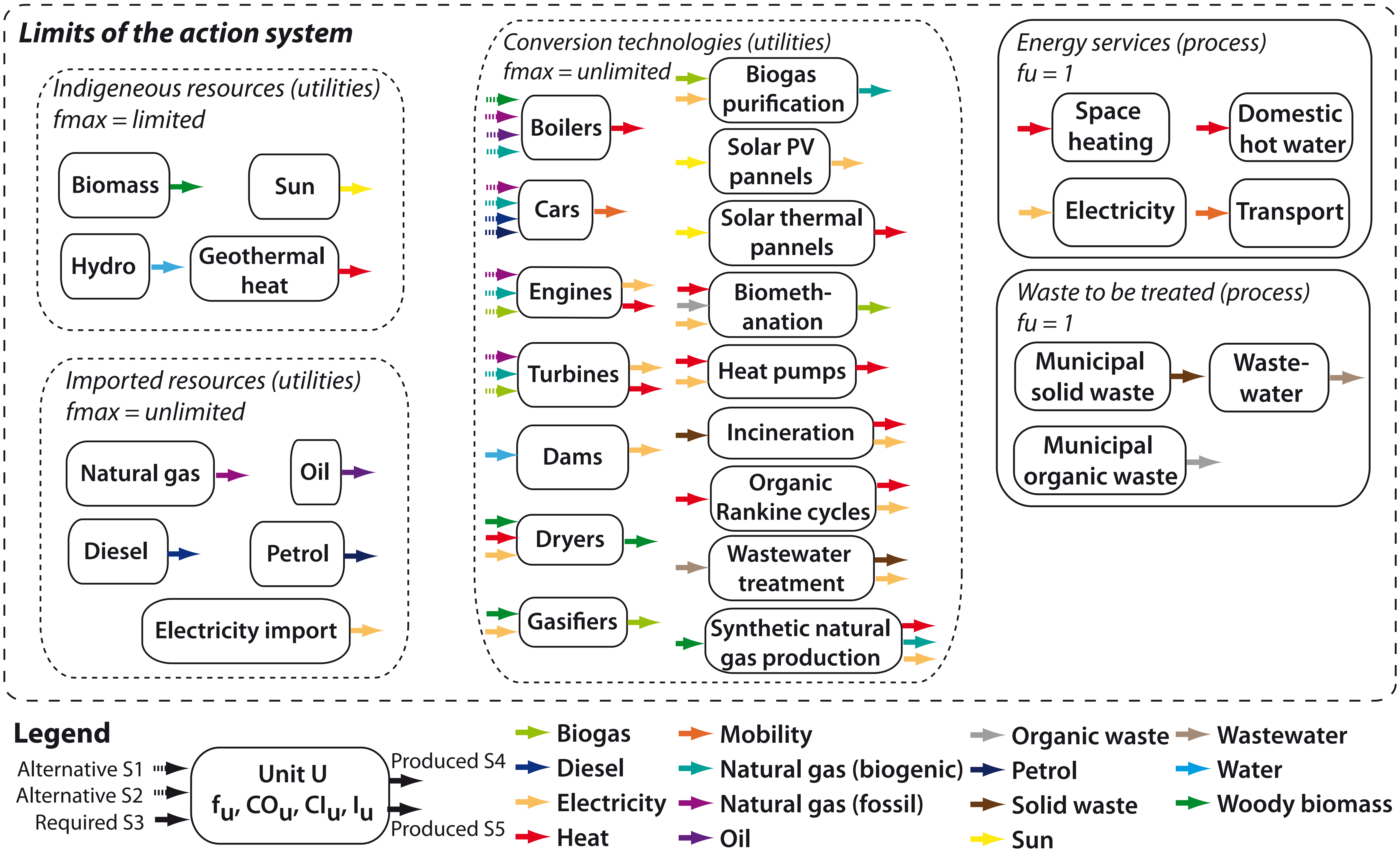

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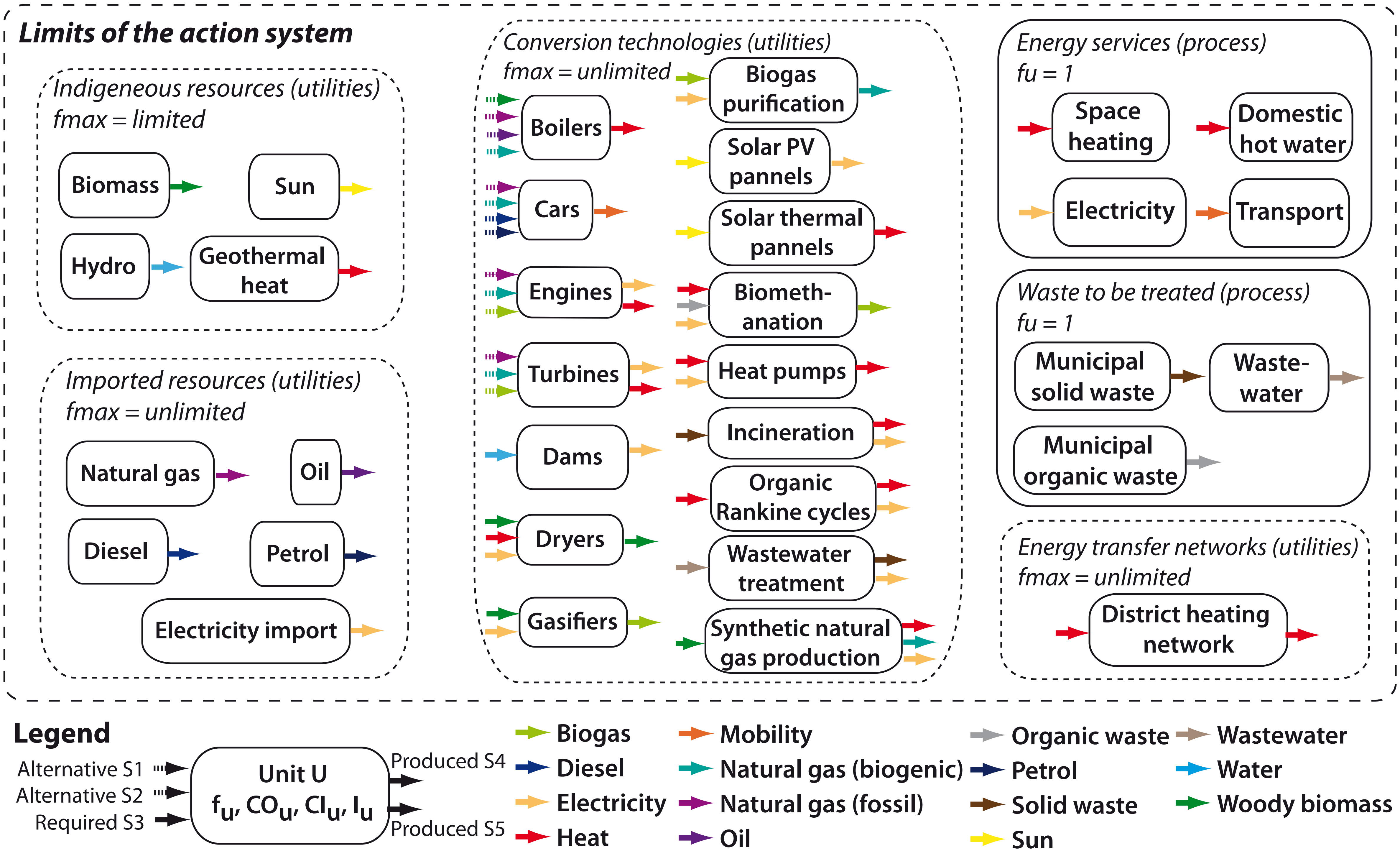

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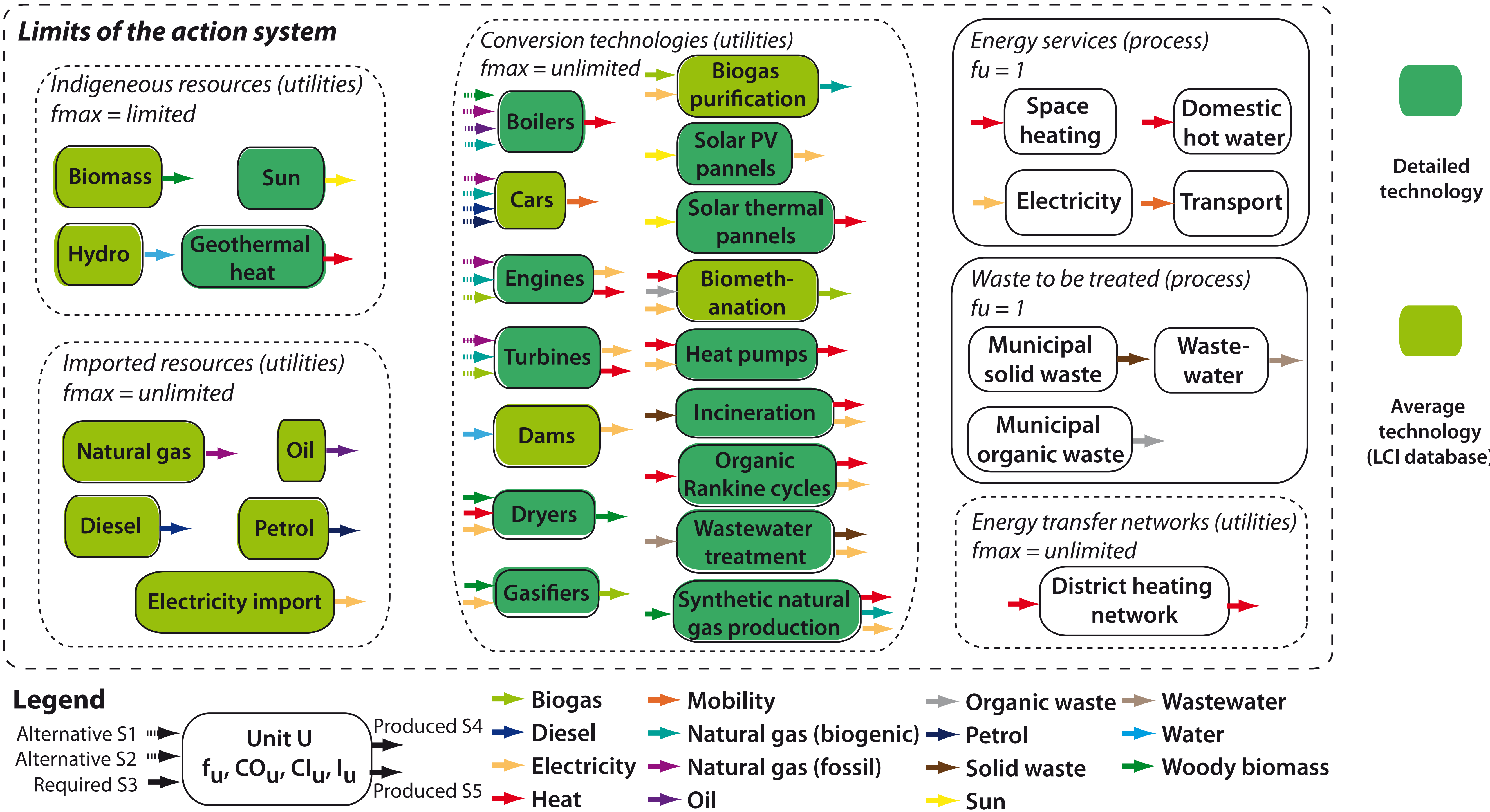

Simulation and Optimization

- Year subdivided in 6 operation periods (average days)

	May, July, August	June (MSWI shuts down)	April, September	March, October	November-February	Design (-10°C)
Operating time [h]	2190	730	1460	1460	2920	0.1
Electricity demand [kWe/cap]	0.886	0.903	0.931	1.020	1.110	1.4
District heating demand [kWth/cap]	0.142	0.142	0.238	0.412	0.559	1.139
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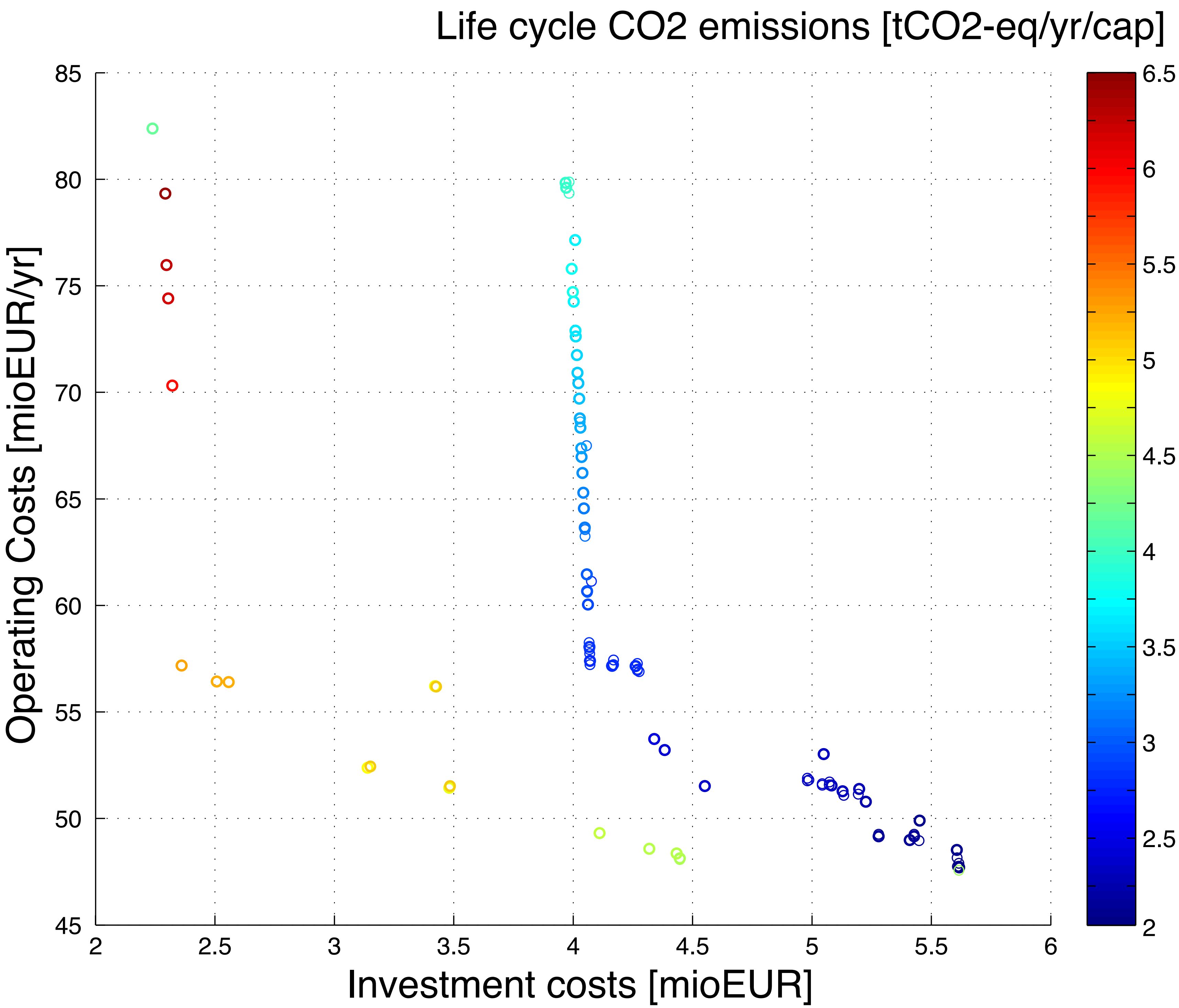
- Min Cinv, Cop, GWP 100a
- 36 decision variables for master problem
  - use of technologies, co2 tax (0-200 EUR/ton), wood biomass distribution over year, ratio between heat and power for MSWI
- Economic conditions
  - electricity: 0.16 €/kWhe, NG: 0.078 €/kWh, Wood: 0.05 €/kWh, diesel: 1.75 €/kWh, petrol: 1.88 €/kWh, LFO:: 0.083 €/kWh

Pareto curve



- Trade-off between 3 objectives
- 2 clusters

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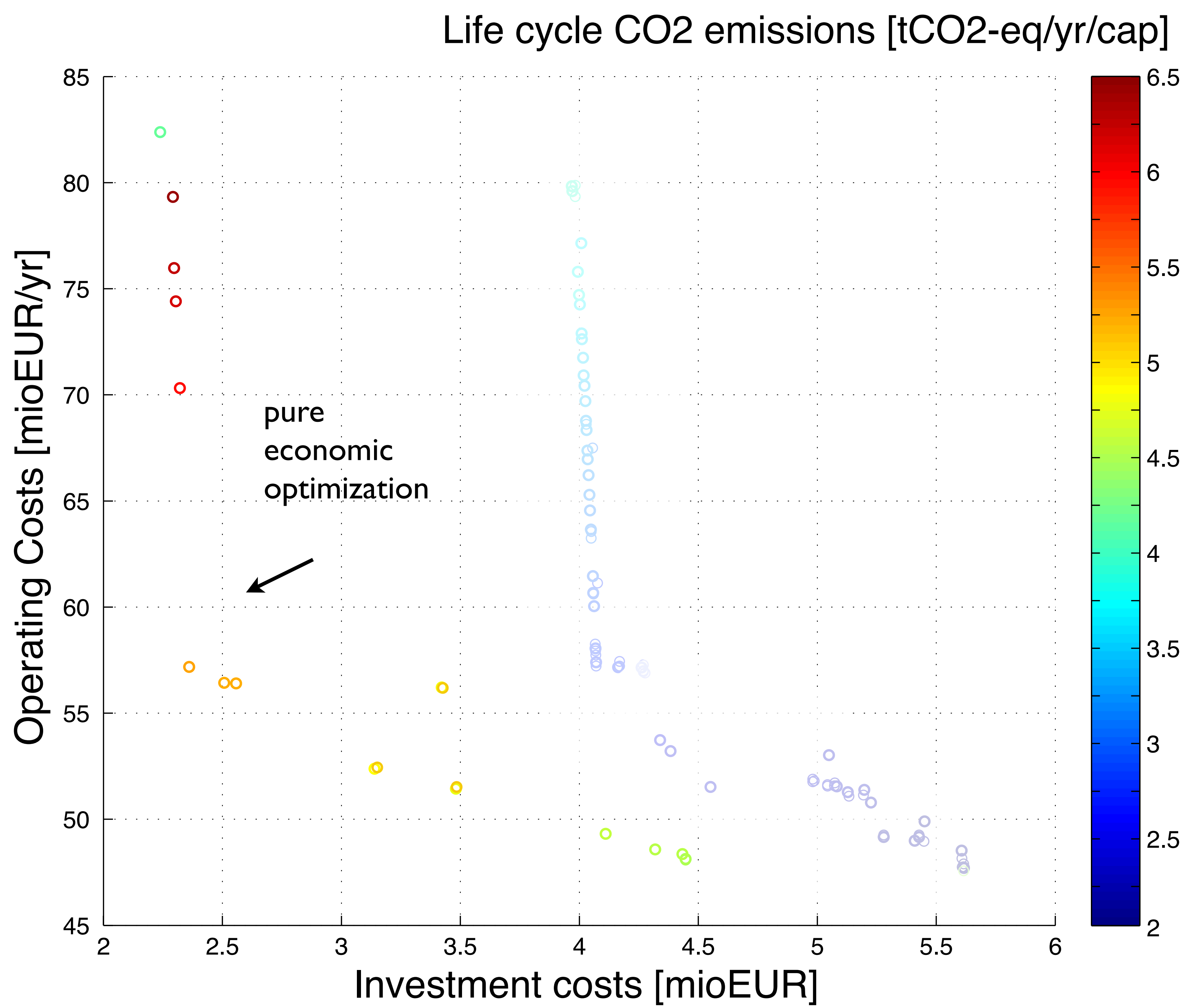

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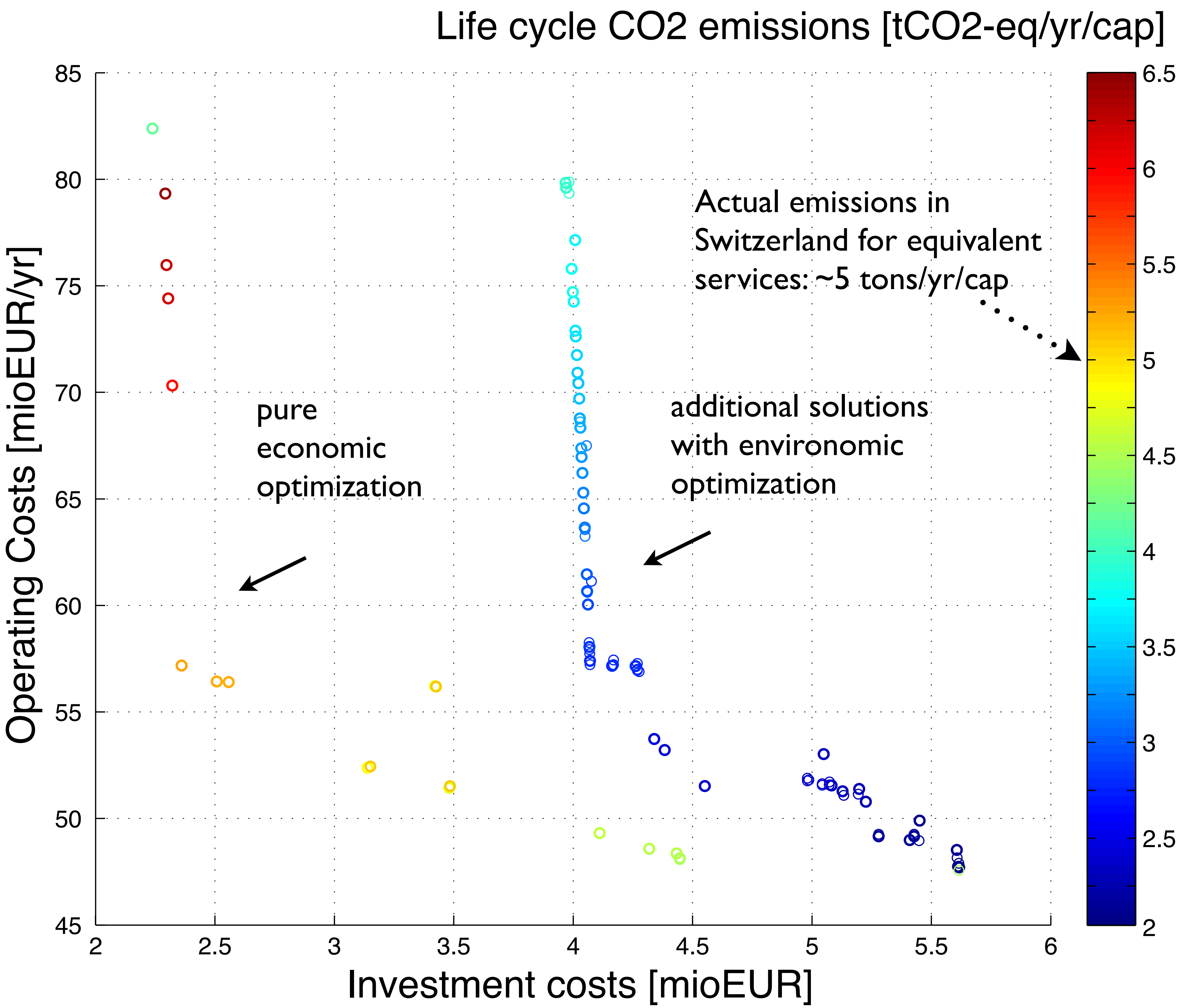

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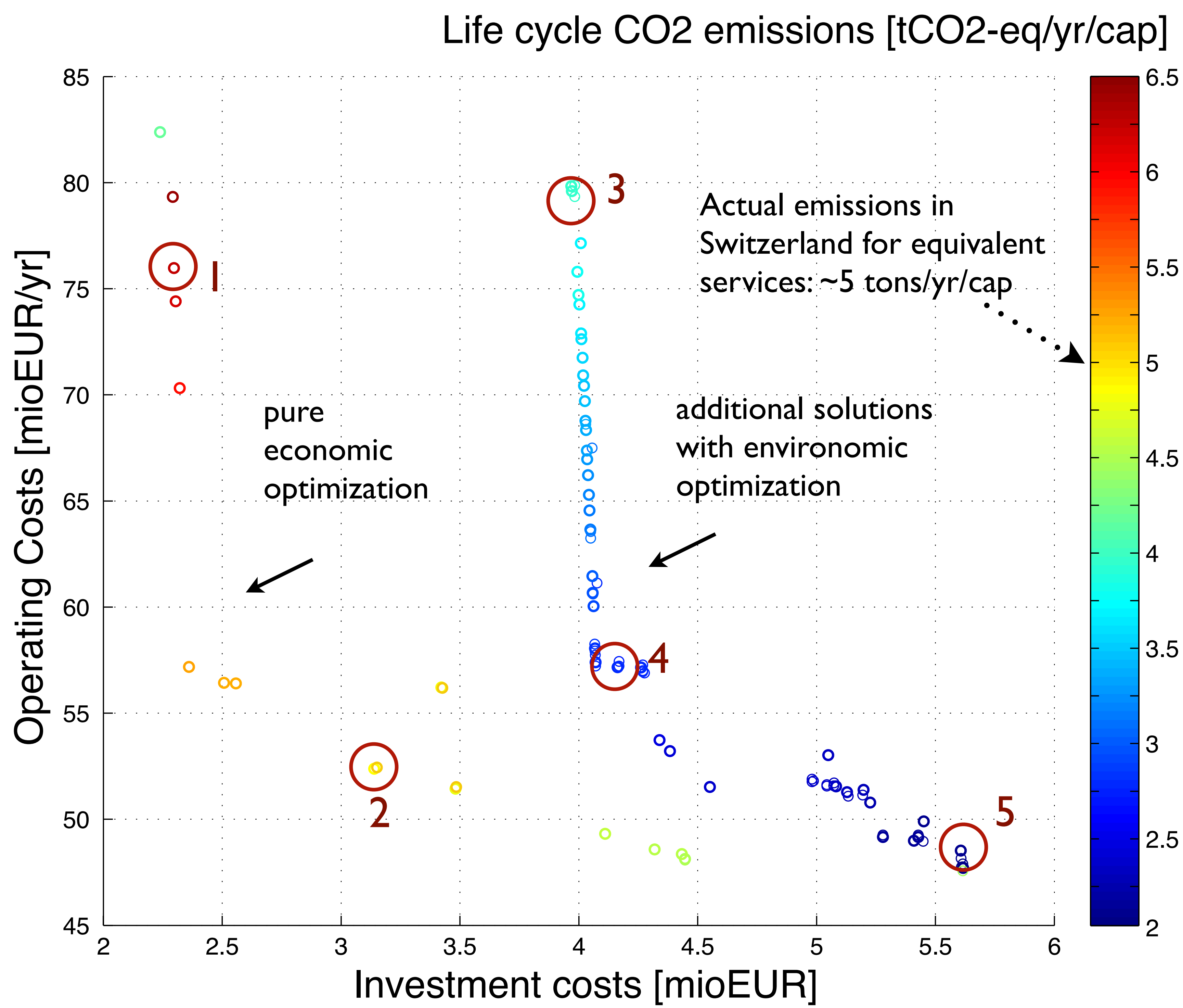

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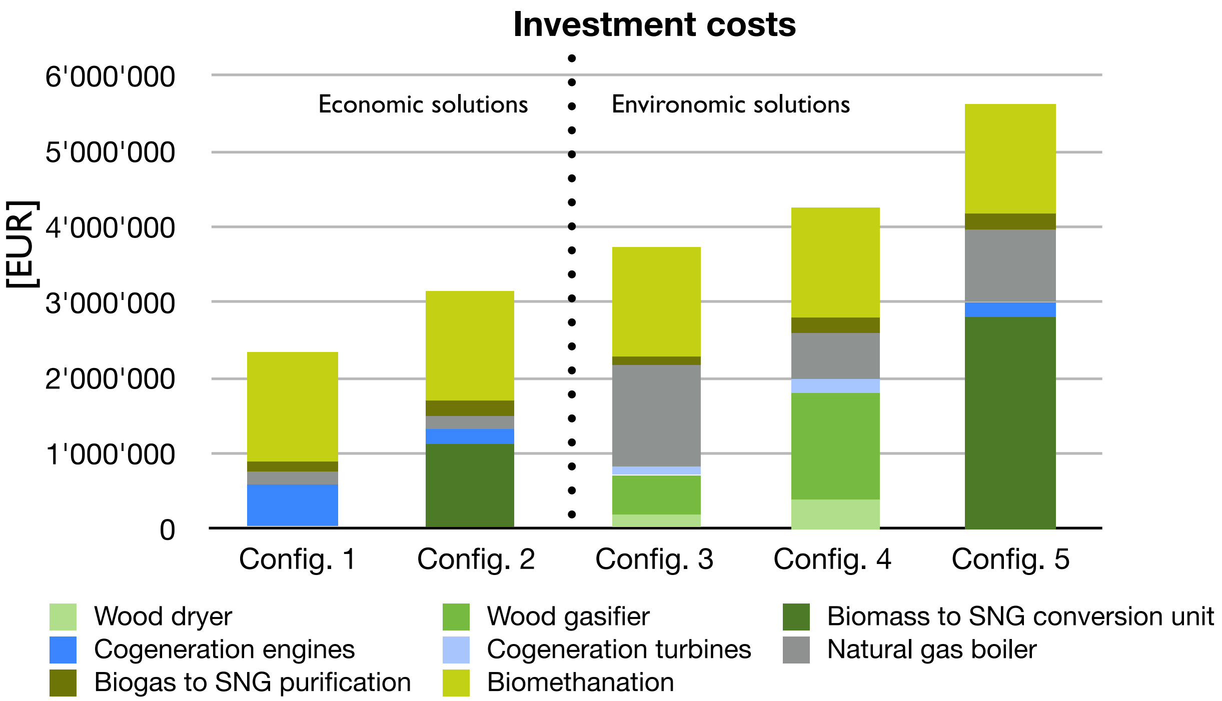
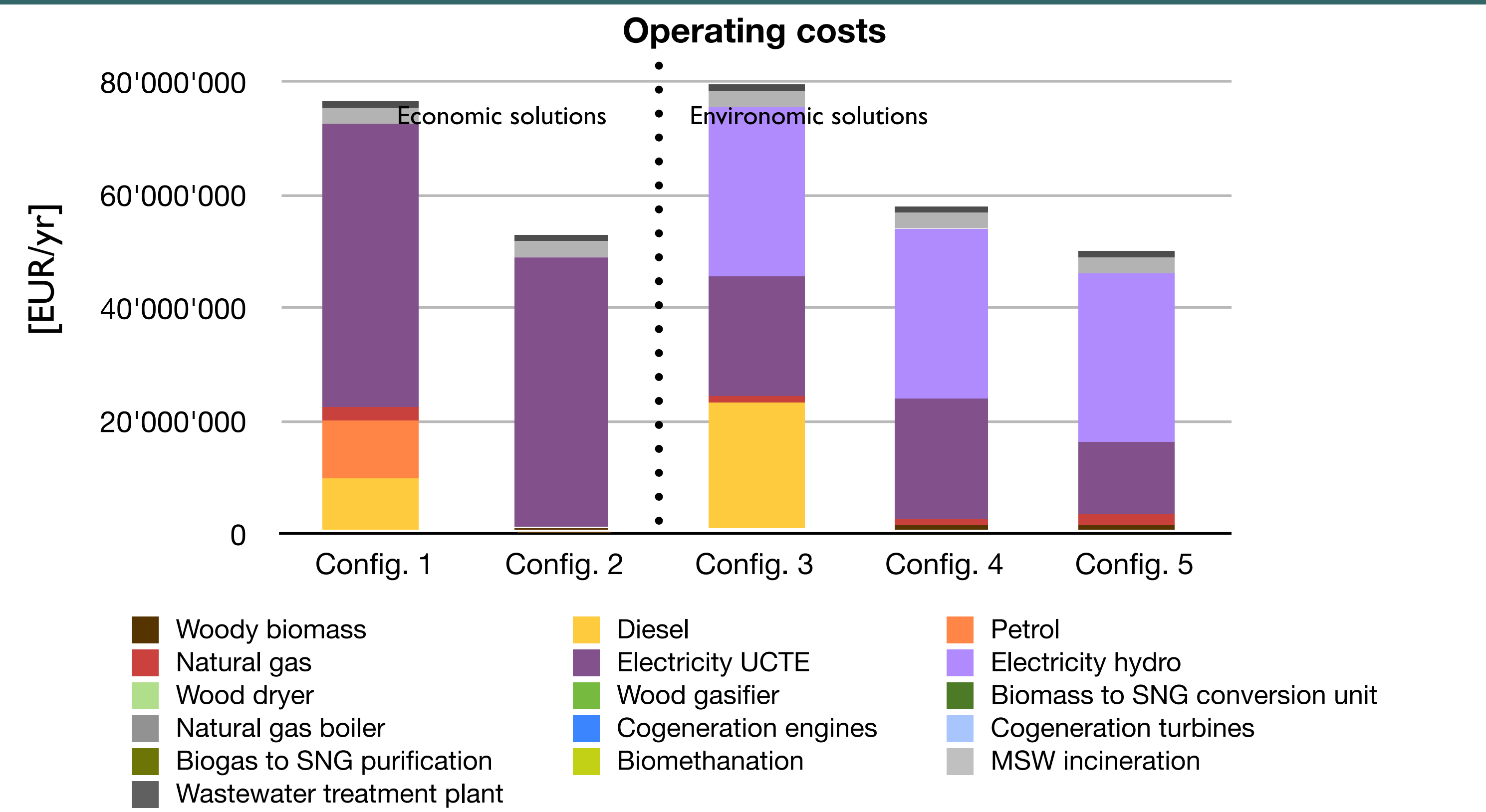
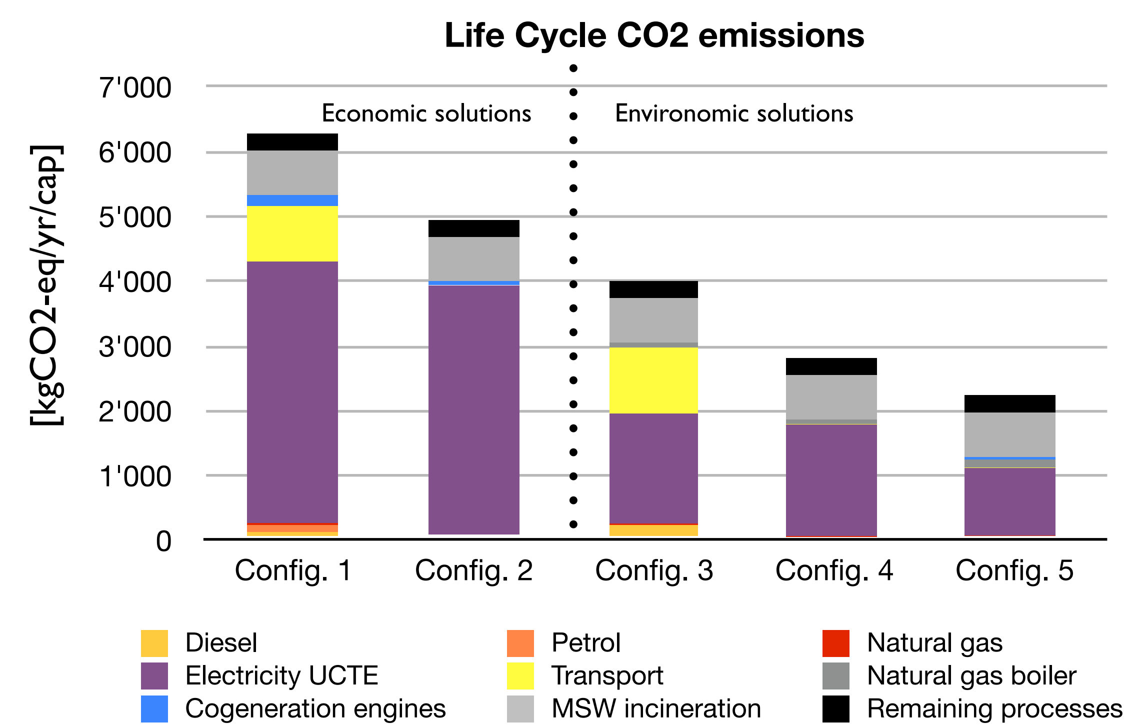
Typical configurations







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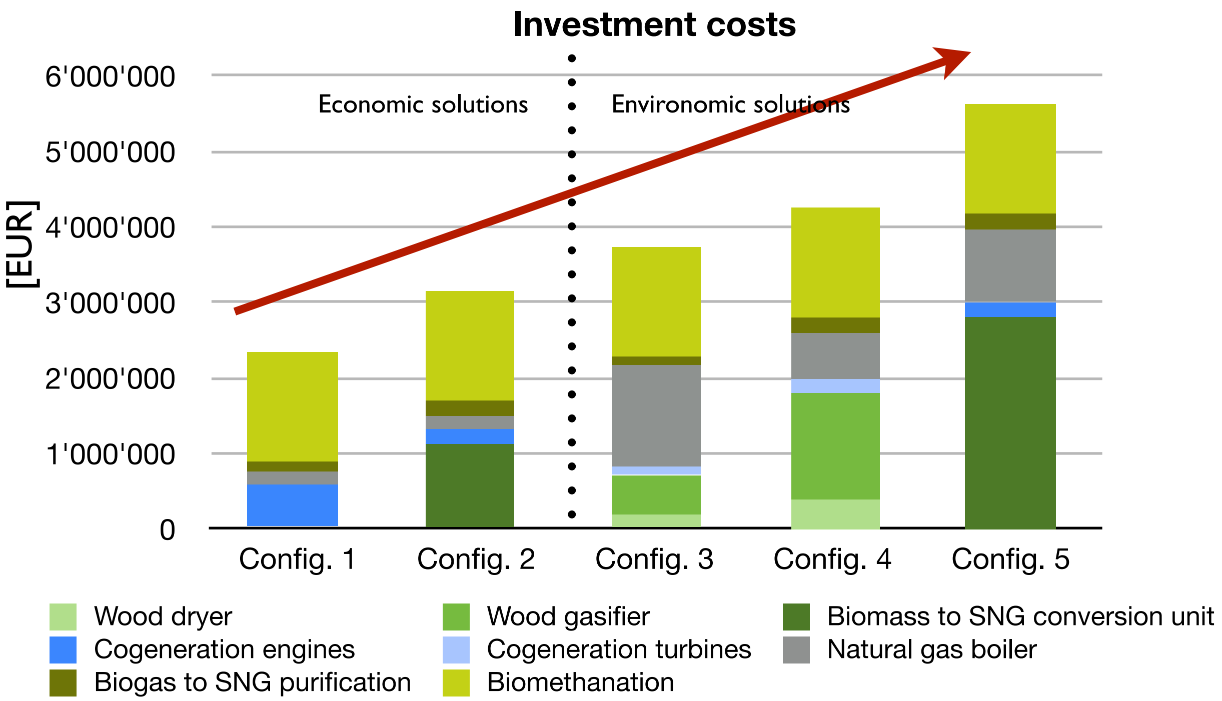

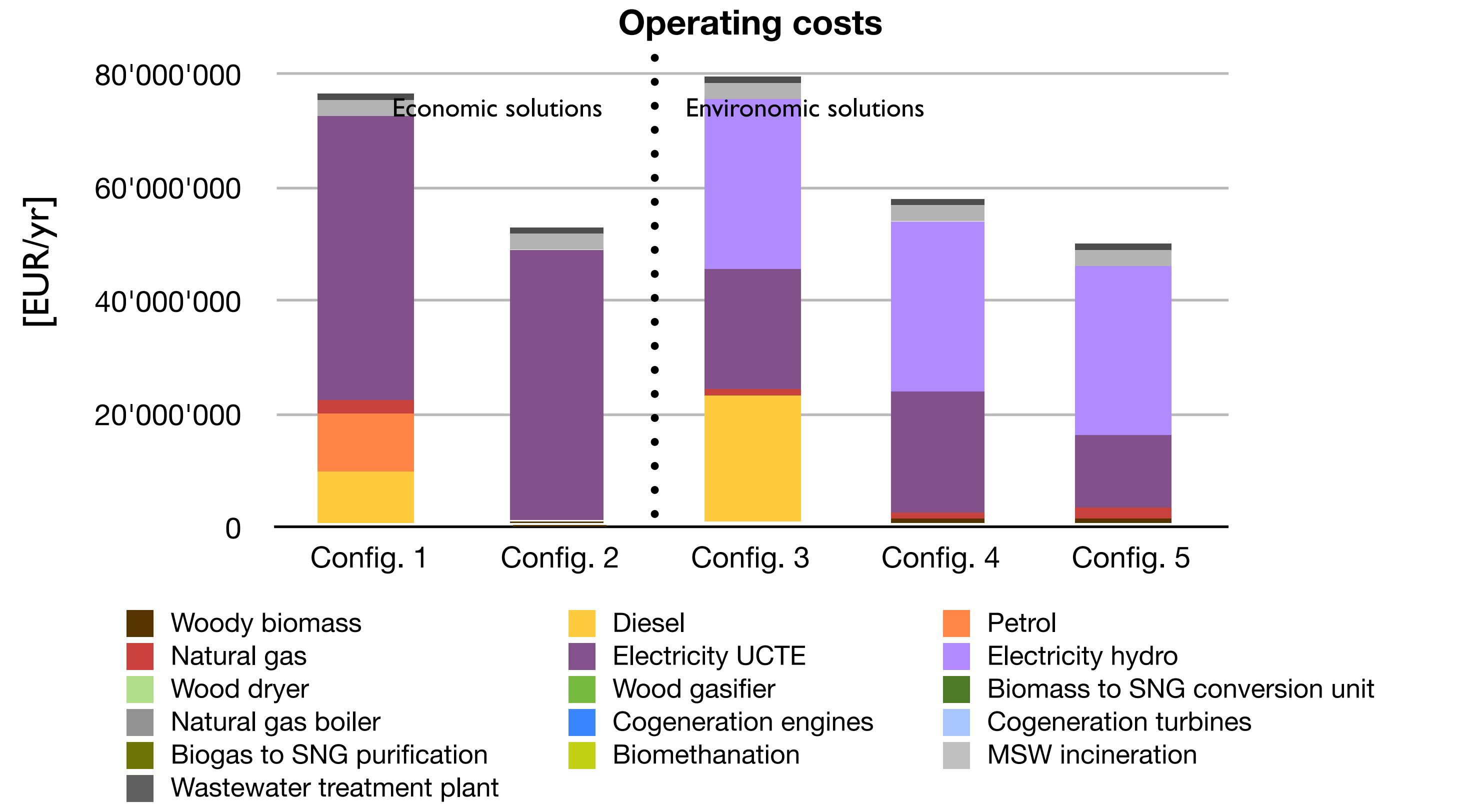

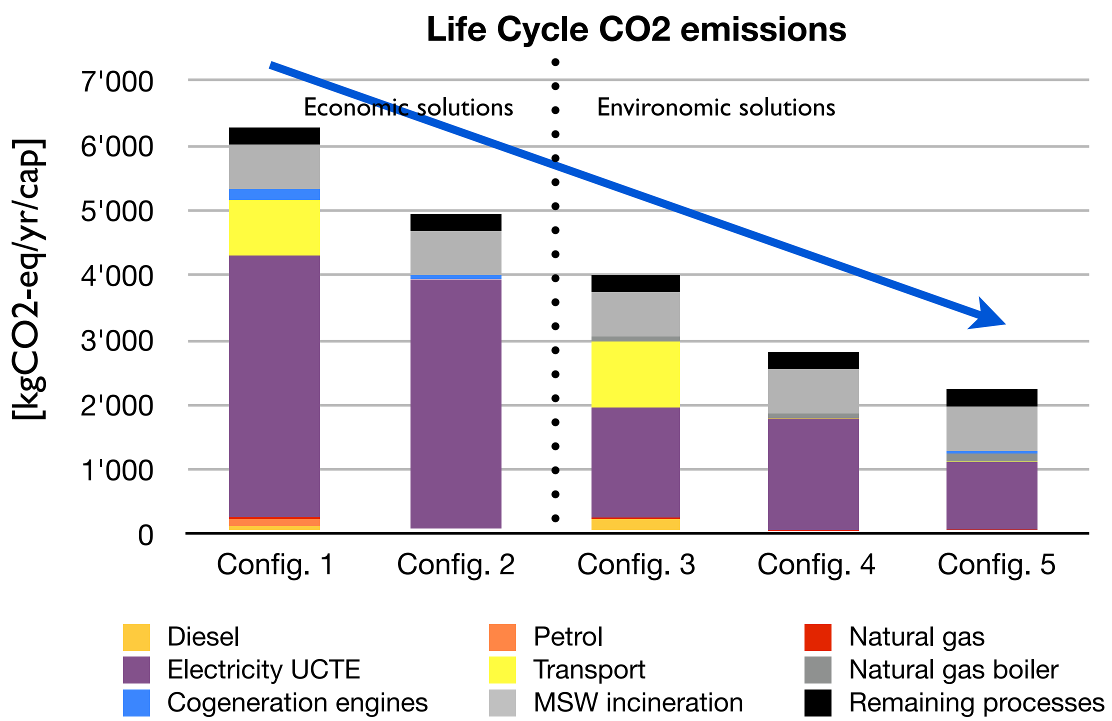

- Substitution of fossil energy sources by biomass and hydro electricity

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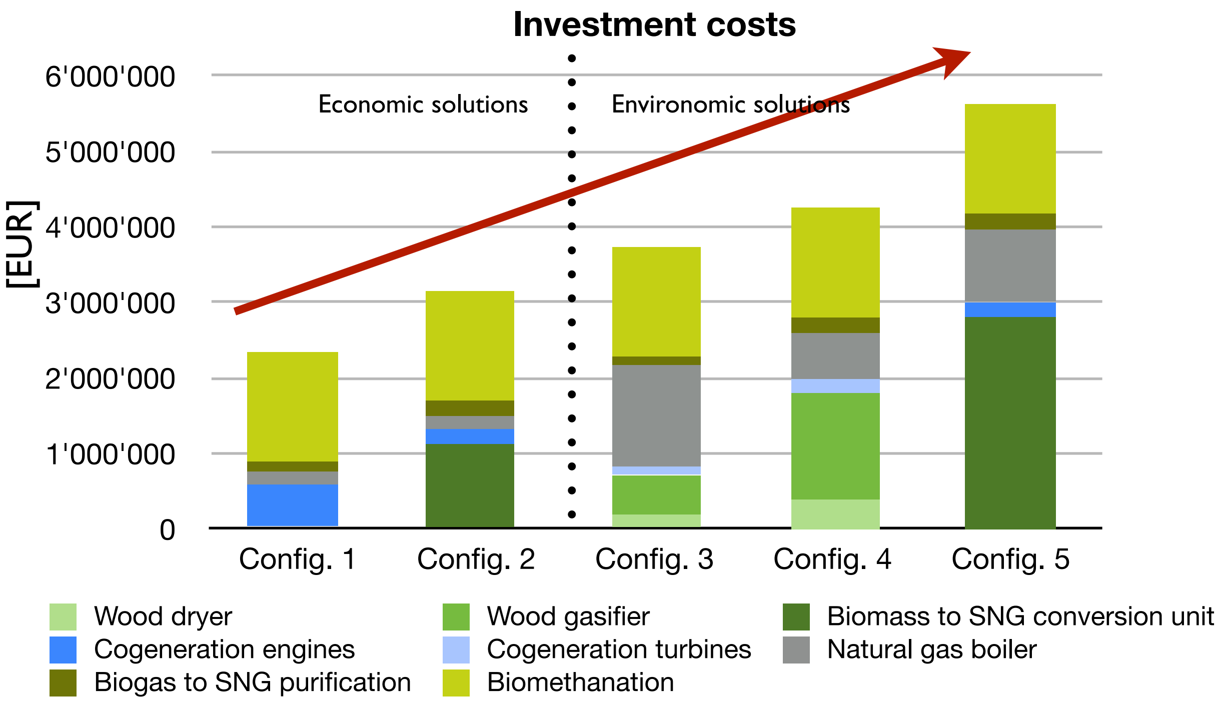

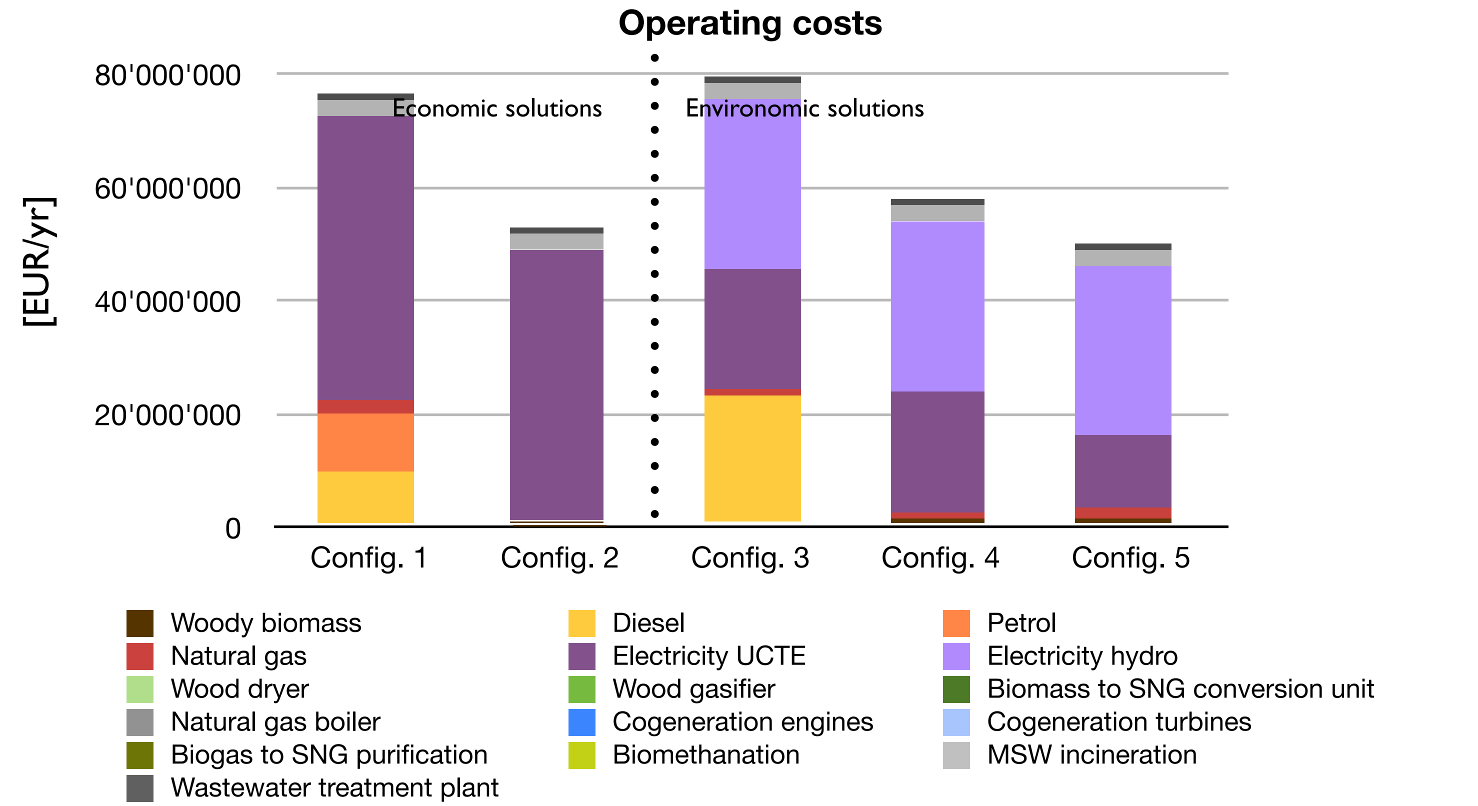

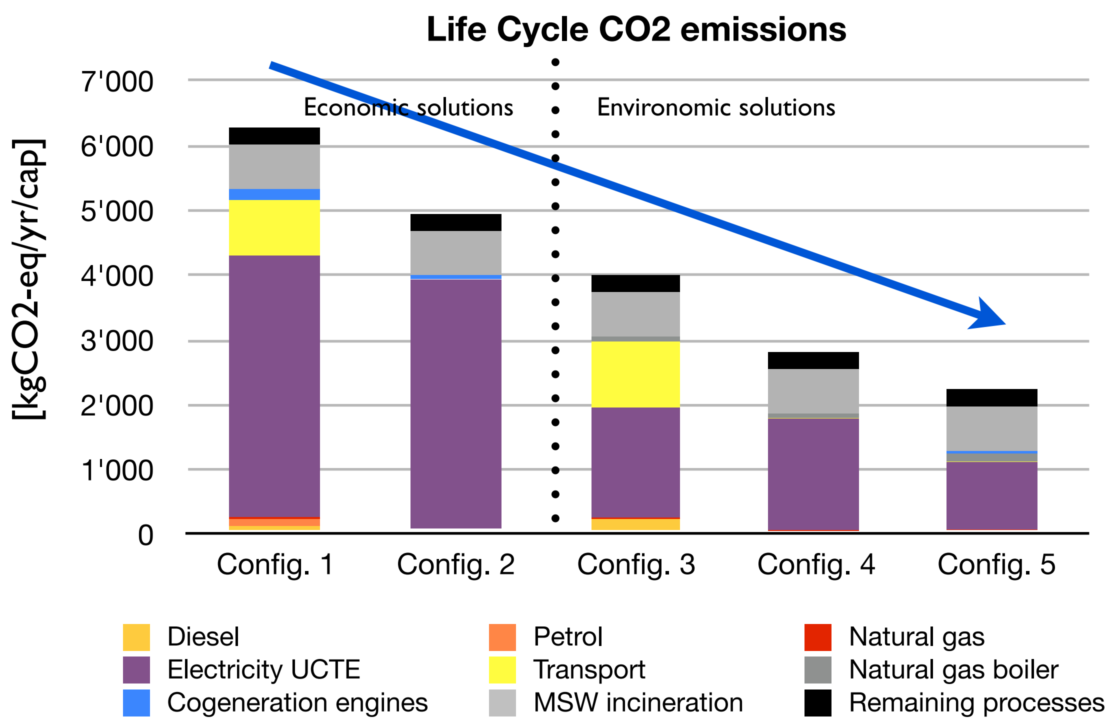

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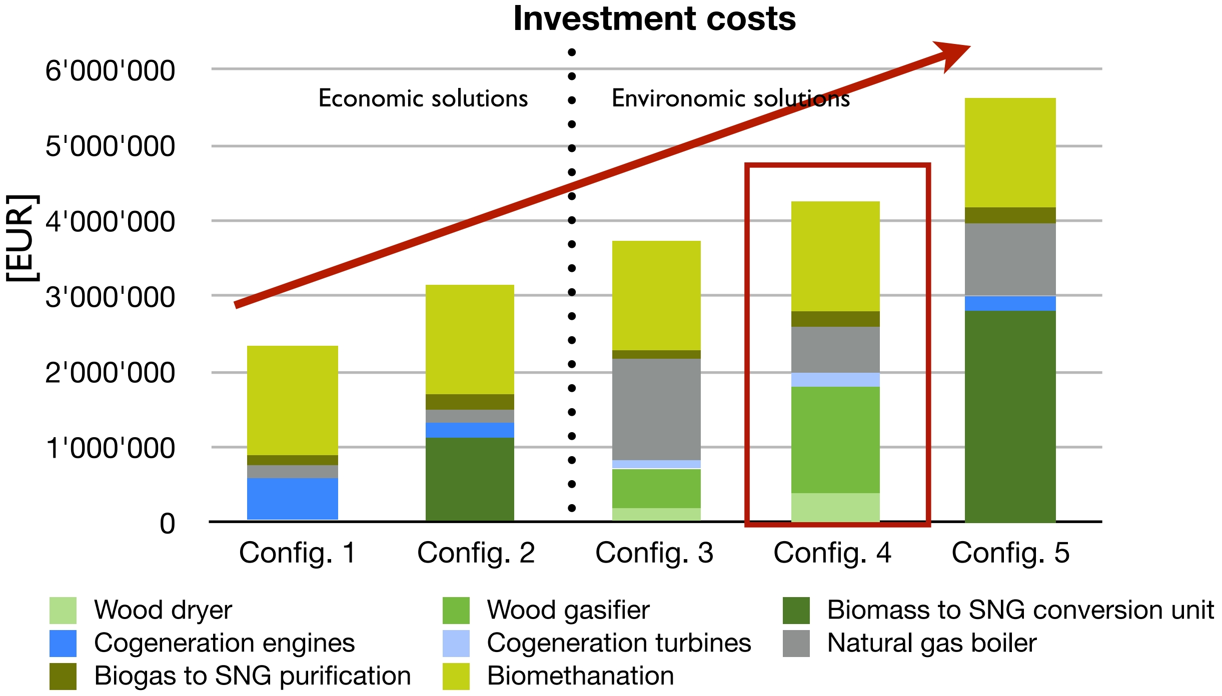

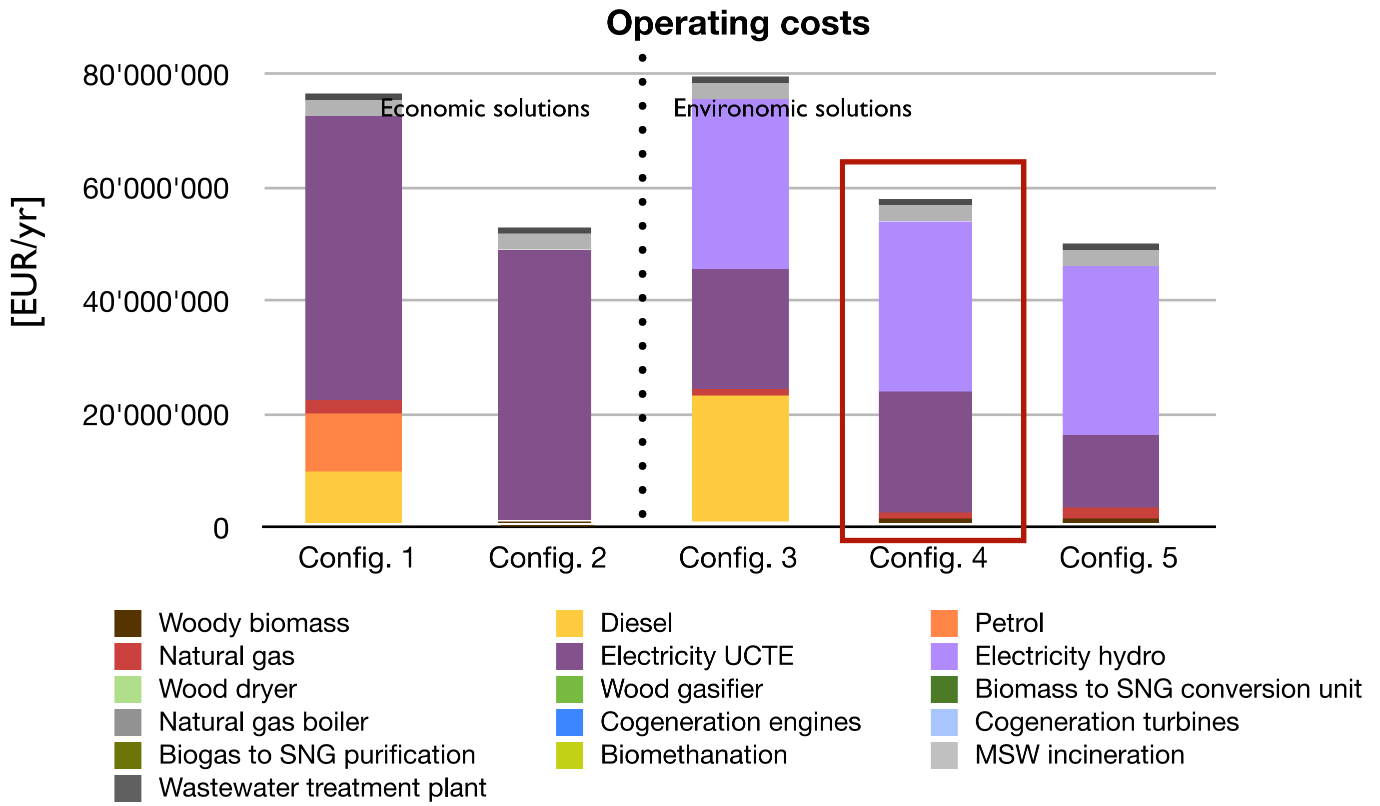

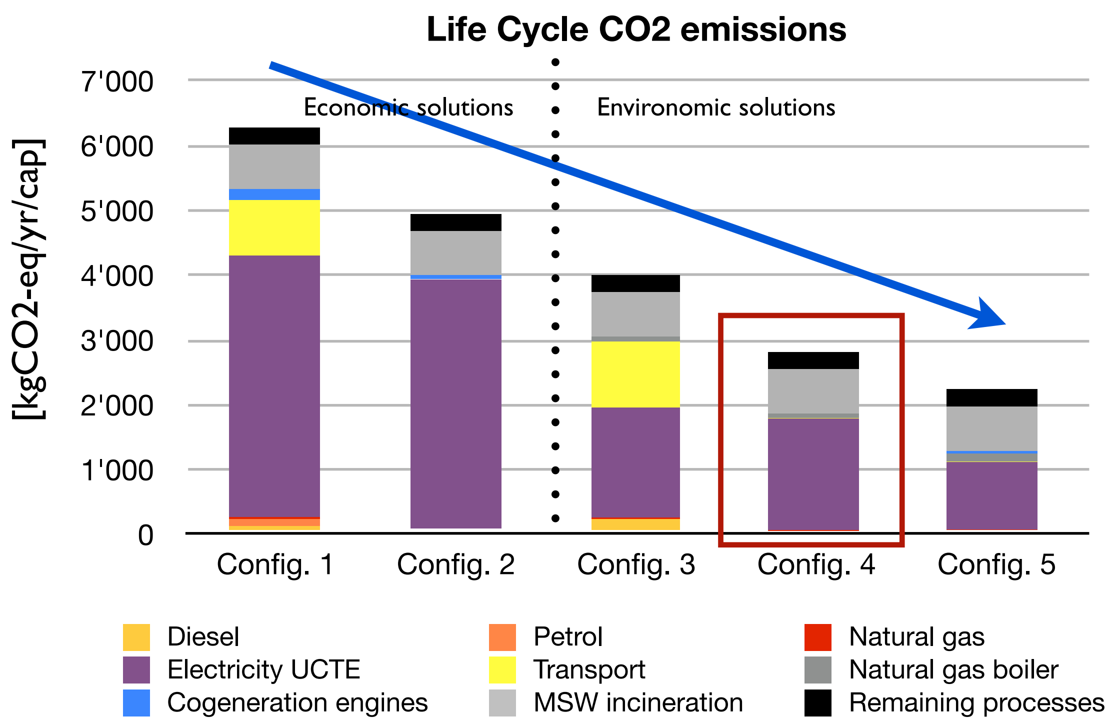

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Optimal system design

- Seasonal operation
  - Example of heat and electricity flows for configuration 4

Cinv: 4.27 mioEUR
Cop: 58.4 mioEUR/yr
I: 2.77 tCO_2-eq/yr/cap

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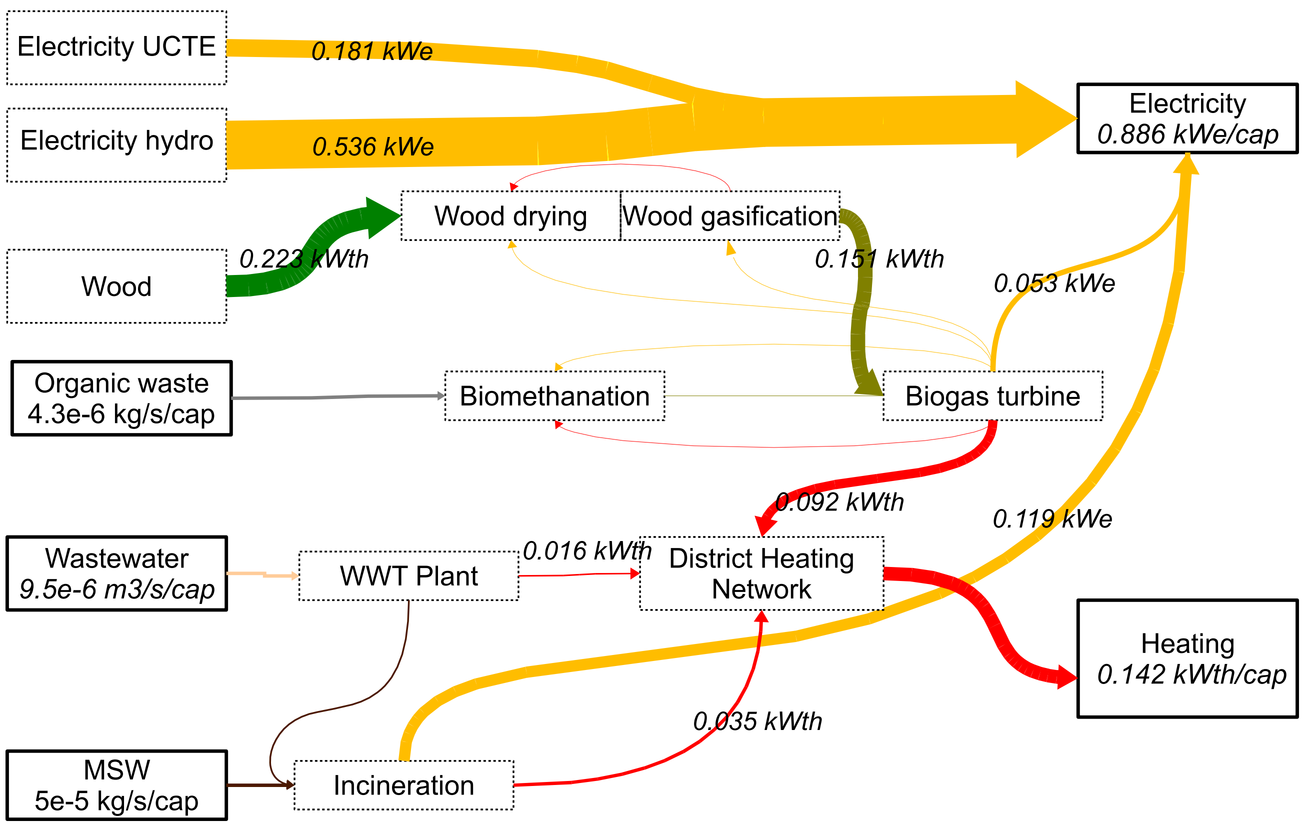

May, July & August

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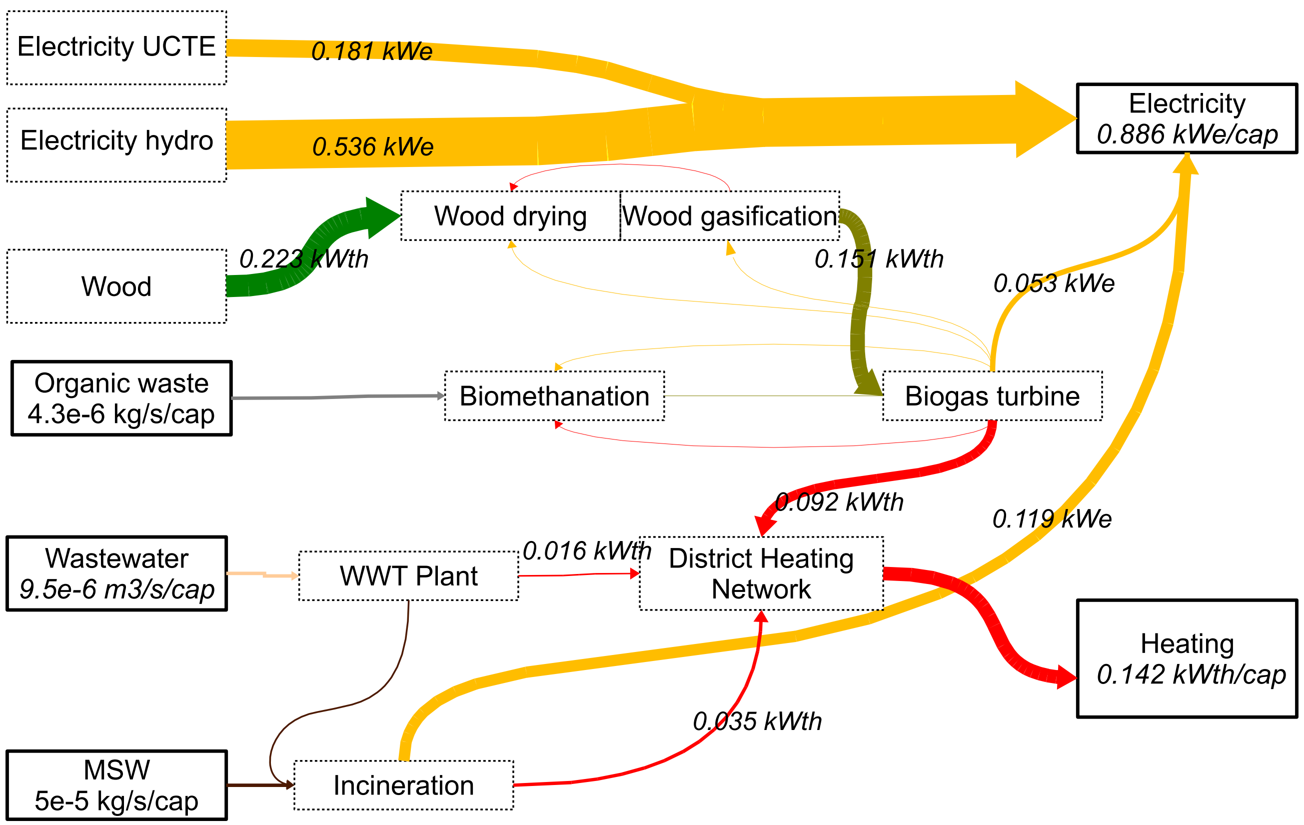

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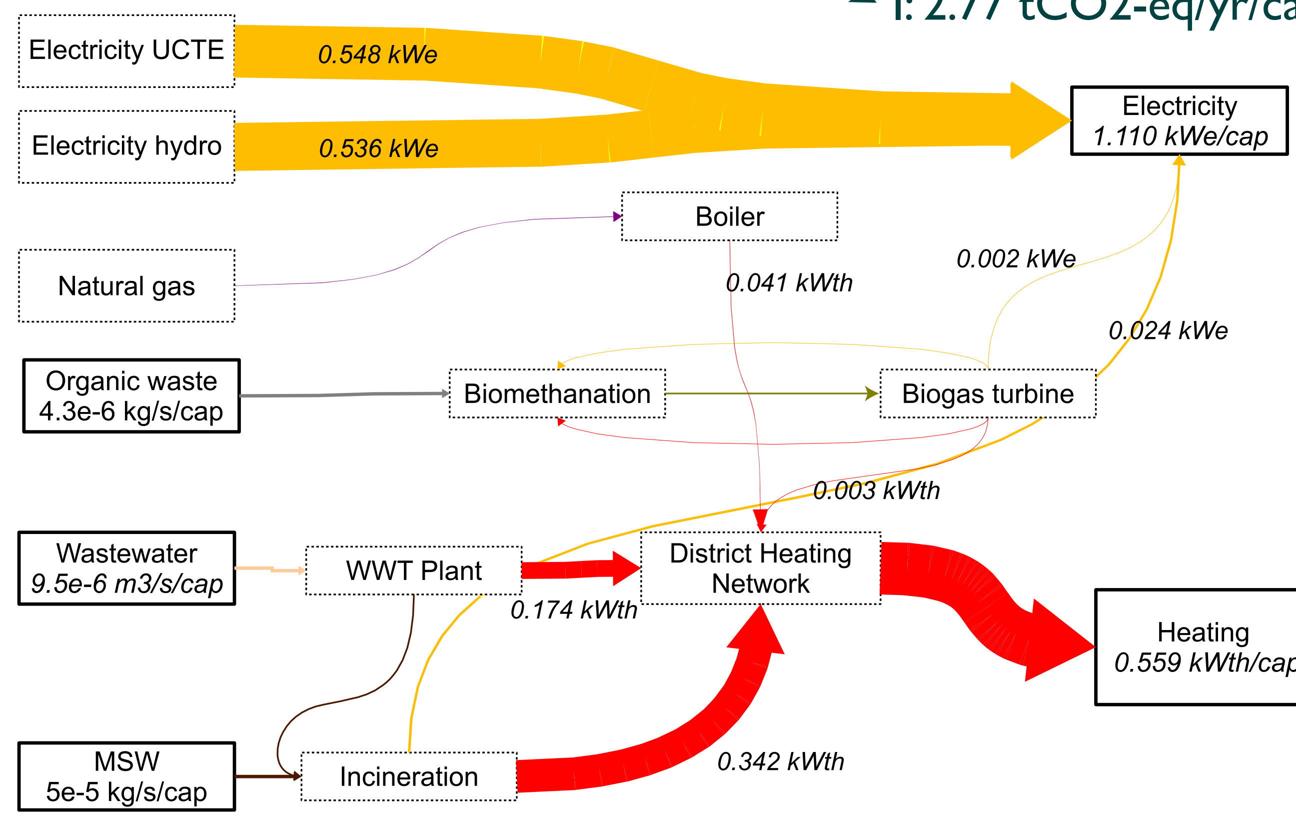

November-February

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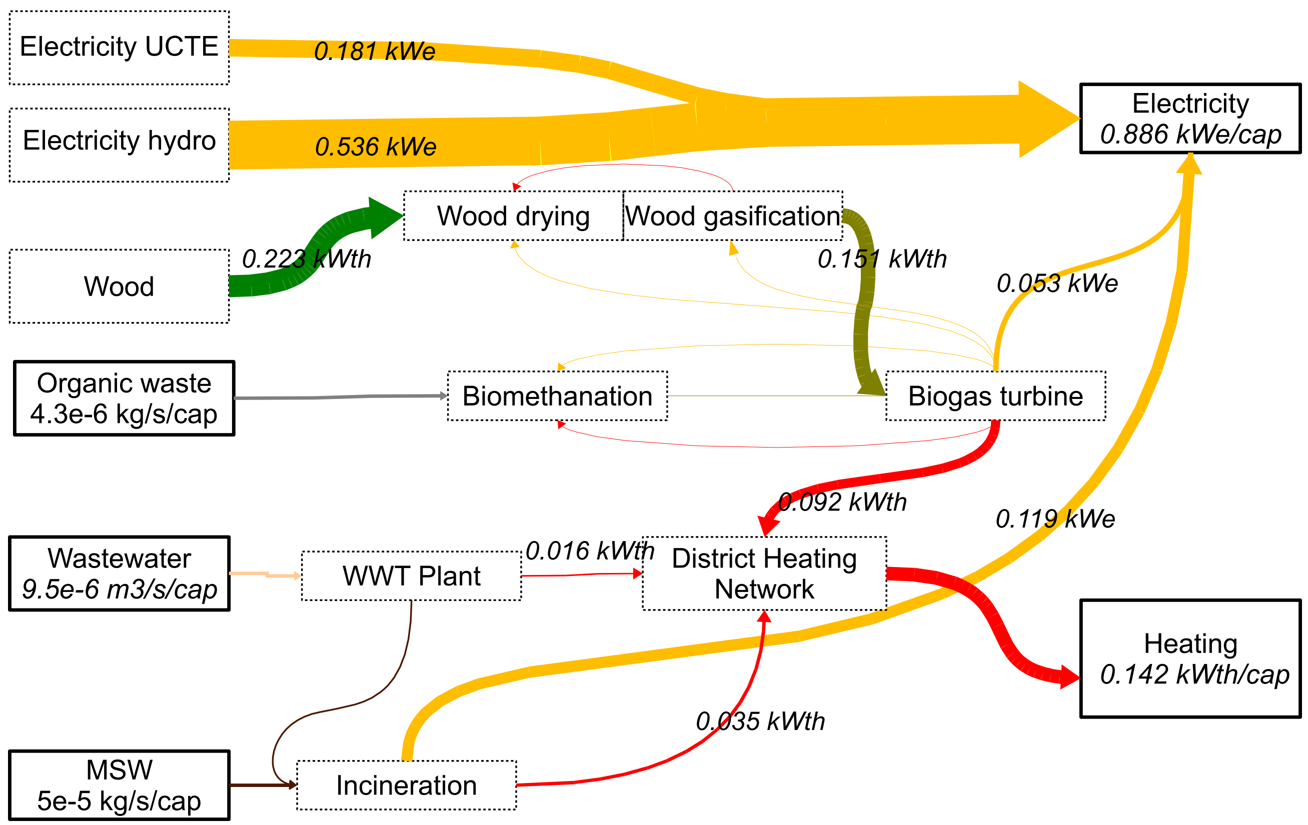

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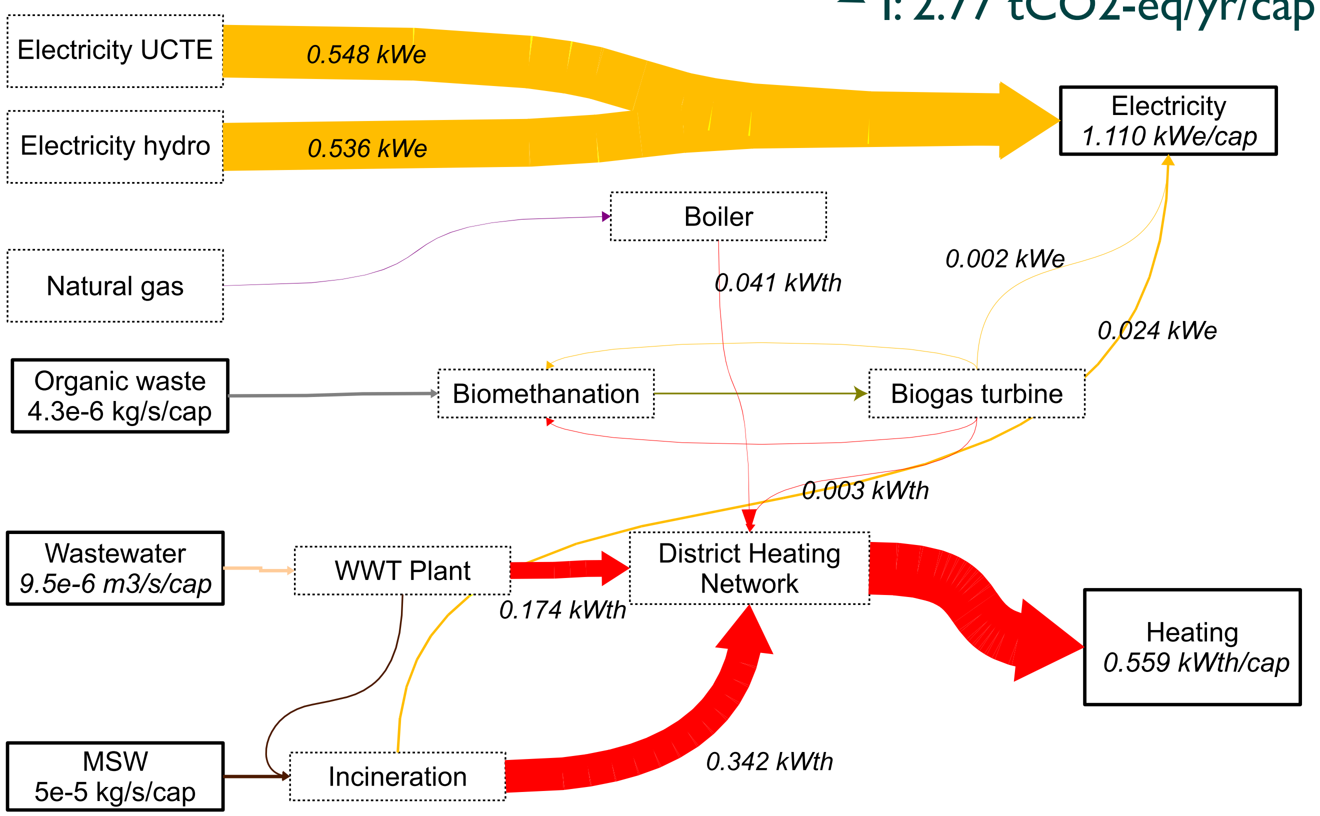

November-February

- *Adapted operation of waste treatment facilities*

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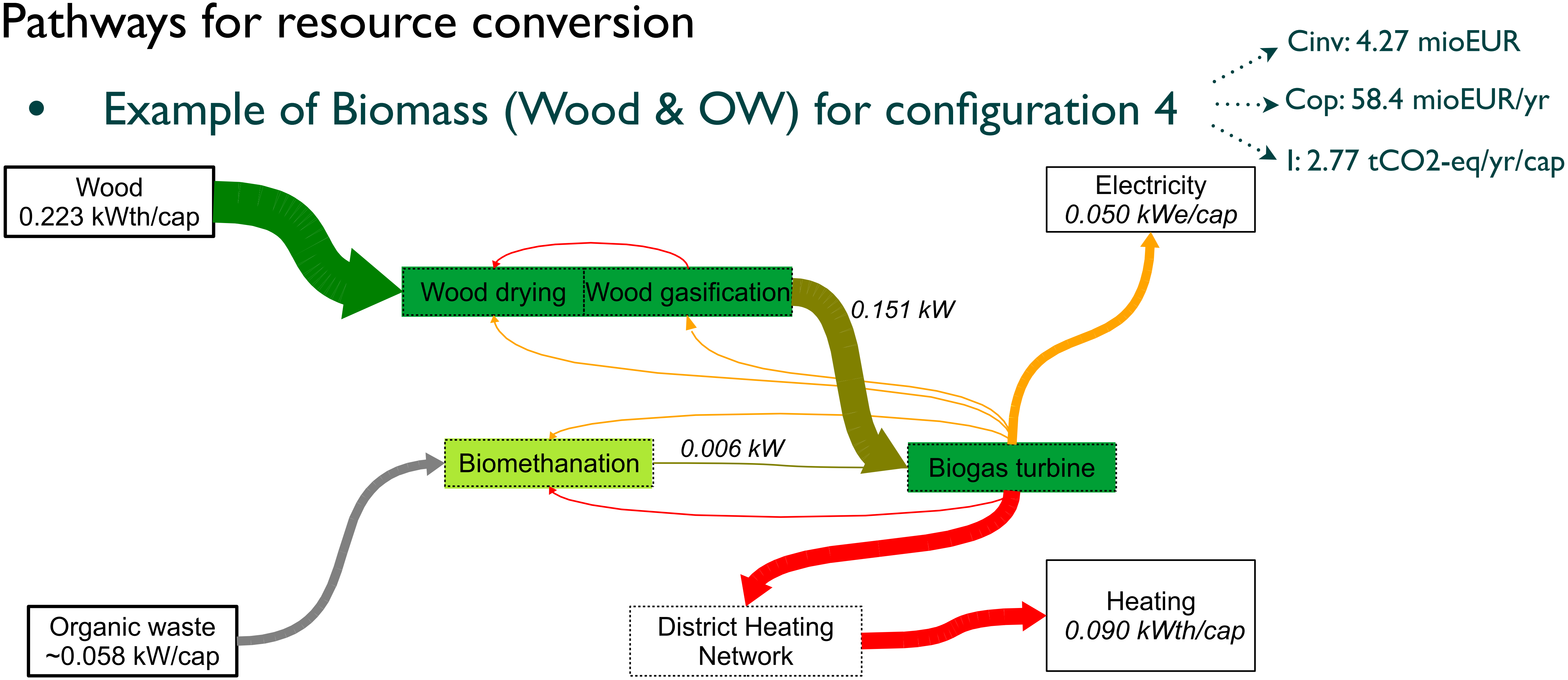
- Pathways for resource conversion
  - Example of Biomass (Wood & OW) for configuration 4



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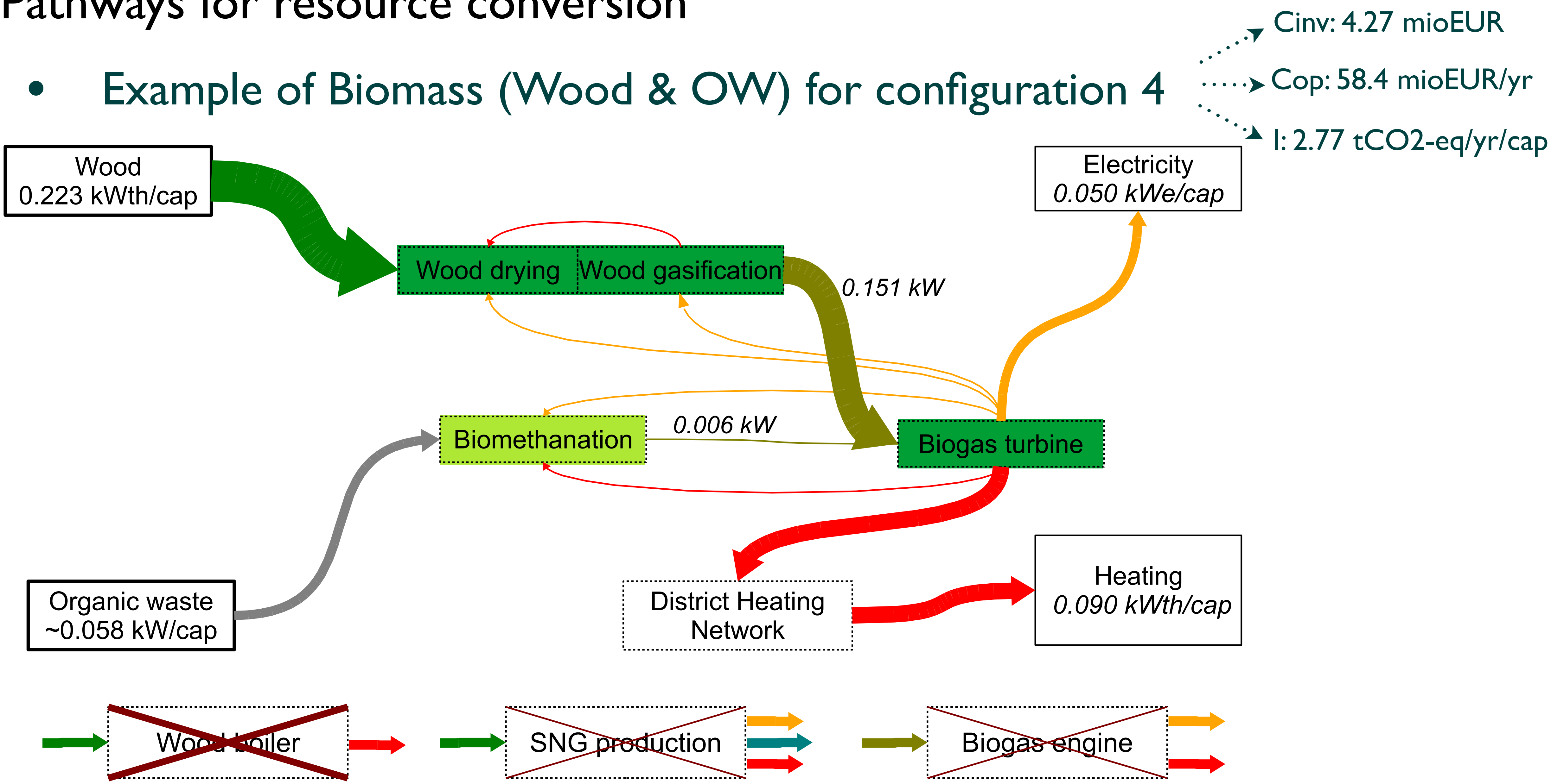

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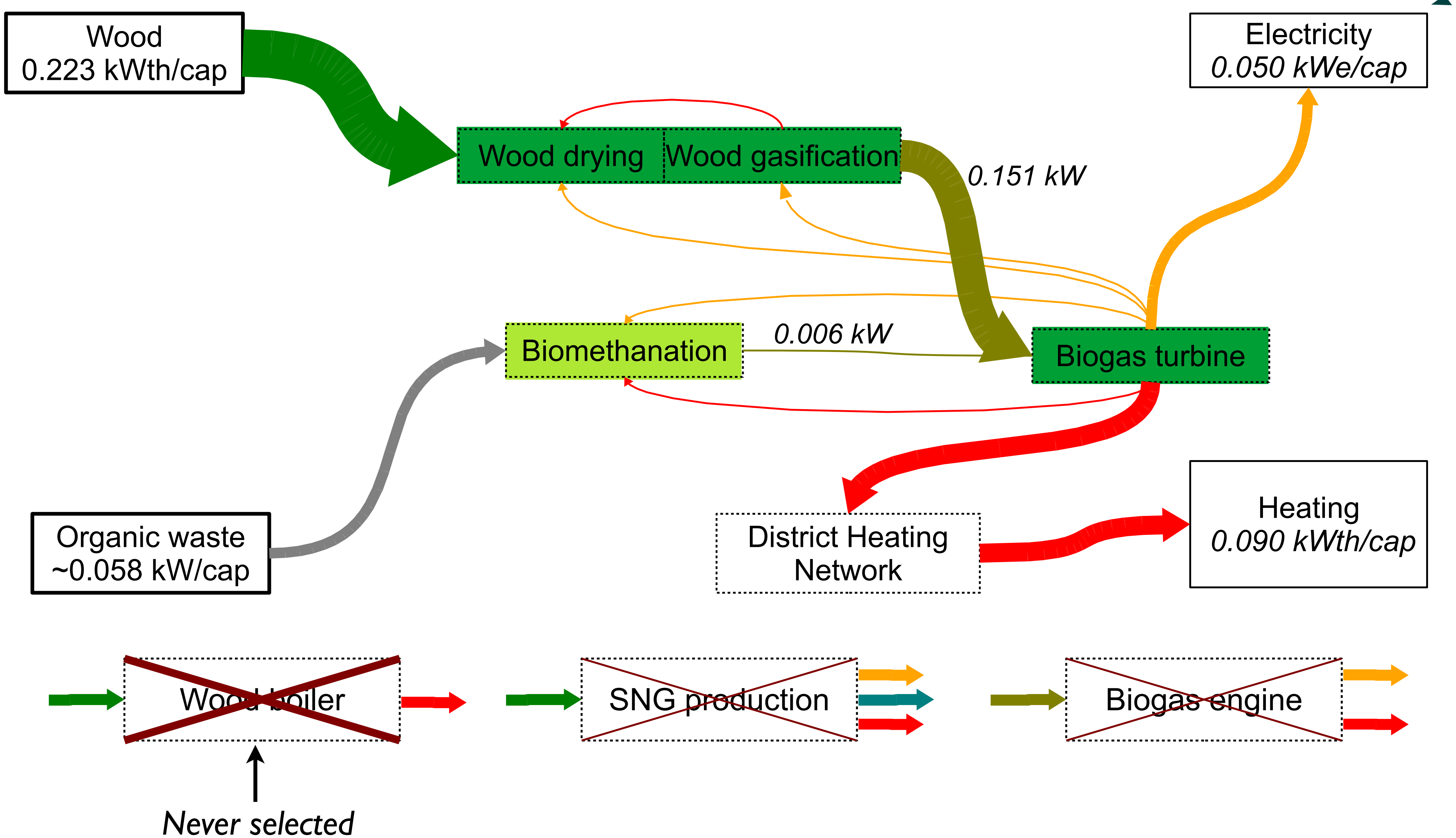

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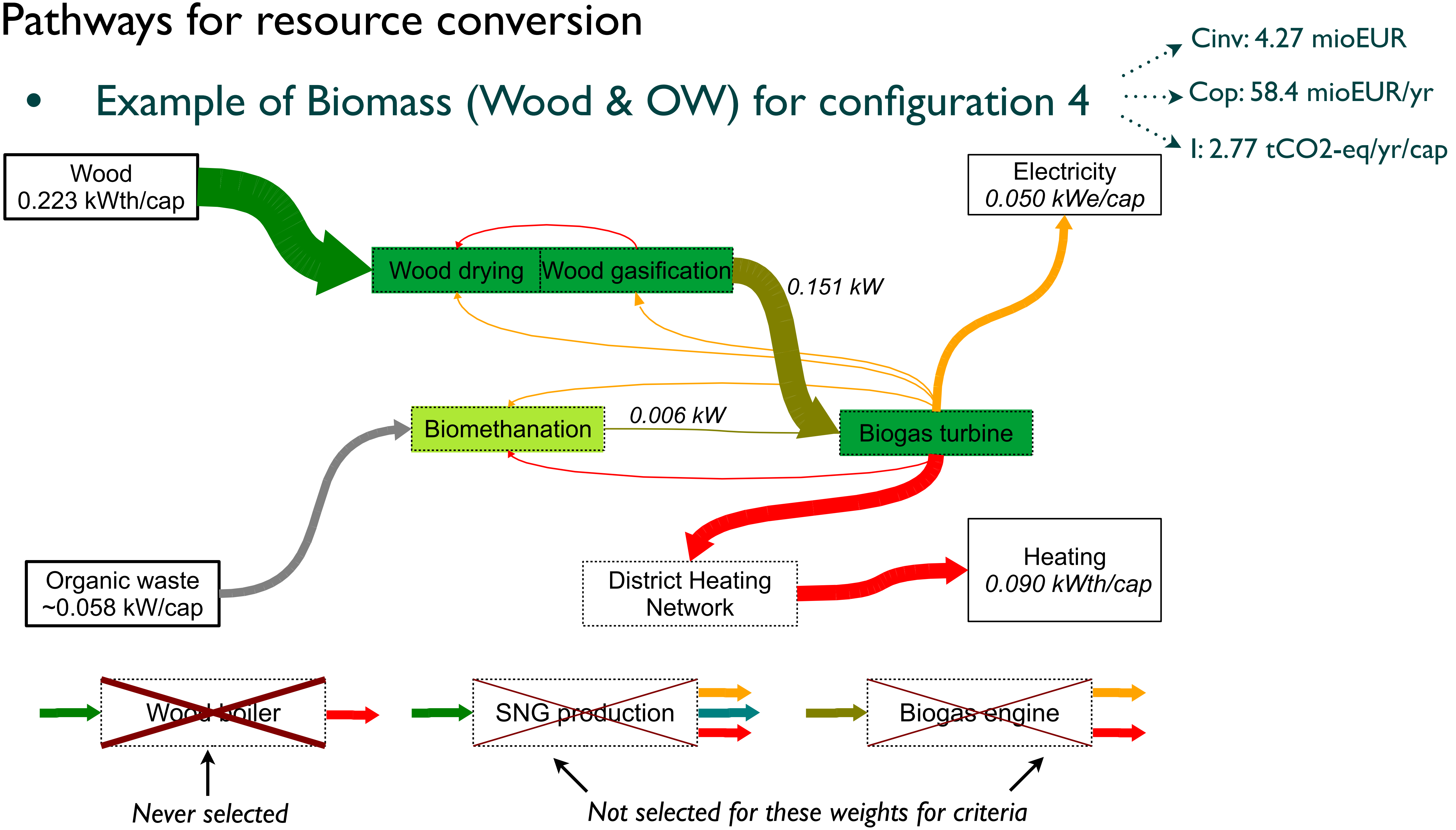

Conclusions

- Systematic methodology for design of urban energy systems
  - Process design and integration
  - Life cycle assessment
  - Industrial ecology
- Help for decision-making and territorial planning
  - Inclusion of environmental objectives
    - Influences design decisions
  - Identification of best pathways for waste treatment and resource valorization
    - Seasonal variations accounted for

Perspectives

- Energy and mass storage possibilities
  - Optimal distribution over the year
- Extension to larger territories
  - Constraints on locations of resources and services distribution
  - Logistics has to be accounted for
- Integration of Geographic Information Systems in the computational framework
- Application to eco-industrial parks

Thank you for your attention!