# ON THE ROLE OF PROCESS SYSTEM ENGINEERING FOR THE ENERGY TRANSITION

**Prof. François Marechal @fmarech**
**Industrial Process and Energy Systems Engineering, EPFL, Switzerland**

youtube : TEDx Martigny Marechal

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# We want Switzerland to be Independent and Neutral !

The Youths Revolution


and The Scientists Revolution

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# Our chalenge : Engineering a Net-Zero future

**Renewable resources**

Where-When-How much ?

**Investments**

(**New**) Technologies

sizes : conversion and storage

Infrastructure => synergies & mutualisation

**Demand**

Products

Services

Security of supply

**Management**

Operation + Storage

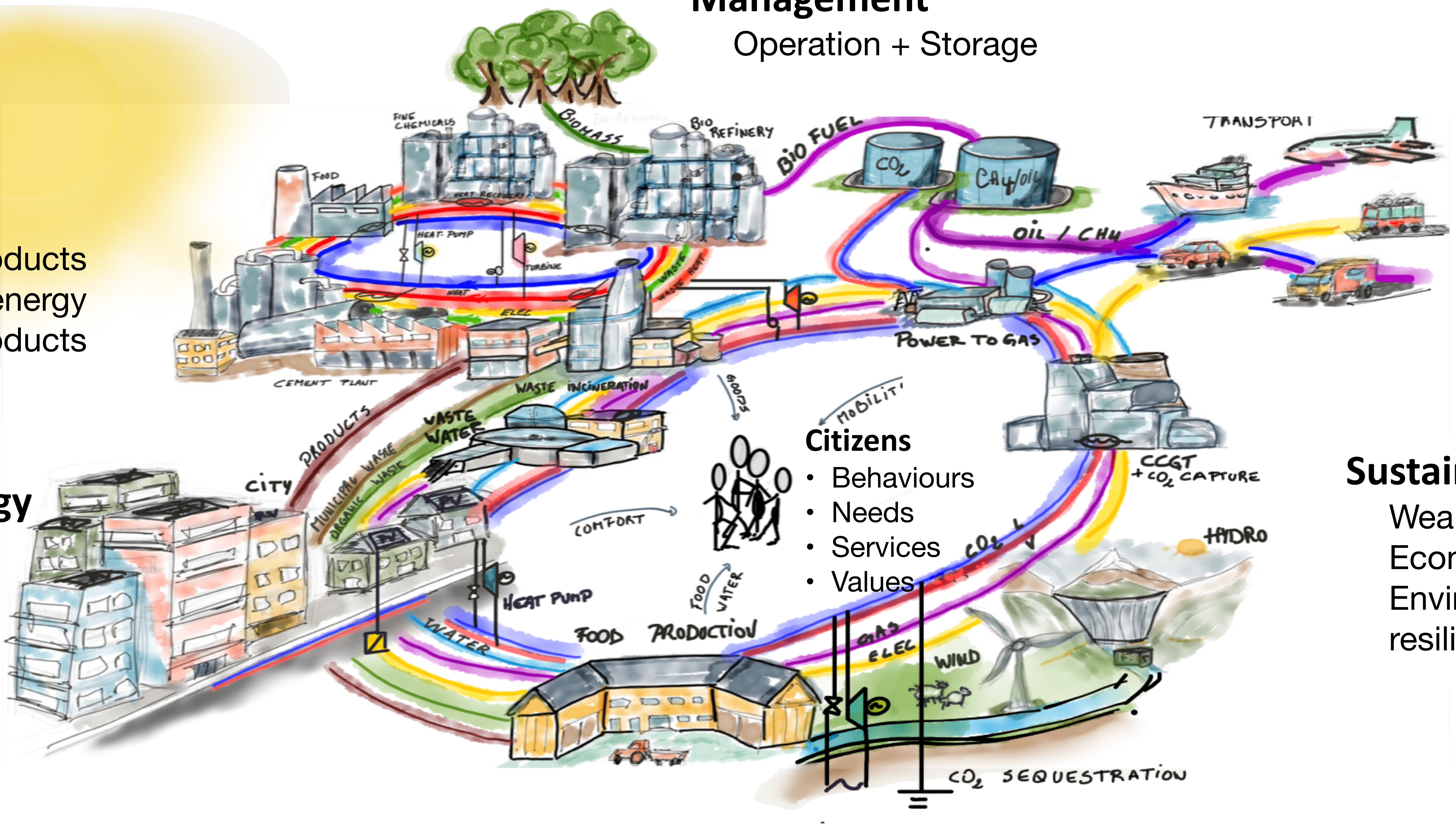
**Circularity**

Waste to products

Waste to energy

CO2 to products

**Waste-Water-Energy**




**Citizens**

- Behaviours
- Needs
- Services
- Values

**Sustainability metrics**

Wealth

Economy

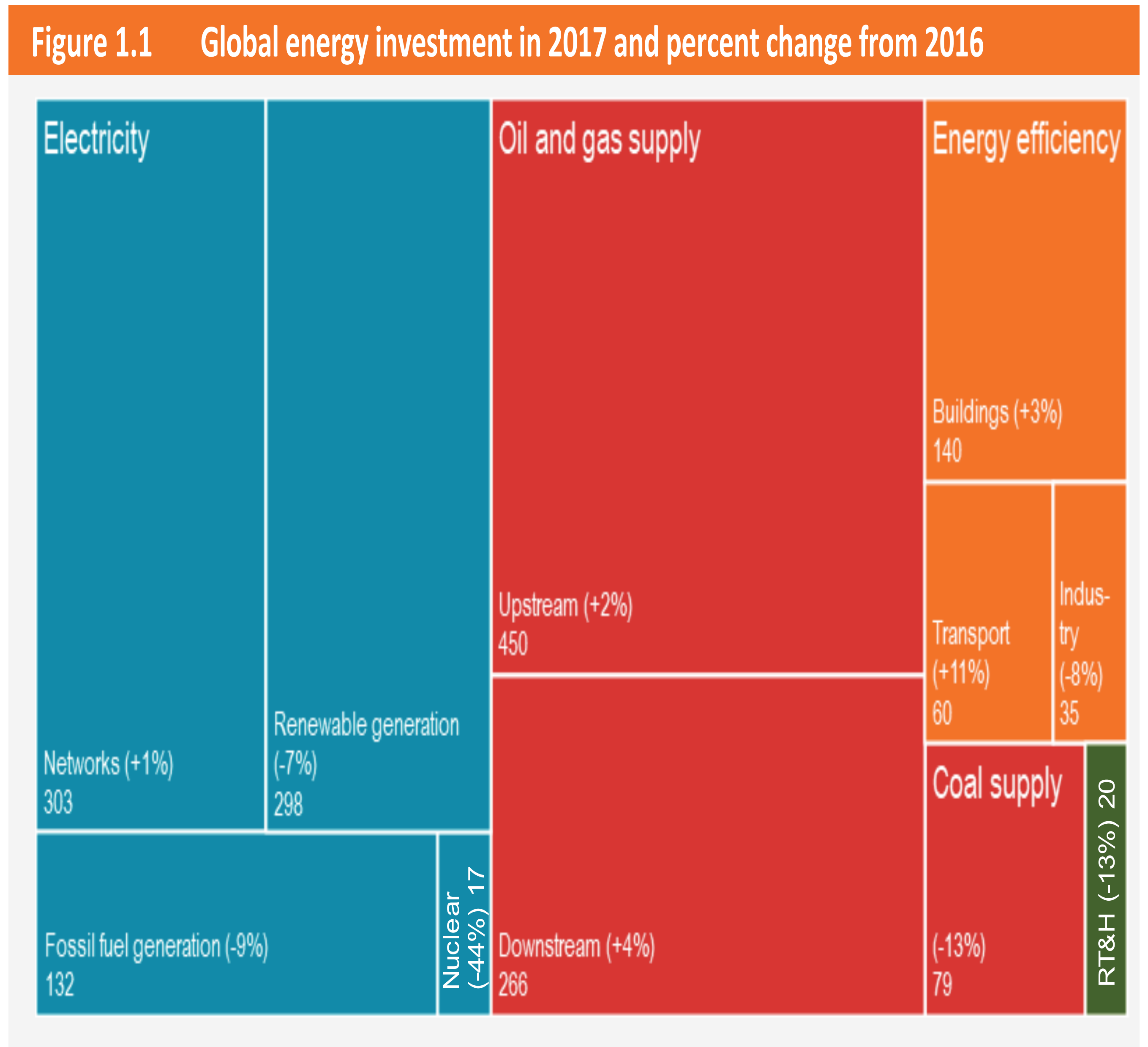
Environment

resiliency

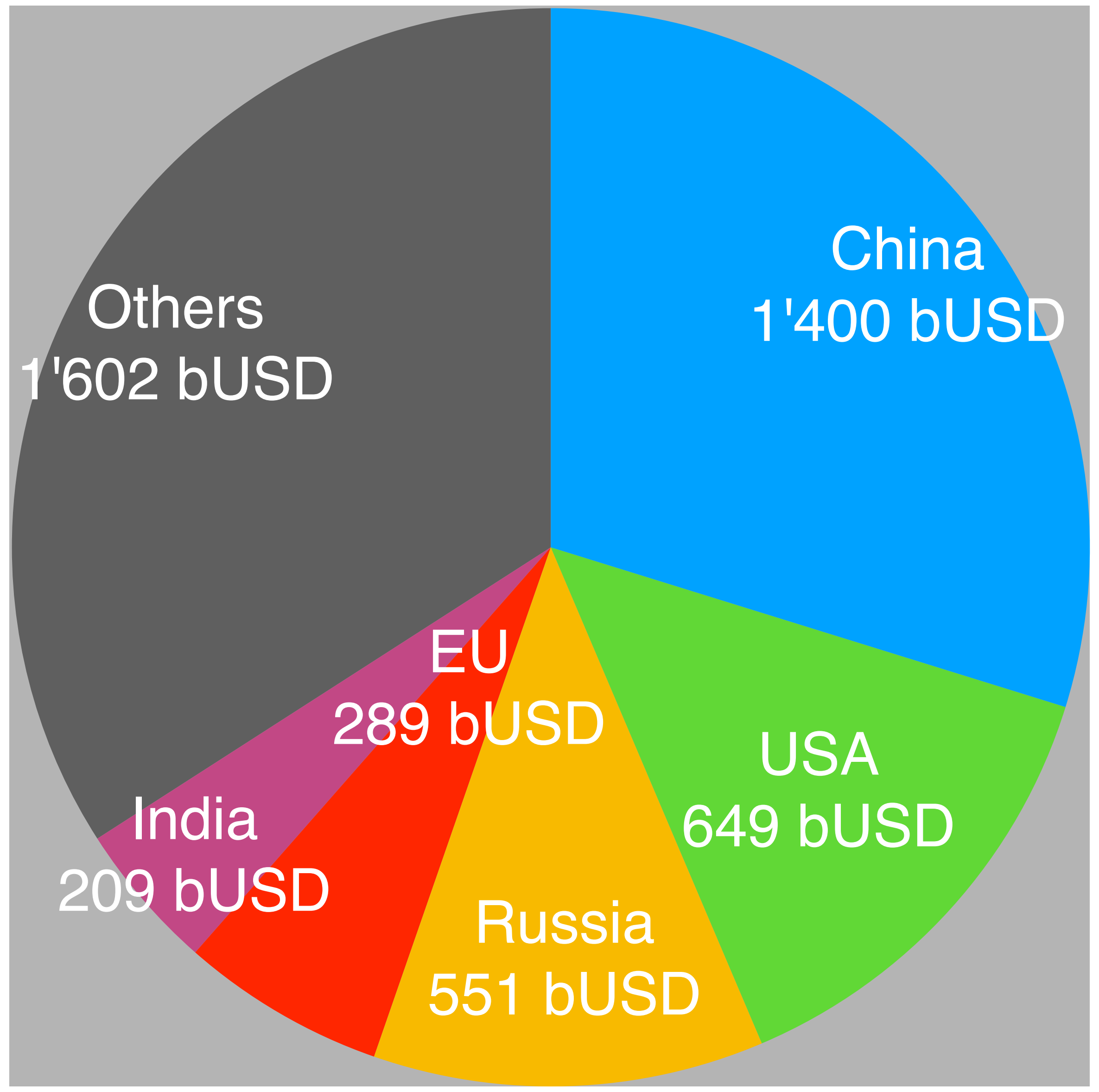
**CO2 sequestration**

# EPFL do we have the money ? : 2015 fossil spendings world wide

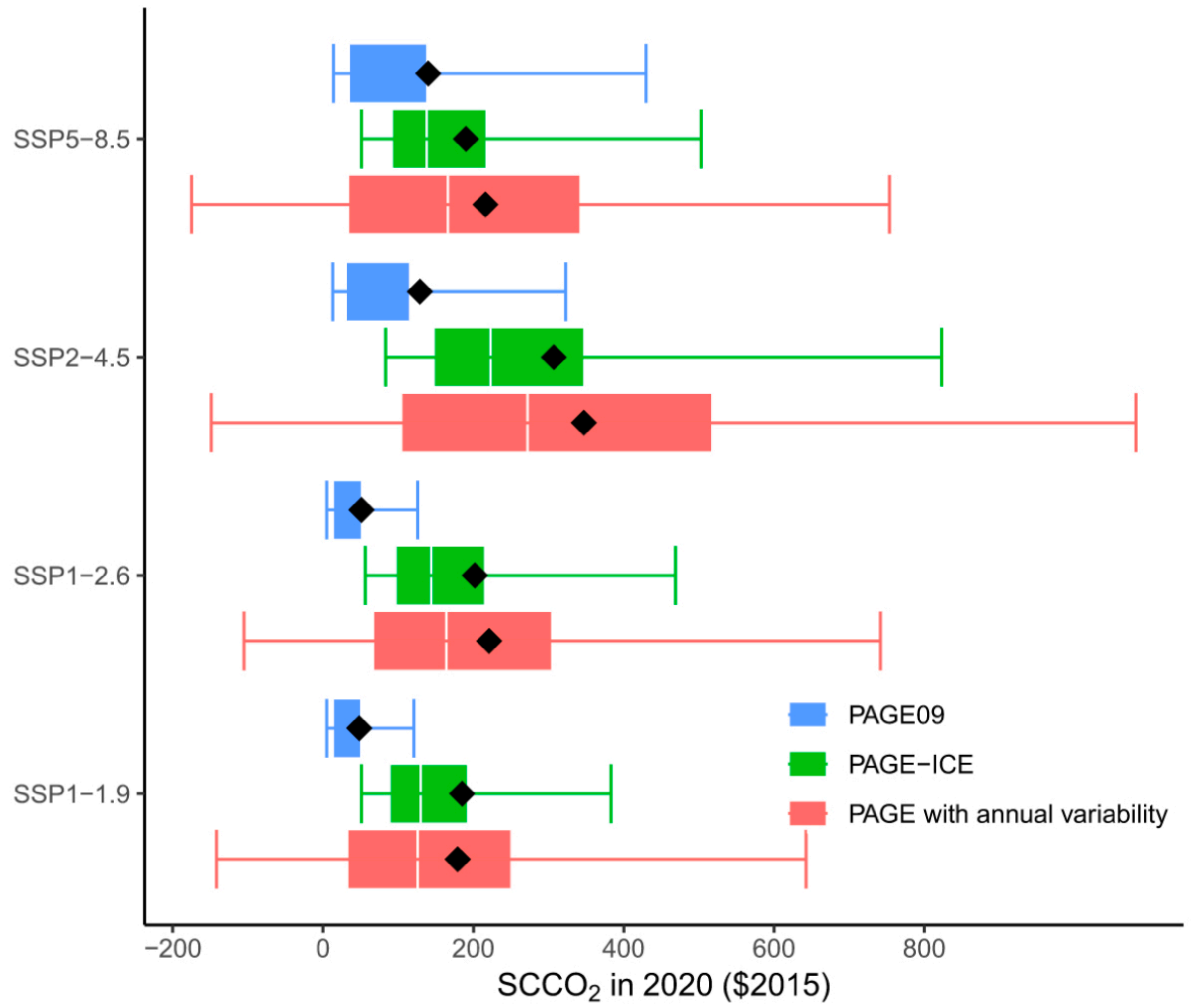
| 1.0 US$ | 2.5 US$ | 4.0 US$ |
|---|---|---|
| Investment by industry | Subsidies by countries | Social cost to be paid by next gen |
| 1'800 | 4'700 | 7'200 |
| bUS$/year (2017) | bUS$/year (2015) | bUS$/year (2015) repairing the damages |




World energy investment 2018 IEA.org




World energy subsidies 2015 imf.org




200 USD/t CO2

Jarmo S Kikstra et al 2021 Environ. Res. Lett. 16

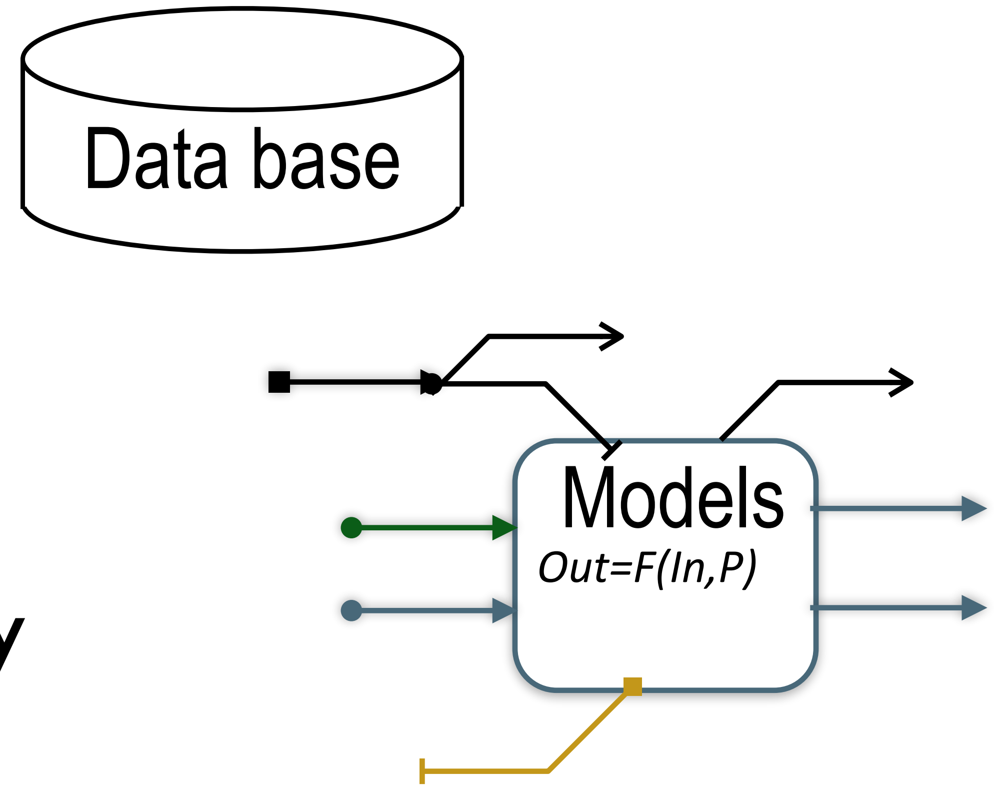
François Maréchal – francois.marechal@epfl.ch

ME-409 ENERGY CONVERSION AND RENEWABLE ENERGY

# Decision support for system engineering

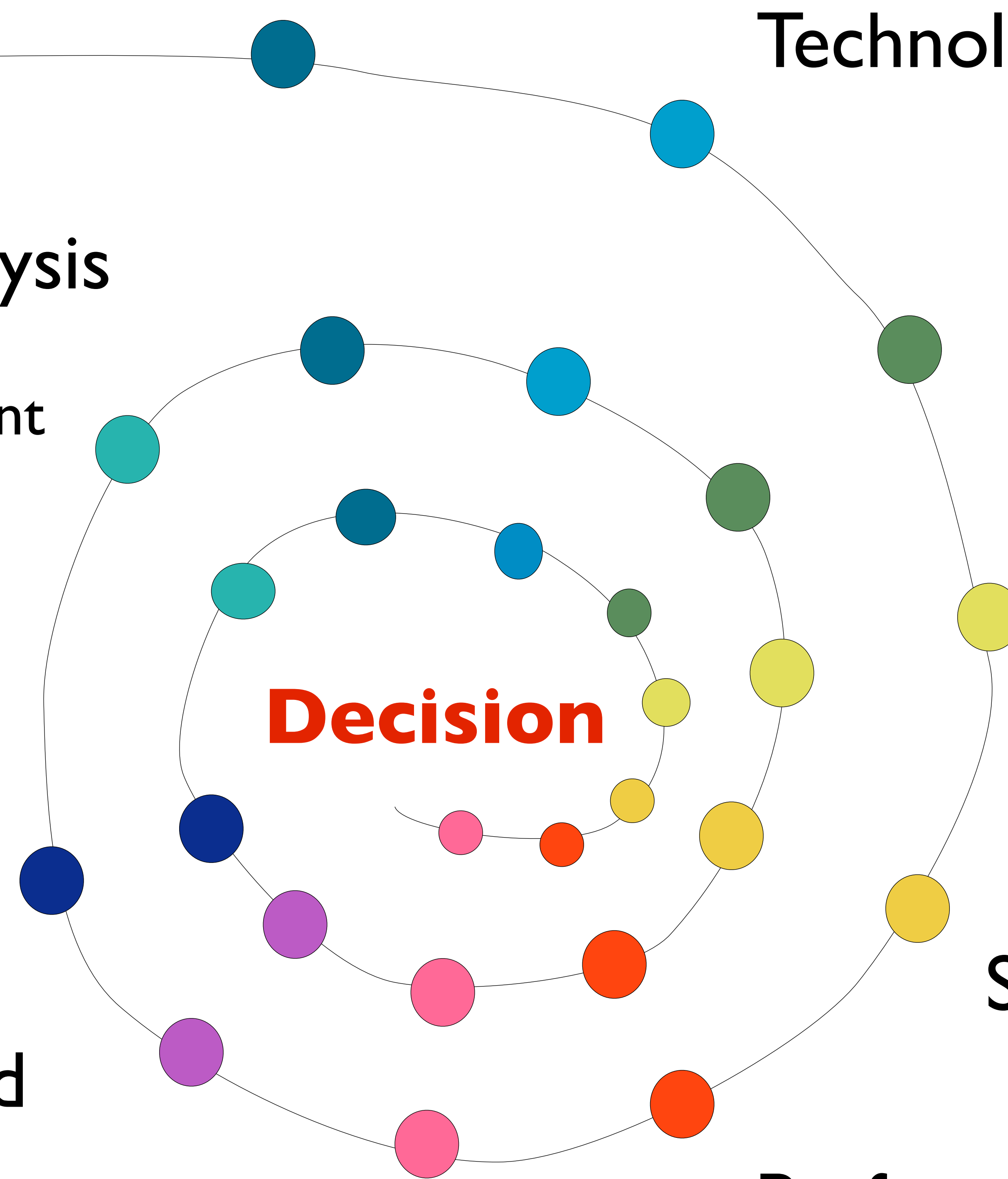
**Context & Constraints**
**Resources**
**Product and services**

System Boundaries

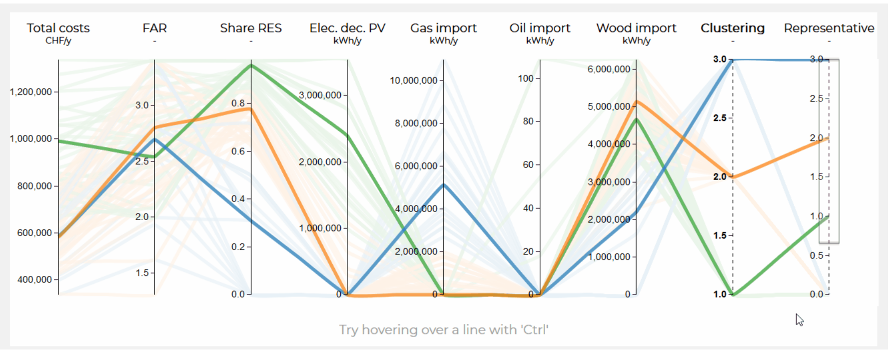



Technology options

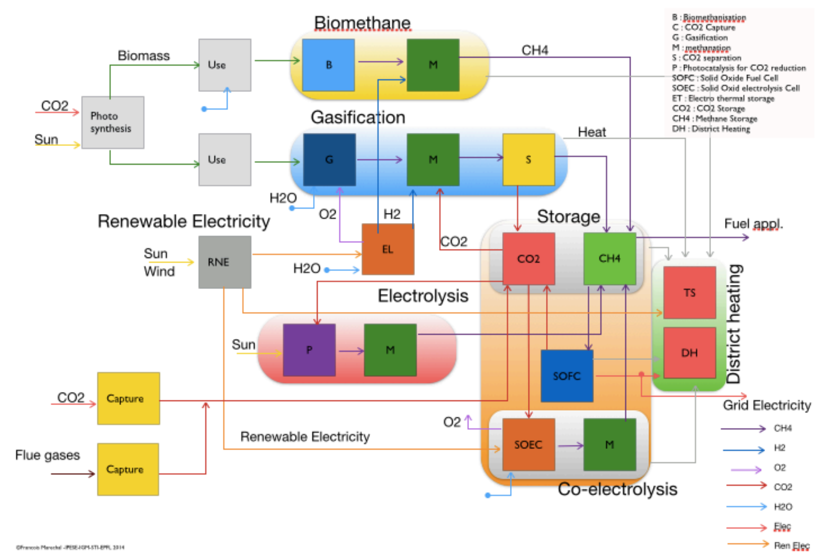
Connectivity




Results analysis
- Exergy analysis
- Sustainability assessment
- Sensitivity analysis
- Multi-criteria analysis
- Uncertainty

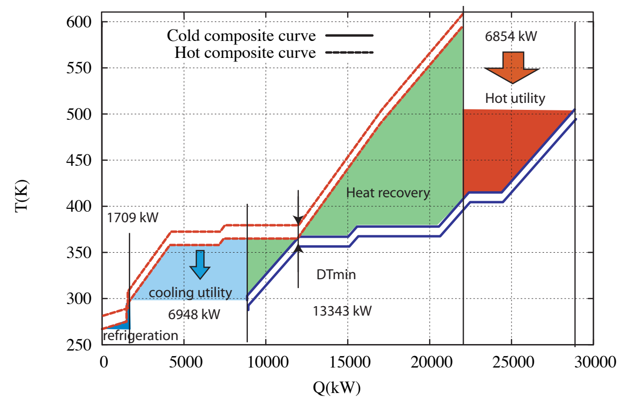



System superstructure

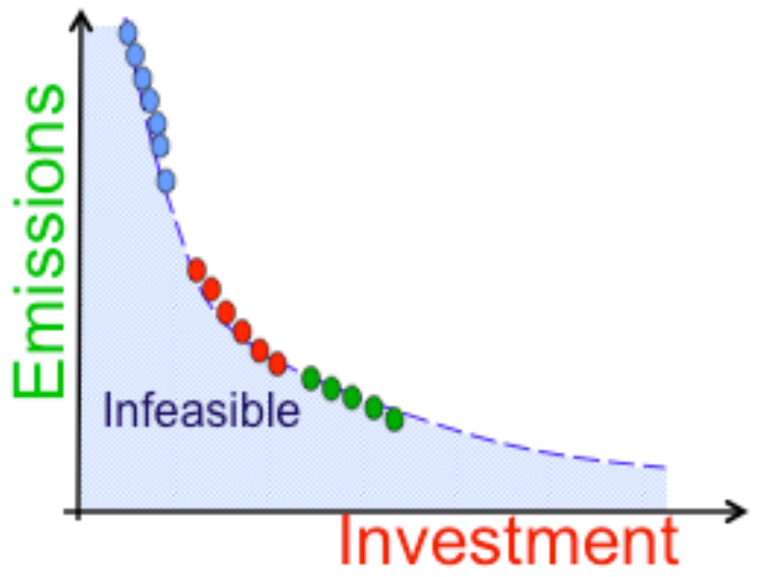



Configurations generation

System integration




Solving method




Decision variables

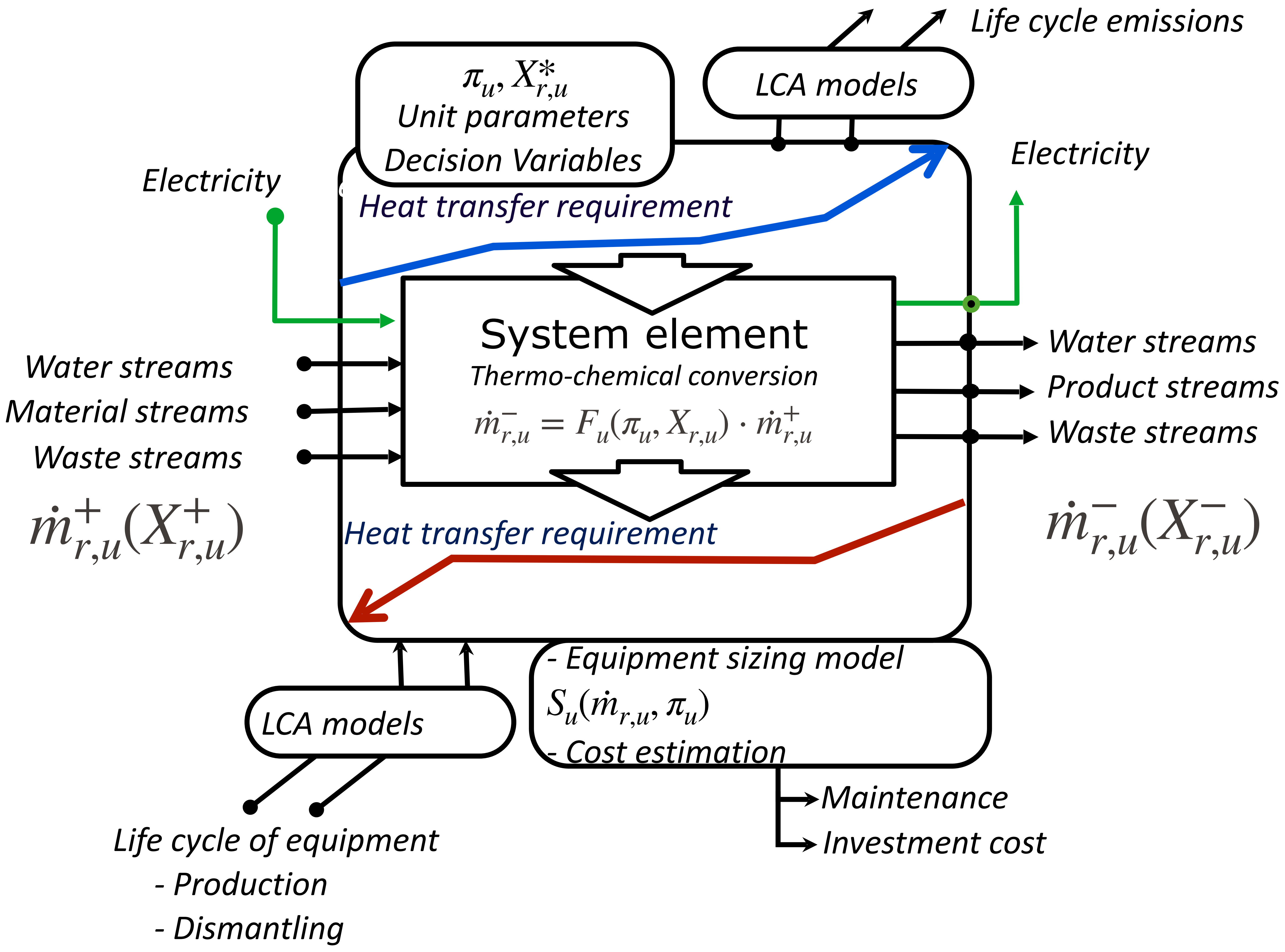
Performances
- Economic
- Thermodynamic
- Resilience
- Life cycle sustainability impact

**AGIR** : Analyse - Generate - Interpret - Report

**OSMOSE** : computer platform for decision support in integrated energy system design

IPESE
Industrial Process and Energy Systems Engineering

# Sub-system's elements models




- Interconnectivity
  (mass & energy exchanges)
- Life cycle emissions
  (Equipment, Emissions)
- Sizes
  (Investment, Maintenance, Life cycle)
- Model : $\dot{m}^-_{r,u}(X^-_{r,u}) = F_u(\pi_u, X^*_{r,u}) \cdot \dot{m}^+_{r,u}(X^+_{r,u})$
  $\pi_u$ : model parameters (knowledge)
  $X^*_{r,u}$ : specification of the system
  $\dot{m}^+_{r,u}(X^+_{r,u})$ : state of input flows
  $\dot{m}^-_{r,u}(X^-_{r,u})$ : state of output flows

# OPTIMAL DESIGN : MI(N)LP MULTI PARAMETRIC FORMULATION

$\forall \quad KPI_i^{\pi} \in \{\pi_o \dots \pi_{n_{pi}}\} by \Delta\pi$ => multi-parametric optimisation

$\min_{x_{u,t_p,p}, S_u, y_{u,t_p,p}, y_u, \pi_u, a_u} \quad OBJ = KPI_o$ => define technologies, sizes and flows for a selected key performance indicator "o"

=> Performances as total cost, environmental impact, capital, wallets, employment

s.t. $KPI_i = \sum_u^{n_u} \sum_p^{n_p} \sum_{t_p}^{n_{tp}} \delta t_{t_p} \cdot (\sum_f^{m_{f,u}} c_{f,i} \cdot \dot{f}_u(\pi_u, x_{u,t_p,p}) \cdot x_{u,t_p,p}) + \sum_u^{n_u} \frac{1}{\tau} \cdot (y_u I^0_{u,i}(\pi_u, S_u) + S_u I^1_{u,i}(\pi_u, S_u) \qquad \forall i \in \{performances\}$

$KPI_i \leq KPI_i^{\pi} \qquad \forall i \neq o$ => parametric epsilon constraints (e.g. capital)

=> mass and energy balances and accumulations and unit performance

$\sum_u^{n_u} \dot{f}_u(\pi_u, x_{u,t_p,p}) \cdot x_{u,t_p,p} + a_u \cdot x_{u,t_p-1,p} + a_u \cdot x_{u,t_p,p} = d_{s,t_p,p} \qquad \forall t_p, p, s \in flows, services$

$x_{u,t_p,p} \leq s_u(x_{u,t_p,p}, \pi_u) \cdot S_u \qquad \forall u, t_p, p$ => sizes

$x_{u,1,p} = x_{u,t_{np},p} \qquad \forall p$ => cyclic constraints & model based strategic operation

$S_u^{min} \cdot y_u \leq S_u \leq S_u^{max} \cdot y_u \qquad \forall u$ => existence of technology u

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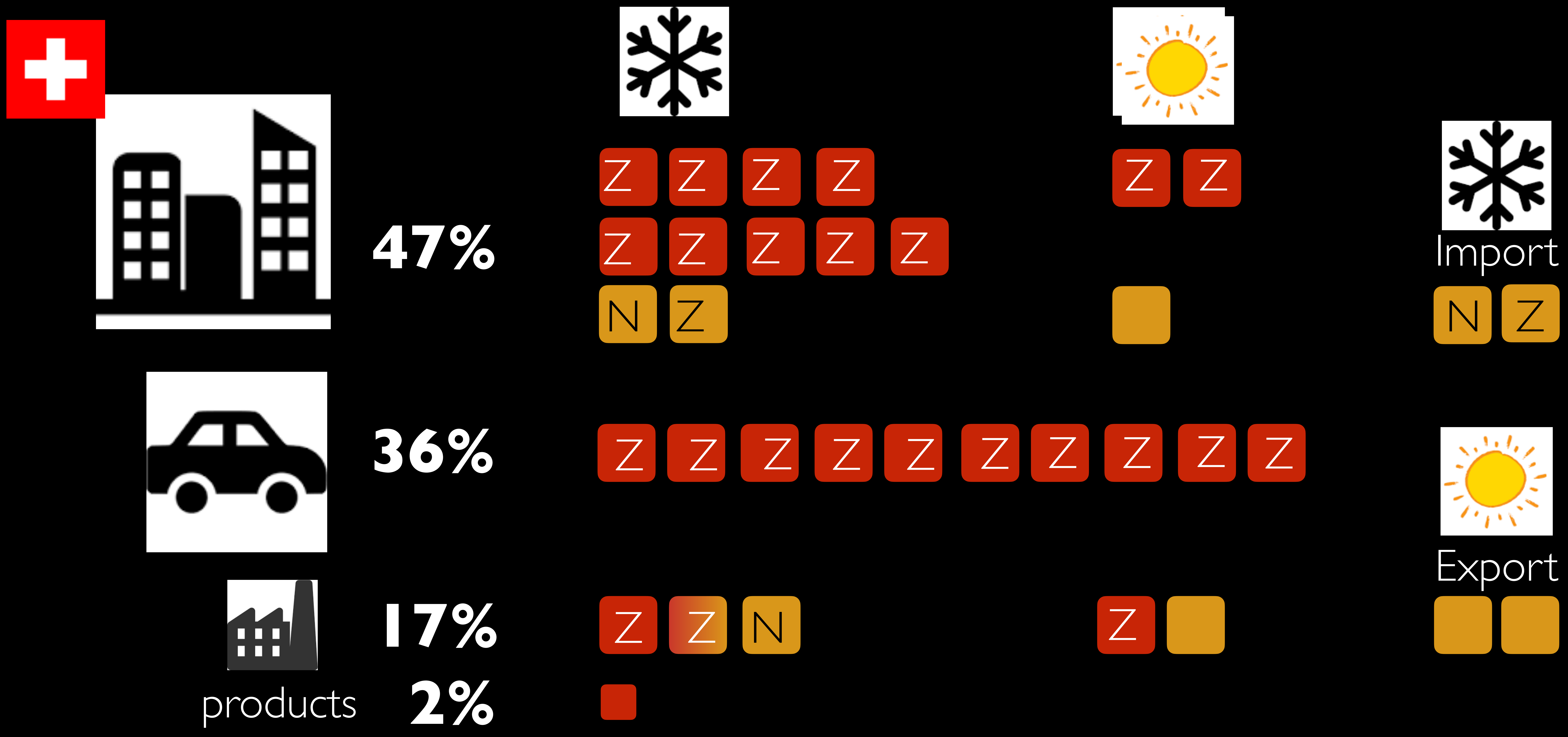
# ENERGY NEEDS




100 l gasoline/hab/year

Electricity

# HEATING BUILDING IS 50% OF COUNTRY ENERGY CONSUMPTION

**170-280**

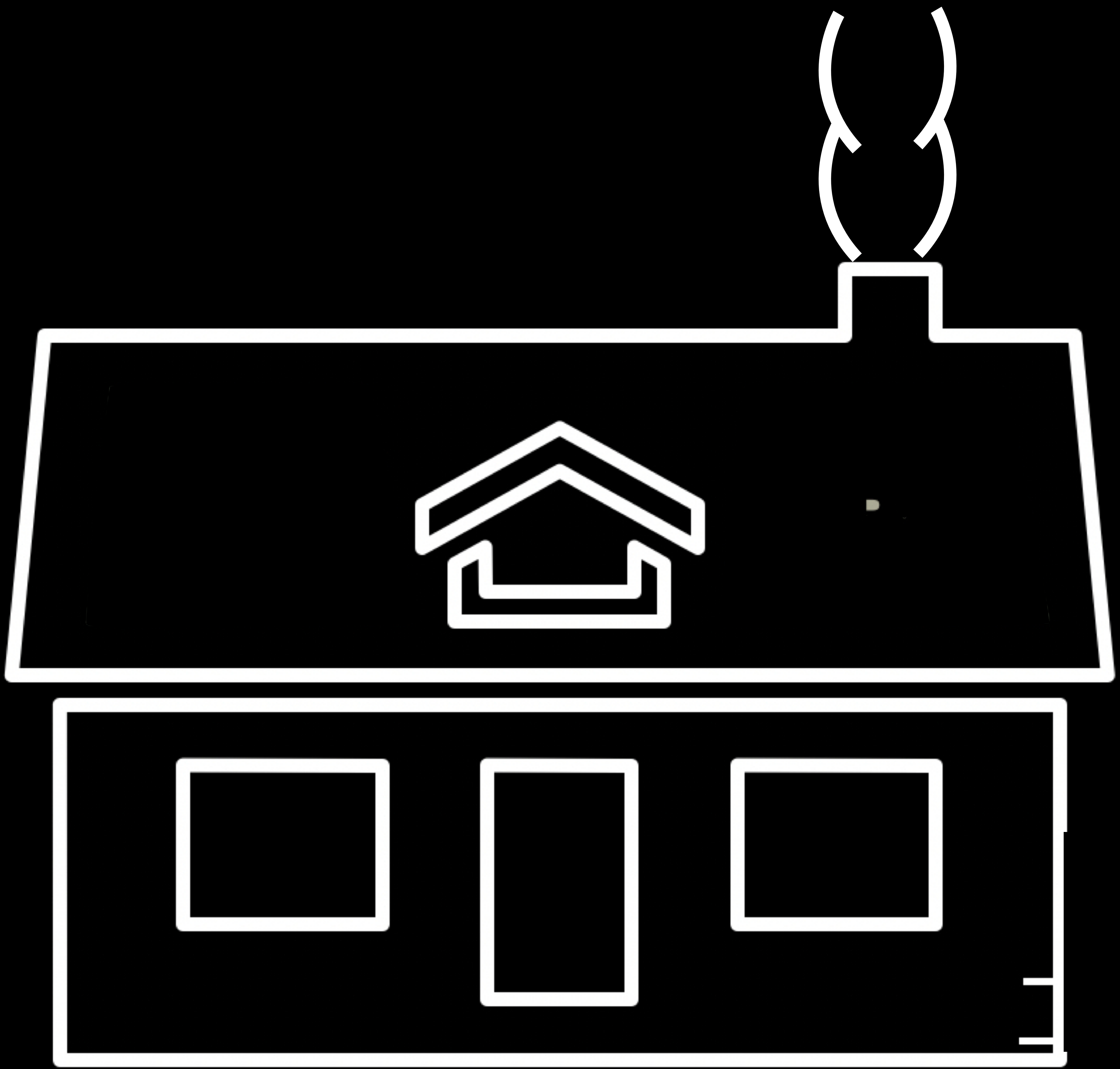
CHF/month/100 m²

**Energy (Oil)**

140-250 CHF/month/100 m²
in which 105-215 CHF/month/100 m² import

**Boiler**

30 CHF/month/100 m²



**3.8**

tons **$CO_2$** /year/100 m²

**63**

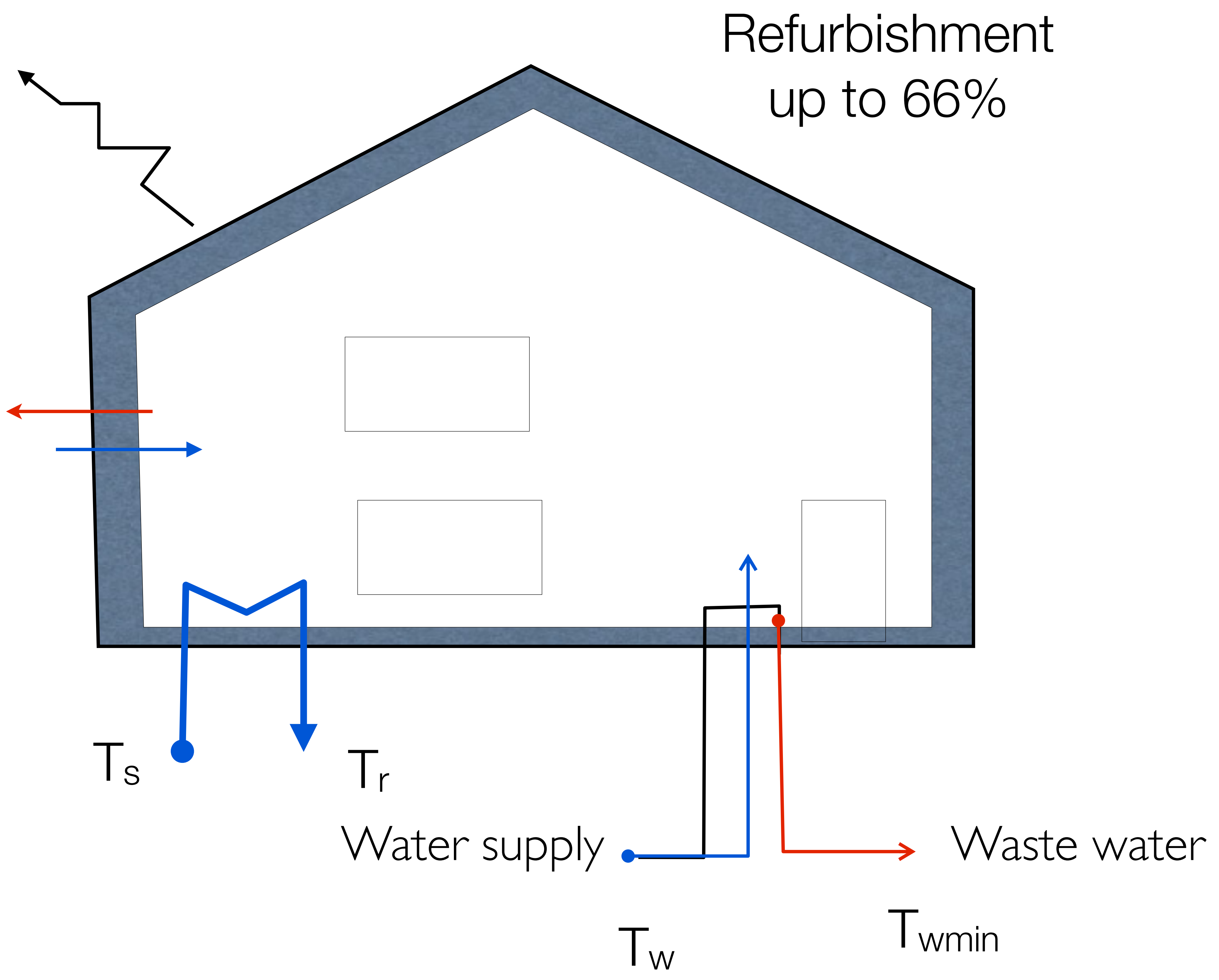
$CHF_{children}$/month/100 m²


Social cost of CO2: 200 CHF/ton CO2

# Buildings as a process system unit

## Definition of the energy requirements

- Heating
- Air renewal
- Hot water
- Waste Water
- Air renewal

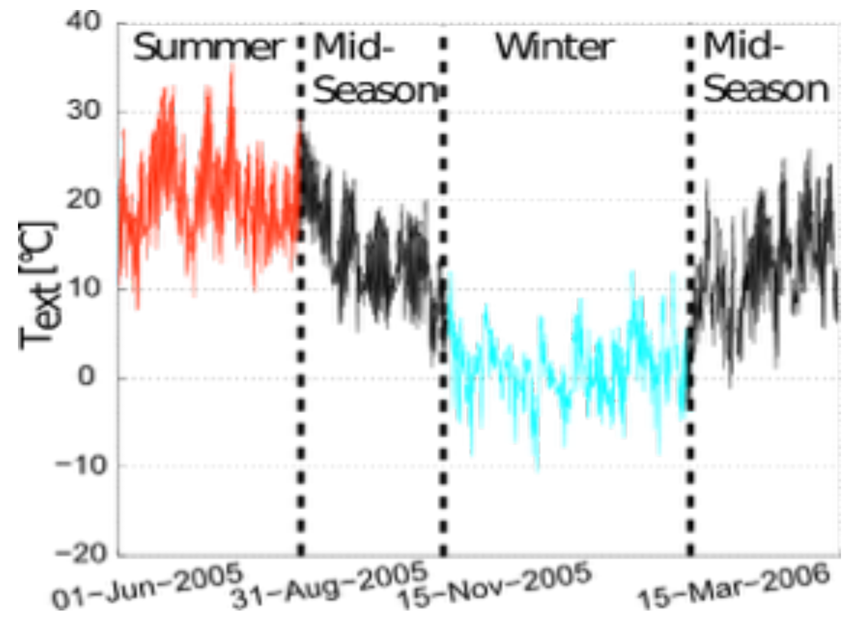


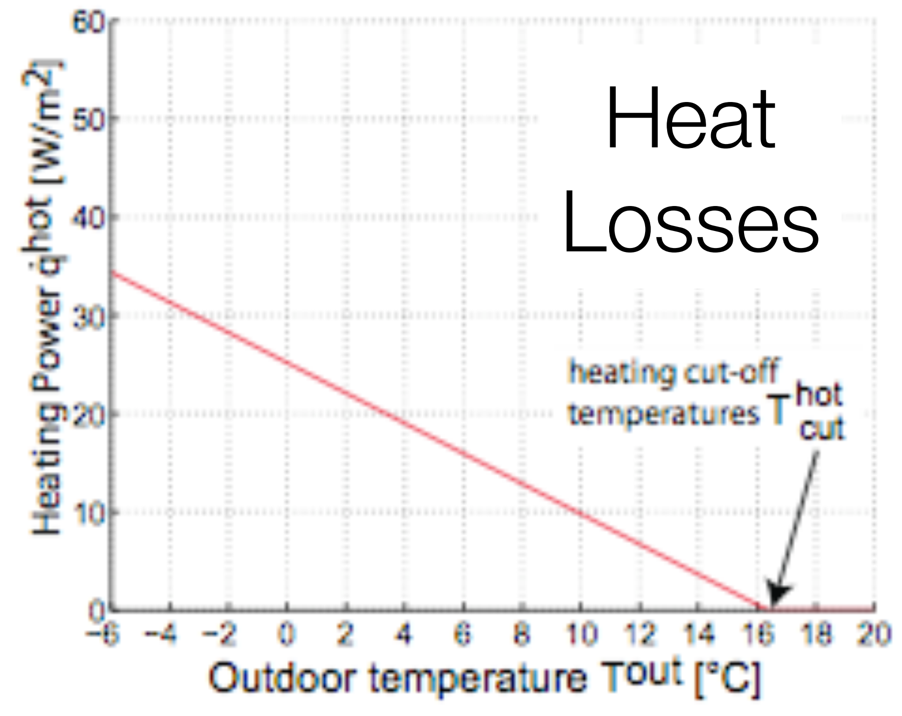

Heat exchange interface :

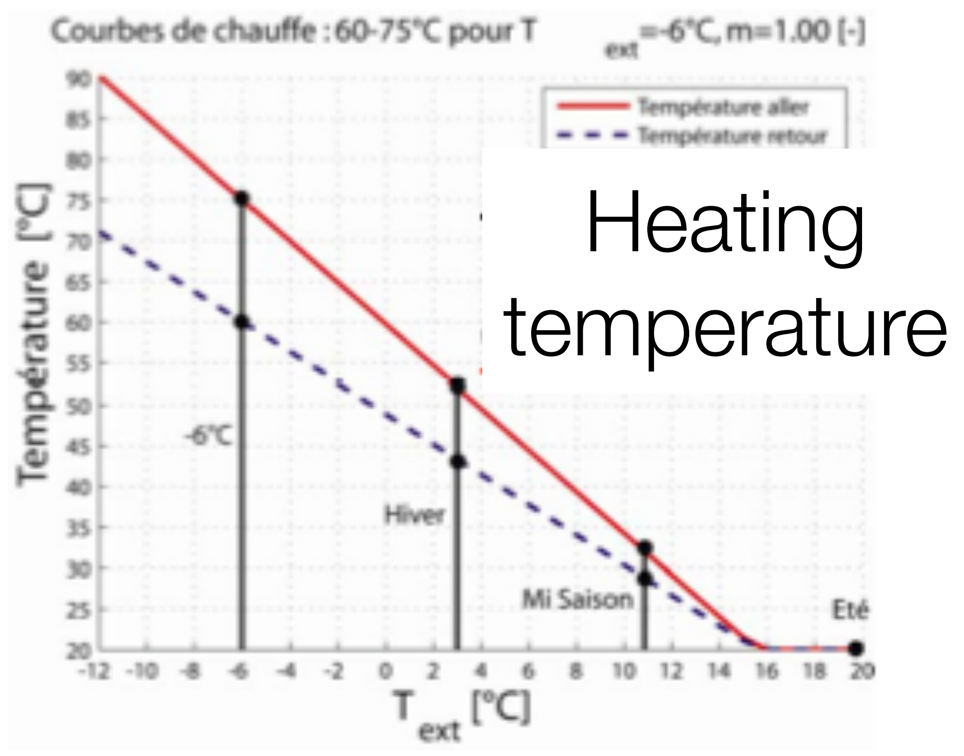
* Heat with the lower possible temperature
* Cool with the highest possible temperature

Multi-states problem (seasonal variations)

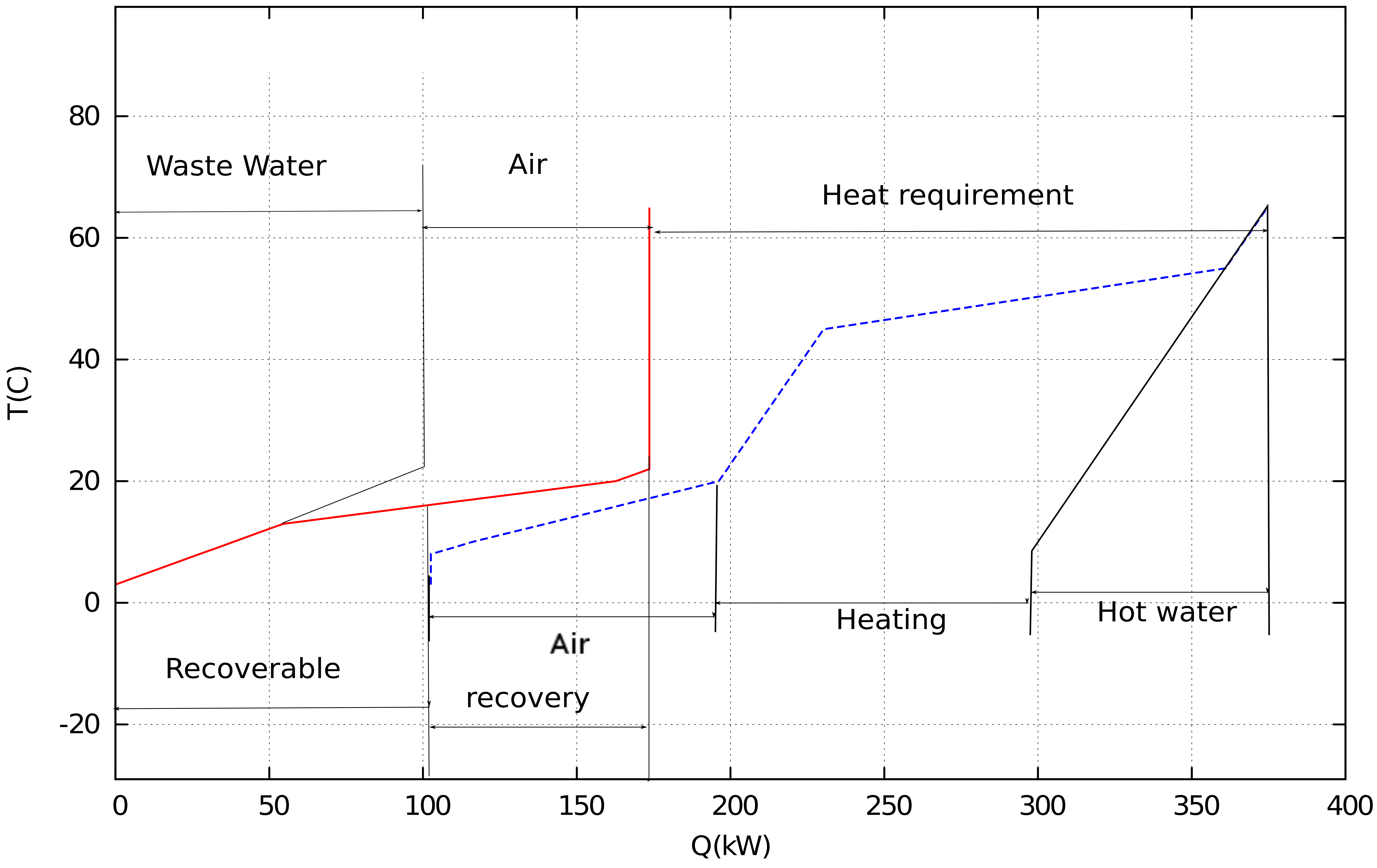
Seasonal temperature variation



# Smart building : heat recovery by pinch analysis ;-)



# (1830) CARNOT : THE MAGIC FORMULA

Nicolas Léonard Sadi CARNOT (F)

1796 - 1832

Electricity

your soberty

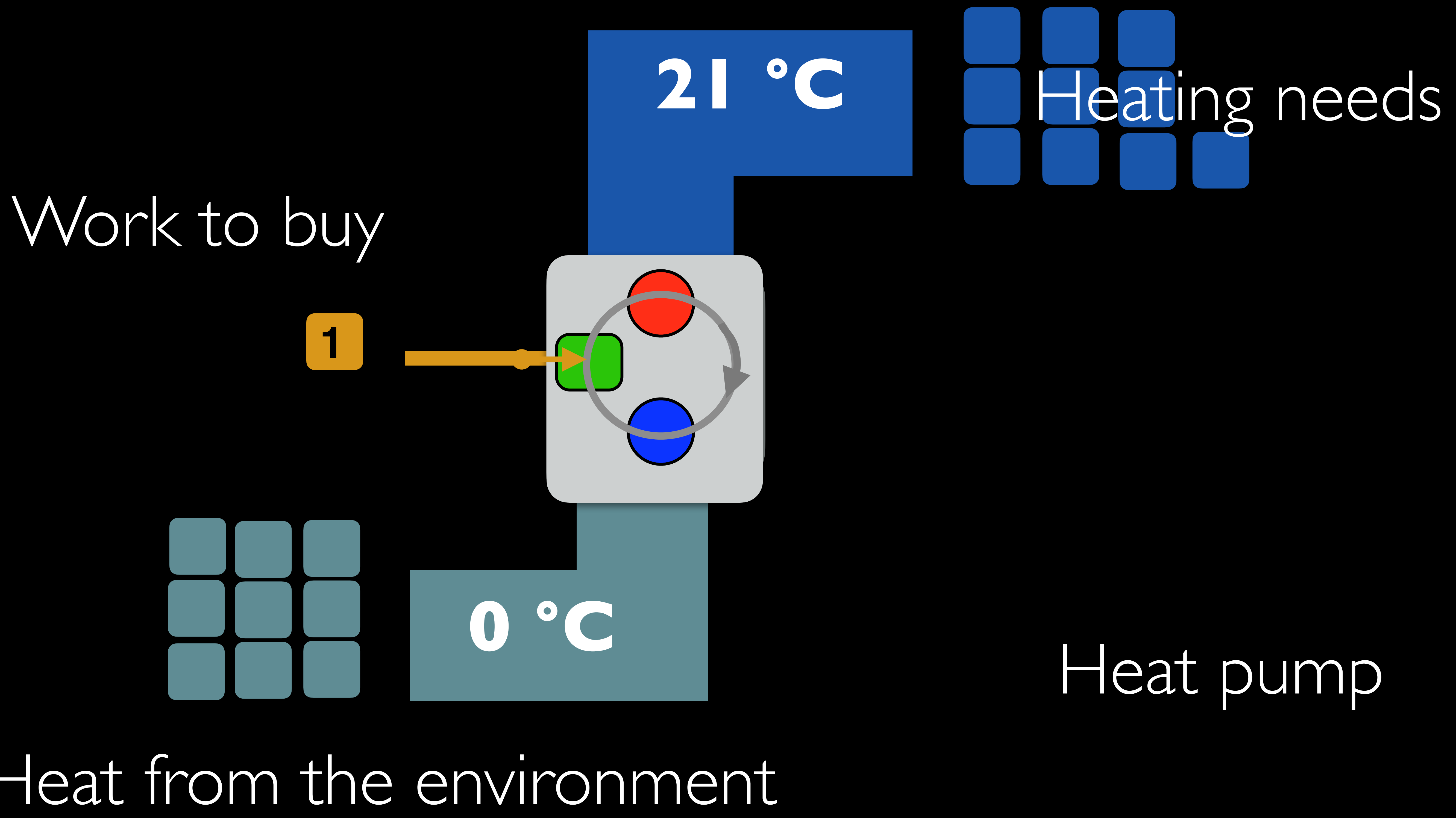
$$\dot{E}_{work} = \dot{Q}_{heating} \cdot \left(1 - \frac{T_{source}}{T_{heating}}\right)$$

Fraction of heat from the environment

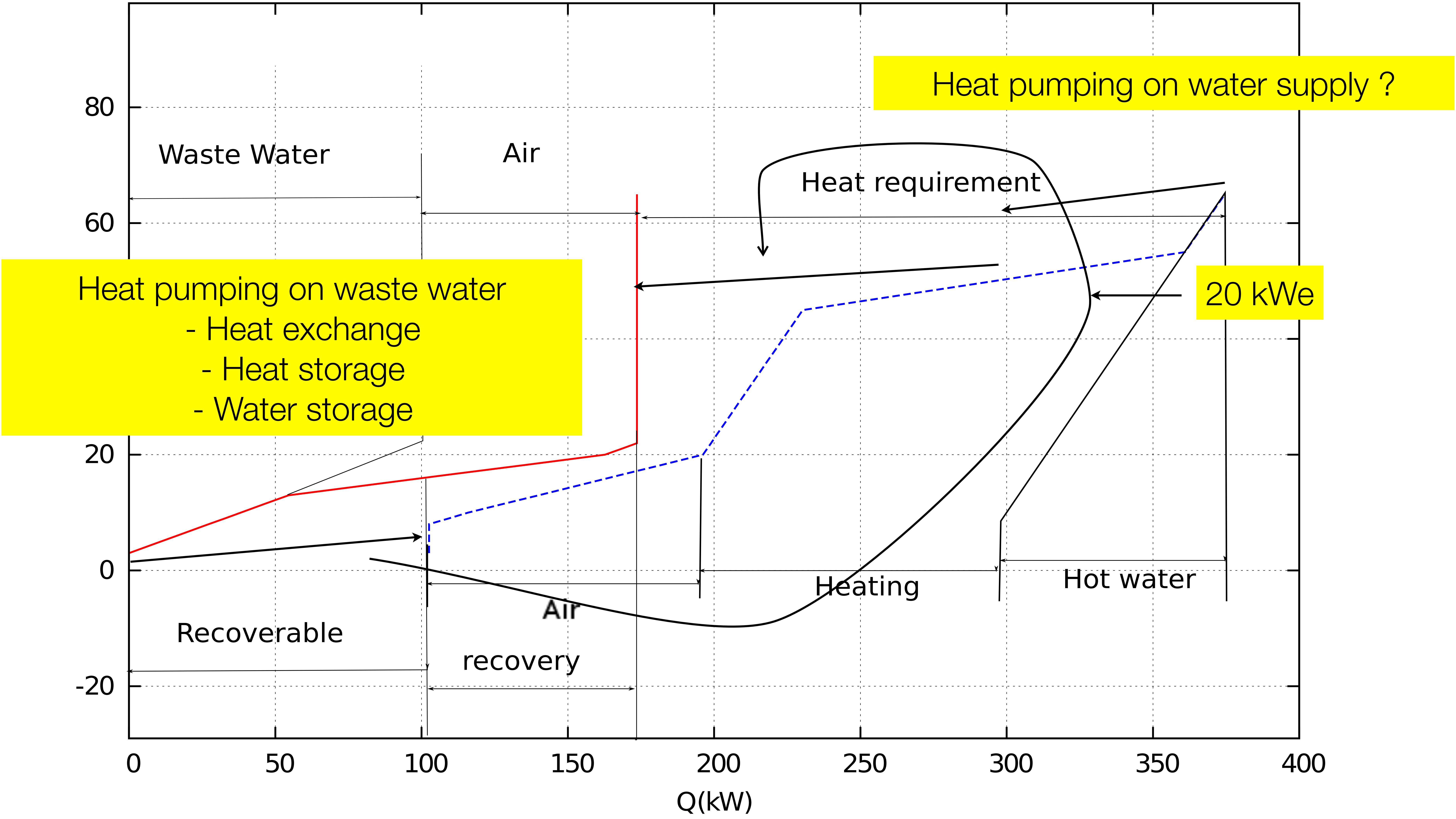
# (1830) CARNOT : THE MAGIC FORMULA

$$\dot{E} = \dot{Q}_{Heating} \cdot (1 - \frac{T_{source}}{T_{Heating}})$$

For 10 units of heat, 9 come from the environment and 1 as electricity

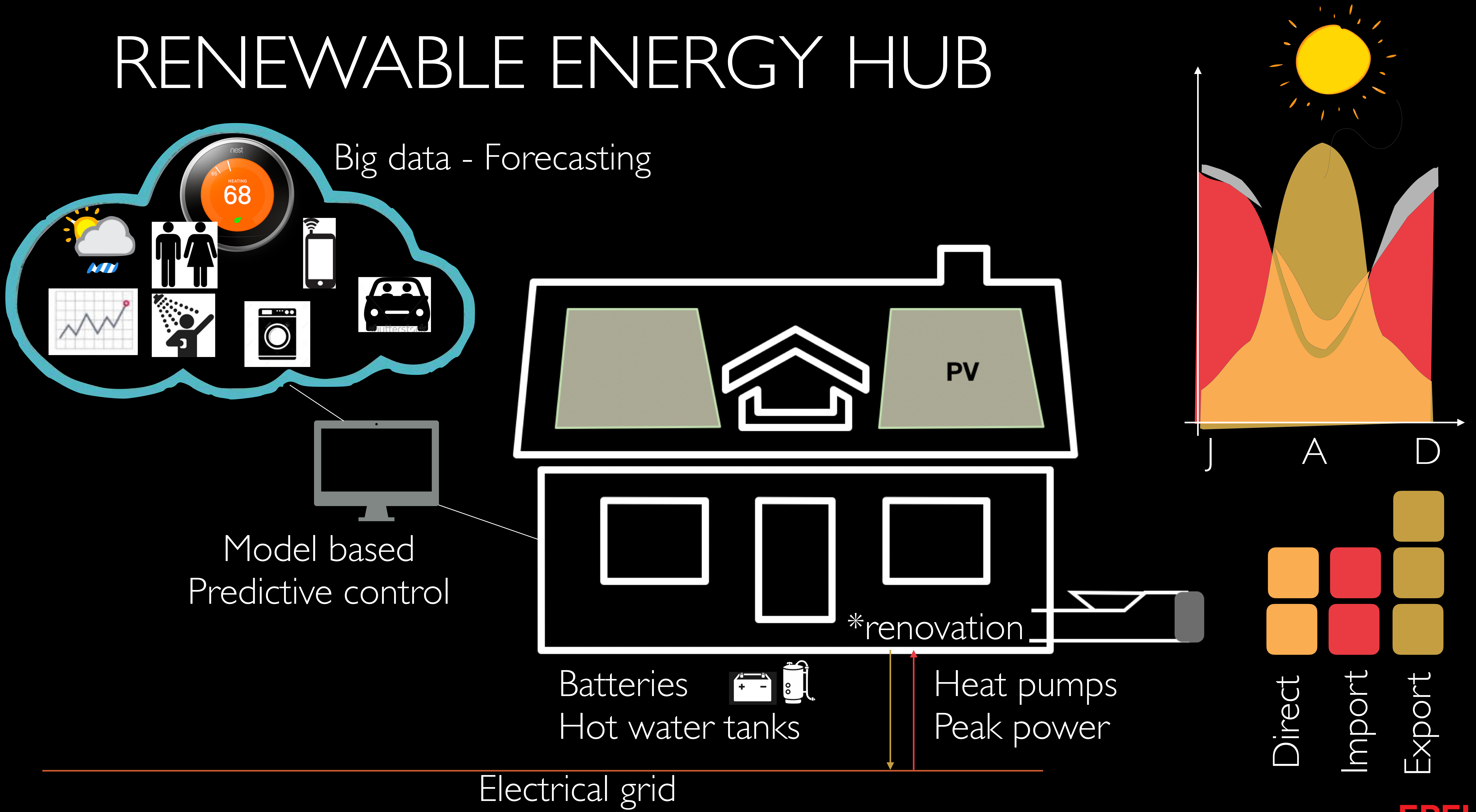



# Local Heat pumping on building waste heat




COP = Heat/Elec = 5 to 6

# RENEWABLE ENERGY HUB

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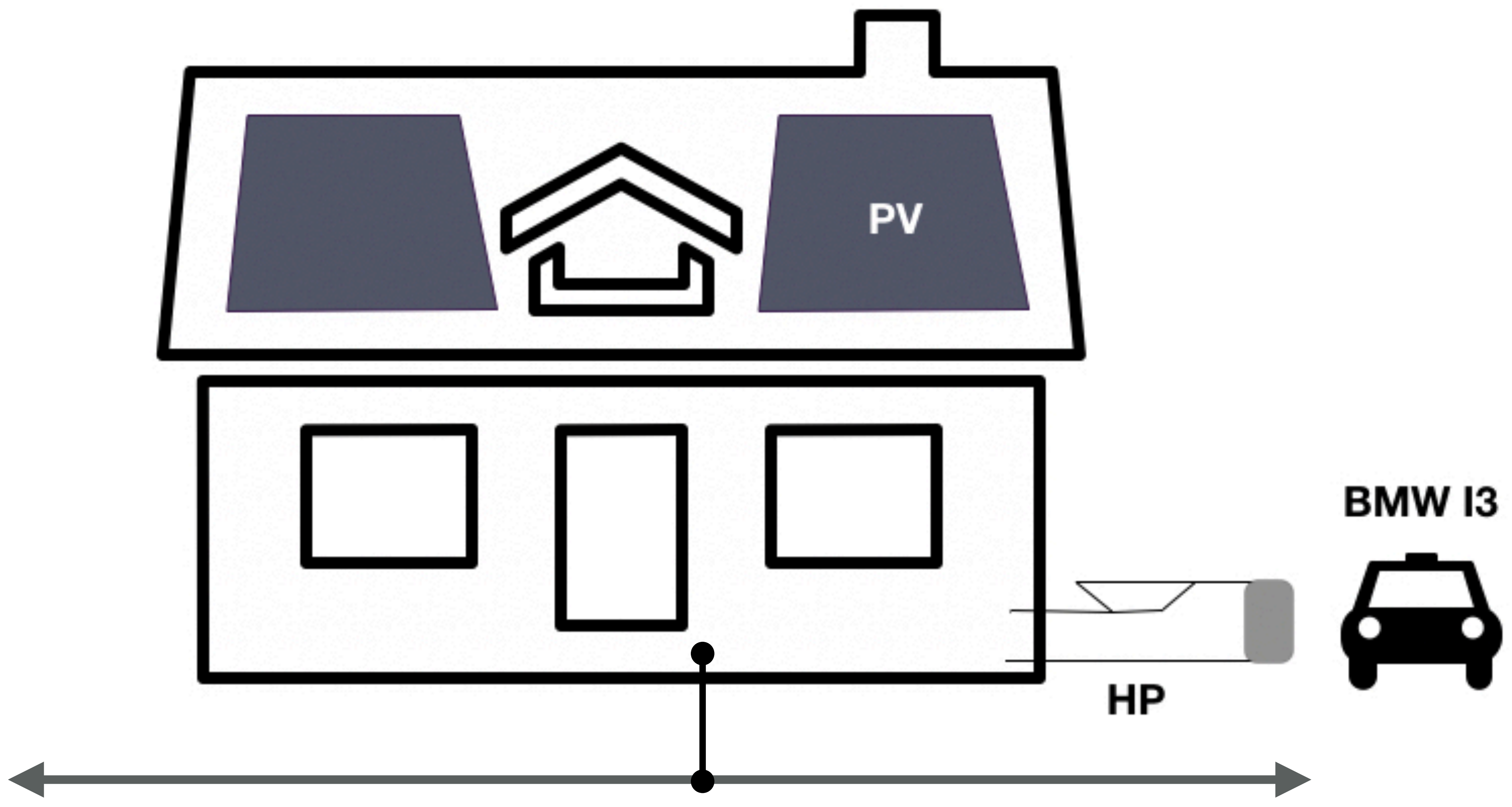
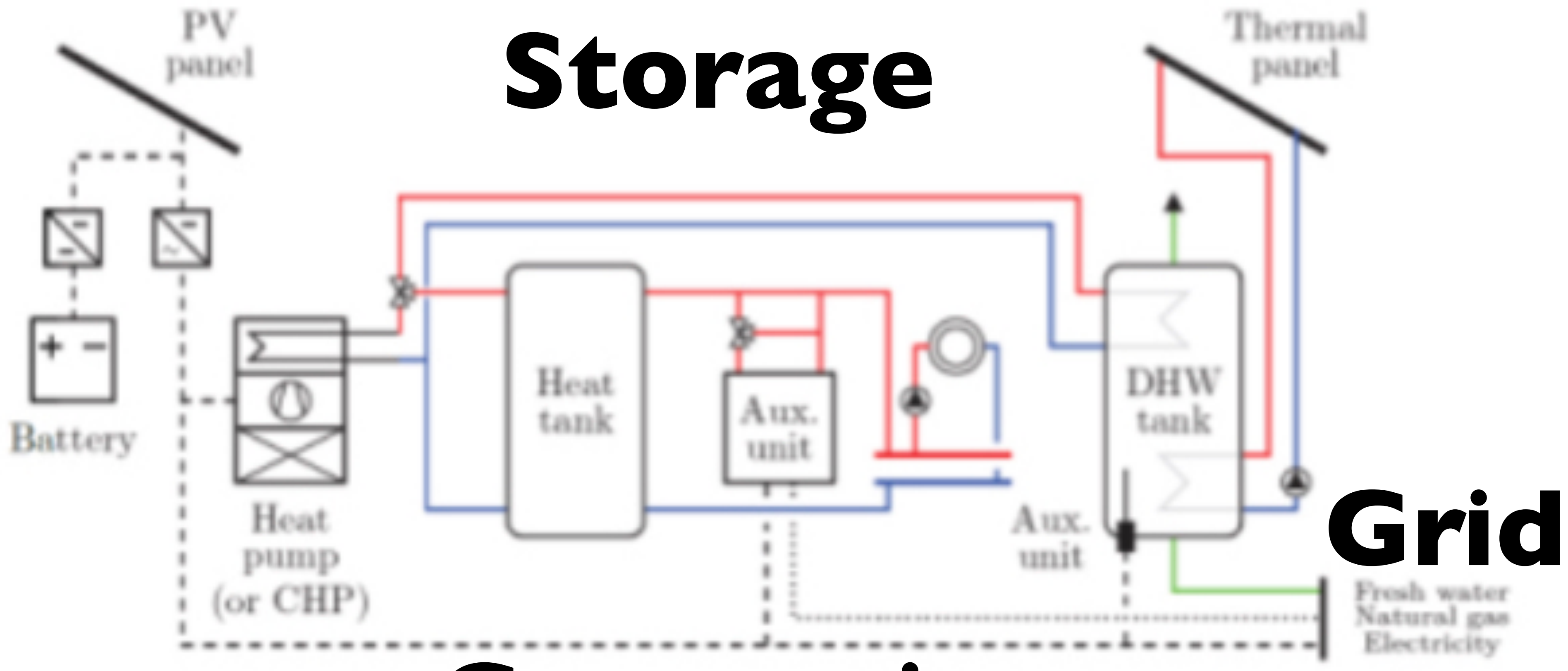
# Generating energy system designs




## Harvesting

## Storage




## Grids

## Conversion

## Predictive Control

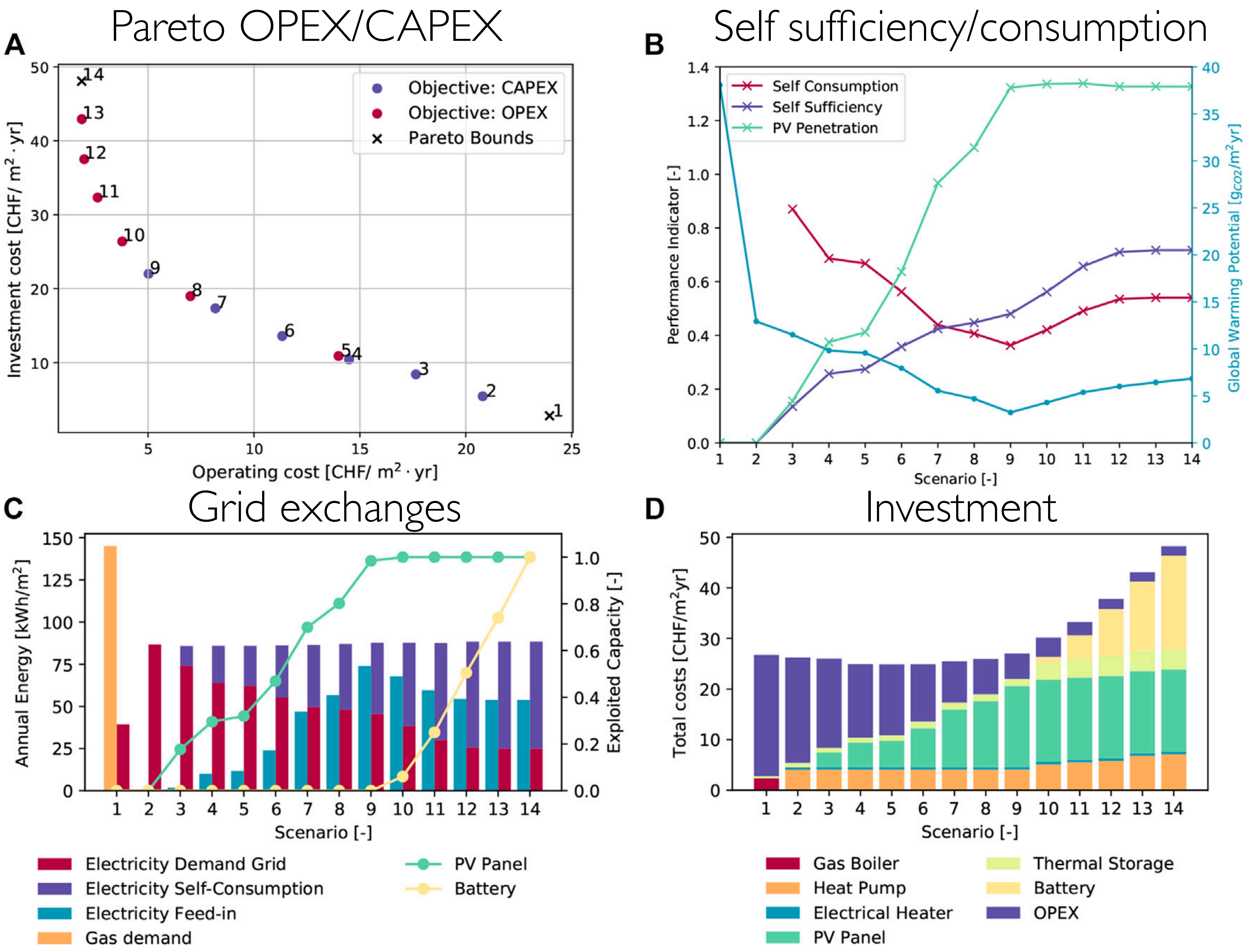


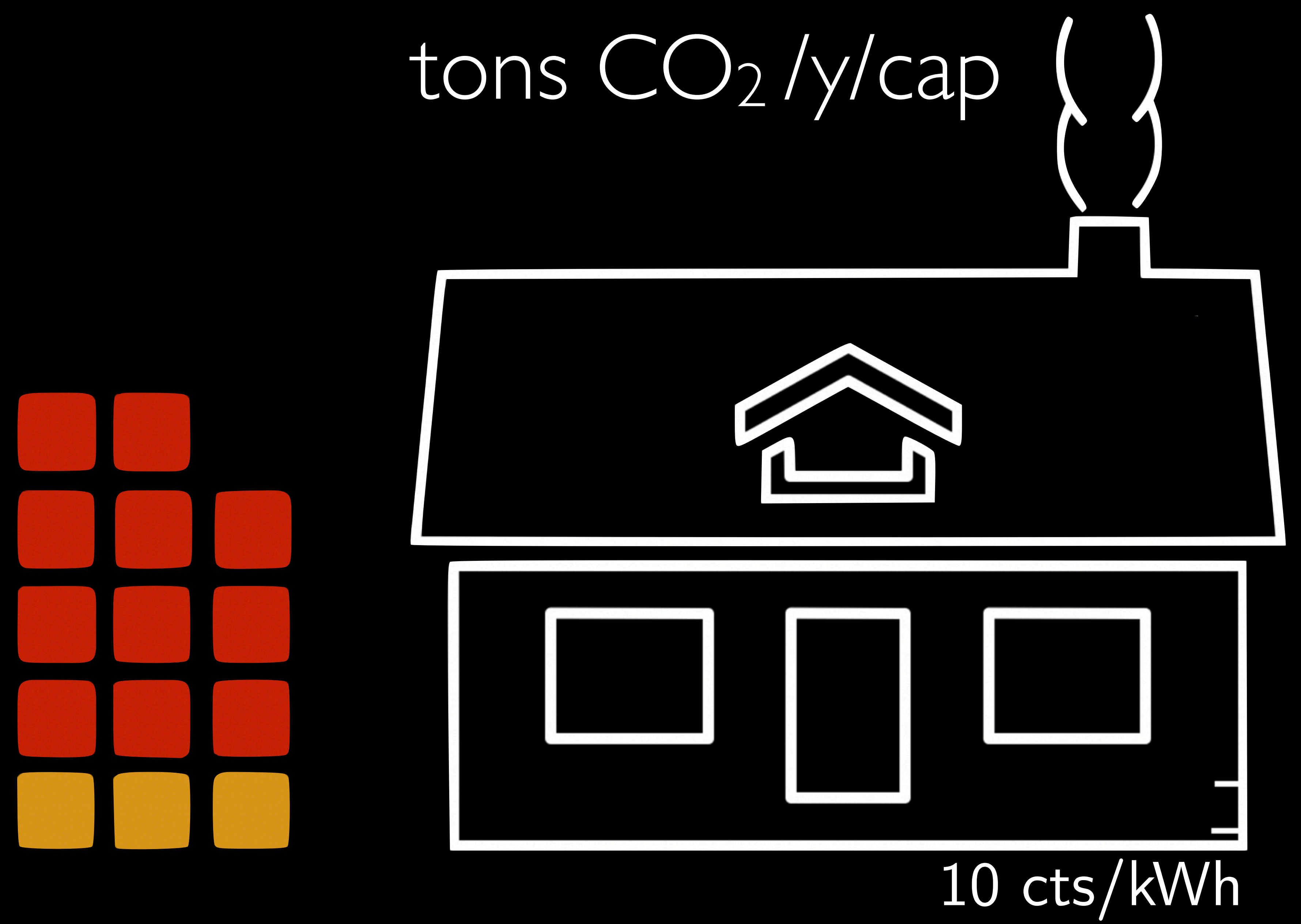

**FIGURE 8 |** Results of MOO of one residential building: **(A)** definition of Scenarios on pareto curve for investment and operation costs, **(B)** performance indicator each scenario, **(C)** usage of resources, and **(D)** distribution of total annual cost in identified energy system configurations.


(1) Middelhauve, L.; Baldi, F.; Stadler, P.; Maréchal, F. Grid-Aware Layout of Photovoltaic Panels in Sustainable Building Energy Systems. *Front. Energy Res.* **2021**, *8*, 573290. https://doi.org/10/gh43wd.

# RENEWABLE ENERGY HUBS
# 75+ % $CO_2$ EMISSIONS REDUCTION

**1.10**

tons $CO_2$ /y/cap

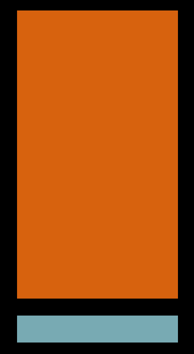



**592**

CHF/y/cap

Energy : **542** CHF/y/cap

Investment : **50** CHF/y/cap

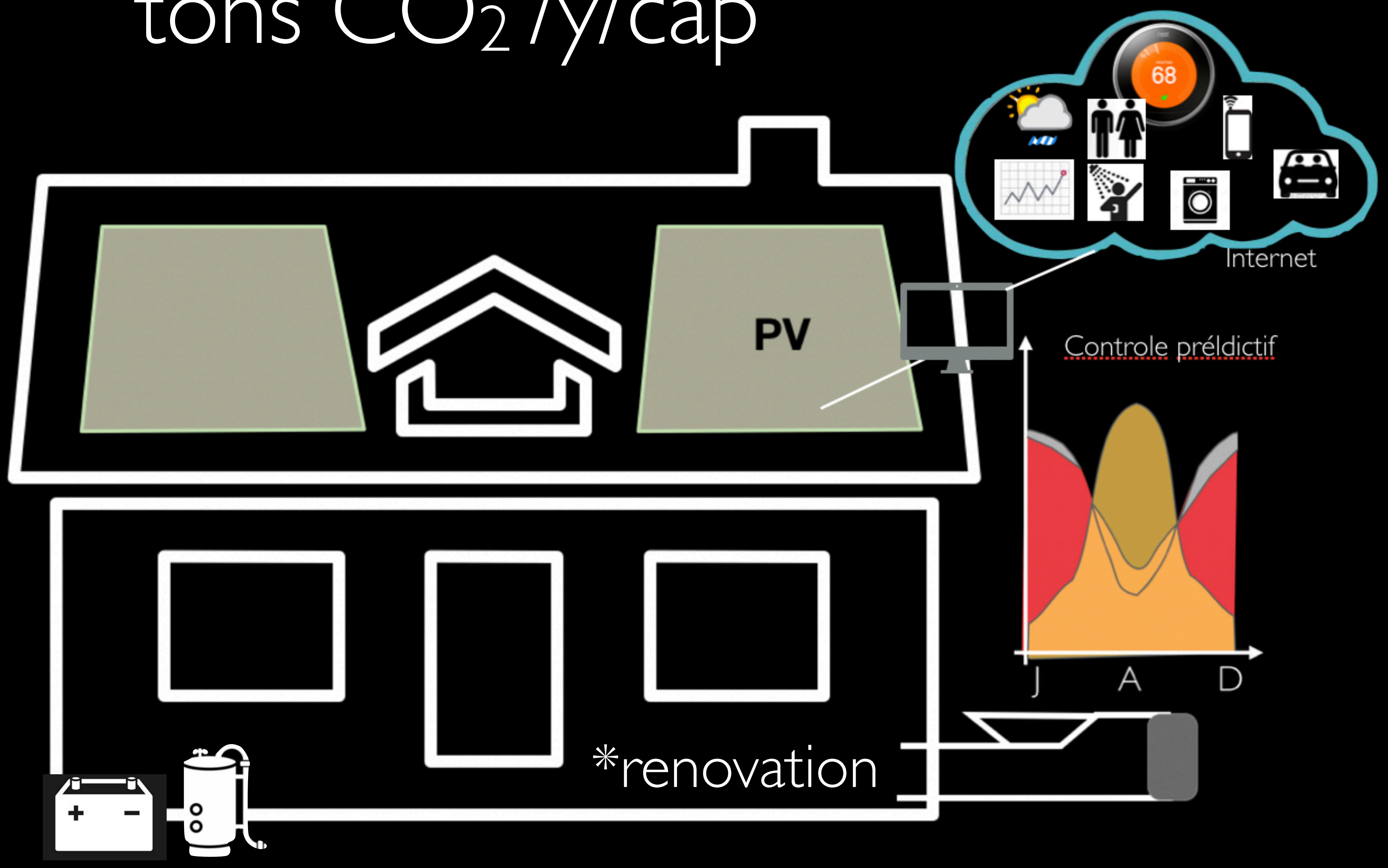


**0.25 - 0.04**

tons $CO_2$ /y/cap

**3.8**

m2PV/cap

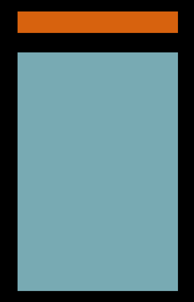




**493**

CHF/y/cap

Energy : **43** CHF/y/cap

Investment : **450** CHF/y/cap



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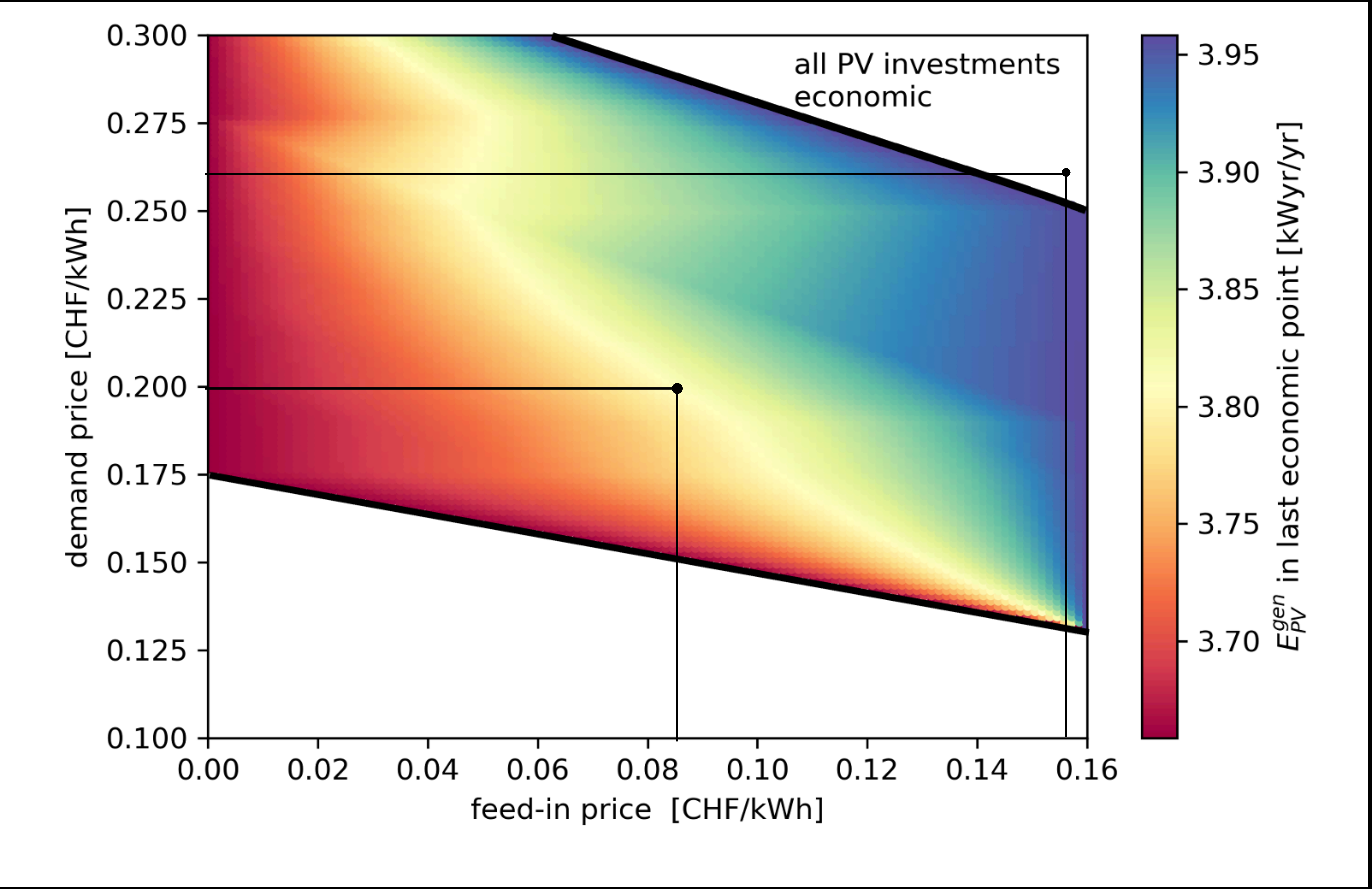
# RENEWABLE ENERGY HUB
# FEED-IN AND ELECTRICITY PRICES DECIDES THE INVESTMENT




Multi-owners dwelling (880m2) - 1980
22 residents - 6 electrical vehicles

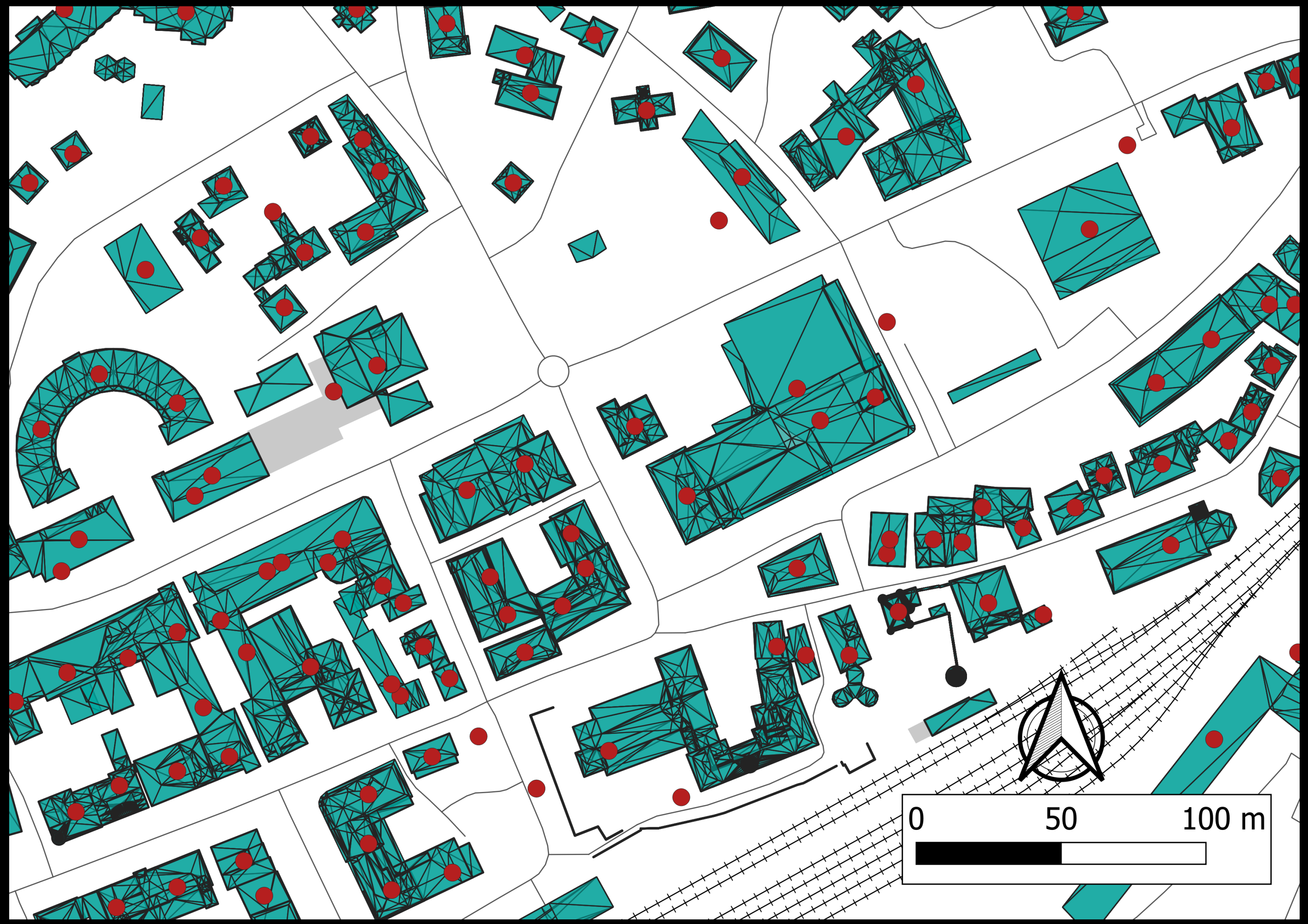
Electricity:
feed-in 0.083 CHF/kWh
retail 0.20 CHF/kWh

Fuel
heating oil: 0.9 CHF/L, or 0.09 CHF/kWh
gasoline: 2 CHF/L, or 0.20 CHF/kWh

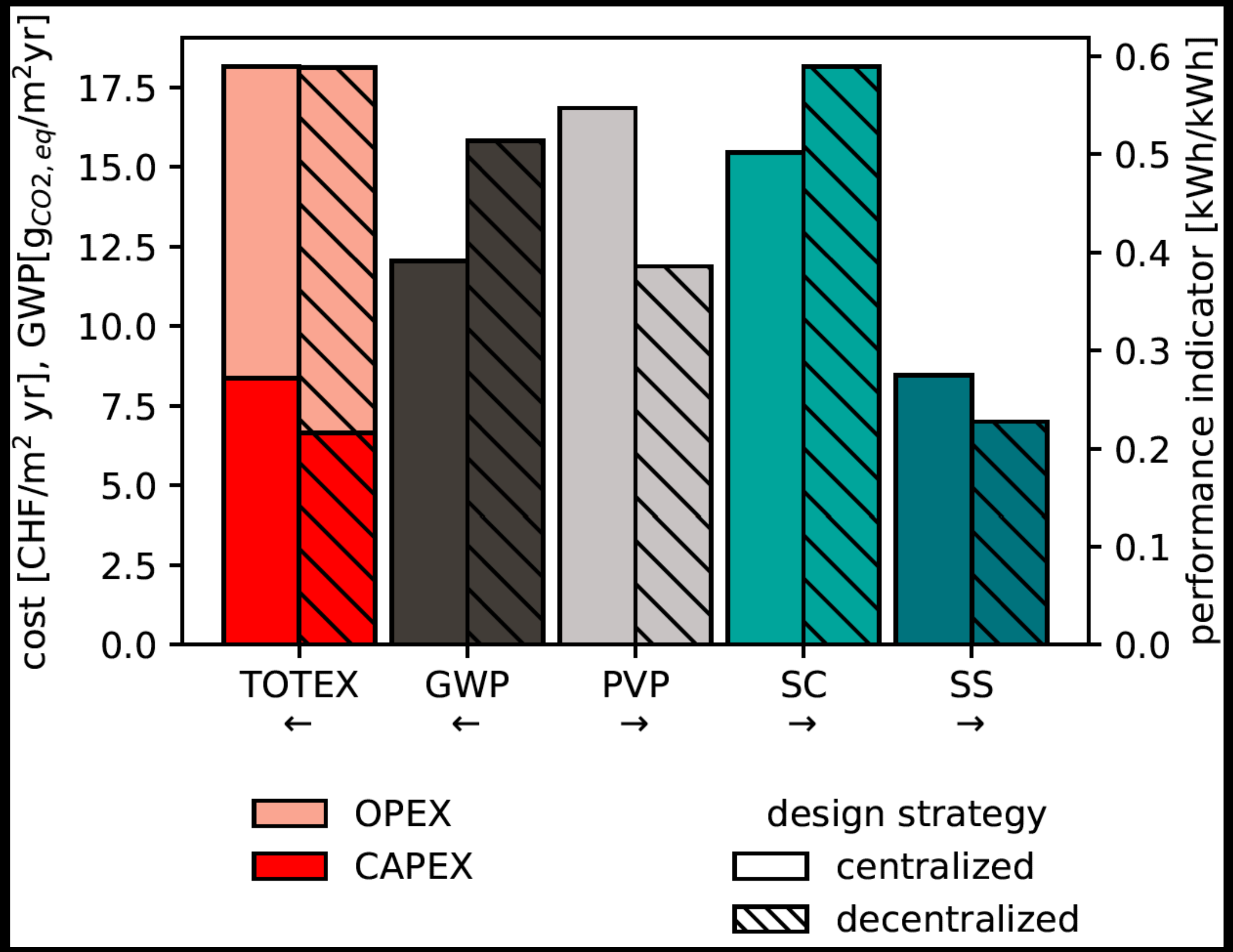
CO2 emissions
electricity: 0.17 kgCO2/kWh
heating oil: 0.28 kgCO2/kWh
gasoline: 0.28 kgCO2/kWh

# INTEGRATING RENEWABLE ENERGY HUBS : SYSTEMS IN SYSTEMS

- District scale => interactions between buildings




building vs community




For the same feed-in/feed-out prices

→PV + 40%
→Invest + 30%
→- 20% GWP
→ facade from 16 to 40%

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# SYSTEMS IN SYSTEMS

## Dantzig-Wolf Decomposition

System problem

$$\min_{x_{b_o}} \sum_{b=1}^{n_b} \sum_{r=1}^{n_r} \sum_{t=1}^{n_t} \dot{m}^+_{b,r,t} \cdot c^+_{r,t} + \frac{1}{\tau} \cdot I_b$$

$$I_b = \sum_{o=1}^{n_o} x_{b_o} \cdot I_{b_o} \qquad \forall b \in \{1..n_b\}$$

$$\dot{m}_{b,r,t} = \sum_{o=1}^{n_o} x_{b_o} \cdot \dot{m}_{b_o,r,t} \qquad \forall b \in \{1..n_b\}$$

$$\sum_{o=1}^{n_o} x_{b_o} = 1 \qquad b \in \{1..n_b\}$$

→ Duality

$$c^+_{b_o,t} = f(x_{b_o})$$

→ Convergence

$$|c^+_{b_o,t} - c^+_{b_{o-1},t}| \leq \epsilon ?$$

→ yes = solution

↓

Sub-system problems

$\forall b \in \{1..n_b\}$ solve

$$\min_{\dot{m}^+_{b_o,r,t}, I_{b_o}} \sum_{b=1}^{n_b} \sum_{r=1}^{n_r} \sum_{t=1}^{n_t} \dot{m}^+_{b_o,r,t} \cdot c^+_{b_o,t} + \frac{1}{\tau} \cdot I_{b_o}$$

s.t. $F(\dot{m}^+_{b_o,r,t}, I_{b_o}) = 0$

$G(\dot{m}^+_{b_o,r,t}, I_{b_o}) \geq 0$

← $n_o = n_o + 1$

# YOU HAVE ALSO A FREE BATTERY FOR THE ENERGY SYSTEM

## Model predictive strategic operation via $c^{+}_{b,r,t}$ signals

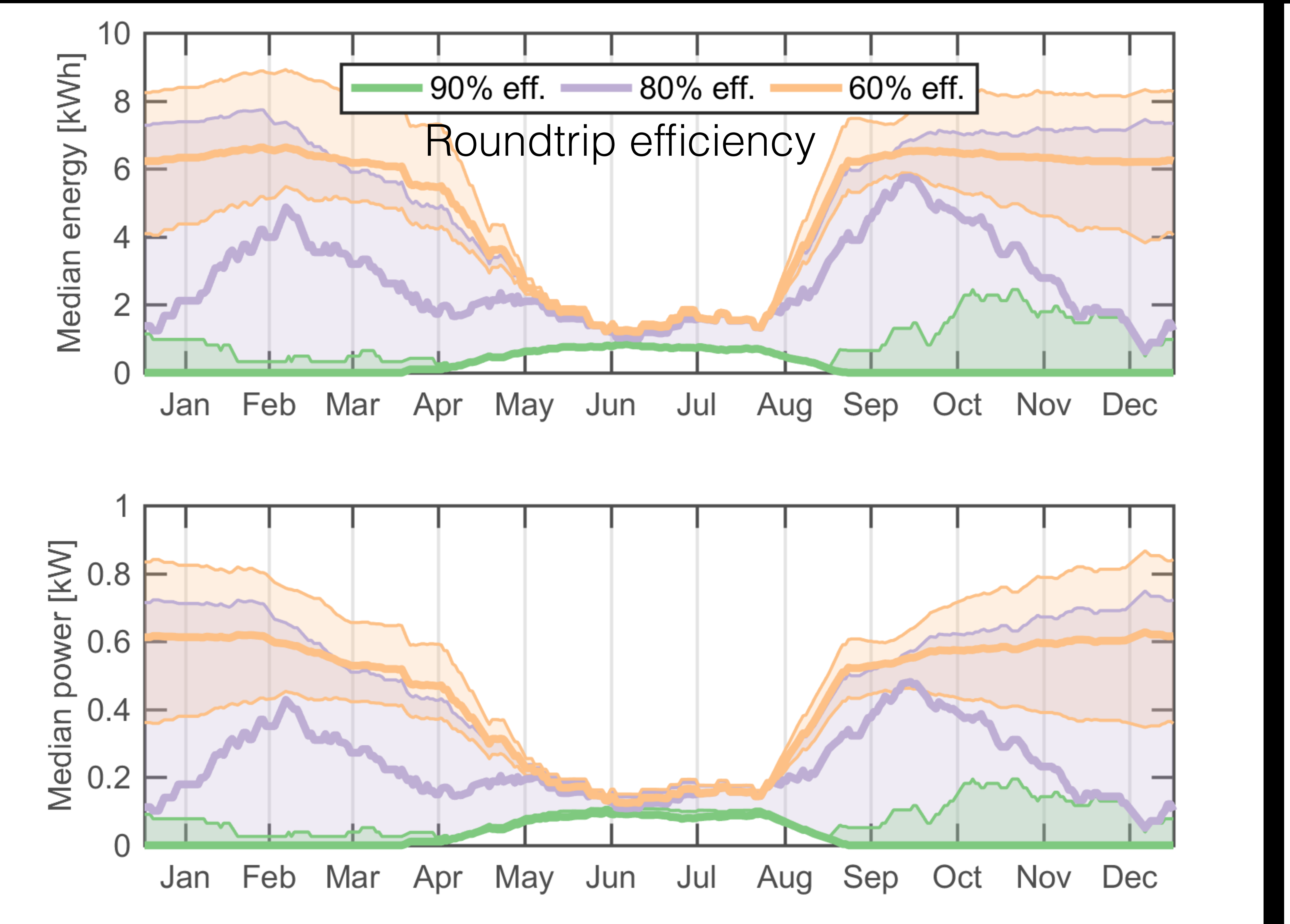
**Building performance (solution I)**

| Ind. | Value (imp/exp/gen) |
|---|---|
| E [MWh] | 34.8 / 00.0 / 00.0 |
| H [MWh] | 00.0 / 00.0 / 00.0 |
| COP [-] | 3.00 |

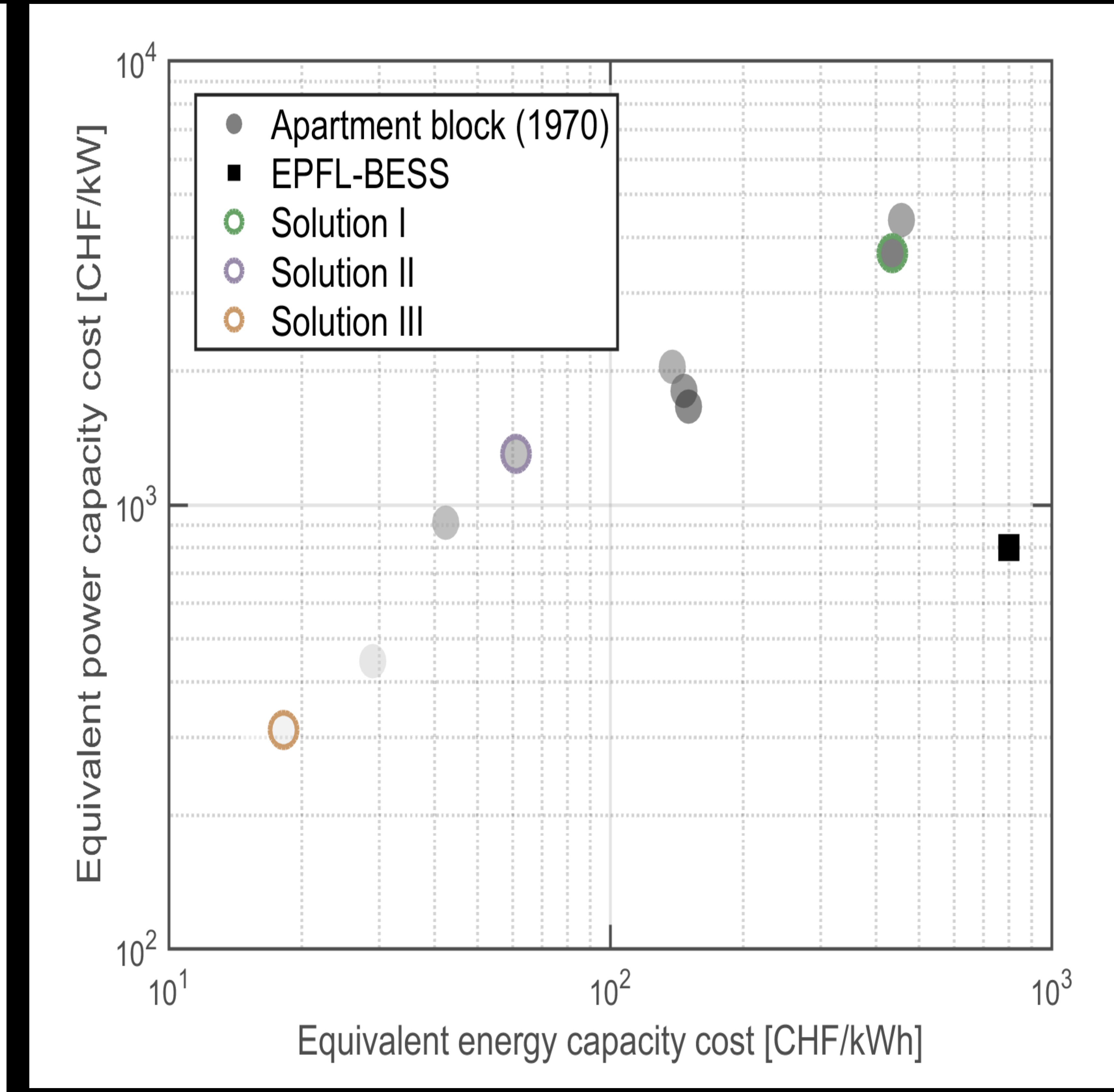
**Building energy system design (solution I)**

| Unit | Size | |
|---|---|---|
| Heat pump | **7.0** | $kW_e$ |
| Battery | 0 | $kWh_e$ |
| Boiler | 0 | $kW_{th}$ |
| Water tank | **0.22** | $m^3$ |
| Electric heater | **14** | $kW_e$ |
| Heat tank | **1.0** | $m^3$ |
| Photovoltaics | 0 | $kW_p$ |
| Solar thermal | 0 | $m^2$ |
| SOFC-CHP | 0 | $kW_e$ |

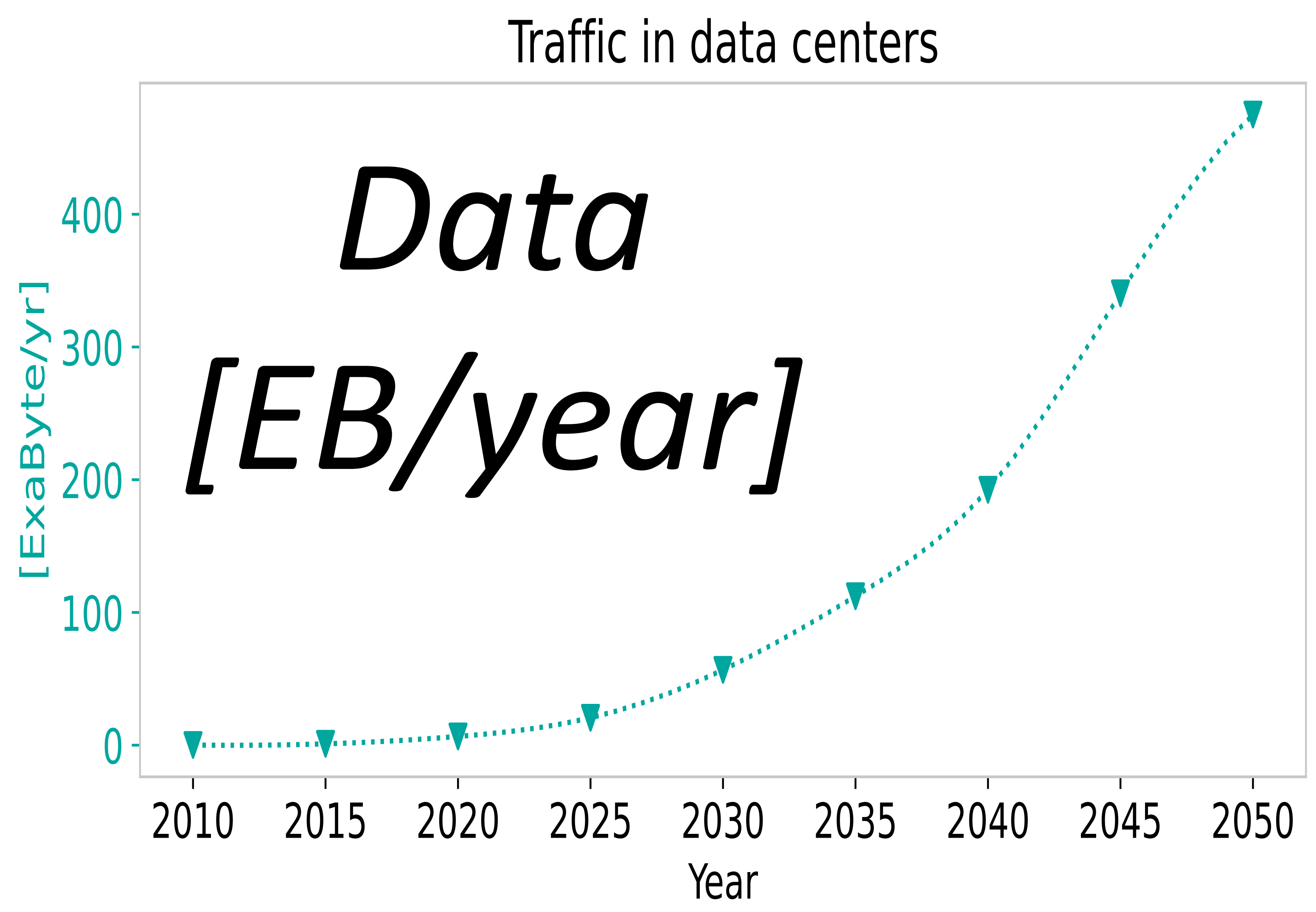
Offered stored energy and power by the system

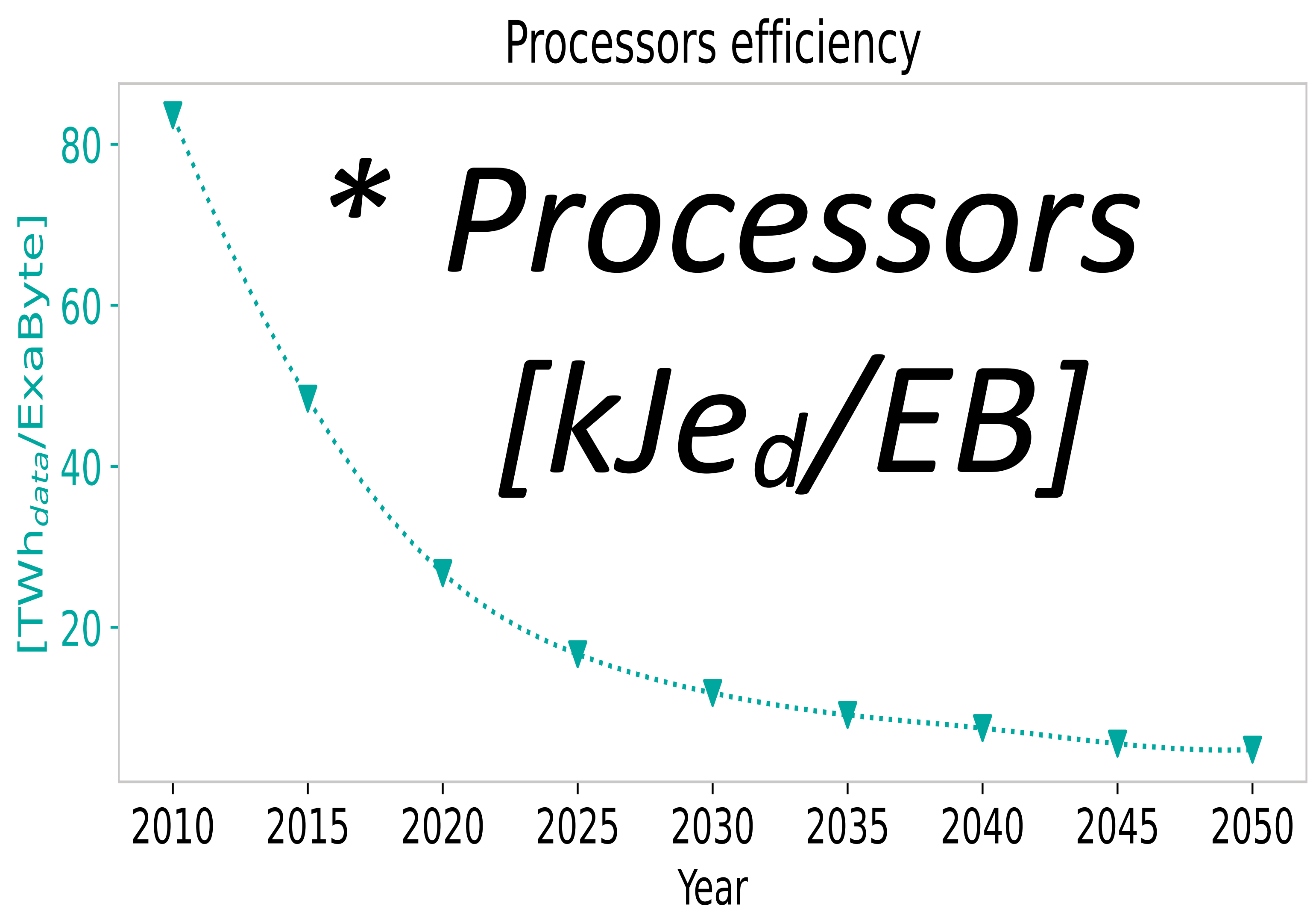


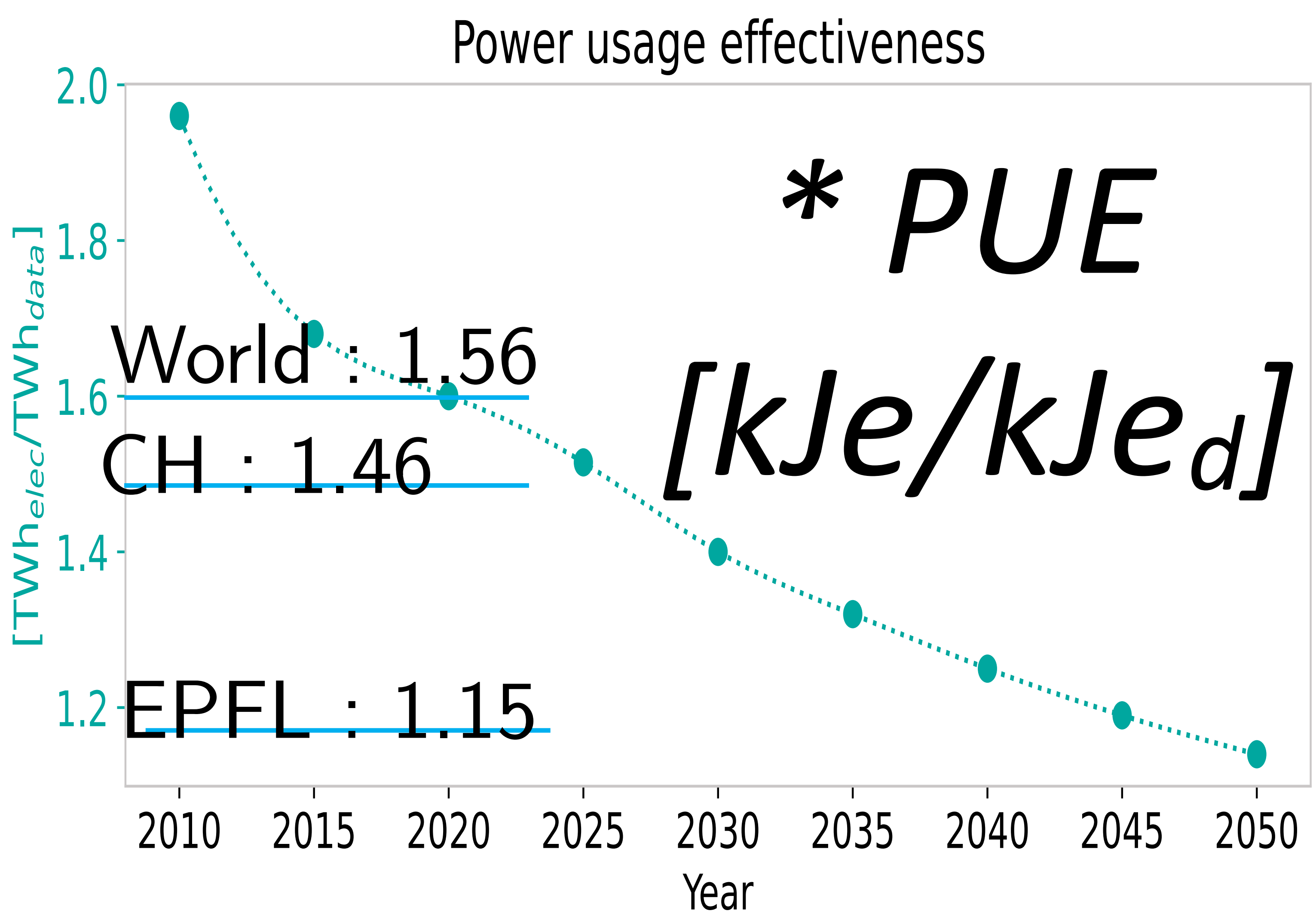

Annual equivalent battery performance

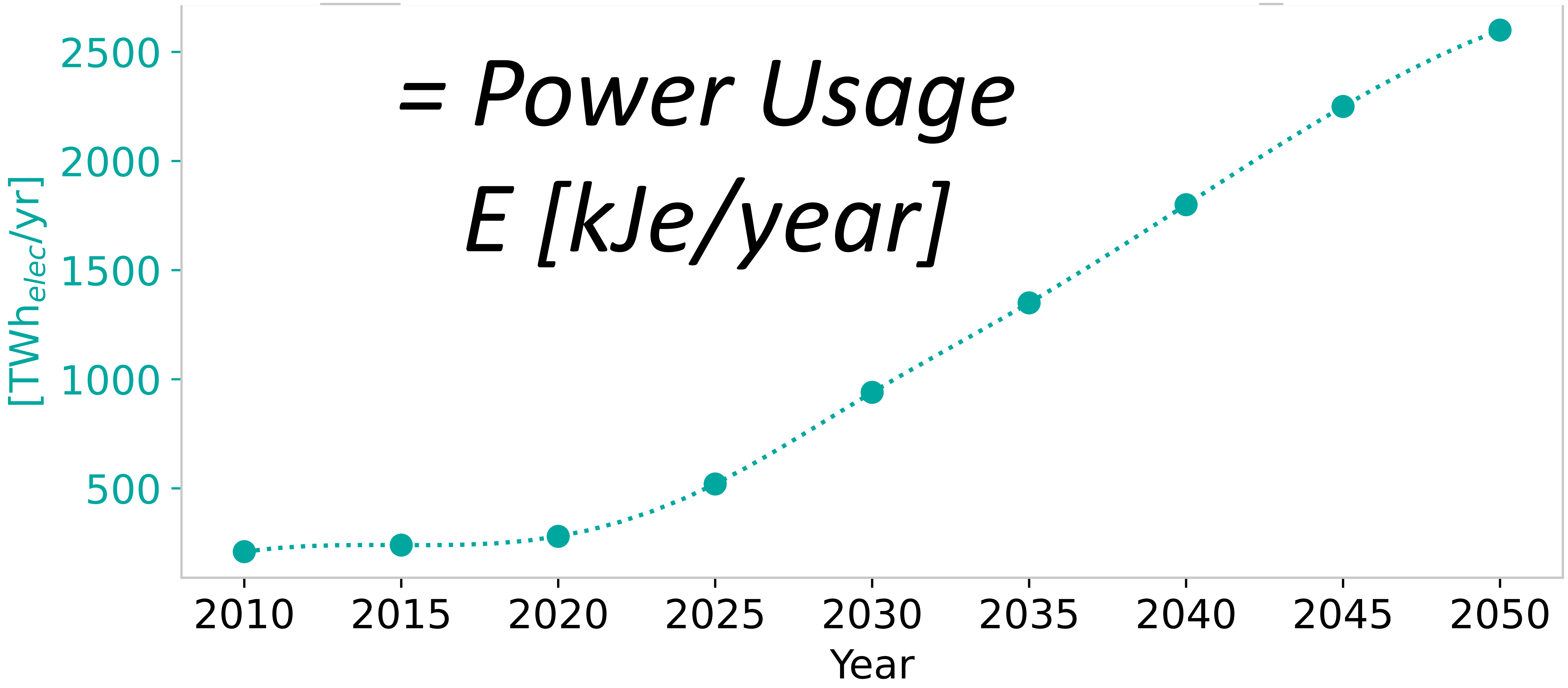


# EPFL Data production energy impact



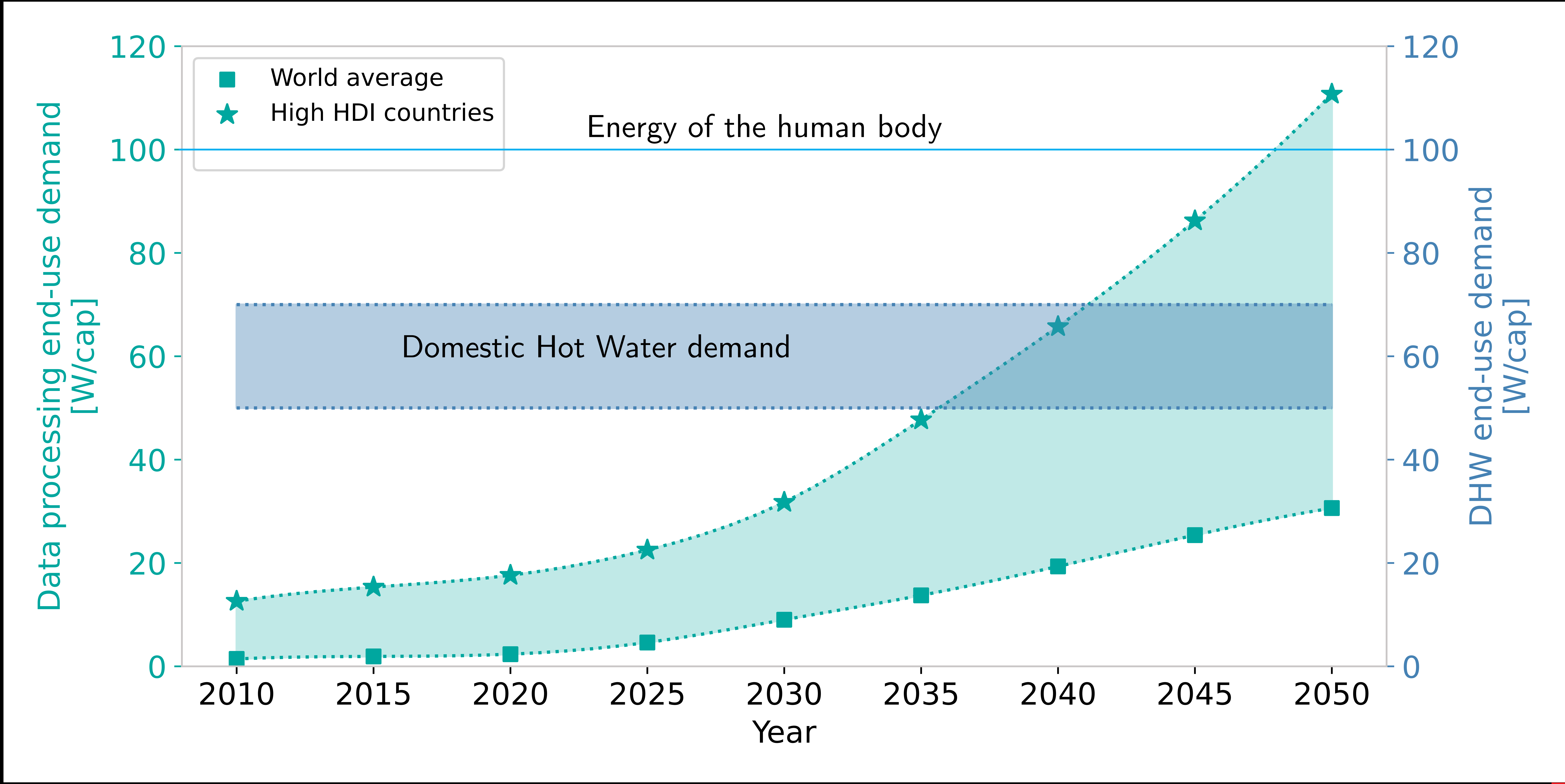






Xiang Li, Dorsan Lepour, Fabian Heymann, and François Maréchal. Electrification and digitalization effects on sectoral energy demand and consumption: a prospective study to- wards 2050. Applied Energy, Special Issue on Energy digitization with spatial intelligence, 2022, under review.

# DATA PRODUCTION AND ENERGY SYSTEM




Lepour et al., (2022) ECOS 2022 proceedings

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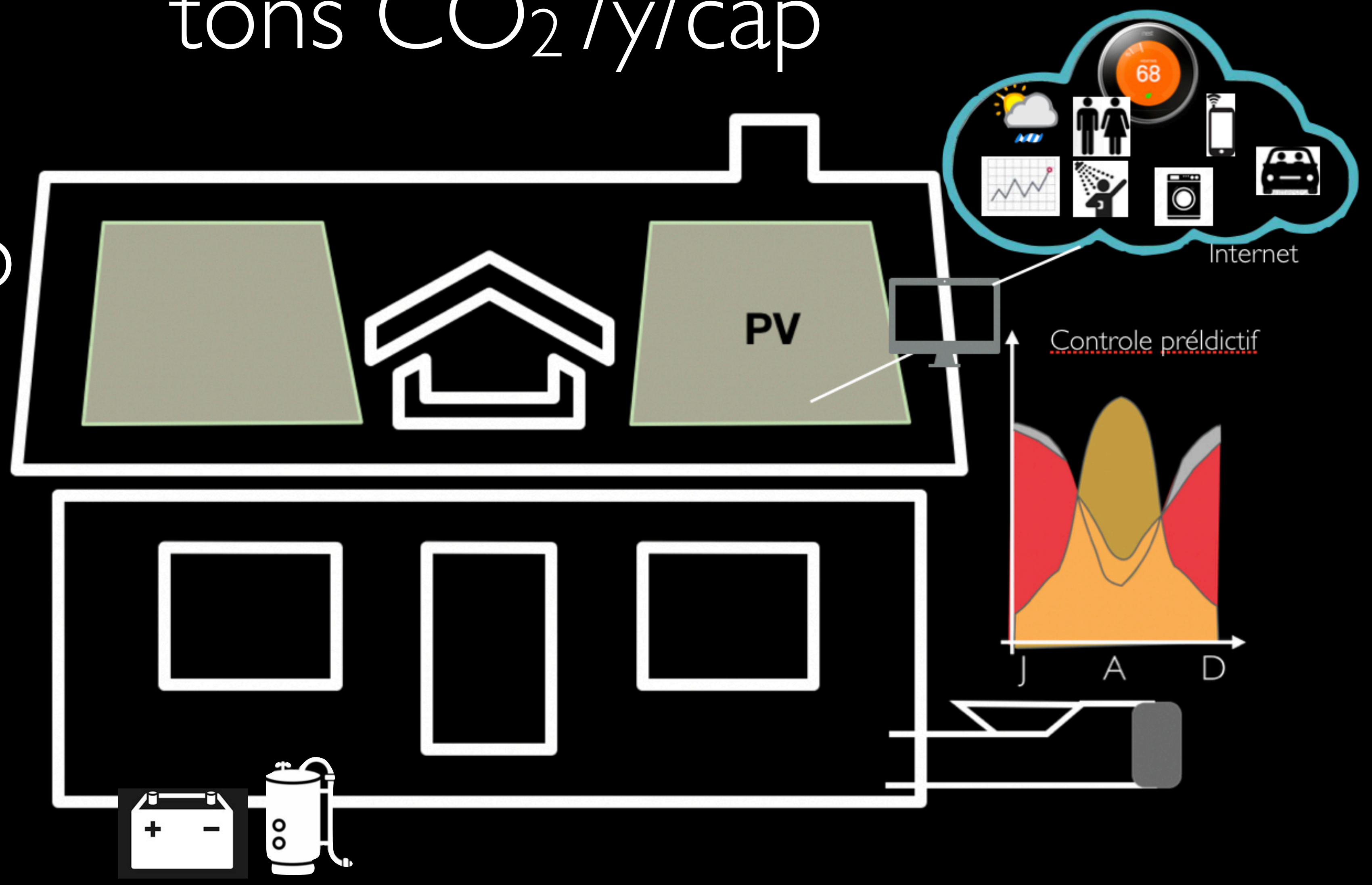
# RENEWABLE ENERGY HUB AND DATA PRODUCTION

**0.25 + 0.24**

tons $CO_2$ /y/cap

**3.8**

m2PV/cap

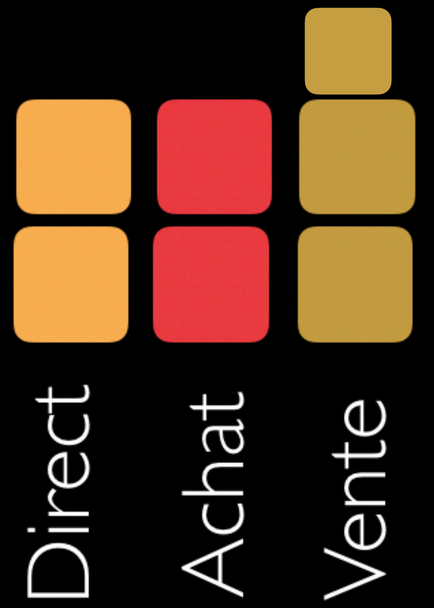



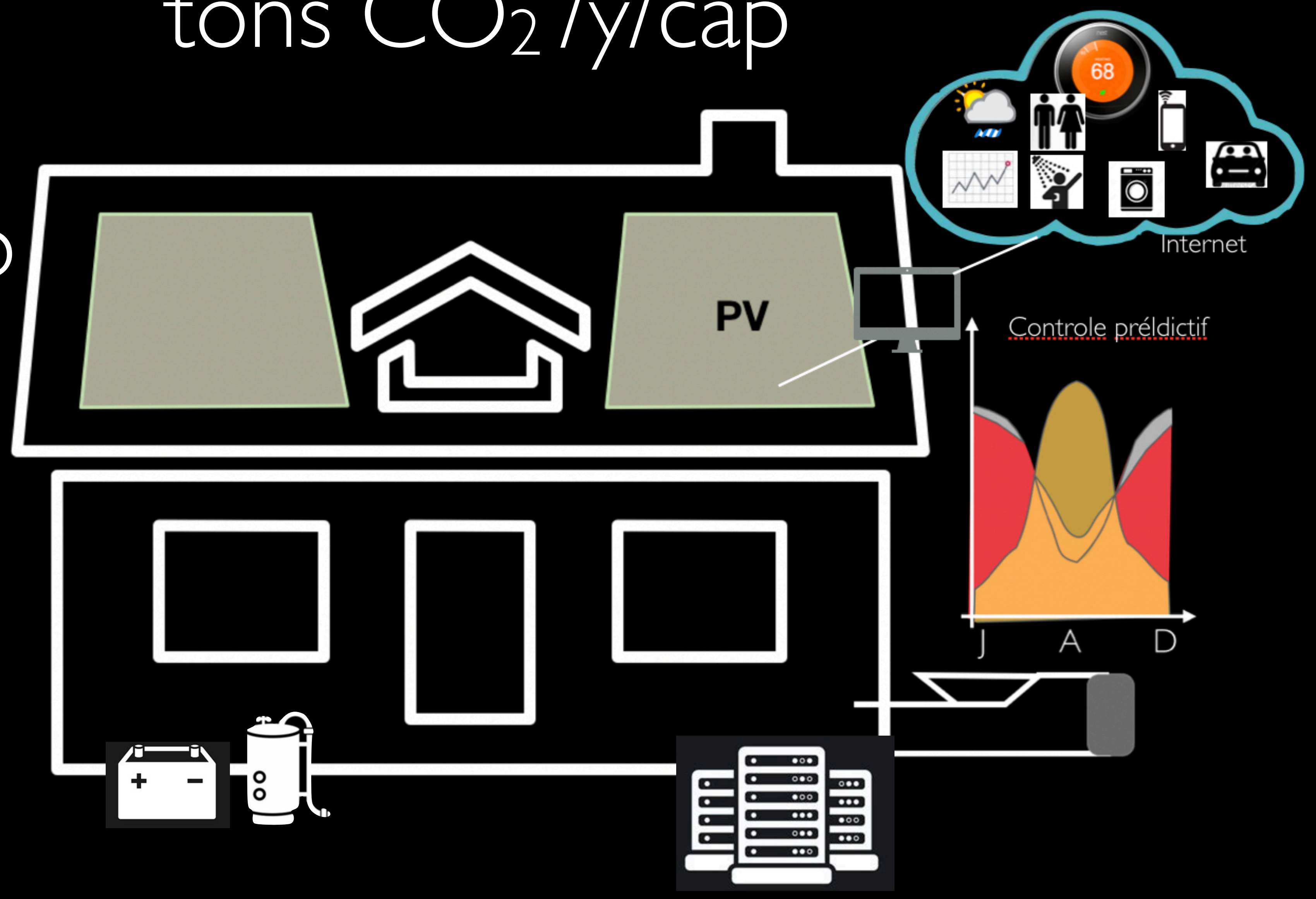

**0.32 (-34%)**

tons $CO_2$ /y/cap

**4.5**

m2PV/cap




**493 + 476**

CHF/y/cap

CHF/y/cap

Energy : **43** CHF/y/cap

Investment : **450** CHF/y/cap

Building

**290** CHF/y/cap

**186** CHF/y/cap

Data center

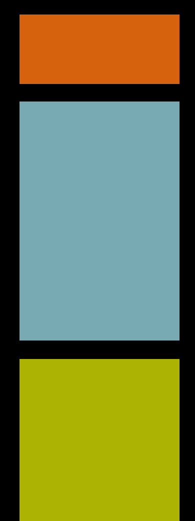
**855 (-12%)**

CHF/y/cap

Energy : **115** CHF/y/cap

Investment : **450** CHF/y/cap

Bits heater : **290** CHF/y/cap



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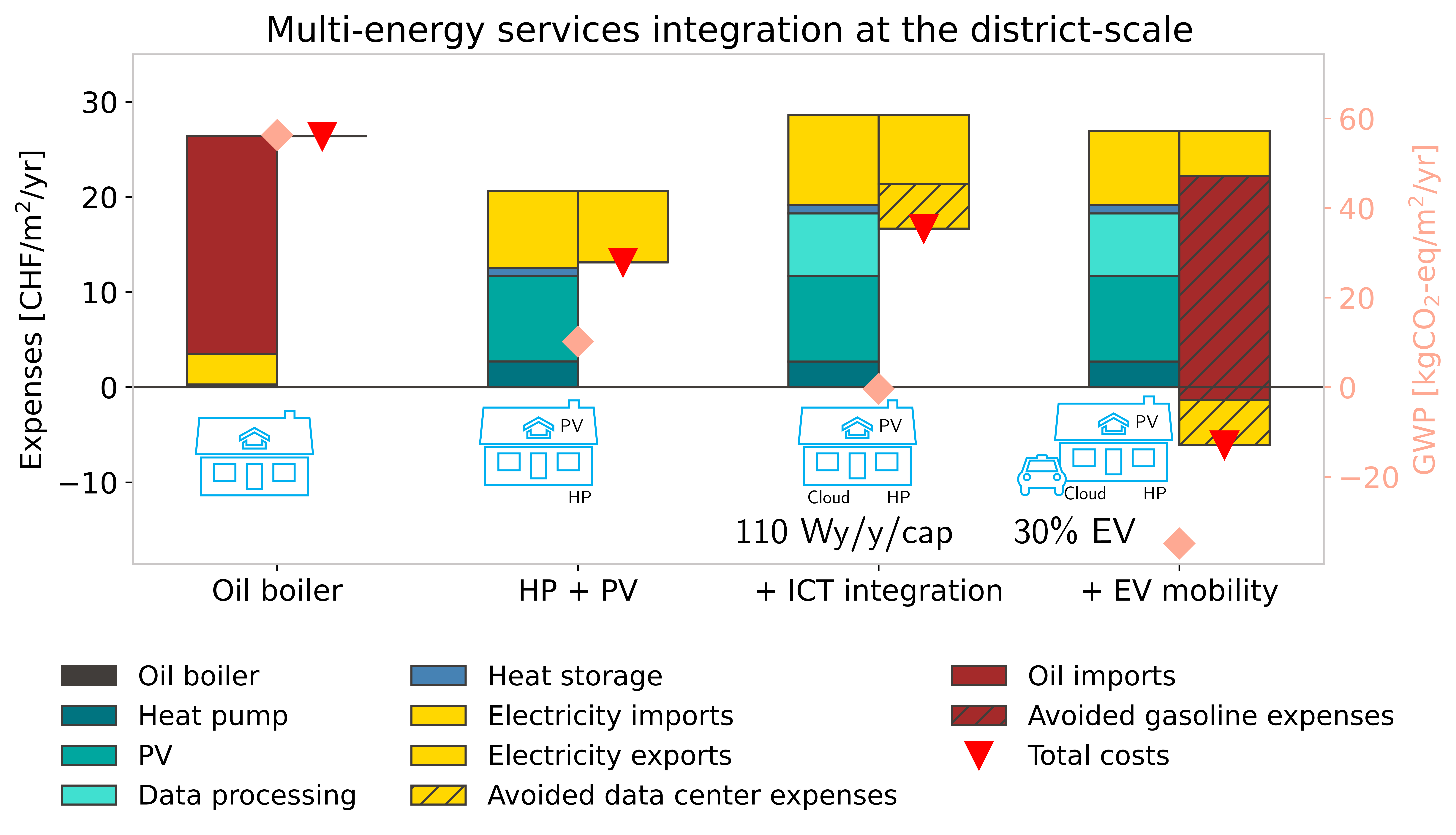
# RENEWABLE ENERGY HUB : HEATING-COOLING-EV-DATA

- Houses in a district (30 buildings)




EPFL

# APPLYING THE MAGIC FORMULA IN THE CITY

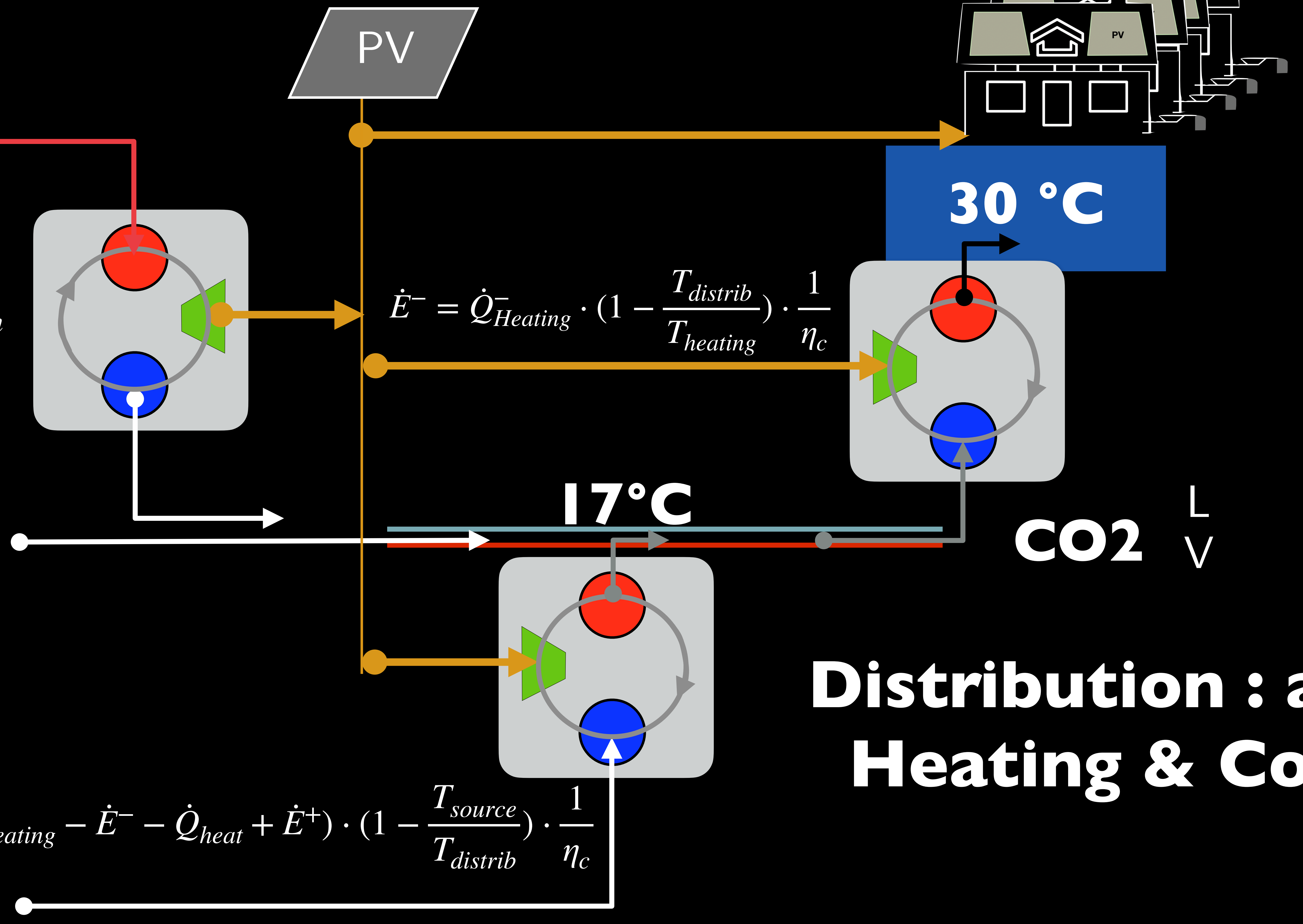
## Heat sources ($T_{source}$)

Industry: **>80**°C

Data center : **30**°C
Waste Water : **13-20** °C

Aquifers : **10** °C
Rivers/Lake : **7**°C
Geothermal : >**10** °C
Refrigeration : **< 0**°C

## Users ($T_{heating}$)
## Heating and Cooling




$$\dot{E}^{+} = \dot{Q}^{+}_{Heat} \cdot (1 - \frac{T_{source}}{T_{distrib}}) \cdot \eta_h$$

$$\dot{E}^{-} = \dot{Q}^{-}_{Heating} \cdot (1 - \frac{T_{distrib}}{T_{heating}}) \cdot \frac{1}{\eta_c}$$

$$\dot{E}^{-}_{source} = (\dot{Q}^{-}_{Heating} - \dot{E}^{-} - \dot{Q}_{heat} + \dot{E}^{+}) \cdot (1 - \frac{T_{source}}{T_{distrib}}) \cdot \frac{1}{\eta_c}$$

## Distribution : anergy
## Heating & Cooling

D. Favrat, C. Weber, CO2 based district energy system, U.S. Patent 2010018668

T
80°C
40°C
15 °C
5 °C
-5 °C
Liquid
Gas
CO2
Temperature = 17°C
DHvap = 160 kJ/kg
Pressure = 50 bar
EPFL

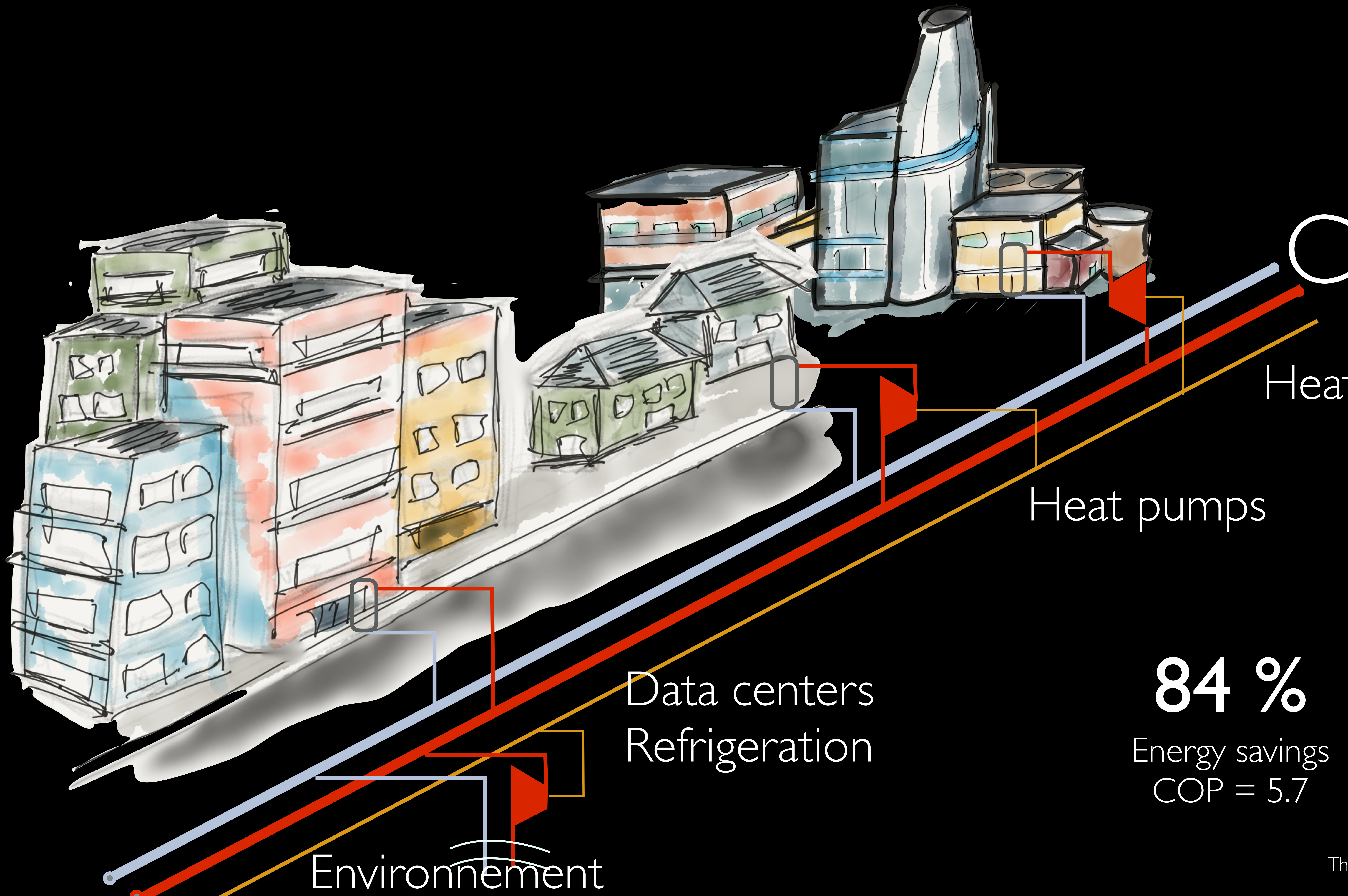

T
80°C
40°C
15 °C
5 °C
-5 °C
Hot water
CO2 heat pump
Heating
Conventional HP
Liquid
Gas
CO2
Temperature = 17°C
Pressure = 50 b
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)
EPFL


S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)


T
80°C
40°C
15 °C
5 °C
-5 °C
Waste Heat
Municipal waste
Industry
Rankine cycle
Hot water
Heating
Heat pumps
Heat pumps
Waste water
Lake
Rivers
Geothermal
Liquid
Vapour
CO2
Temperature = 17°C
DHvap = 160 kJ/kg
Pressure = 50 bar
Cooling
Free cooling
Refrigeration
Shopping malls
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)
EPFL

# URBAN SYSTEMS

ExerGo
www.exergo.ch




City center

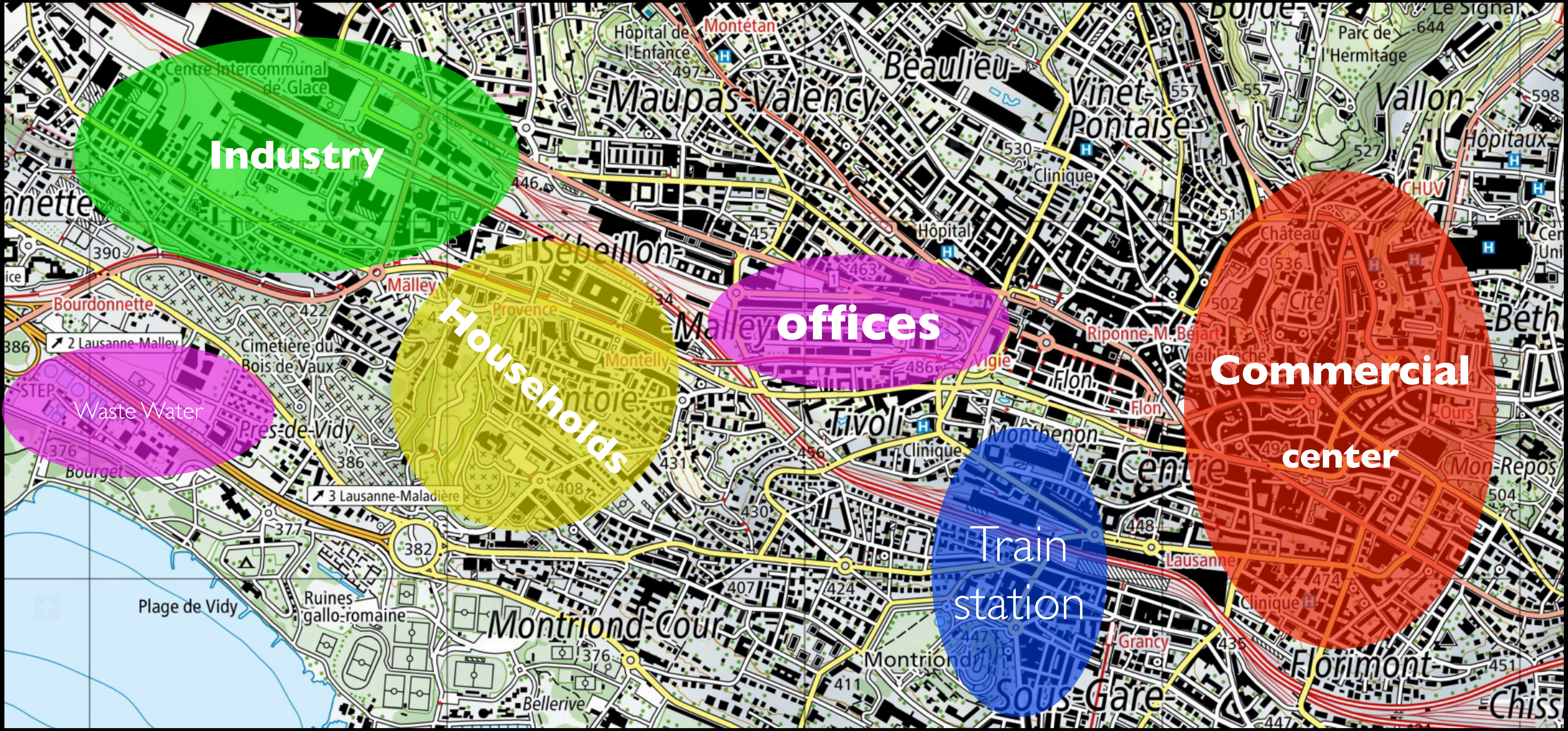
**84 %**
Energy savings
COP = 5.7

**6**
years
return

Thèse EPFL : Samuel Henchoz (2017)

EPFL

# DISTRICT ENERGY HUBS

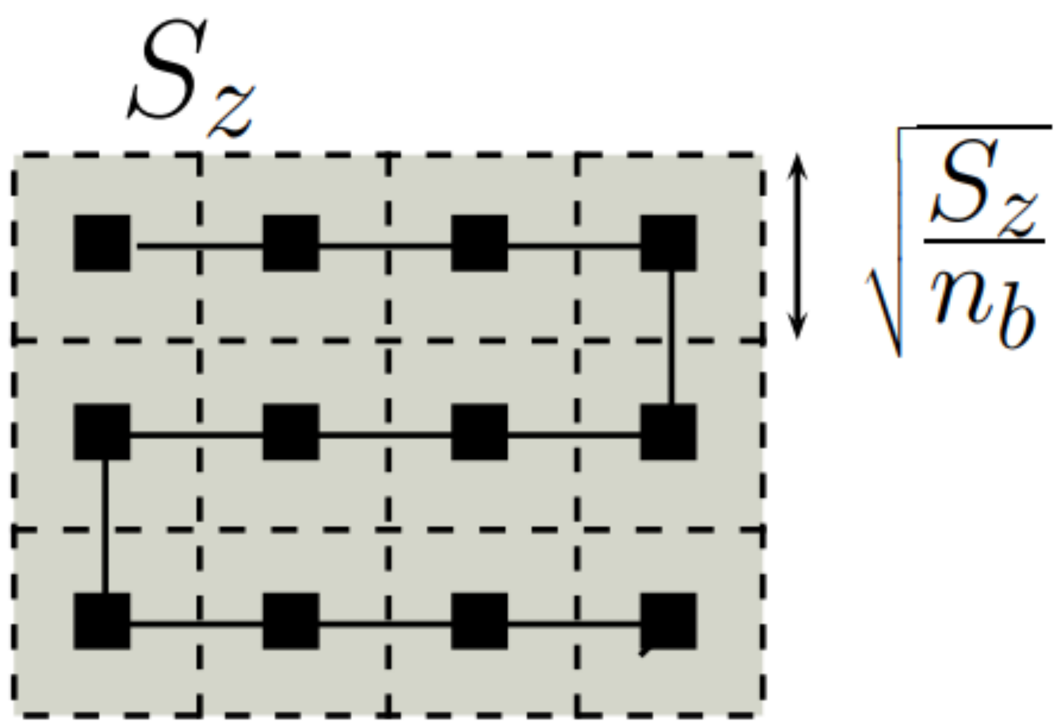


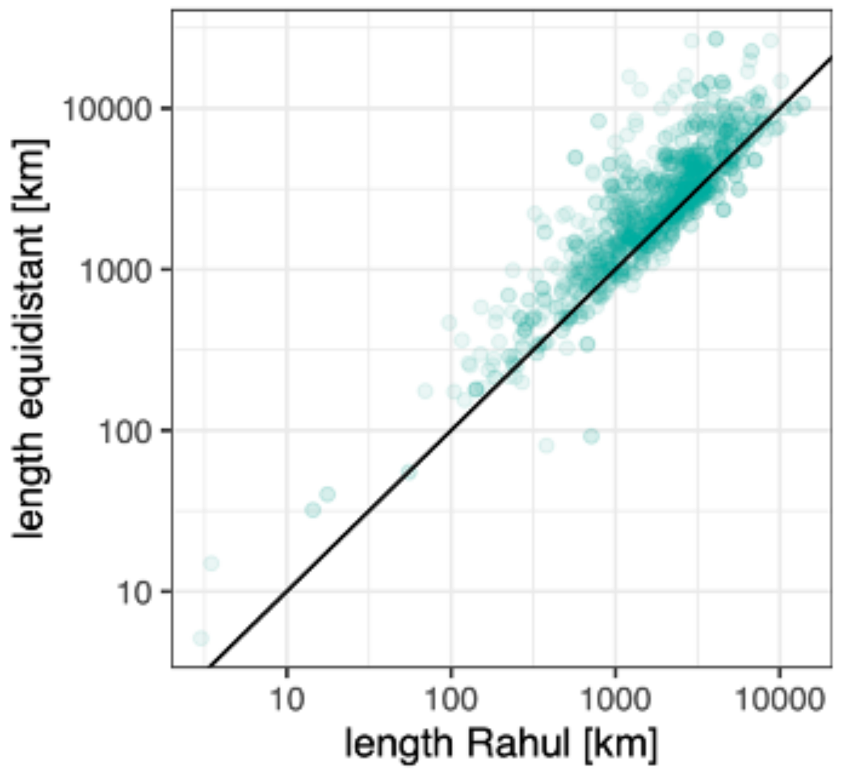

http://urb.io : decision support for urban development

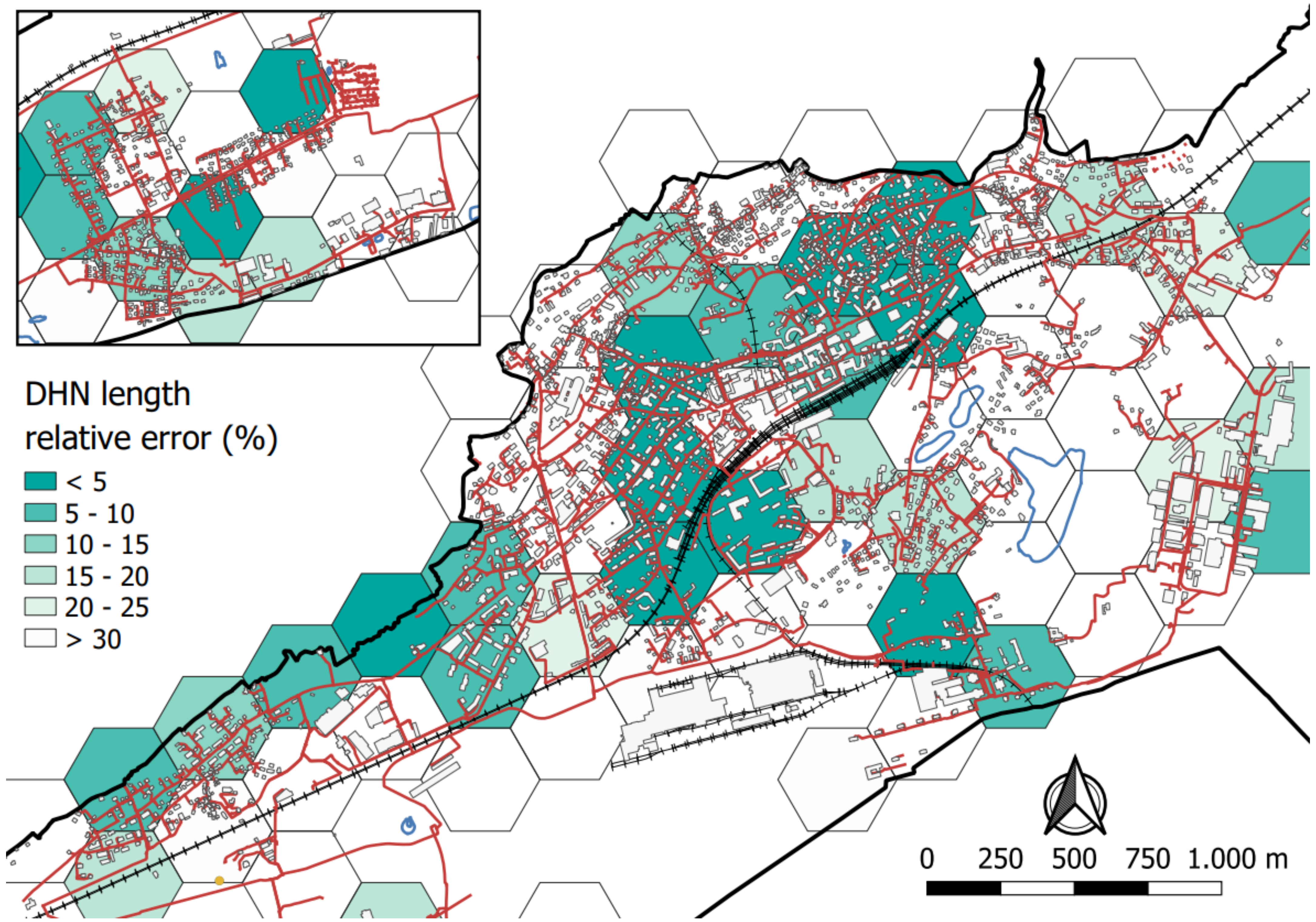
# Intra districts connections : meta model of the district

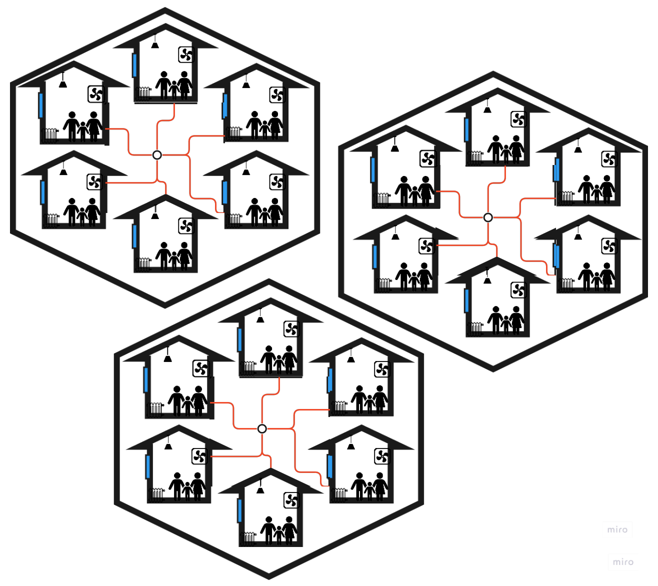






- Estimating lenght

$$L^{dn} \simeq 2(n_b - 1)K\sqrt{\frac{S_z}{n_b}}$$

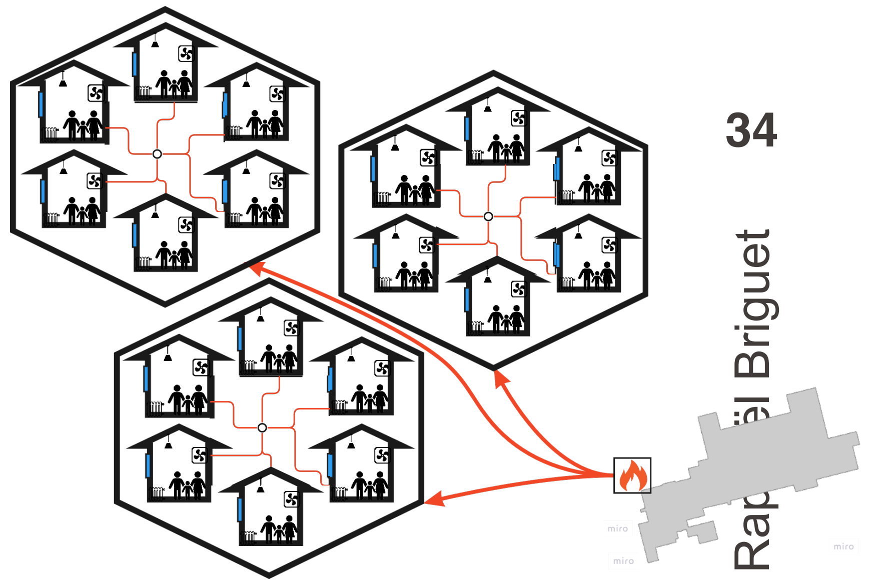
- K calibrated from existing network (Gas/elec)

- ⊕ Based on GIS data
  ⊕ Grids will use similar paths

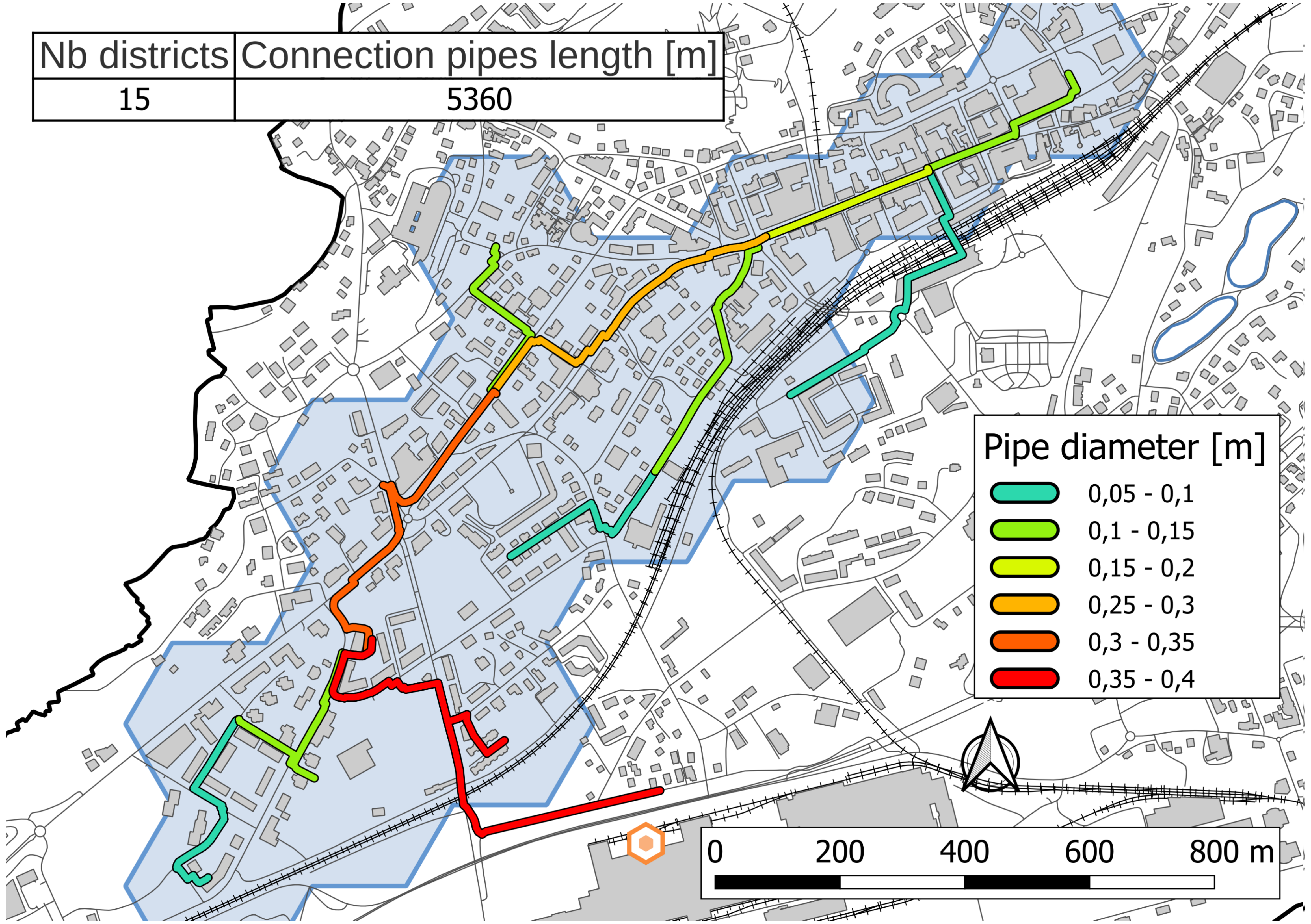
  ⊖ Buildings GIS data base
  ⊖ Node size => clustering

L'estimation de la longueur est calibrée grâce au réseau de gaz, représenté en rouge. La couleur indique l'erreur entre l'estimation et la longueur du réseau de gaz.

# Inter districts connections



| Nb districts | Connection pipes length [m] |
|---|---|
| 15 | 5360 |

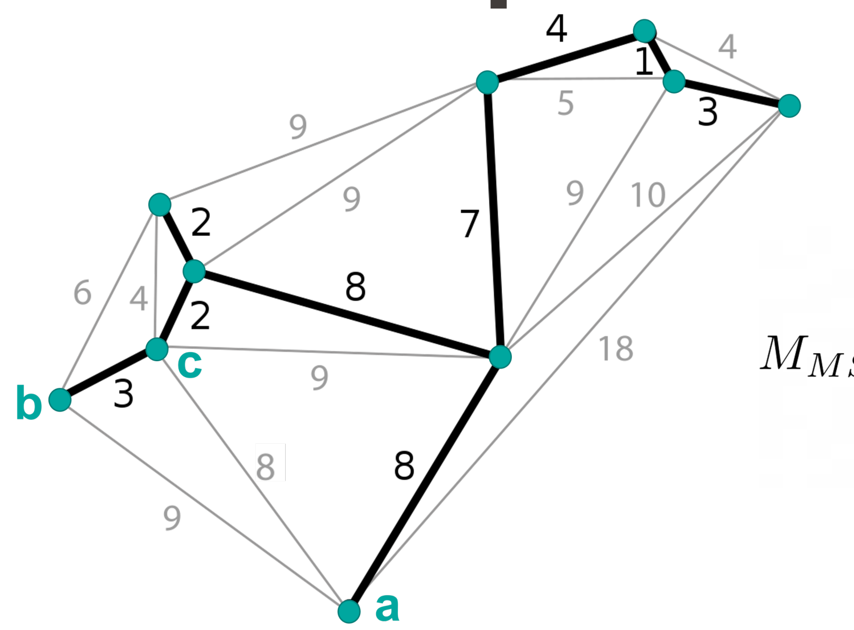



Représentation du réseau de chauffage qui fournit chacun des quartiers sélectionnés.

$$d^{dn} = \sqrt{\frac{4 \cdot \dot{m}^{dn}}{\pi \cdot v_s \cdot \rho}} \quad [m]$$

$$I_C^{dn} = \left(c_1 \cdot d^{dn} + c_2\right) \cdot L^{dn} \quad [CHF]$$

- **Minimum Spanning Tree**




$$M_{MST} = \begin{array}{c c} & \begin{array}{cccc} a & b & c & \end{array} \\ \begin{array}{c} a \\ b \\ c \\ \\ \end{array} & \begin{pmatrix} 0 & 9 & 8 & \cdots \\ 9 & 0 & 3 & \cdots \\ 8 & 3 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \end{array}$$

- ***OpenStreet Map*** **:** routing algorithms

+ Existing path (walking paths) : e.g. bridges, tunnels, roads
+ Constraints

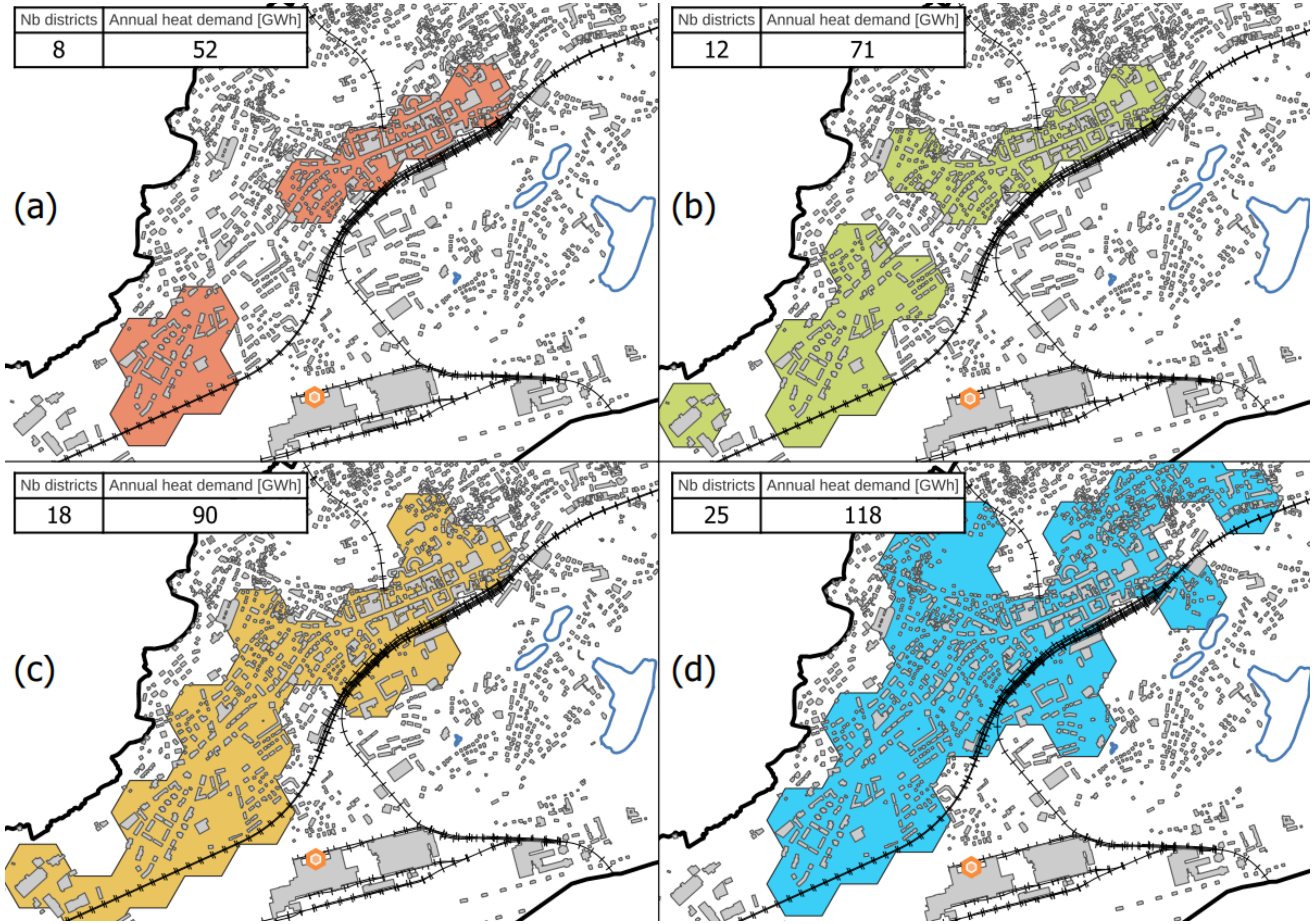
− Computing time
− no size contraints (only length)


IPESE
Industrial Process
and Energy Systems
Engineering

# Parametric geometric network expansion





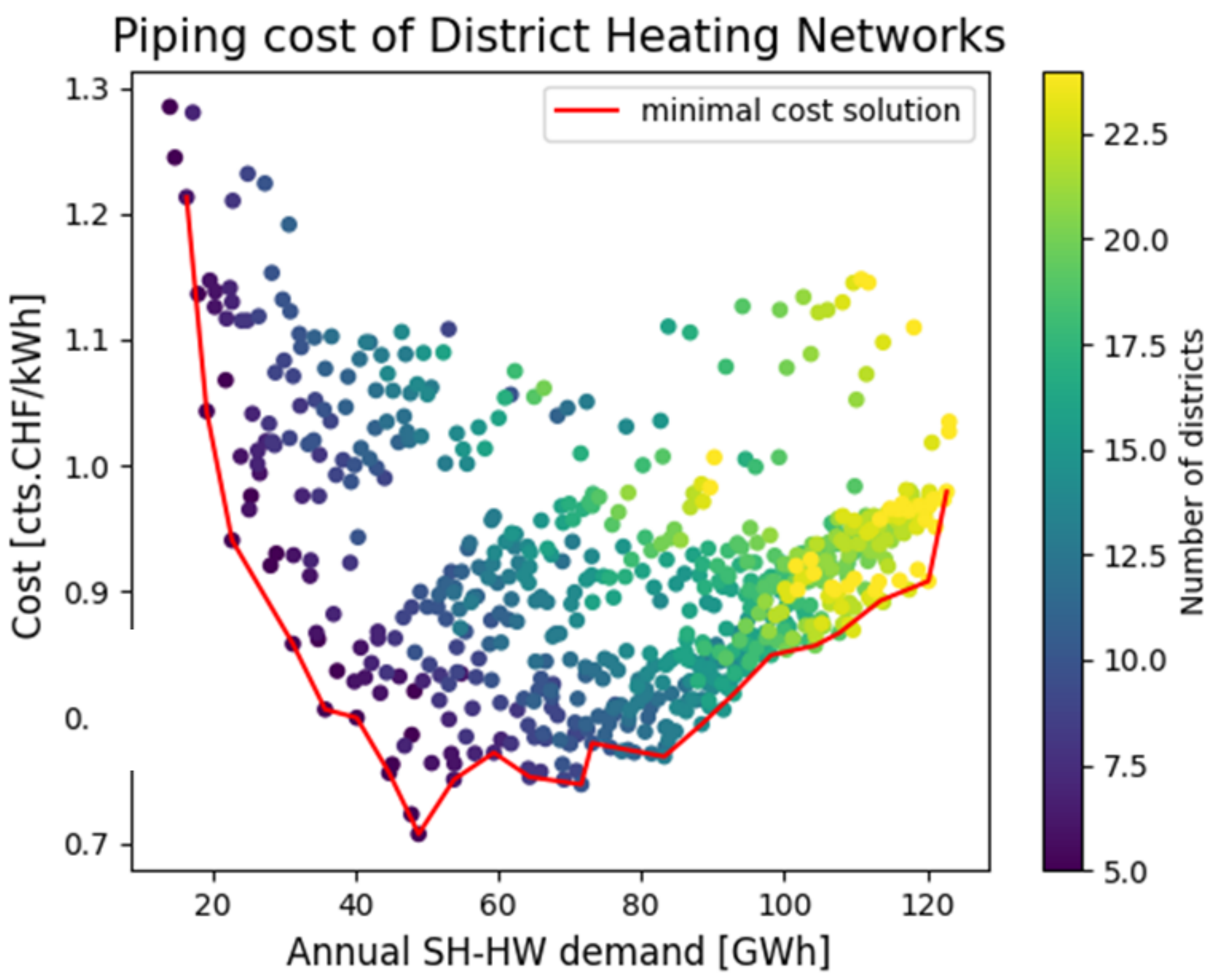



Représentation de l'expansion du réseau.

- (a) from a source point
- (b) sequence of priority
- (c) priorities based on densities

# Optimal configuration as a function of the coverage

Raphaël Briguet




Coût de l'énergie pour différentes configurations. Chaque point représente une configuration de réseau. La ligne rouge indique, pour une taille donnée, la solution la moins coûteuse.

For each network:

- Multi-objective optimisation

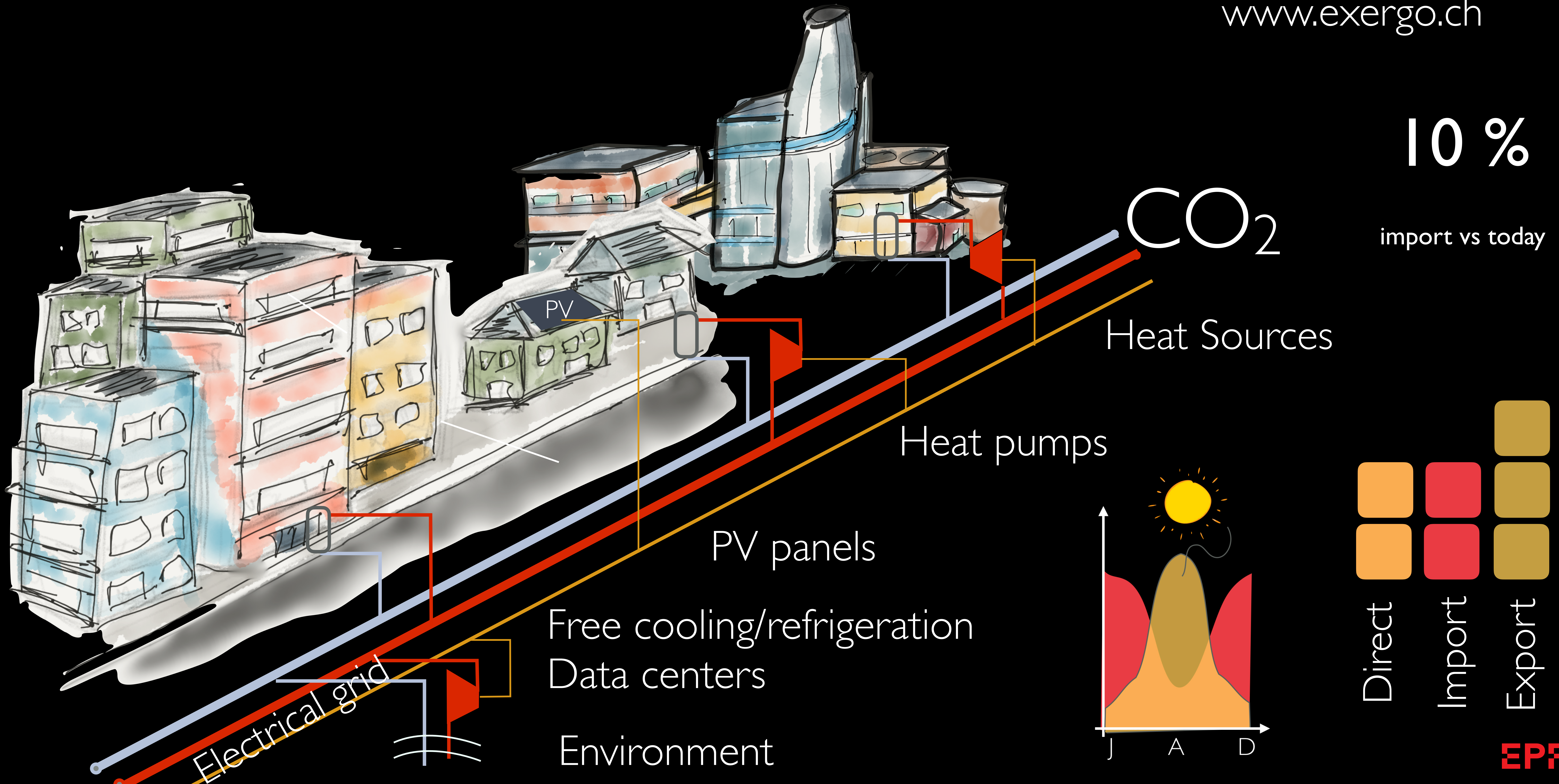
for $\pi \in \{0 ... max\}$ by $\Delta\pi$

$$\min_{pipes,size,flows} Total_{cost}(pipes, size, flows)$$

s.t. $pipes_{investment} \leq \pi$

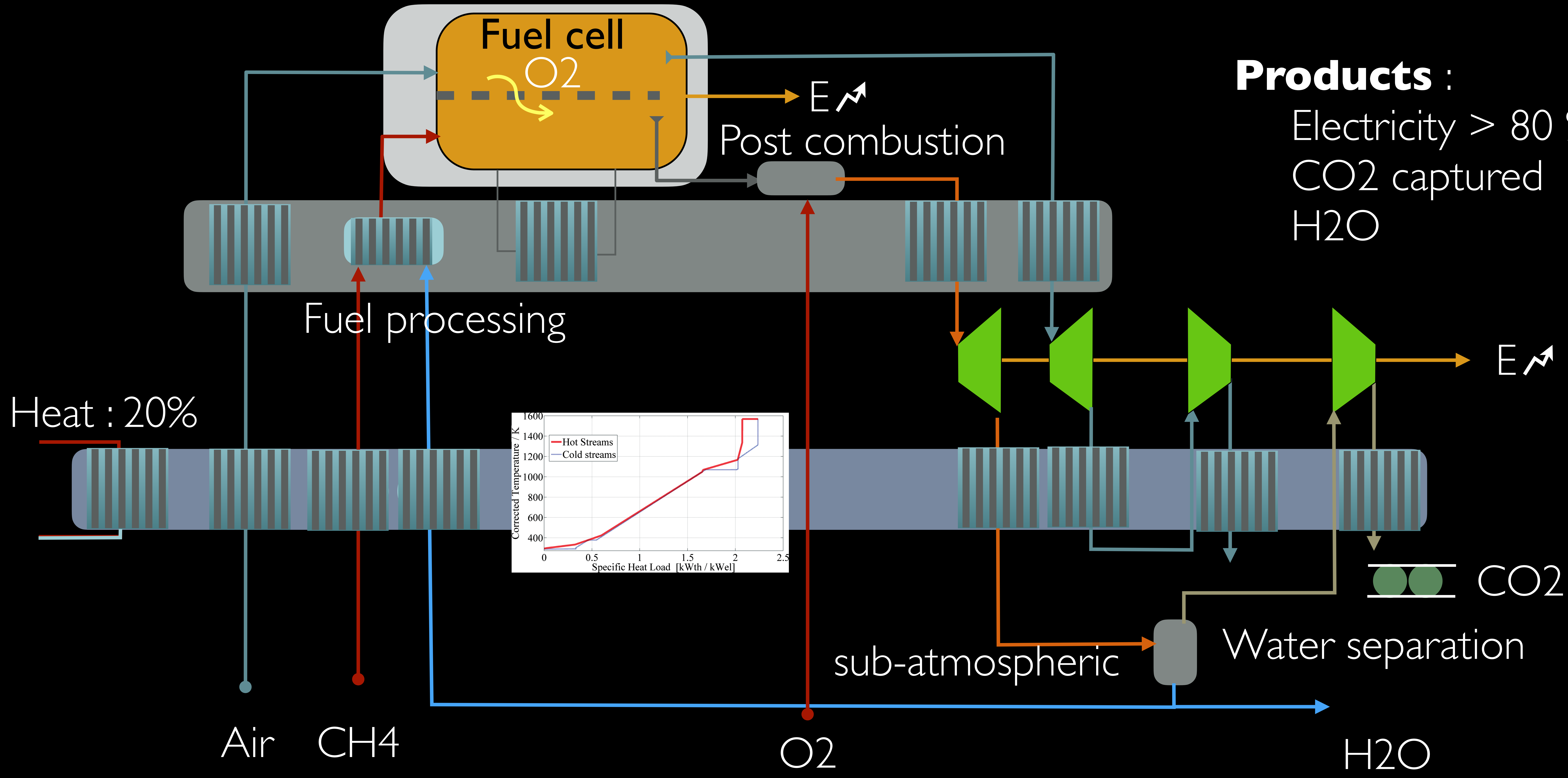
# DISTRICT RENEWABLE ENERGY HUBS

www.exergo.ch




EPFL

# PRODUCING ELECTRICITY WITH ADVANCED FUEL CELL SYSTEM




**Products** :
Electricity > 80 %
$CO_2$ captured
$H_2O$

Facchinetti, M, Daniel Favrat, and Francois Marechal. "Sub-atmospheric Hybrid Cycle SOFC-Gas Turbine with CO2 Separation." *PCT/IB2010/052558, 2011*.

EPFL

# INTEGRATED ENERGY MANAGEMENT

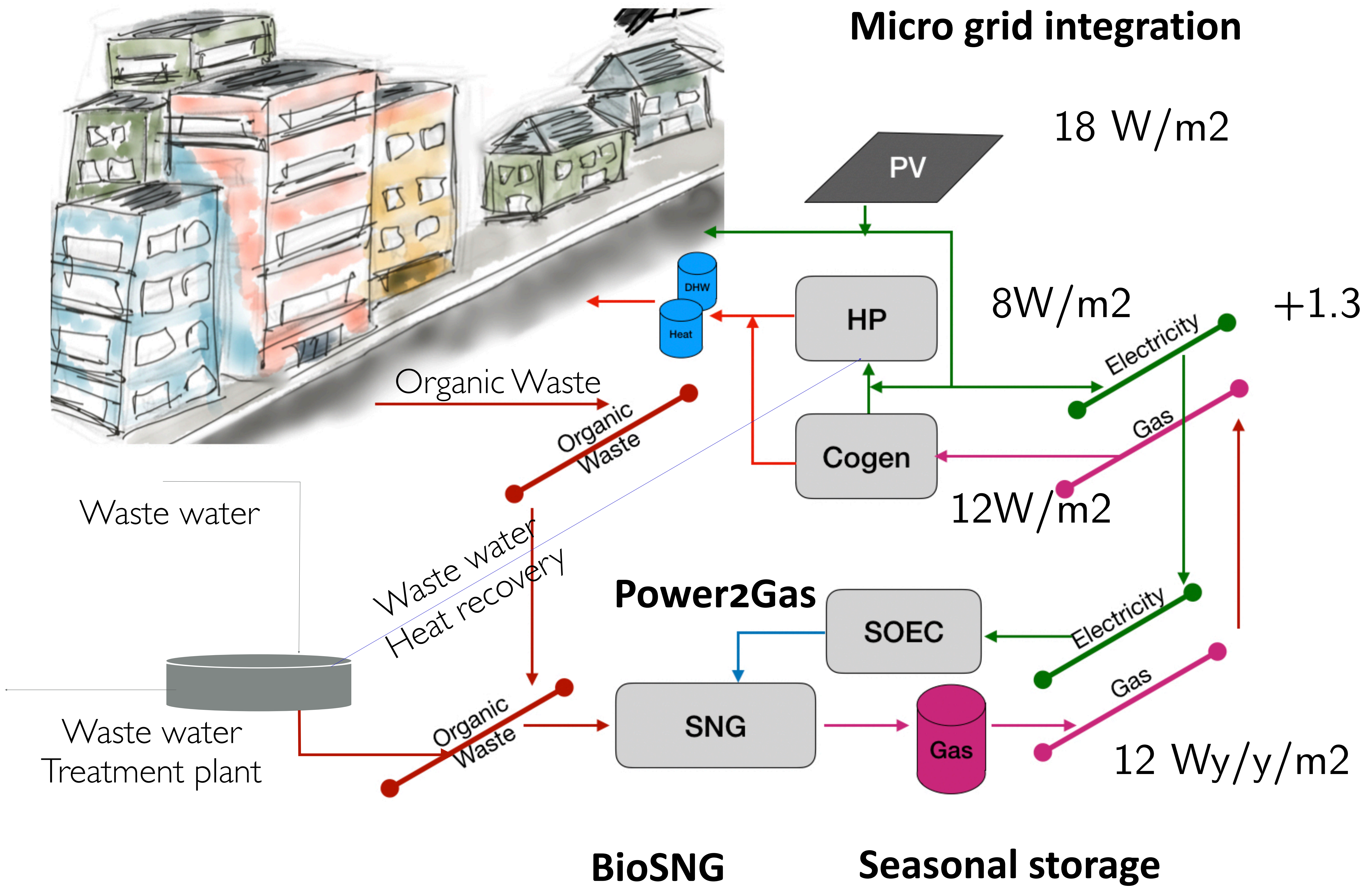
System Roundtrip 80%$=1-\frac{Q_{losses}}{E_{PV}}$


Al-Musleh, Easa I., Dharik S. Mallapragada, and Rakesh Agrawal. "Continuous power supply from a baseload renewable power plant." *Applied Energy* 122 (2014): 83-93.

EPFL

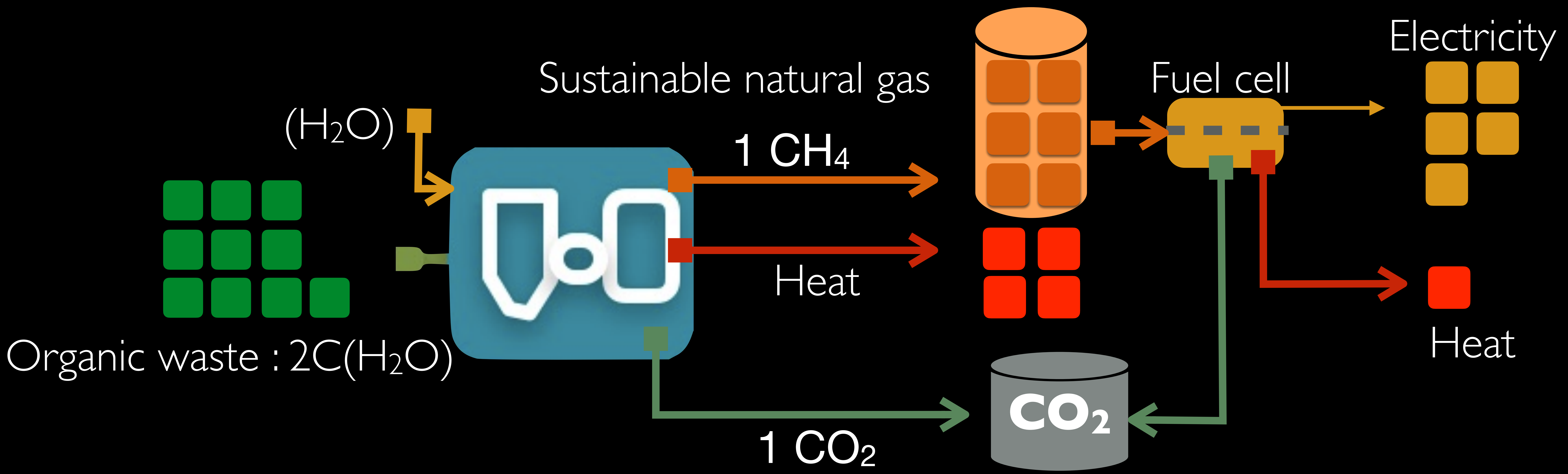
# Integrating Renewable Energy Sources : Biogas + PV+ Power2gas

- District scale => Exploring options




m2 = heated surface

# ORGANIC WASTE TO CLOSE THE ENERGY BALANCE



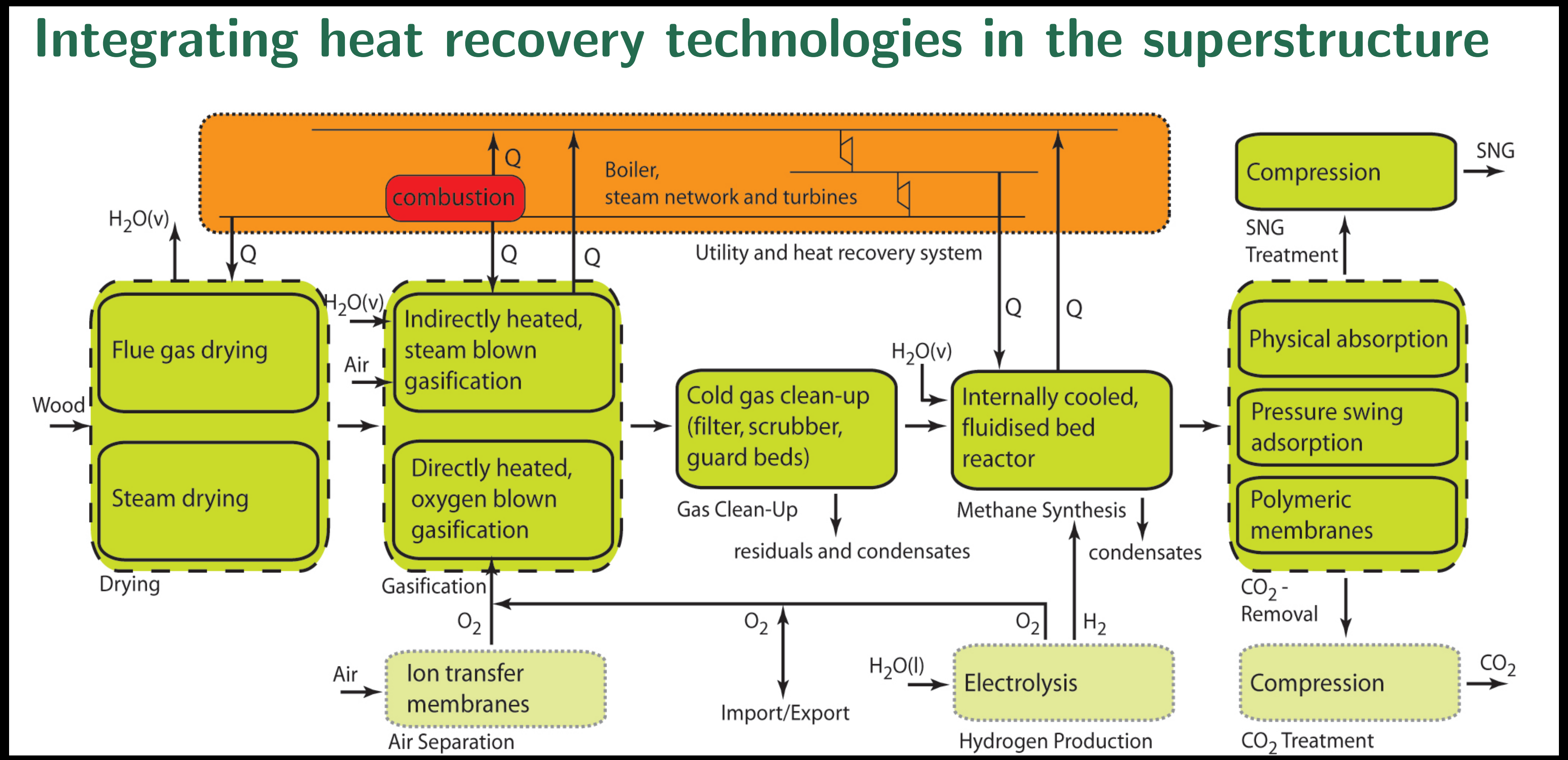

30% : Biomethanisation

70% : Hydrothermal gasification (http://trea-tech.com)

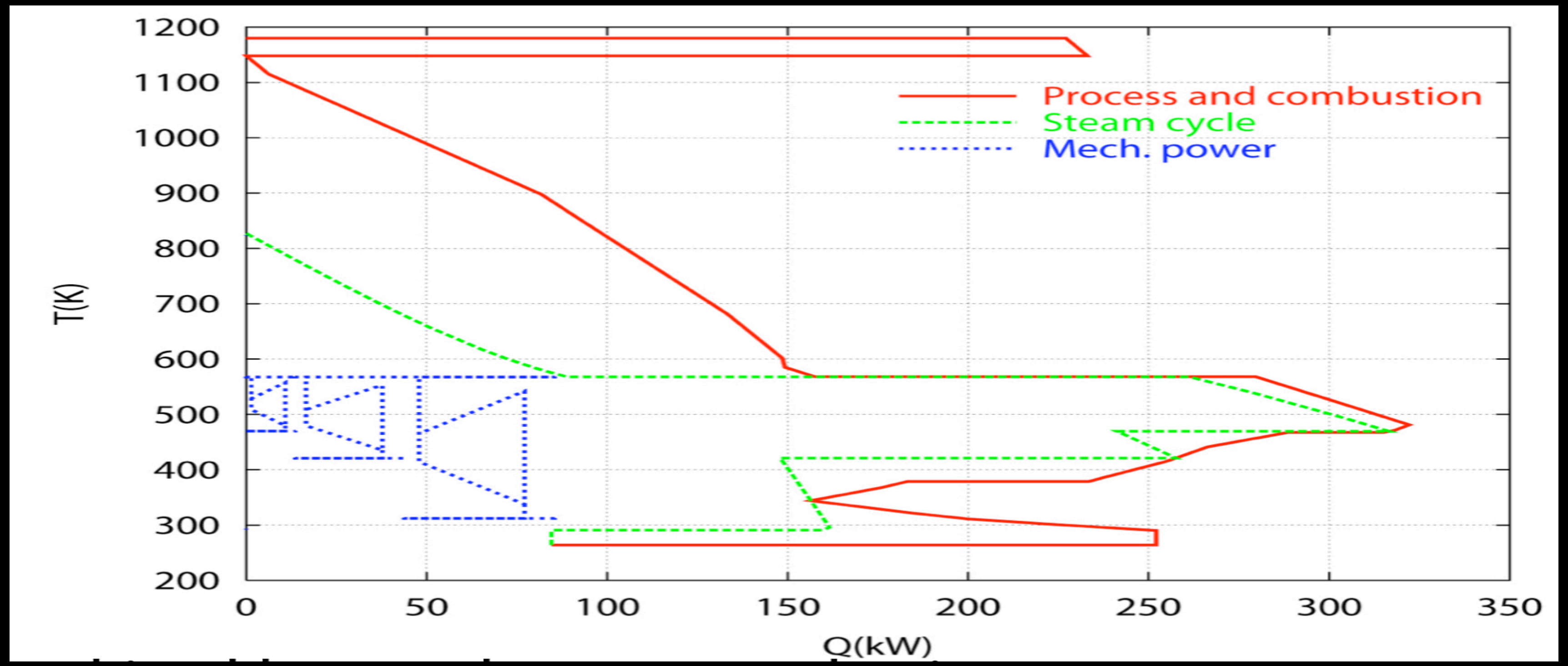
70% : Synthetic Natural Gas

# PROCESS DESIGN MODELS

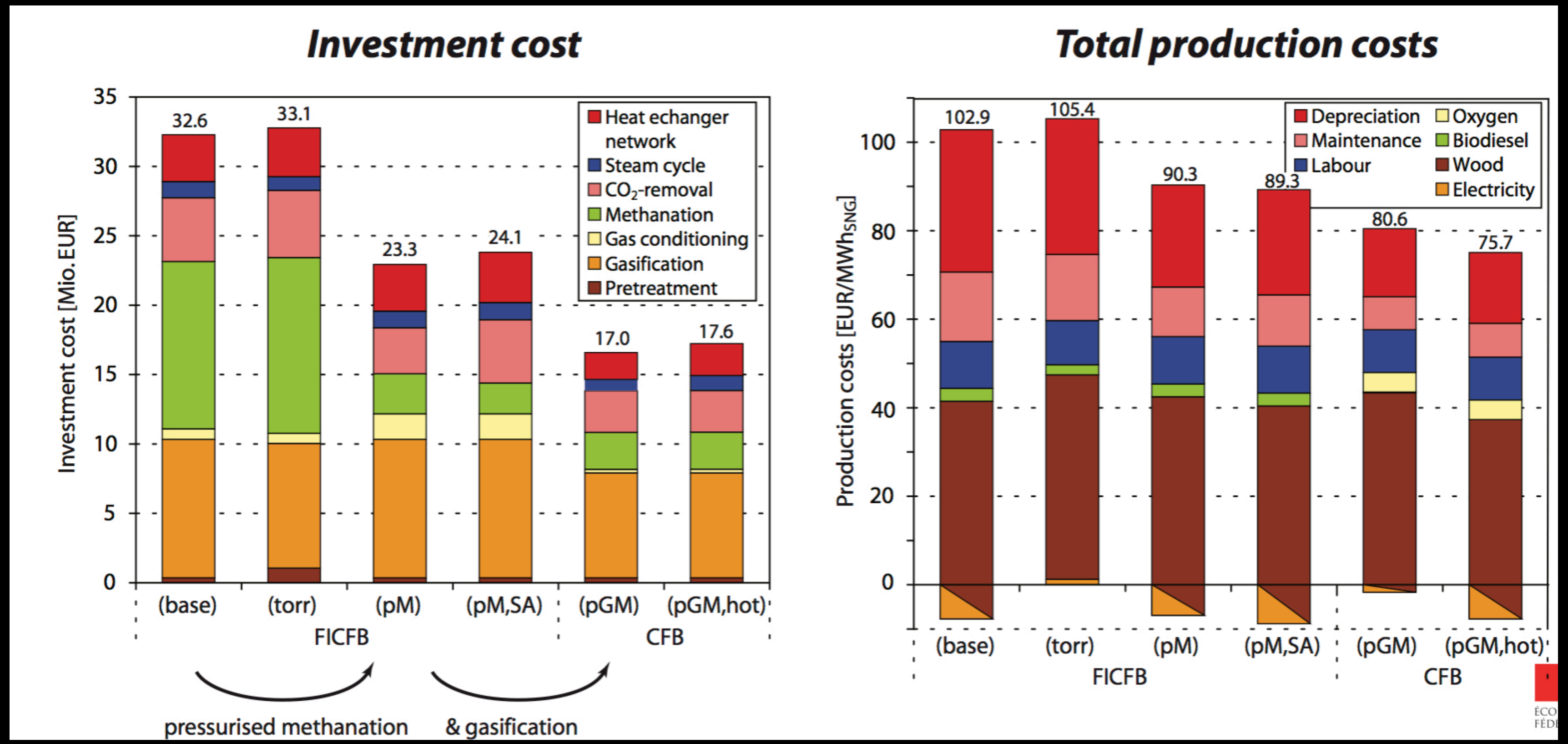
## Super-Structure
- Flowsheeting models
- Process unit model data base




## System integration
- Heat recovery
- Energy conversion
- Waste + Water



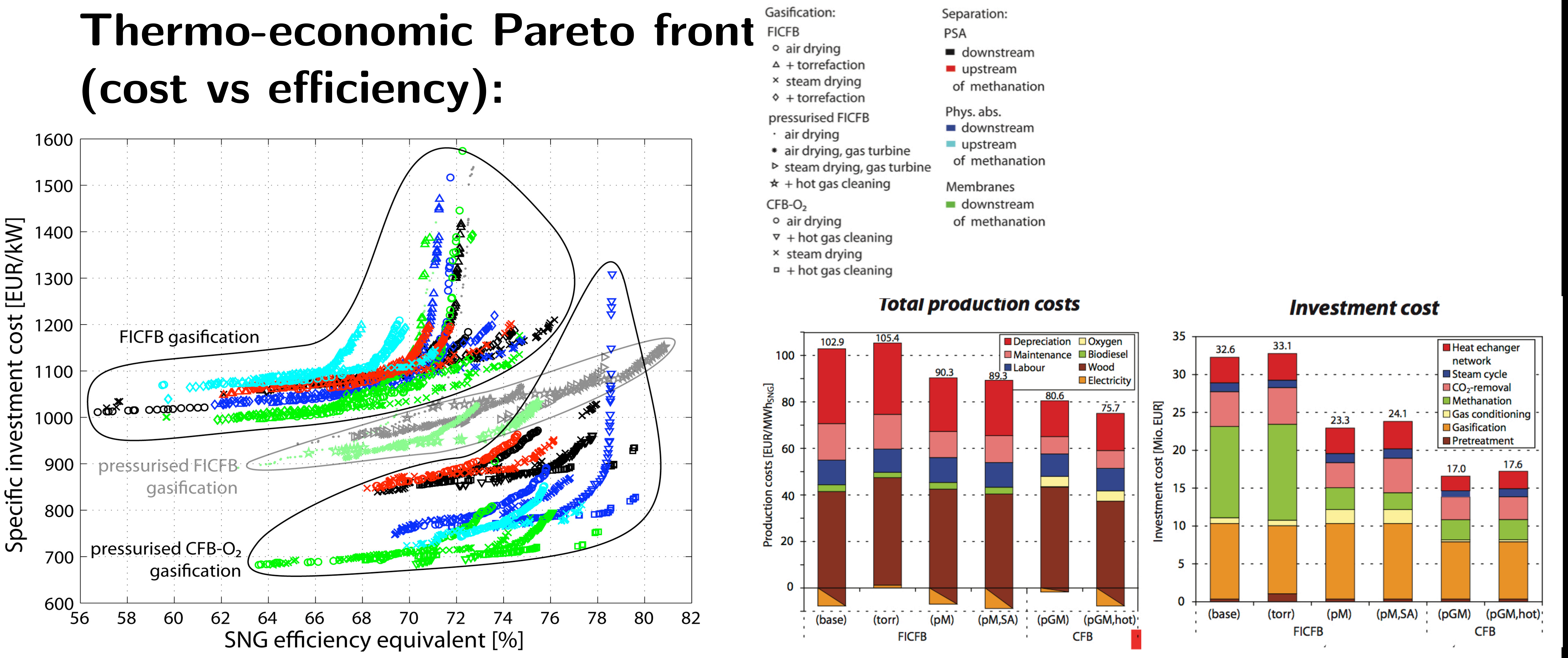

## Performances
- OPEX
- CAPEX
- LCA
- Thermodynamic




(1)
Gassner, M.; Maréchal, F. Thermo-Economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation. *Energy Environ. Sci.* **2012**, *5* (2), 5768–5789. https://doi.org/10.1039/C1EE02867G.

# BIOMASS TO SYNTHETIC NATURAL GAS

**Thermo-economic Pareto front (cost vs efficiency):**






Gassner, M.; Maréchal, F. Thermo-Economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation. *Energy Environ. Sci.* **2012**, *5* (2), 5768–5789. https://doi.org/10.1039/C1EE02867G.

# DEALING WITH UNCERTAINTIES

Taking decision

Generating solutions

What are the most probable best solutions

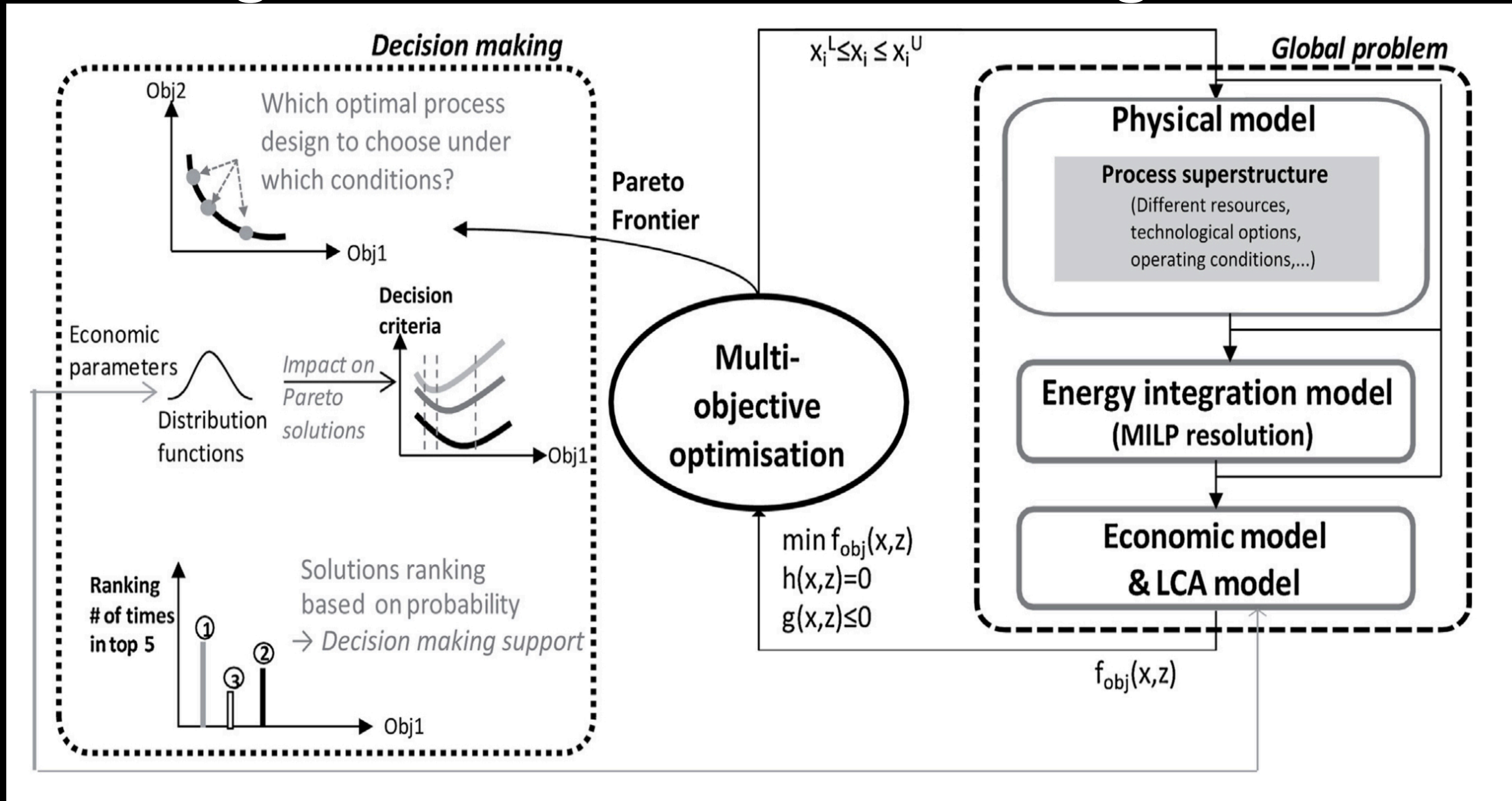
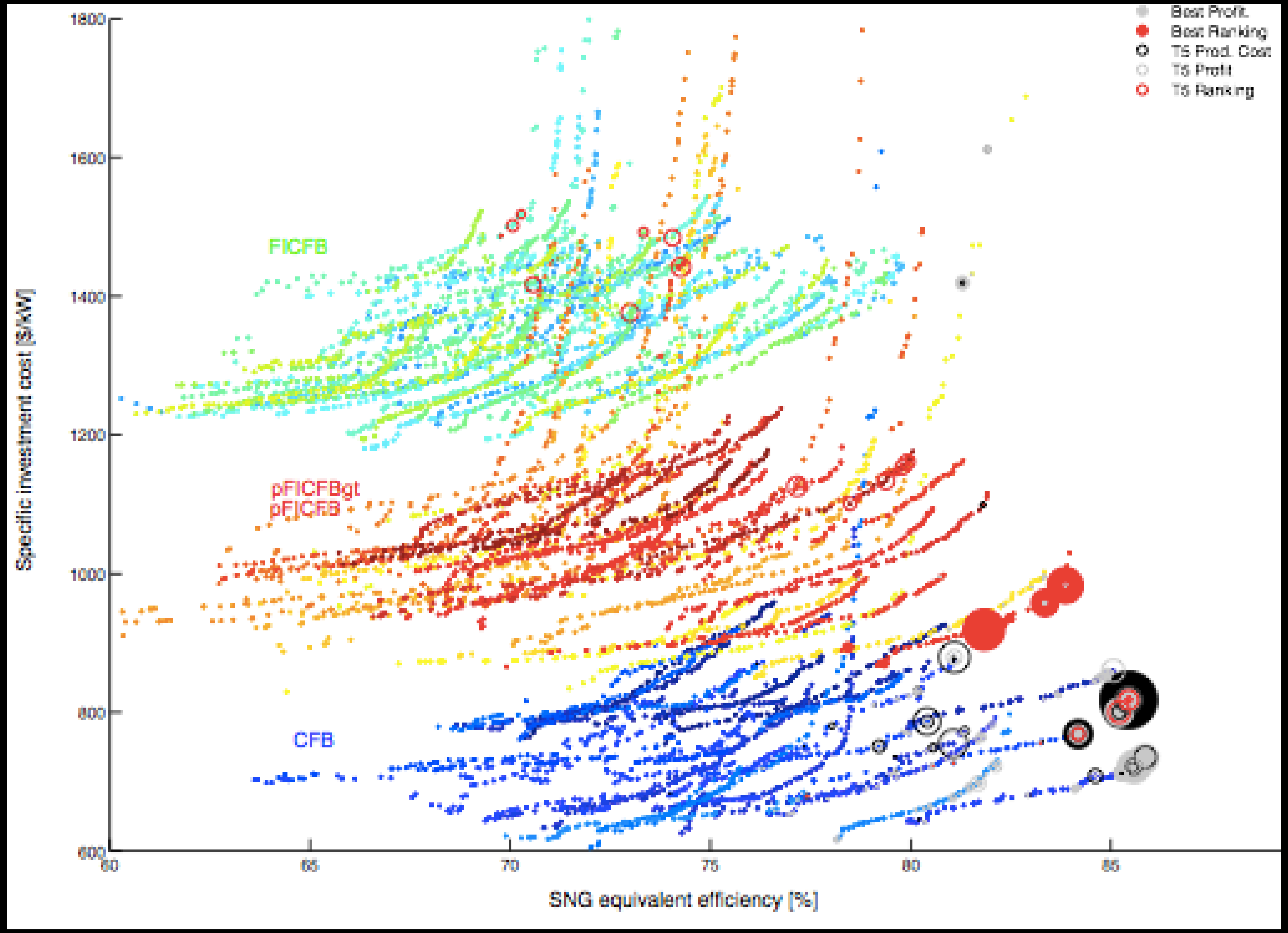


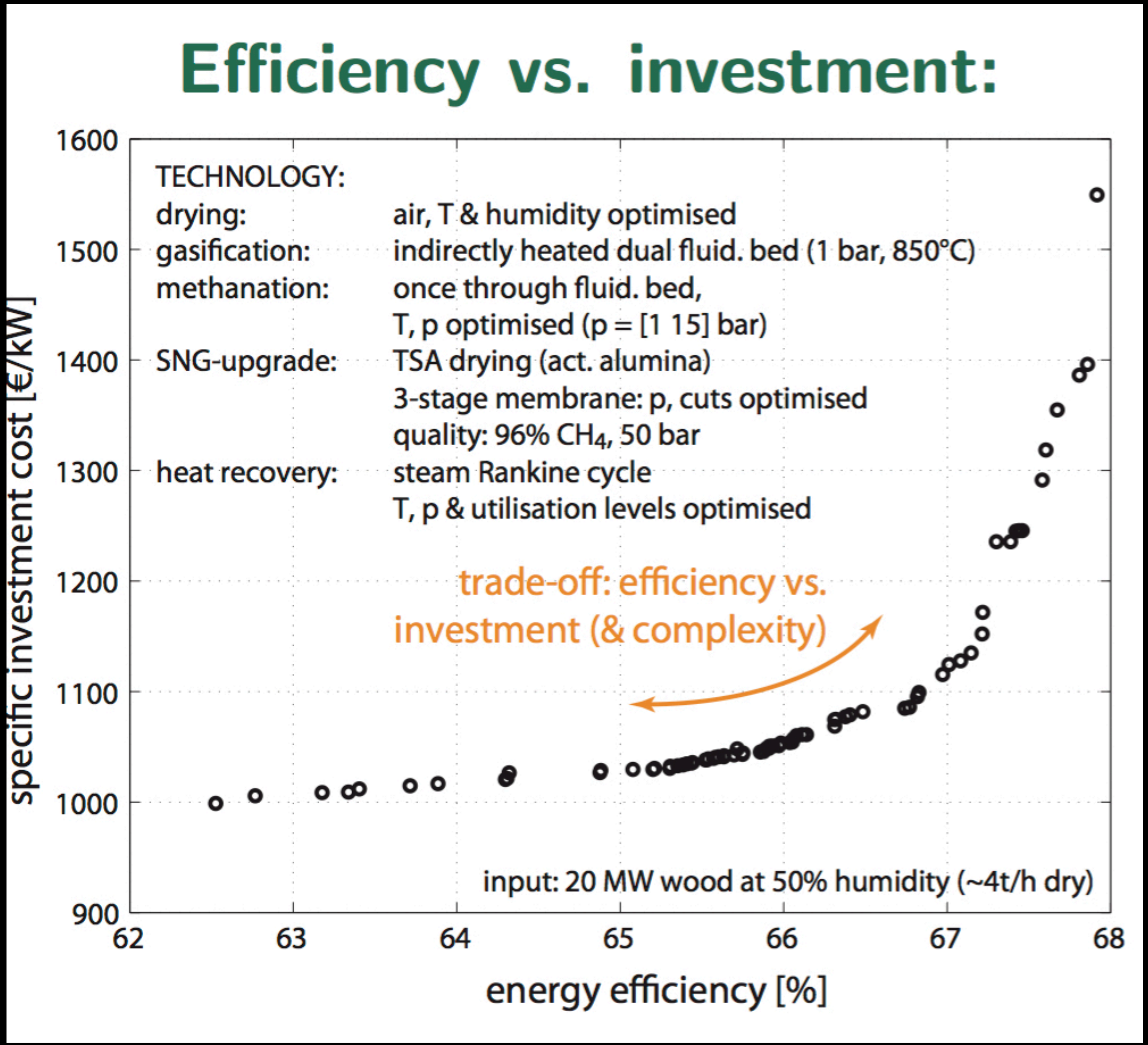

**Fig. 1.** Thermo-environomic optimisation strategy to support decision-making.



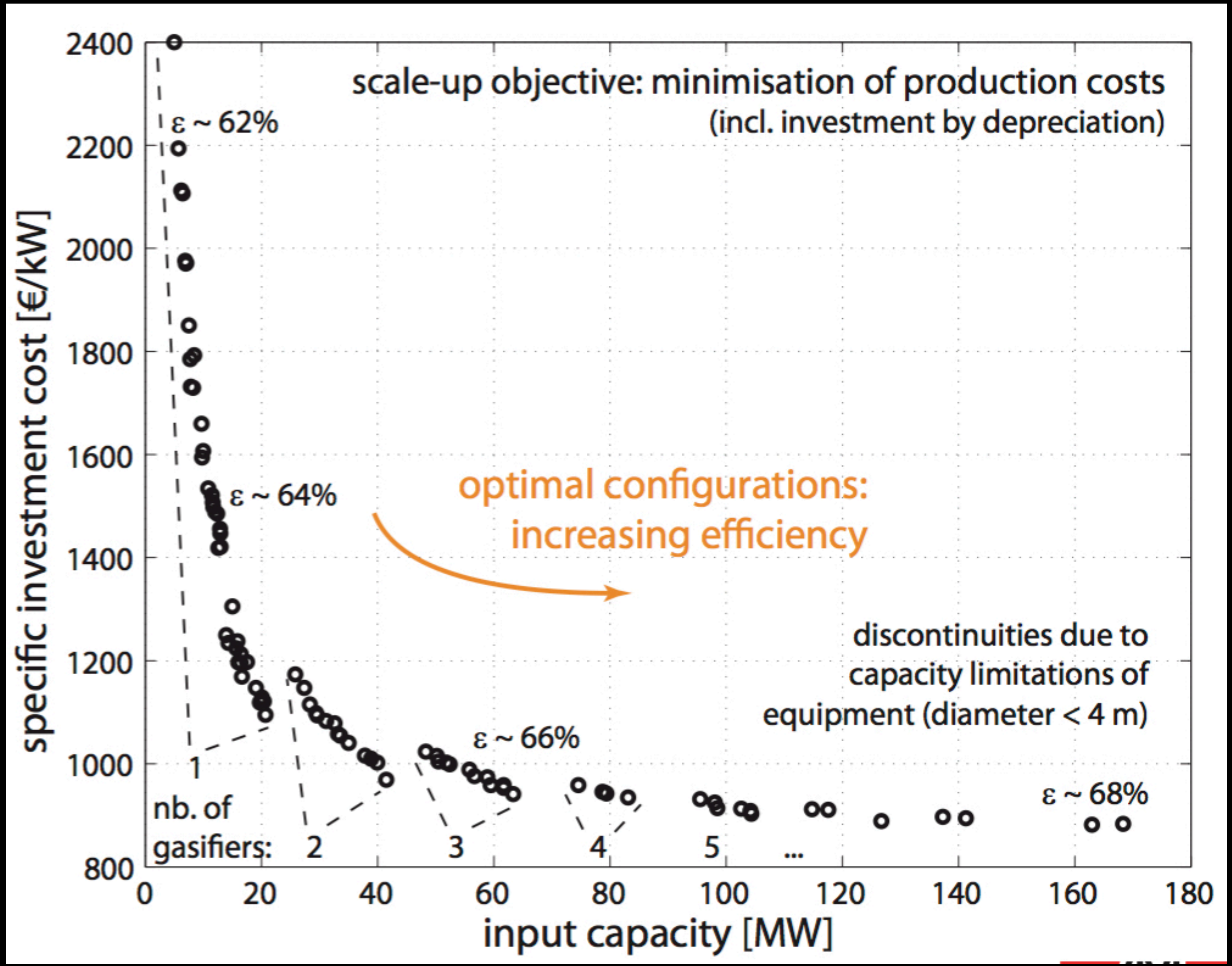

(1)
Tock, L.; Maréchal, F. Decision Support for Ranking Pareto Optimal Process Designs under Uncertain Market Conditions. Computers & Chemical Engineering 2015, 83, 165–175. https://doi.org/10.1016/j.compchemeng.2015.06.009.

# MULTI-OBJECTIVE OPTIMISATION

## Thermo-economic trade-off




## Process sizes




Gassner, M., & Maréchal, F. (2009). Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. *Biomass and bioenergy*, *33*(11), 1587-1604.

# Integrating Life Cycle Impact assessment

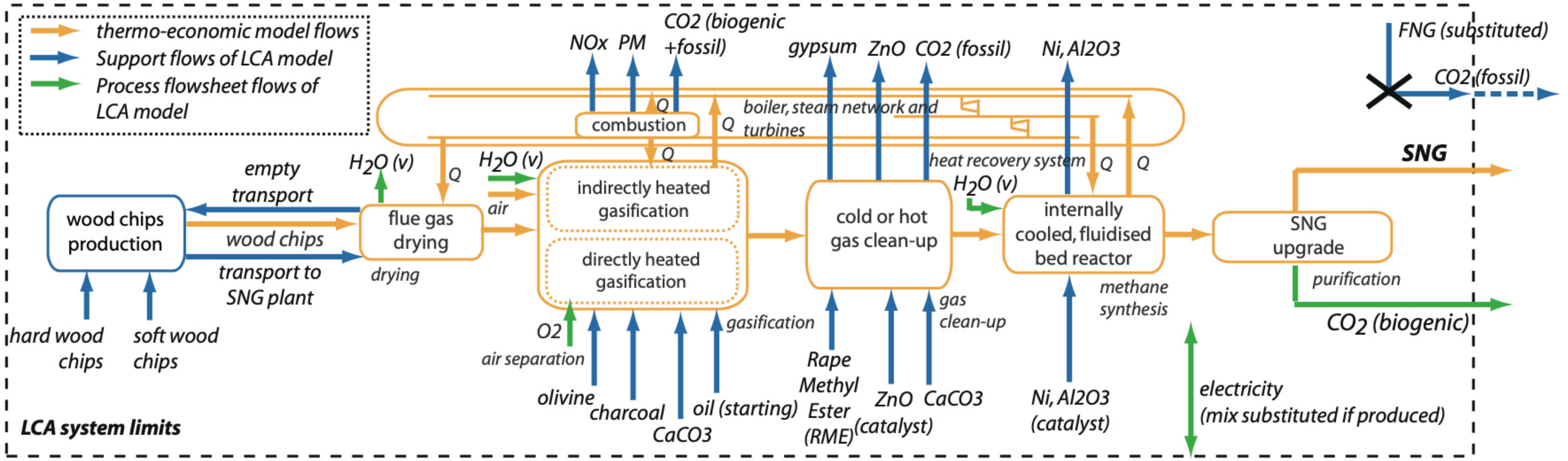
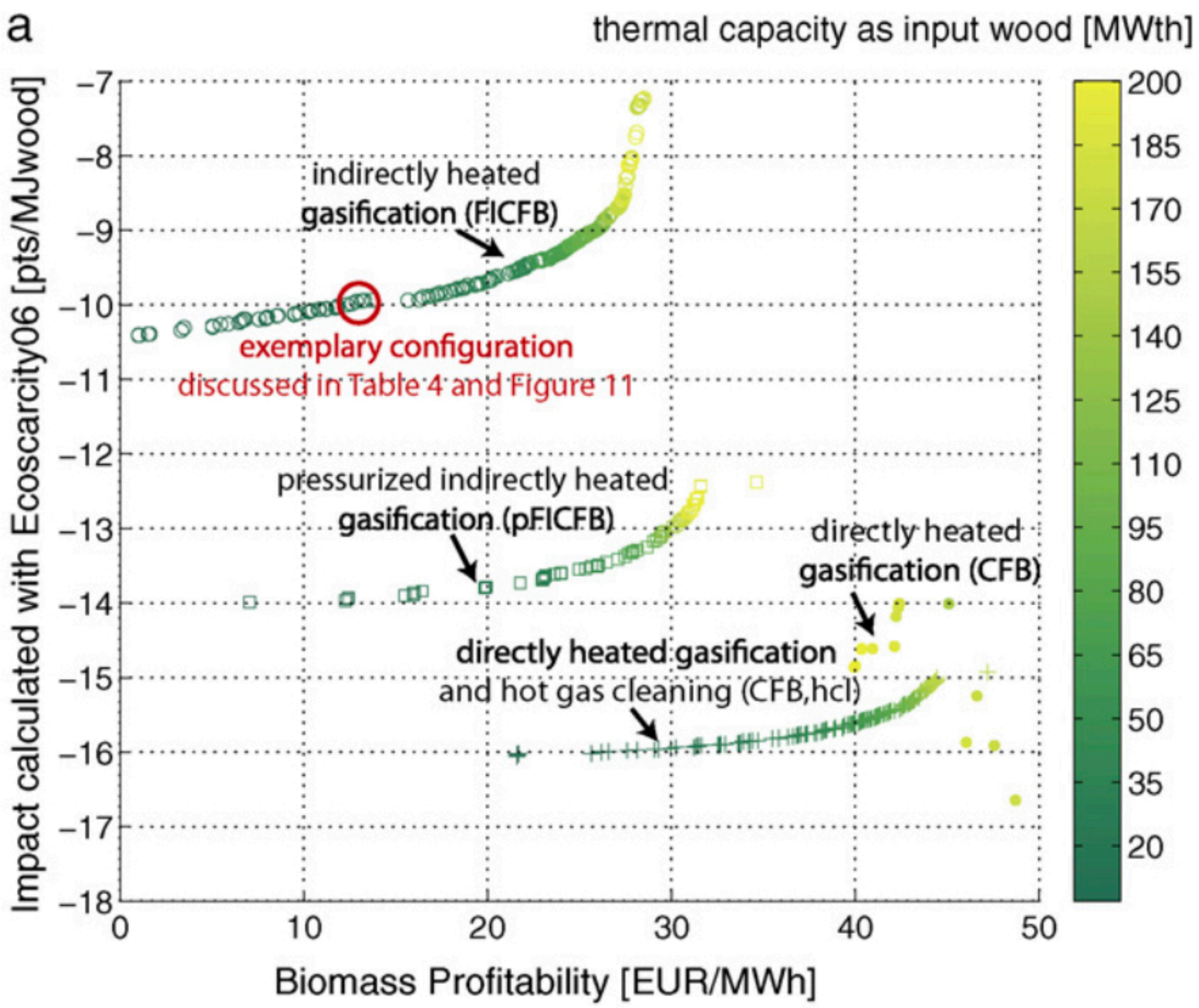


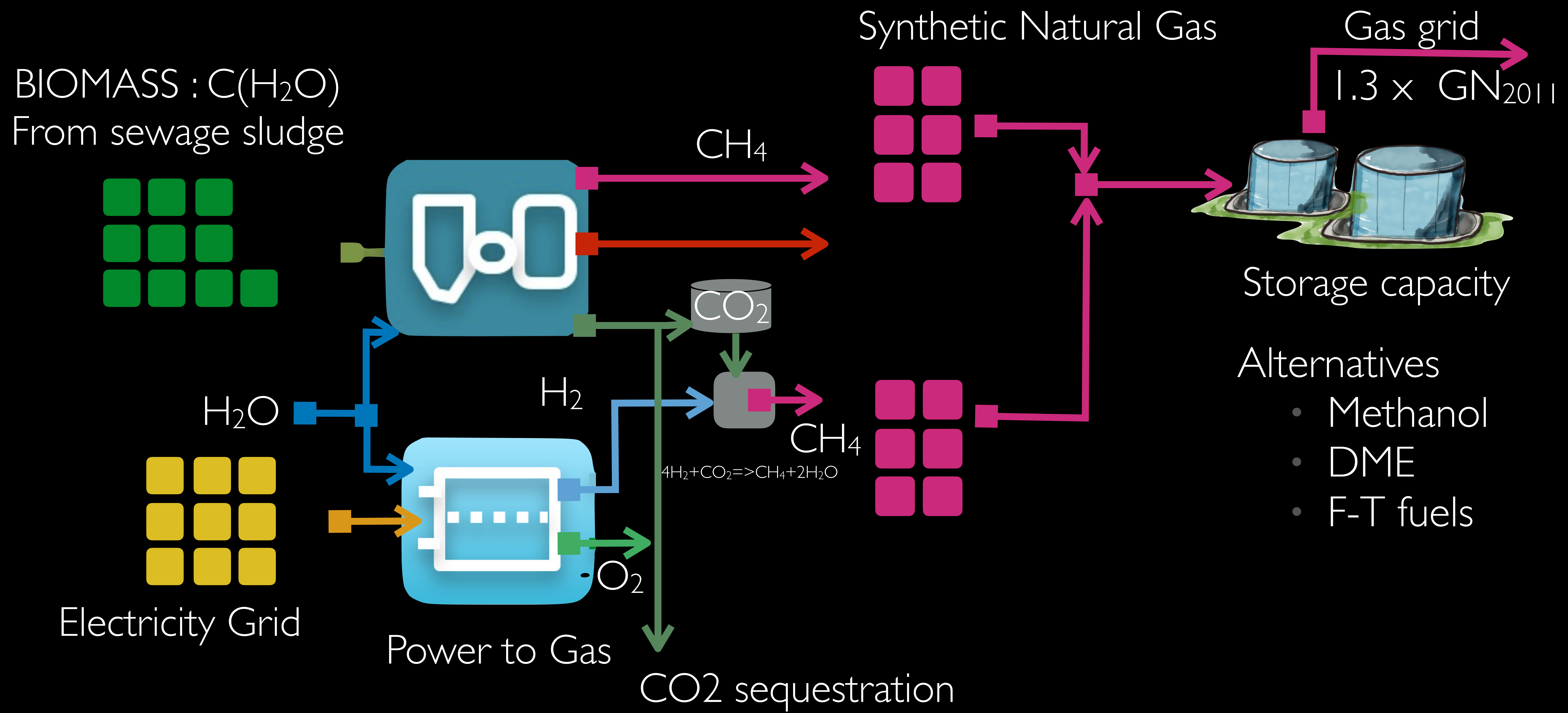

**Fig. 3.** Flows of environmental concern added to the thermo-economic model.

- Multi objective optimisation
  - LCIA indicators
  - Thermodynamic
  - Economic
  - Scale effect
  - Supply chains




Gerber, L., Gassner, M., & Maréchal, F. (2011). Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass. *Computers & Chemical Engineering*, *35*(7), 1265-1280.

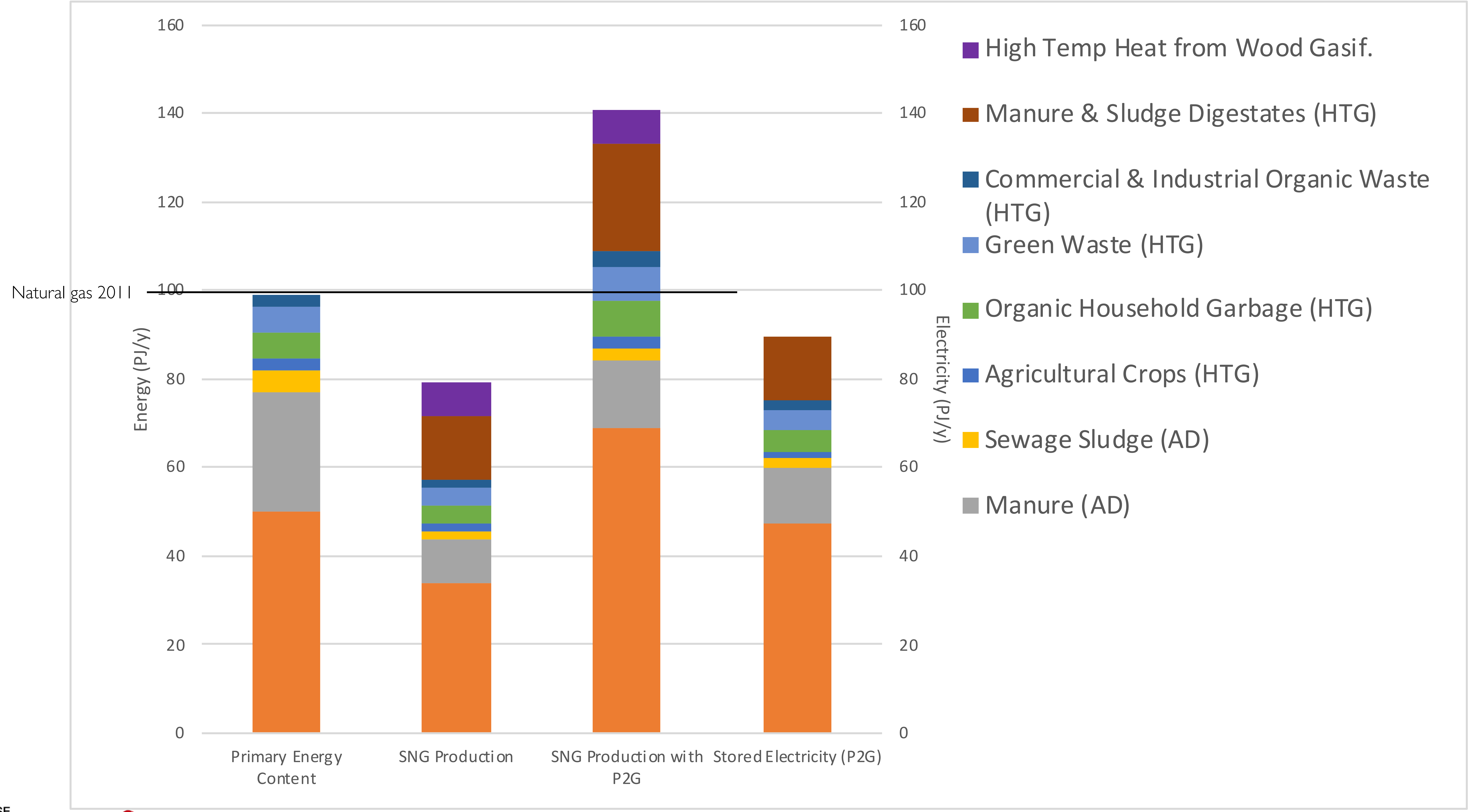
# USE OF DISTRICT WASTE BIOMASS AS AN ENERGY SOURCE



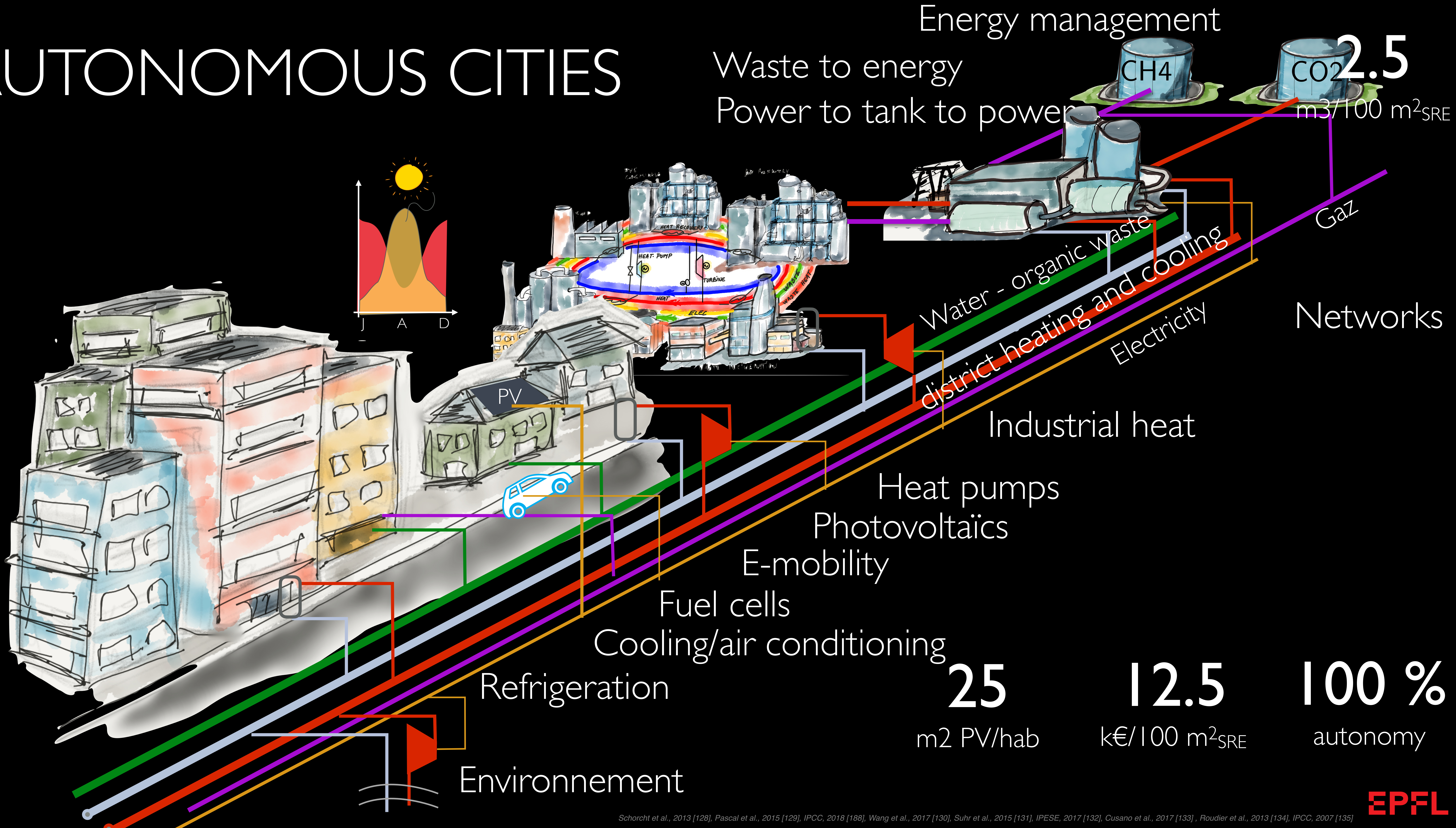

Alternatives
- Methanol
- DME
- F-T fuels

Gassner, Martin, and François Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." Energy 33.2 (2008): 189-198.

# Biomass resource and conversion



# AUTONOMOUS CITIES




Schorcht et al., 2013 [128], Pascal et al., 2015 [129], IPCC, 2018 [188], Wang et al., 2017 [130], Suhr et al., 2015 [131], IPESE, 2017 [132], Cusano et al., 2017 [133] , Roudier et al., 2013 [134], IPCC, 2007 [135]

# Defossilizing industry : thematics

**Efficiency**
*Materials recovery*
*Heat recovery*

**Heat valorisation**
Heat pumping
Waste heat to electricity

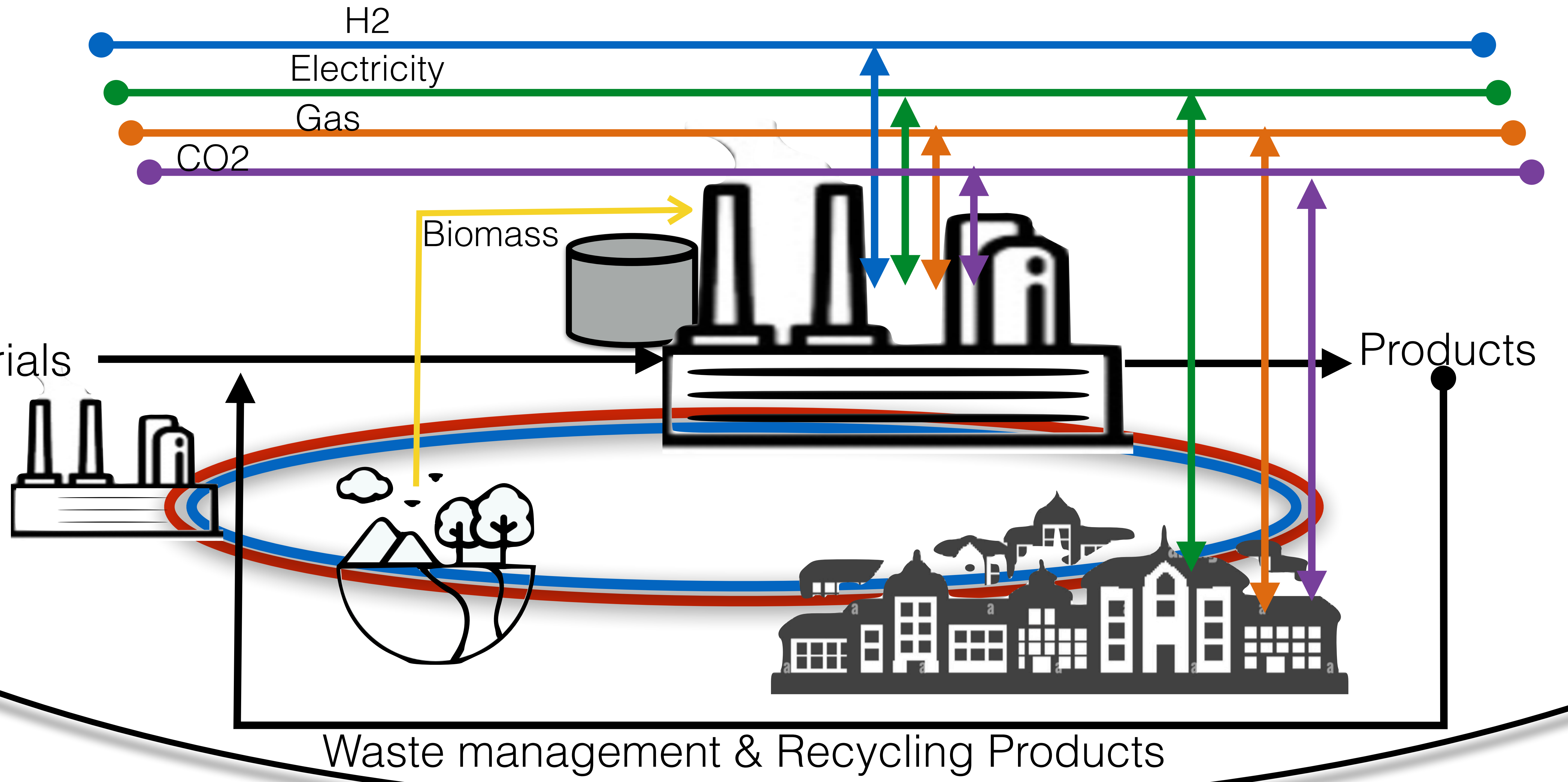
**Energy conversion**
*Renewable energy sources*
*Combined Heat and Power*
*Combined Heat and Fuel*

**Technology efficiency**
*Optimal operation*
*Technology improvement*
*Technology innovation*

**CO2**
*Capture, reuse, sequestrate*

**Energy system integration**
*Energy grids*
*Heat and electricity storage*
*Hydrogen*
*Power2Tanks2Power*

**Energy Audits**
*Energy Drivers*
*Efficiency KPI*
*Monitoring*




**System expansion**
*District heating/cooling*
*Industrial symbiosis*
*Waste-water-energy*
*Circular economy*

**Sustainability metrics**
*CO2 footprint*
*Resources usage*
*Environmental impact*

**Thermodynamic metrics**
*Energy Efficiency*
*Mass balances*
*Exergy*

**Economic metrics**
*CAPEX-OPEX*
*Technology Readiness*
*Retrofit and pay-back*

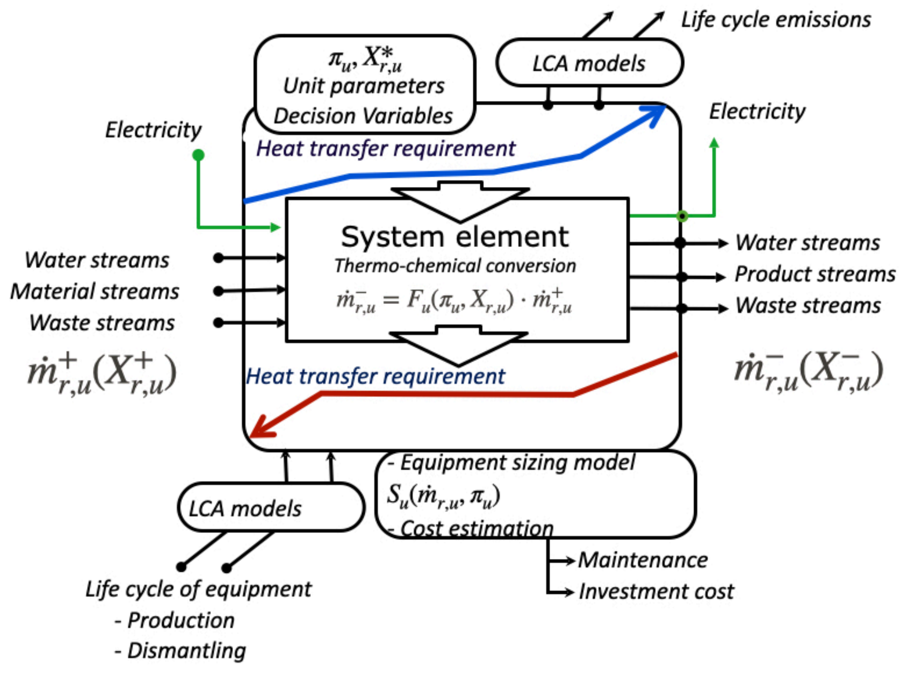
# Defining decarbonisation routes for the industry

## Blueprint models per sector

## Decarbonisation options

- Process models
- Integration models

## Decarbonisation Pathways



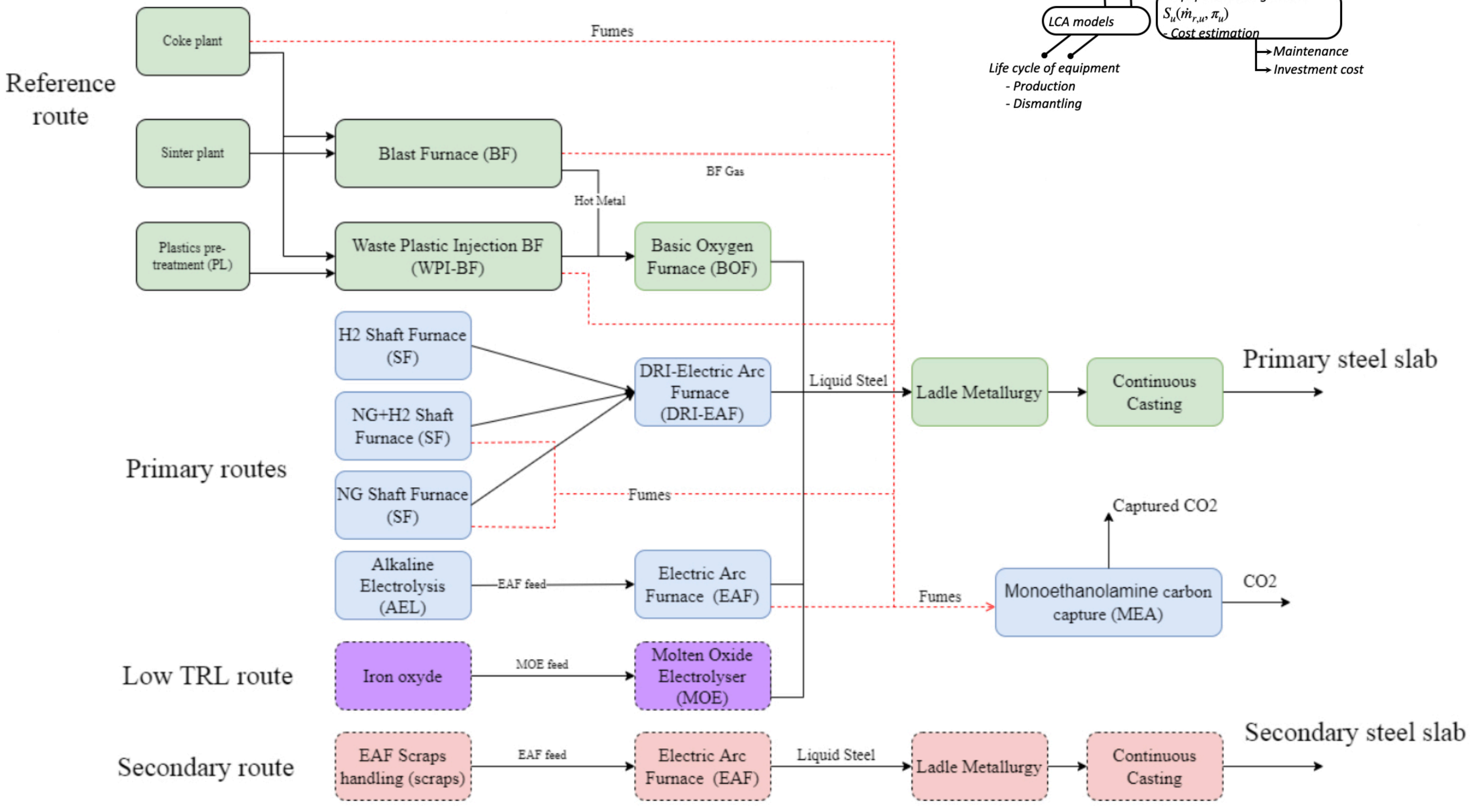




Figure 2.3: steel production routes schematic.

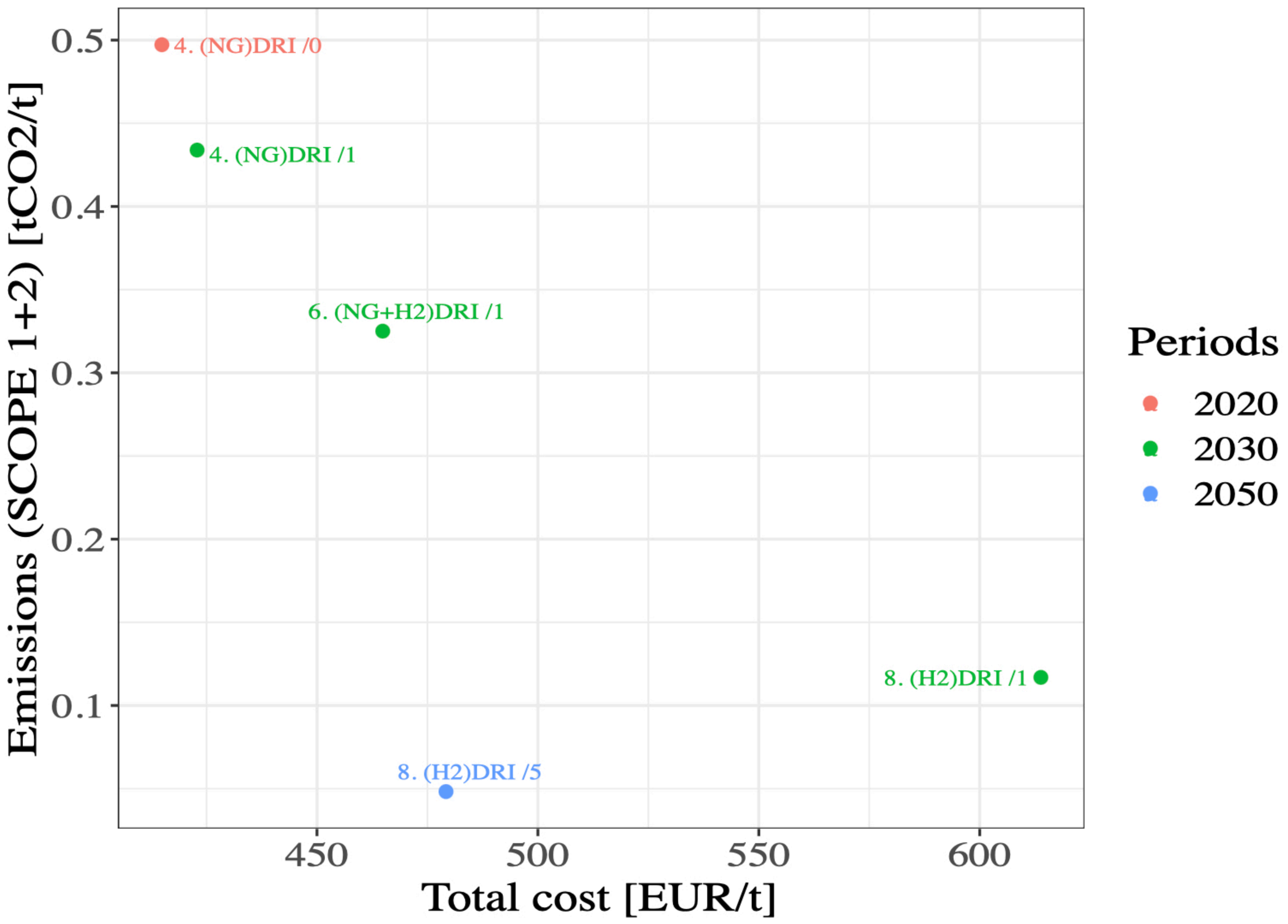


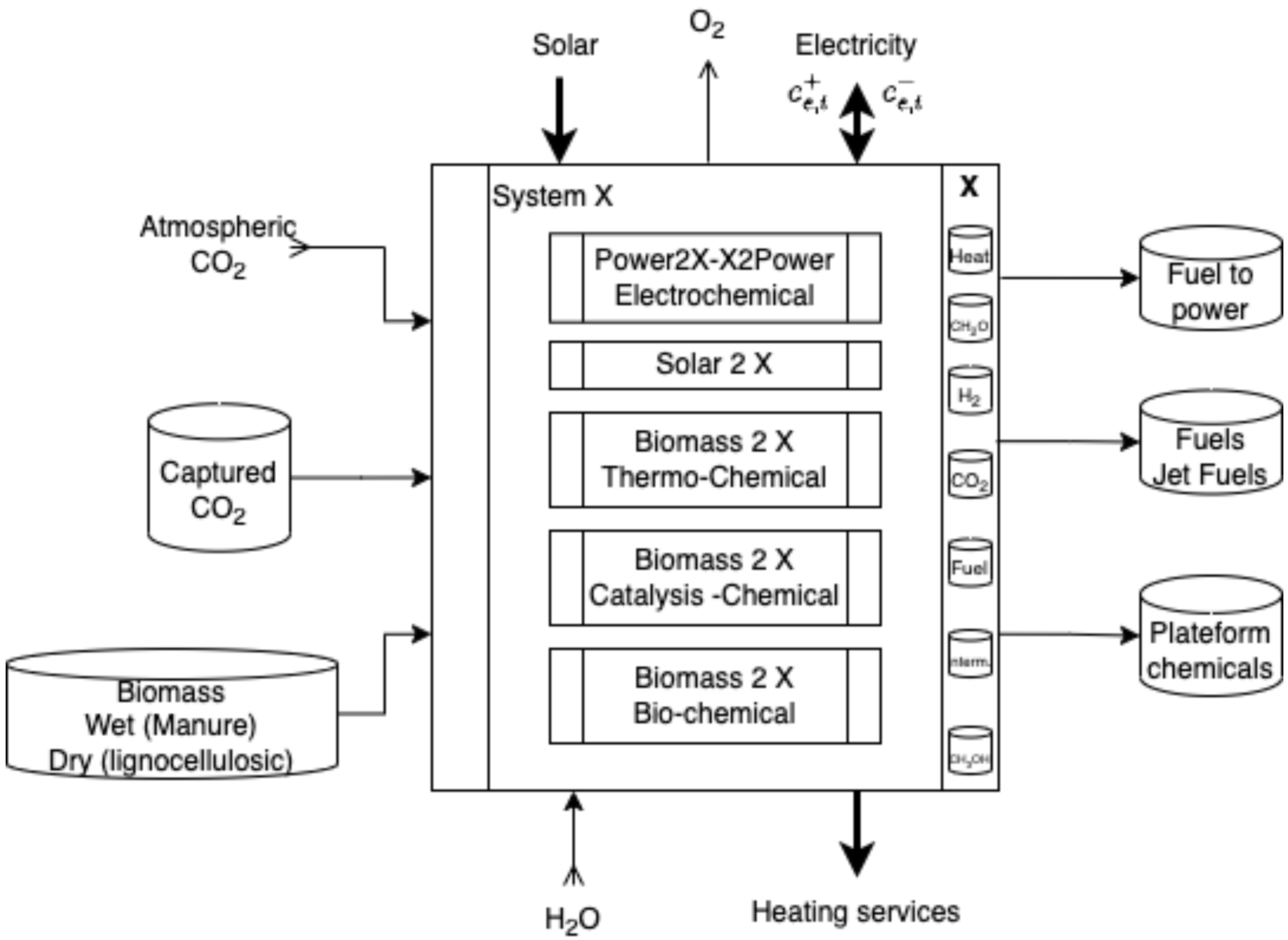

Figure 2.1: Pareto front of total cost and SCOPE 1+2 emissions for primary steel production.

Results of the AIDRES EU project
decarbonisation of the EU industry (EU commission DG Energy)

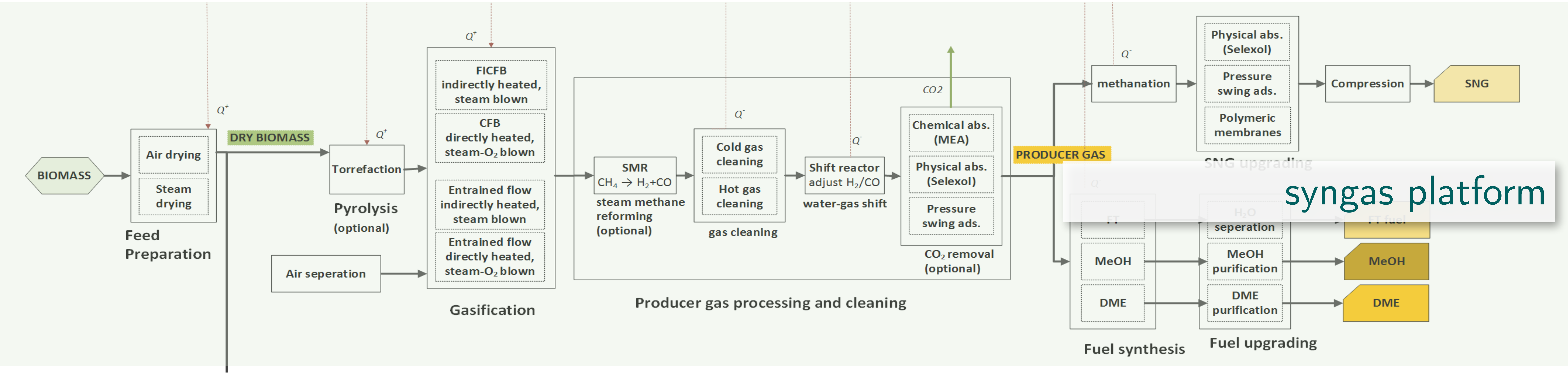
IPESE Industrial Process and Energy Systems Engineering

# Towards new resources for chemical products





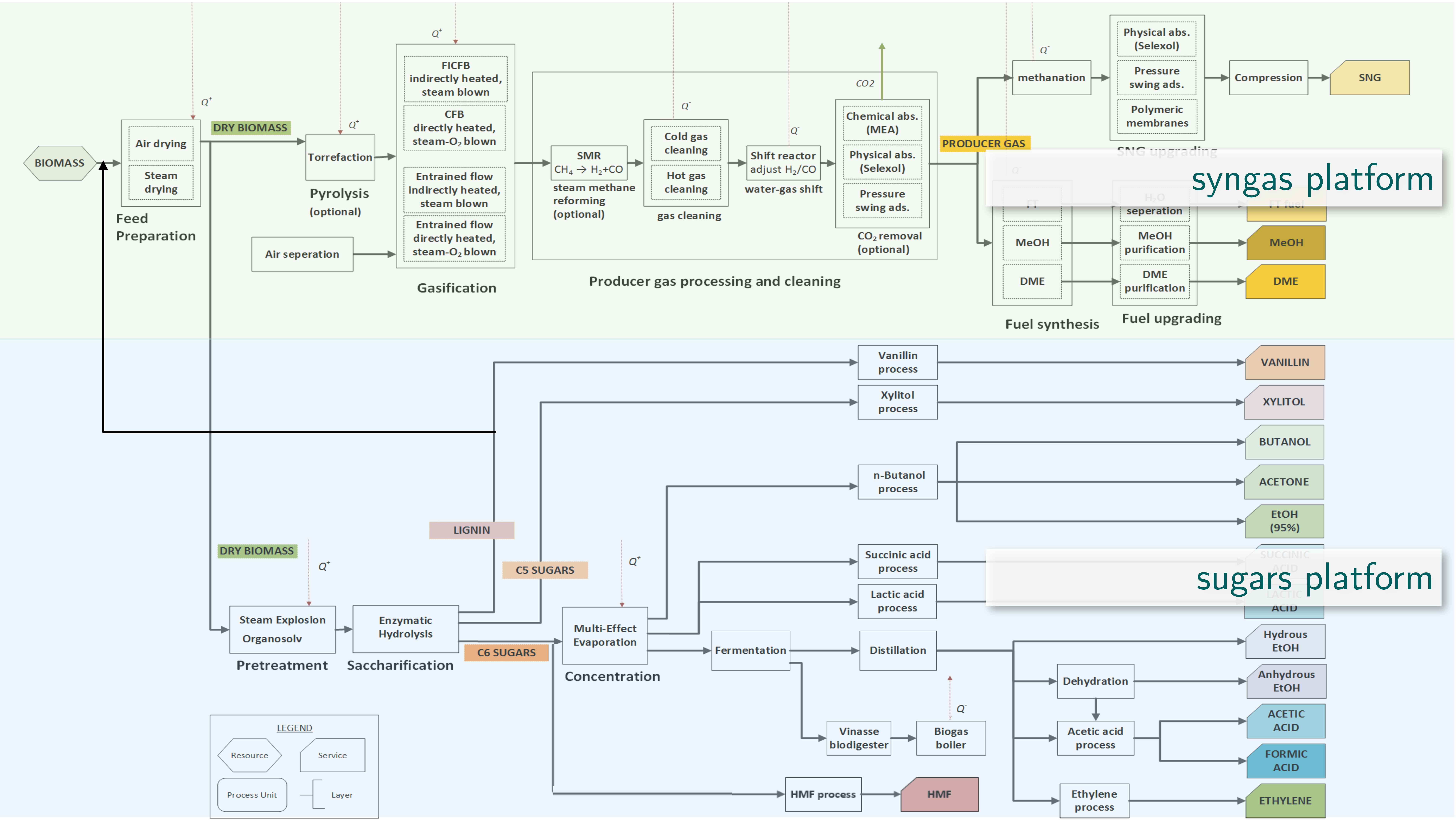
# Biomass as an atoms and energy source : biorefineries




Fuels

Basic chemicals

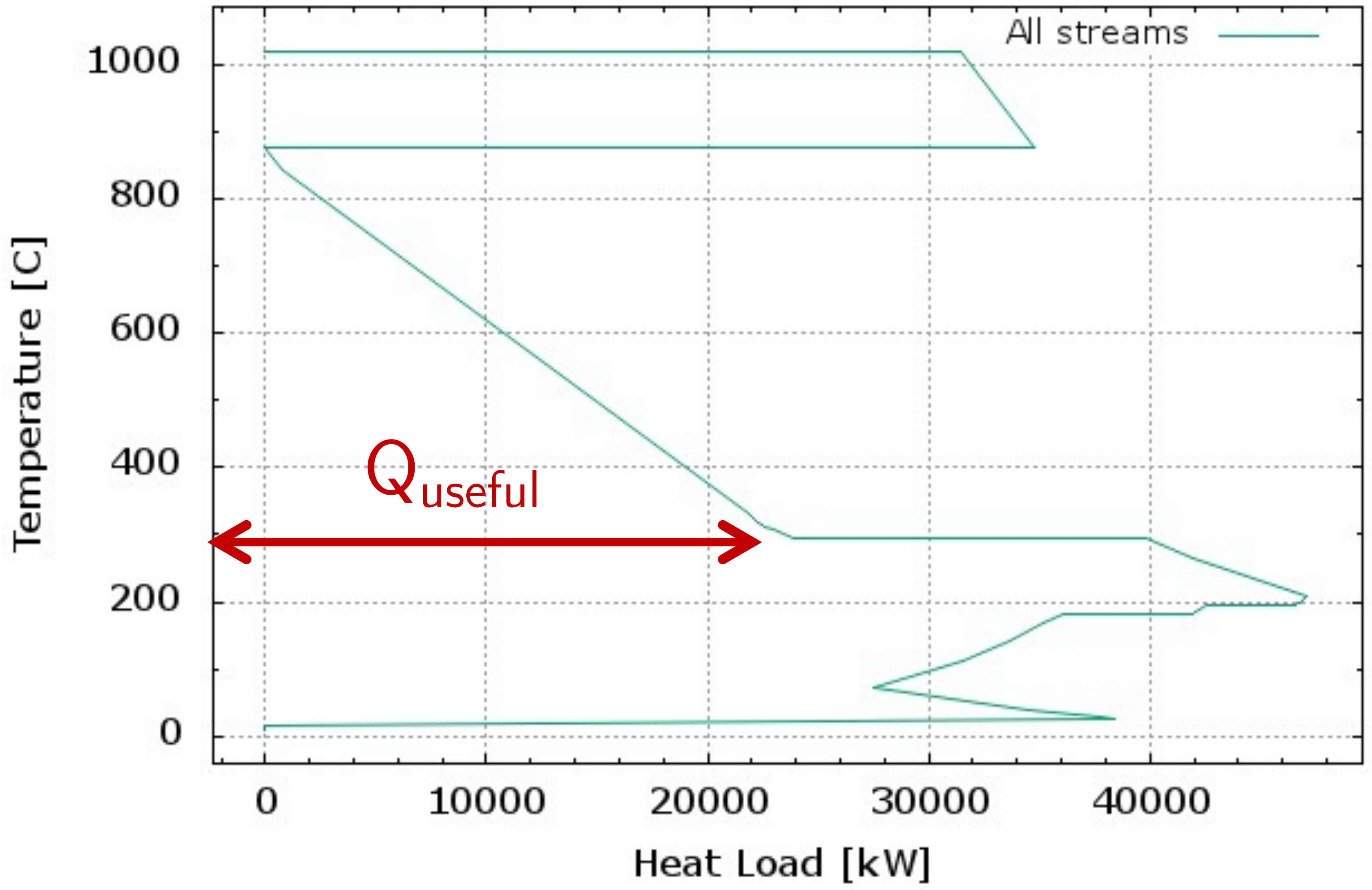
# Biorefinery superstructure



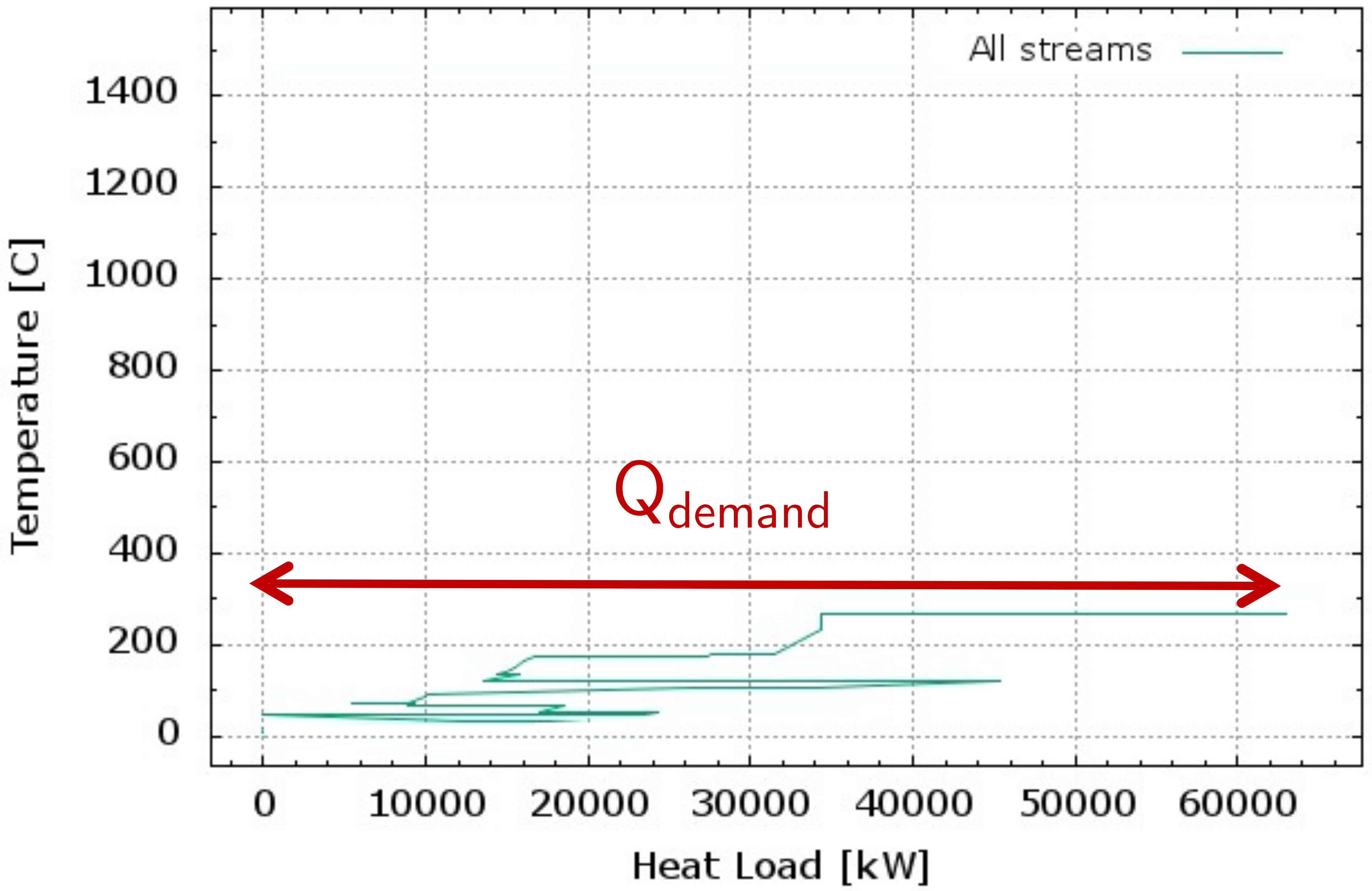

Fuels
Base chemicals

Bio products
Base chemicals

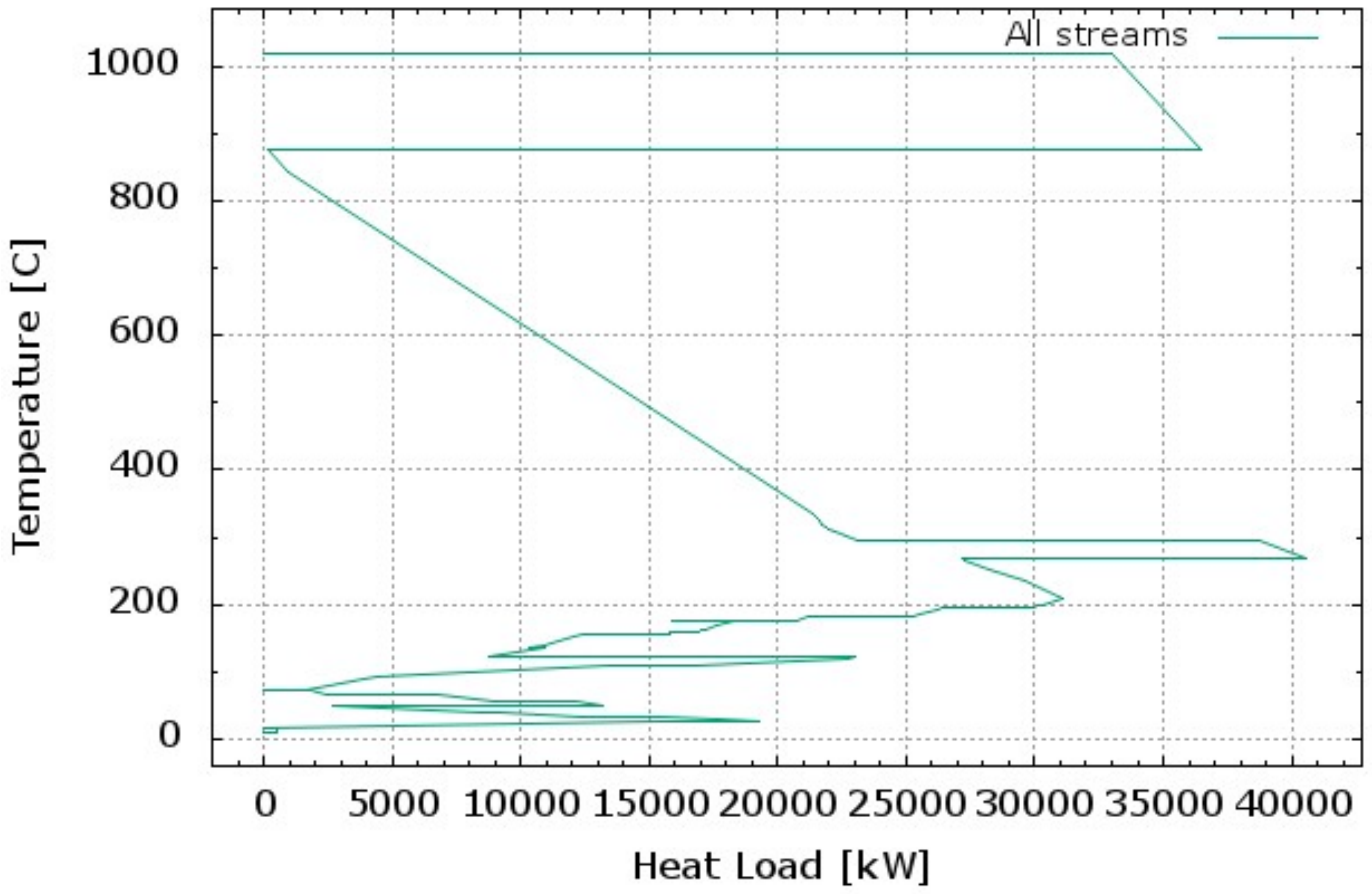
# Bio-refinery synergies




GCC of SNG production




GCC of lactic acid production

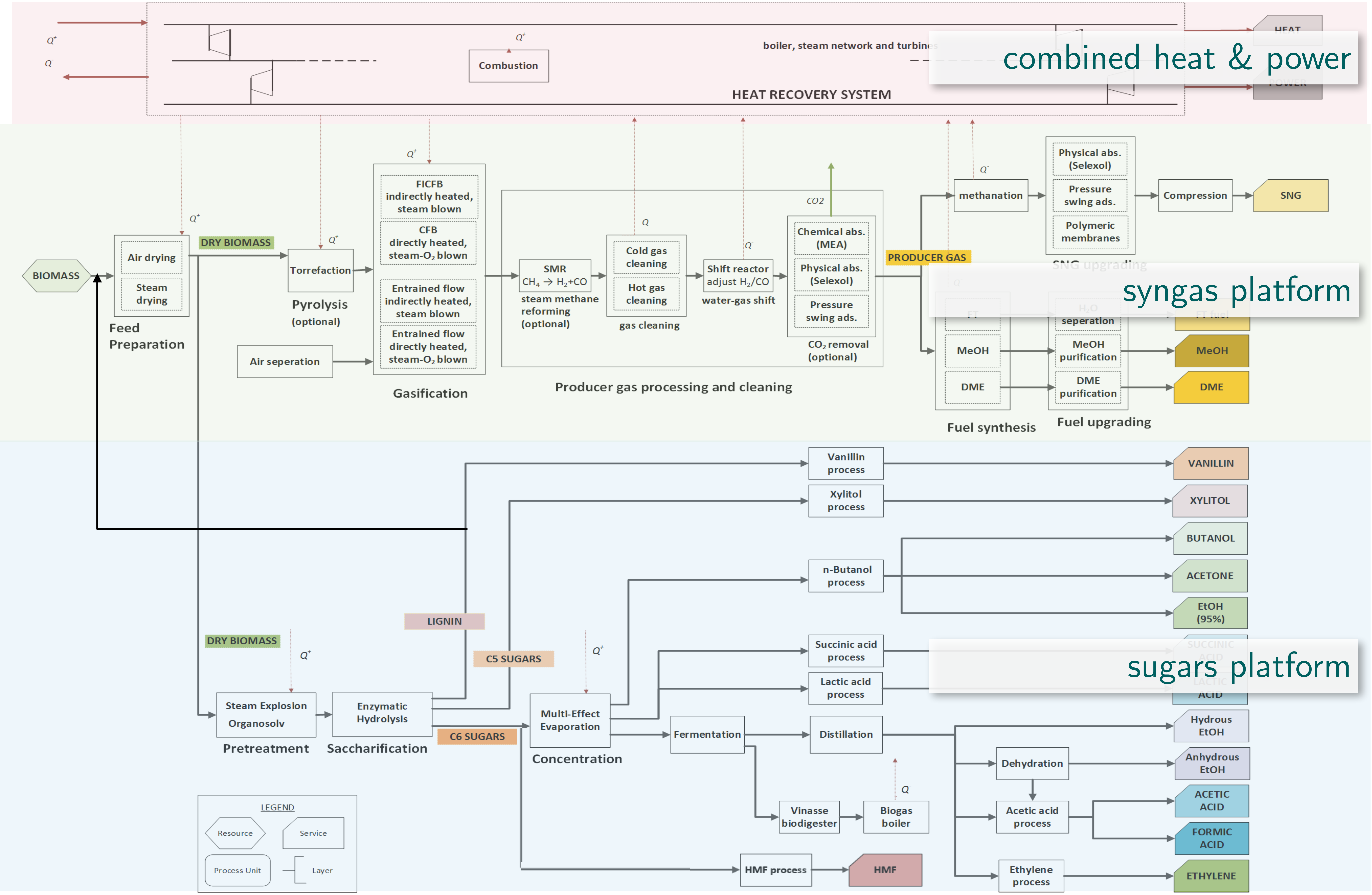



GCC of SNG and lactic acid production

wood allocation:
45 % lactic acid
55 % SNG

# Biorefinery superstructure





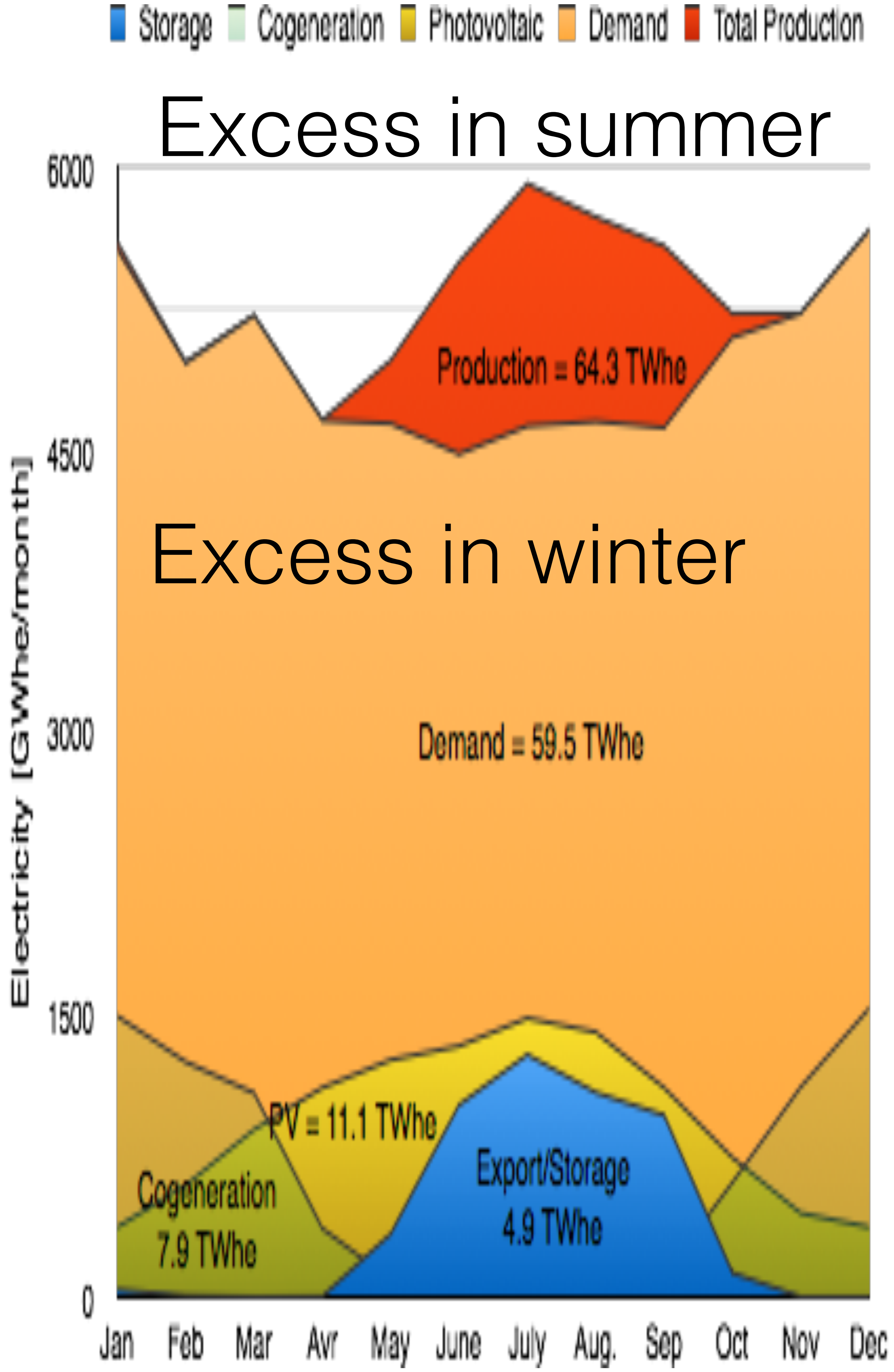

Energy system
District system

Fuels
Base chemicals

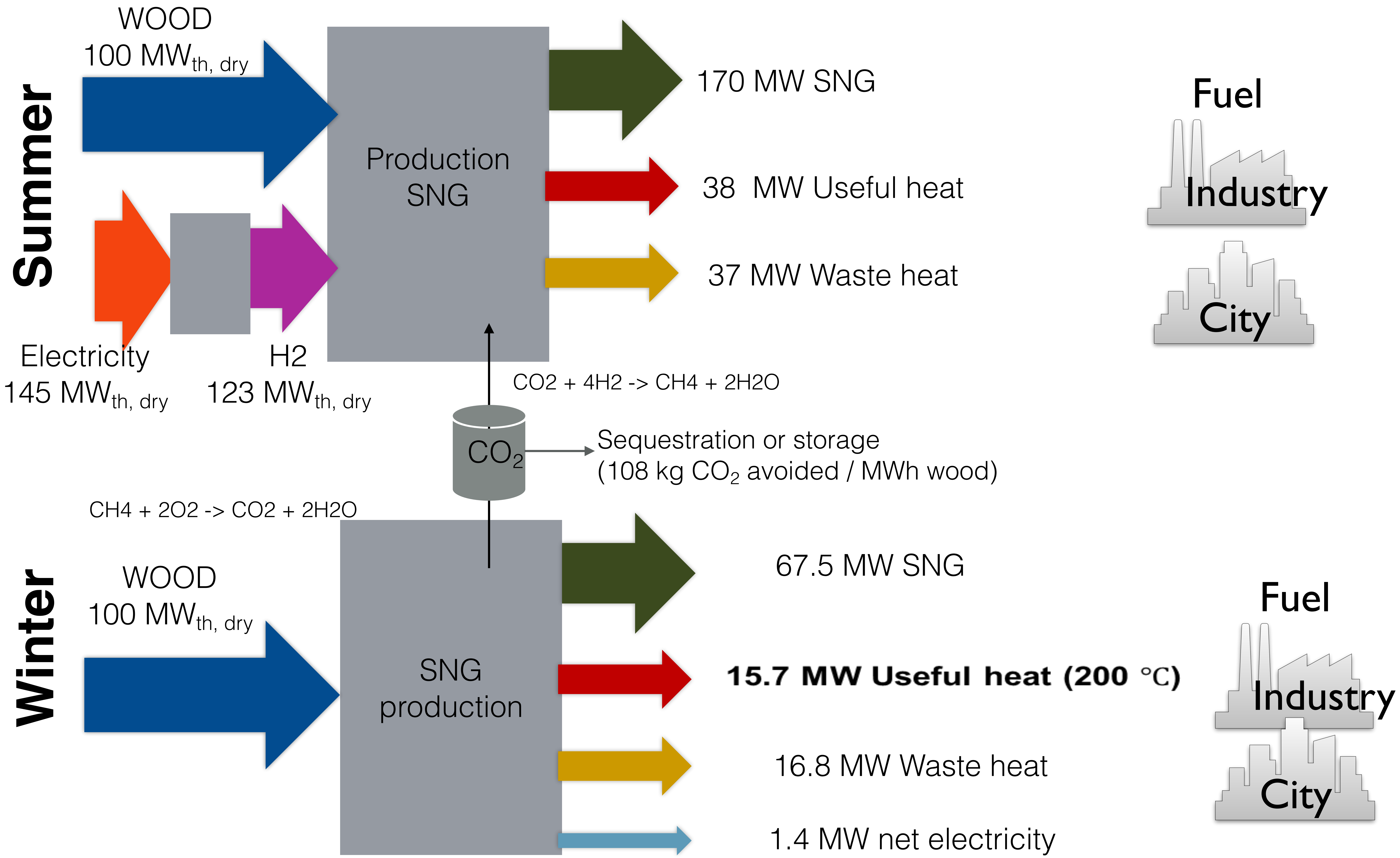
Bio products
Base chemicals

# Integrating with the energy system : Combined heat and fuel production

## Swiss Energy System




$$2C(H_2O) + 4H_2 \rightarrow 2CH_4 + 2H_2O$$



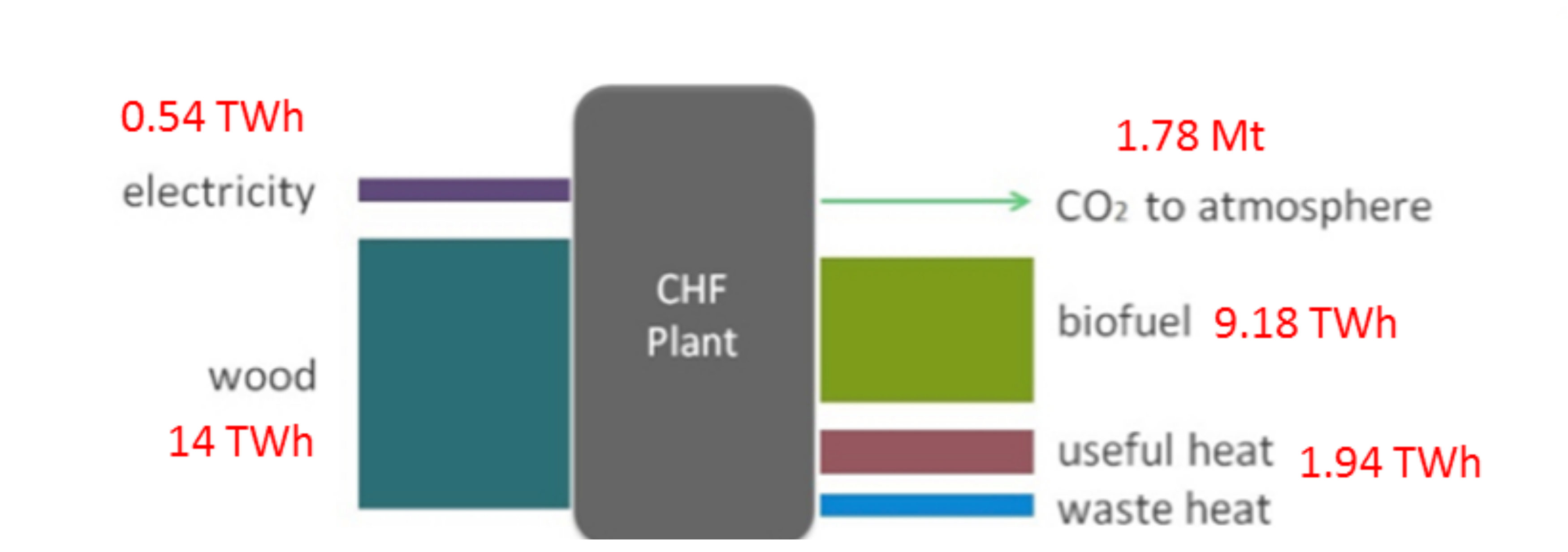

$$2C(H_2O) \rightarrow CH_4 + CO_2$$

IPESE
Industrial Process and Energy Systems Engineering

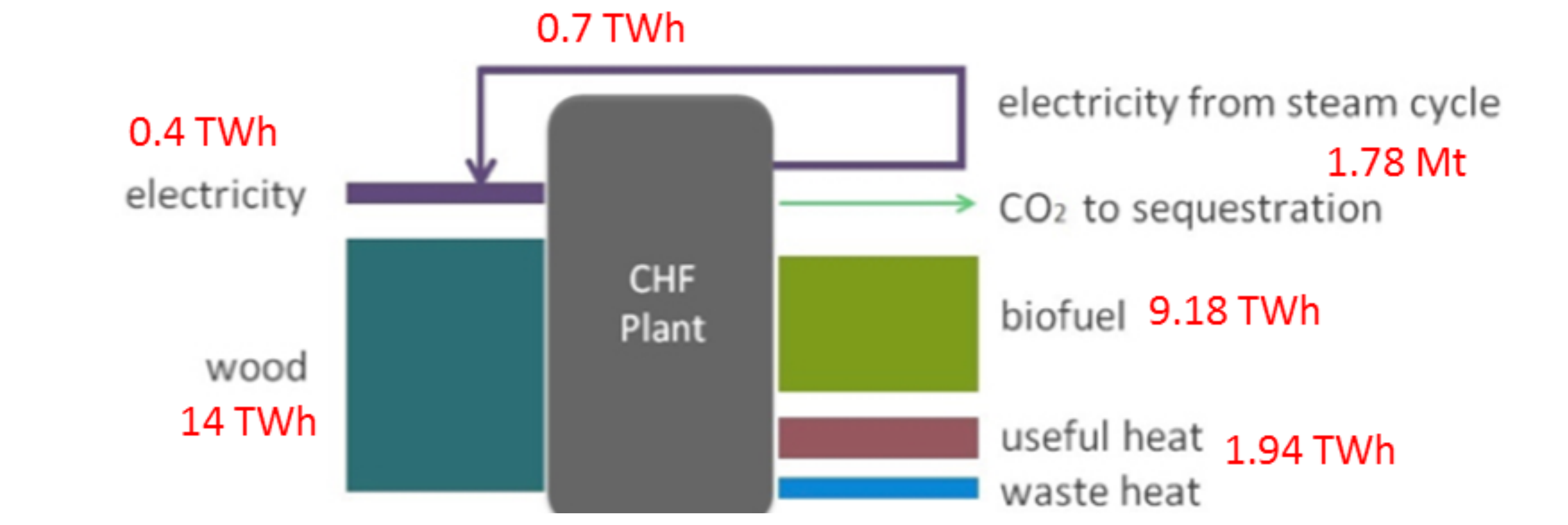
# Combined Heat and Fuel (CHF) production
# Substituted fossil carbon per unit of biogenic carbon in wood

1.6

wood boiler




CHF



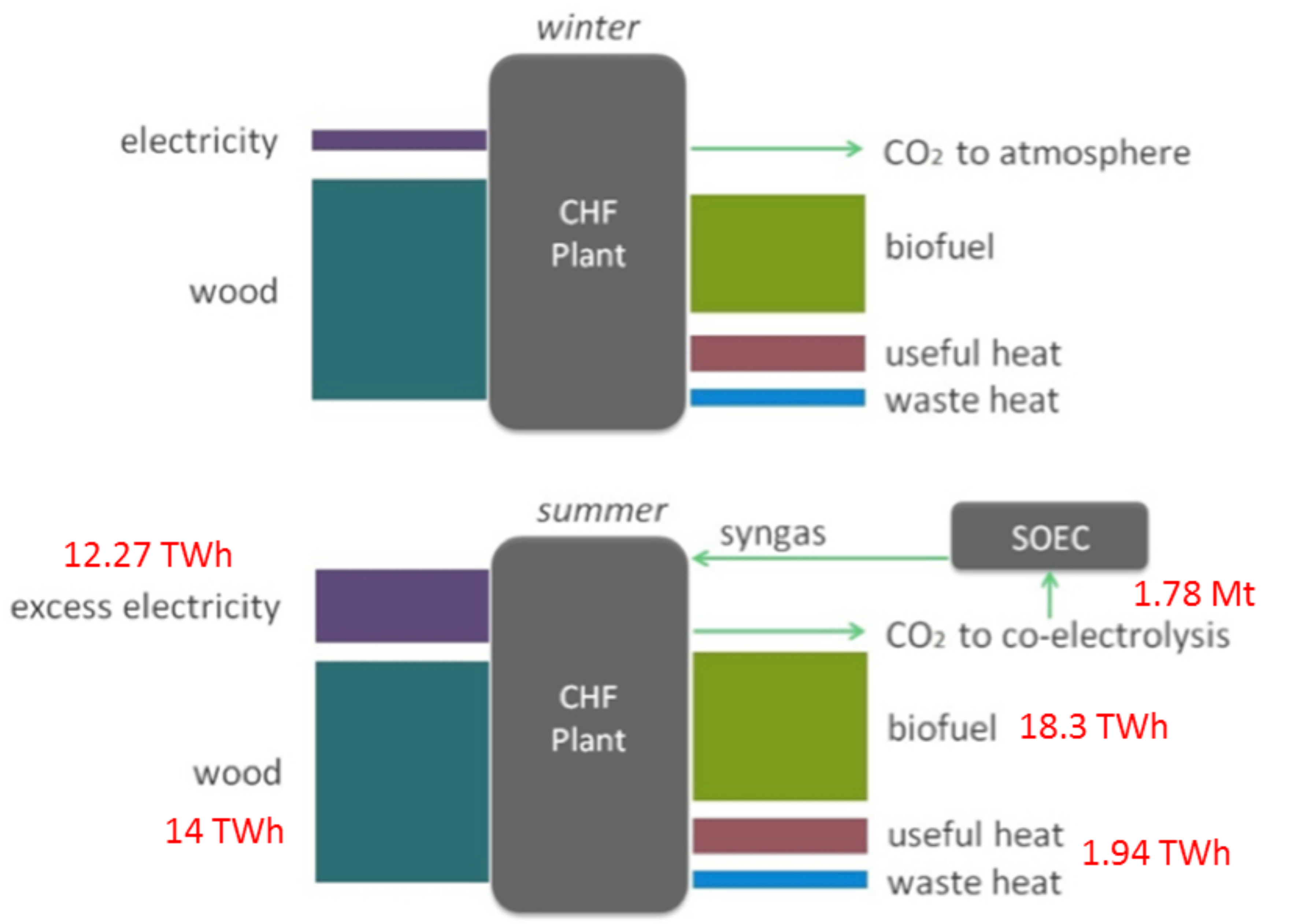

CHF + Carbon sequestration

2.8

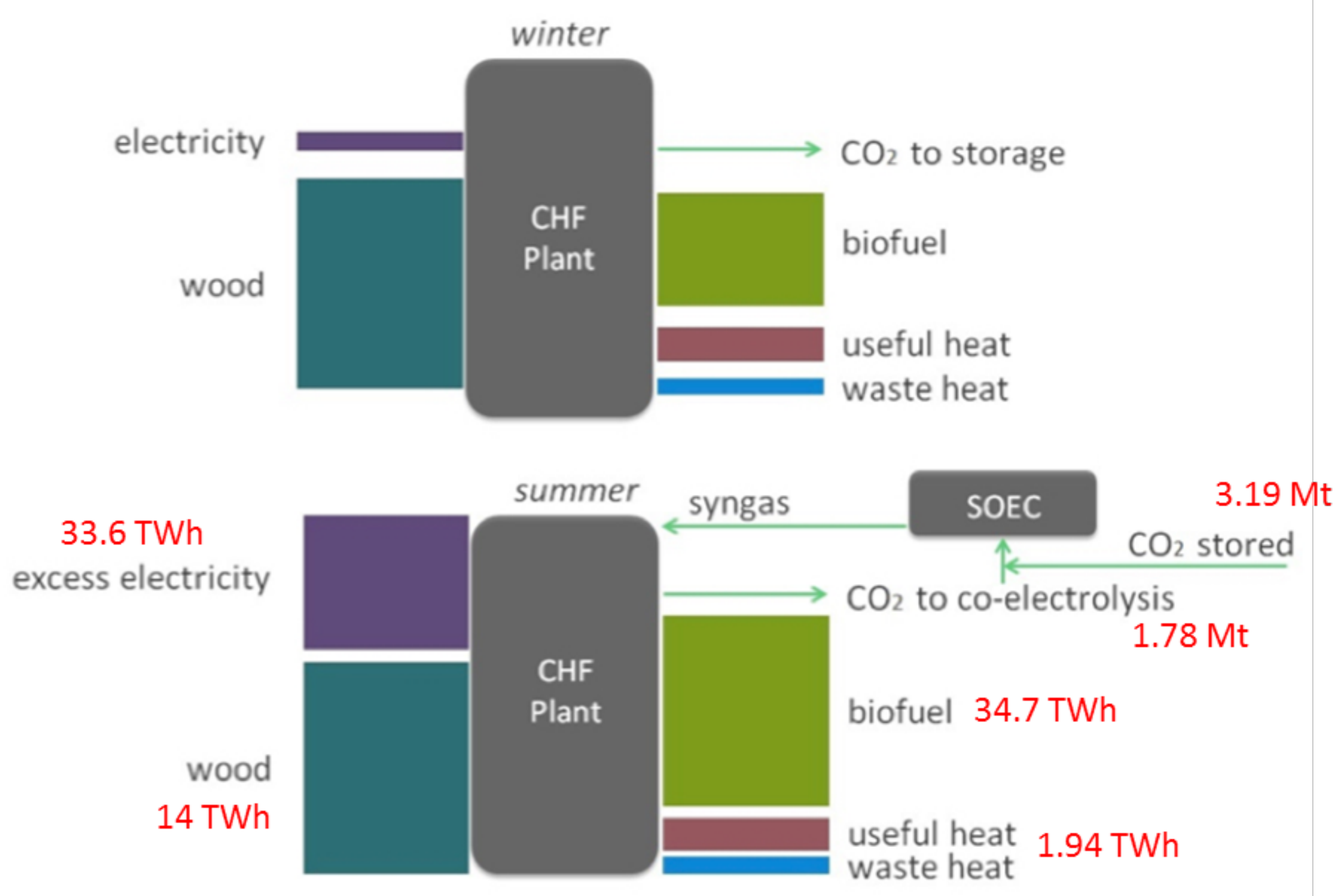
wood boiler

2.1

wood boiler




CHF + P2G without CO2 storage




CHF + P2G with CO2 storage

3.0

wood boiler

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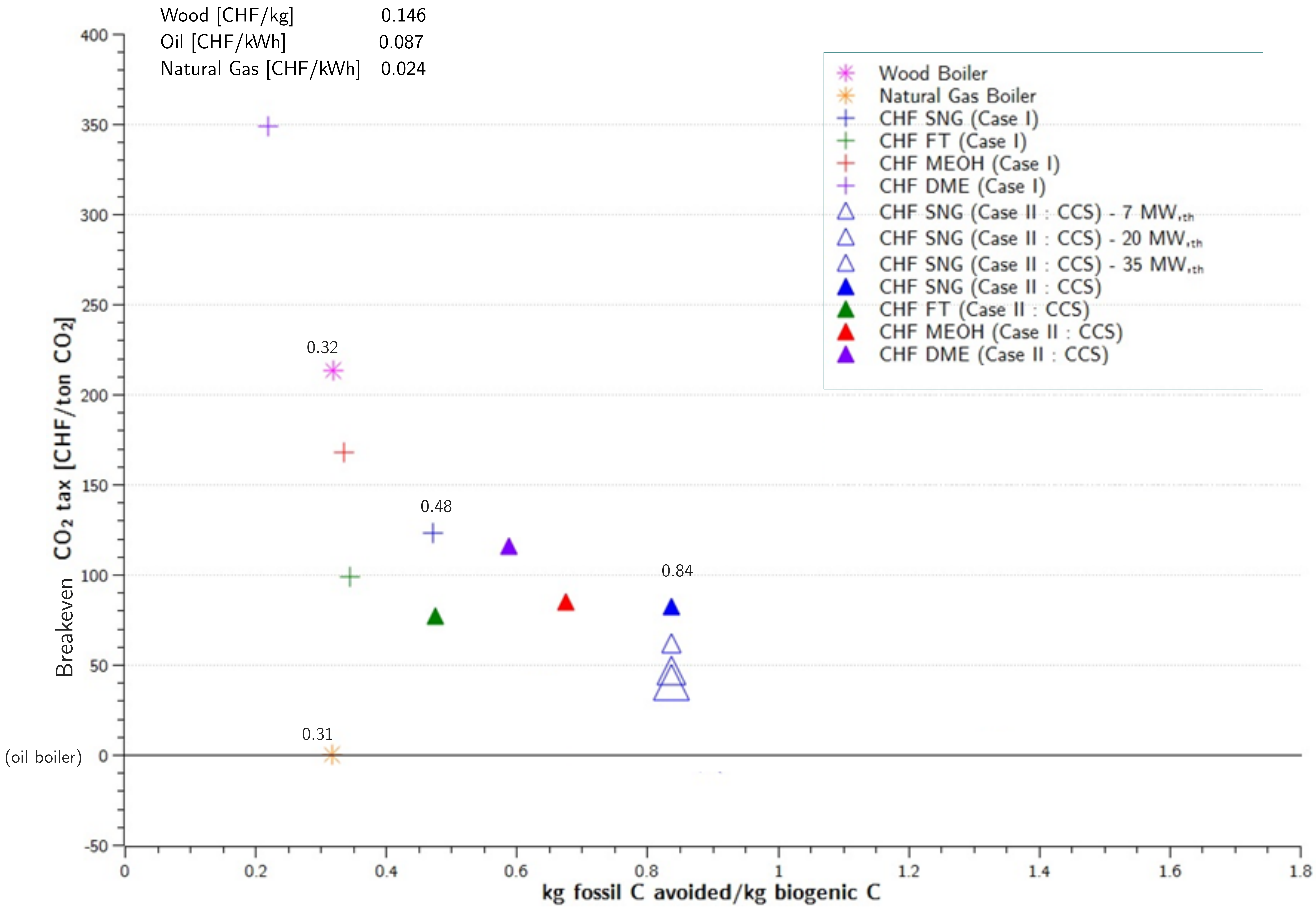
For wood boiler (WB) 0.3 kg of fossil carbon are substituted per kg of biogenic carbon

Celebi, et al. *Chemical Engineering Science* 204 (2019): 59-75.

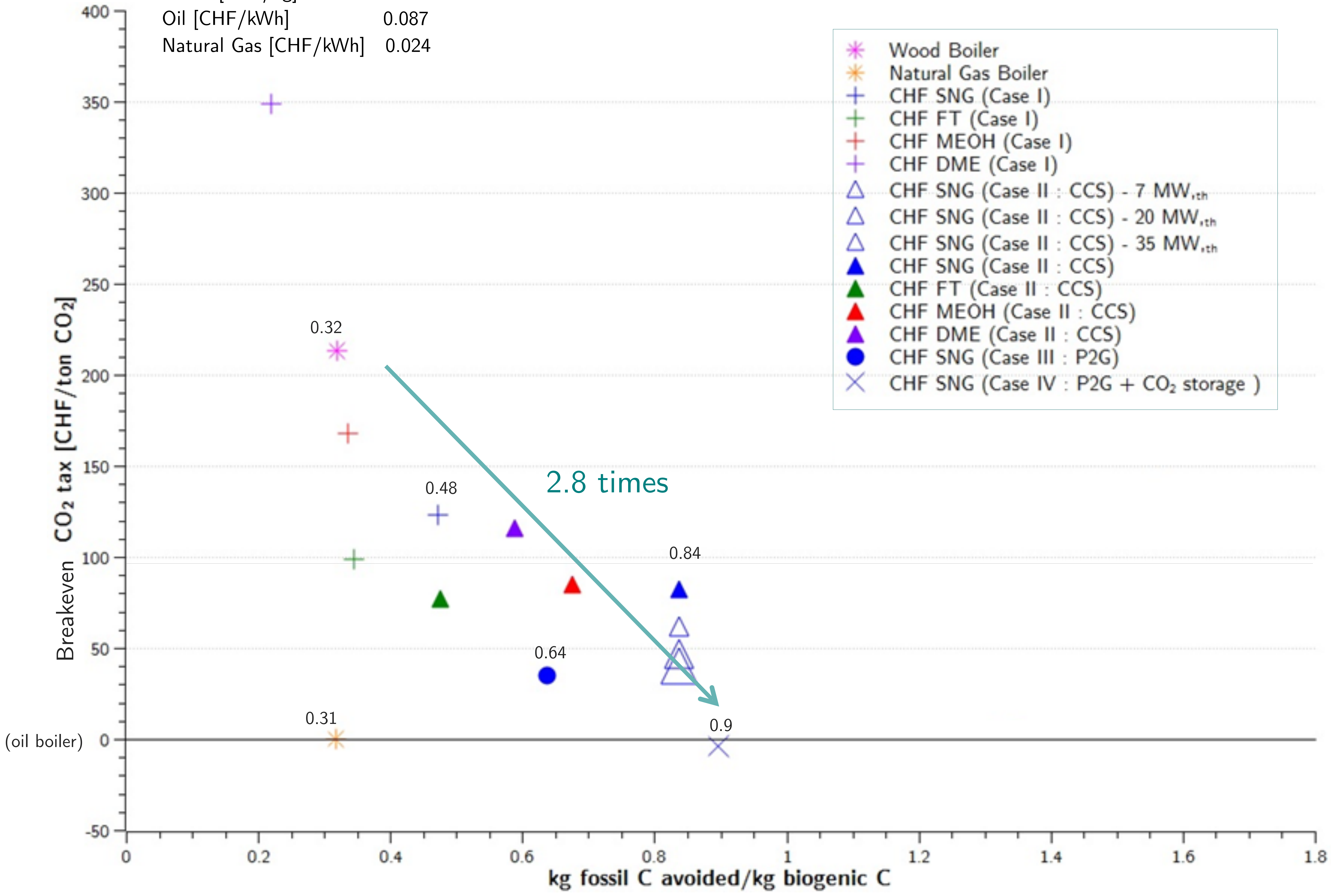
# Carbon savings comparison between technologies



# Carbon savings comparison between technologies

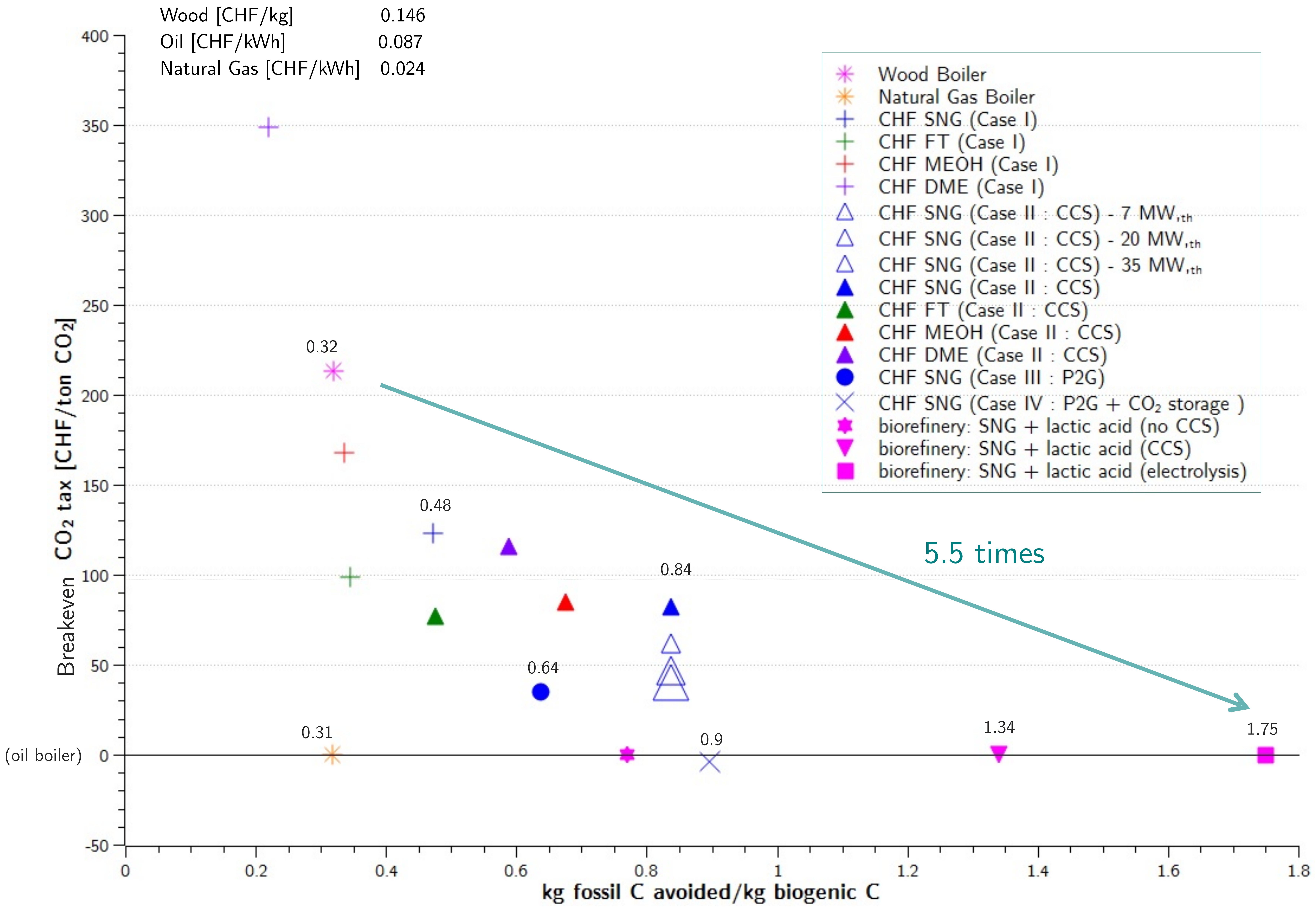


| | |
|---|---|
| Wood [CHF/kg] | 0.146 |
| Oil [CHF/kWh] | 0.087 |
| Natural Gas [CHF/kWh] | 0.024 |



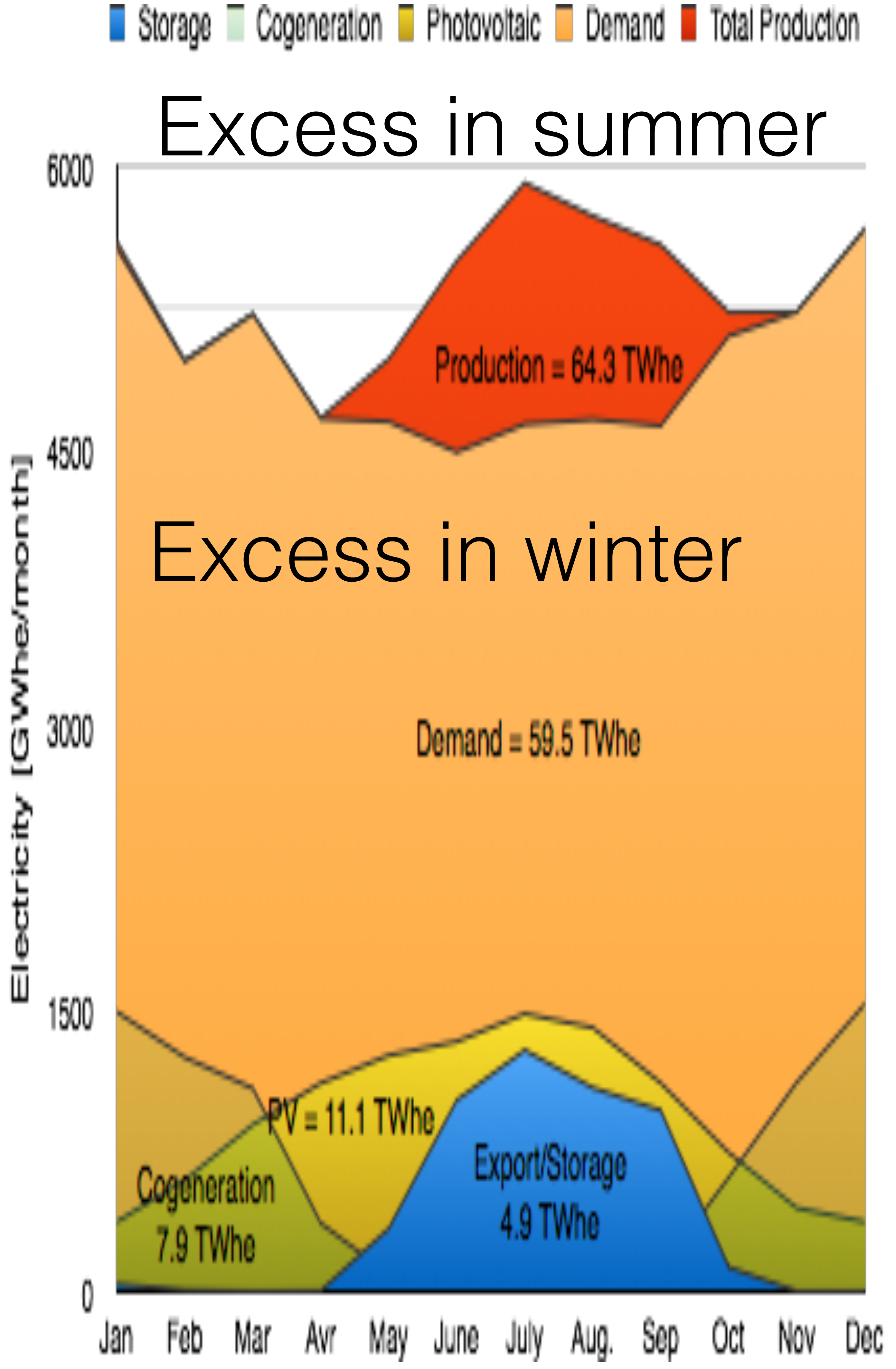
# Carbon savings comparison between technologies



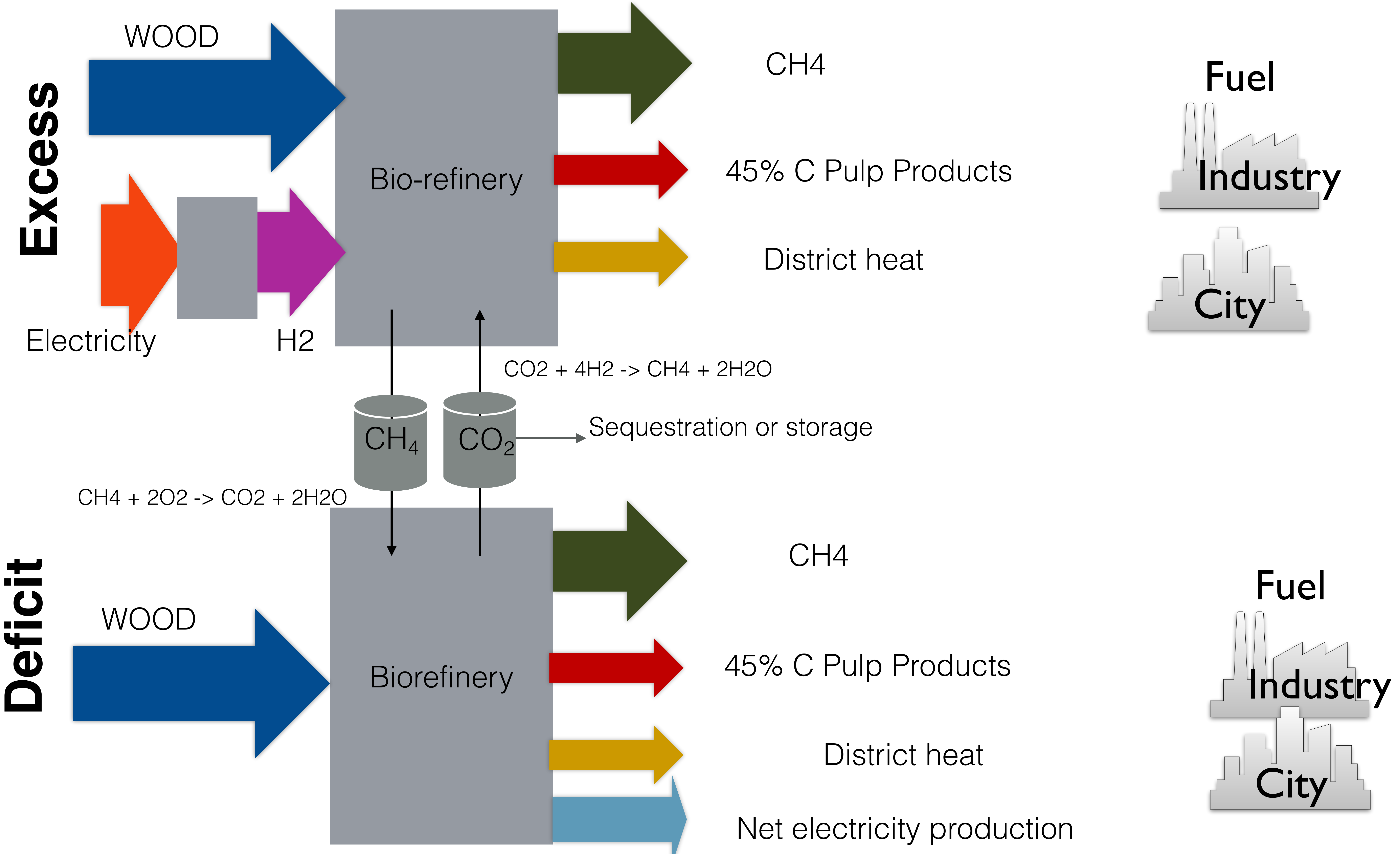


# Integrating with the energy system : Combined heat and fuel production

## Swiss Energy System




$$2C(H2O) + 4H2 \rightarrow 2CH4 + 2H2O$$




$$2C(H2O) \rightarrow CH4 + CO2$$

# CIRCULAR ECONOMY-EFFICIENCY AND INTEGRATION

# MOBILITY

**36%**

Efficacité

Soft Mobility

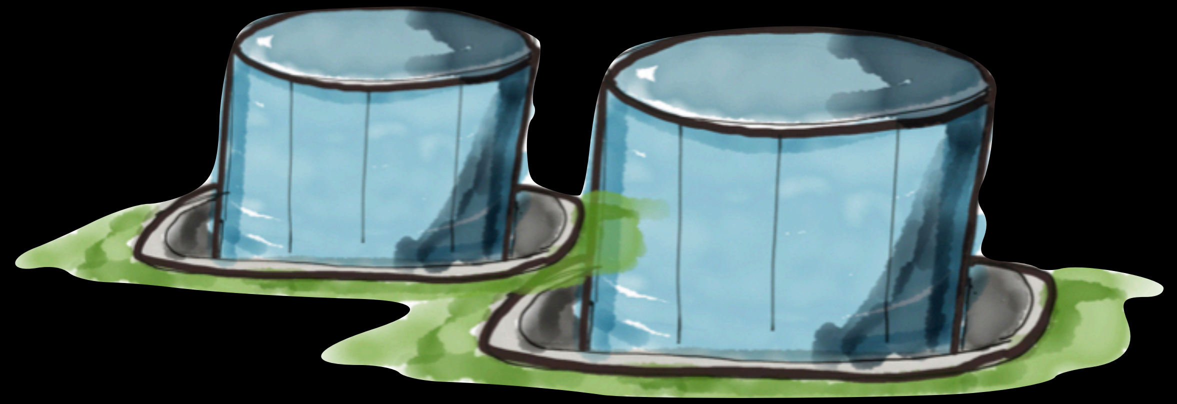
Public transport : électric/hybrid (mobilitylab.ch)

Electric vehicles : 400 km

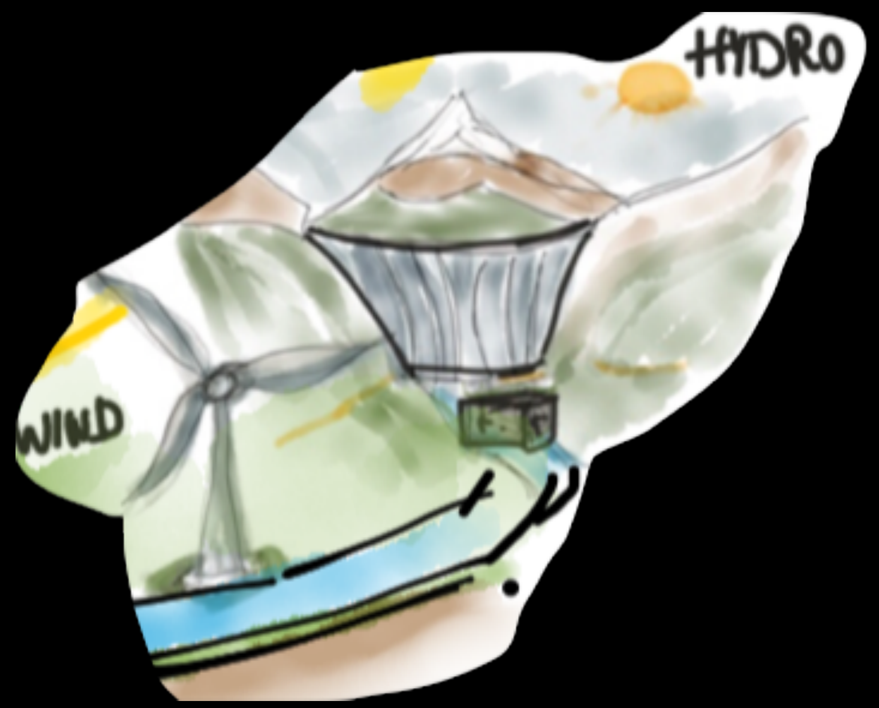
Fast charge (WattAnyWhere)

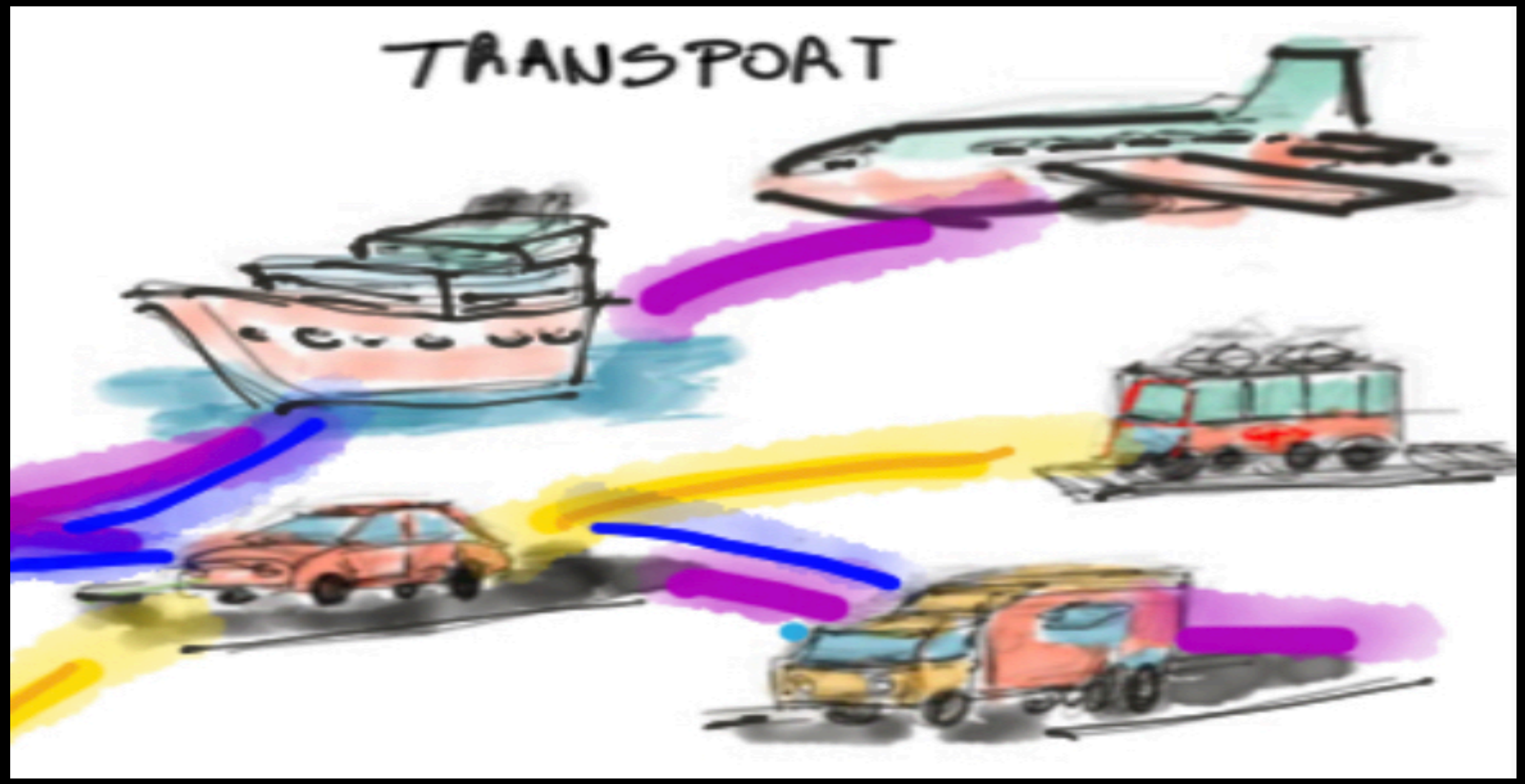
Range extenders vehicules (H2, CH4)

CO2 capture on board



Bio-Fuel



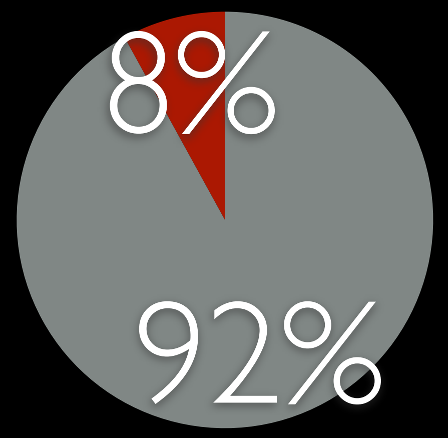

Wind and Hydro

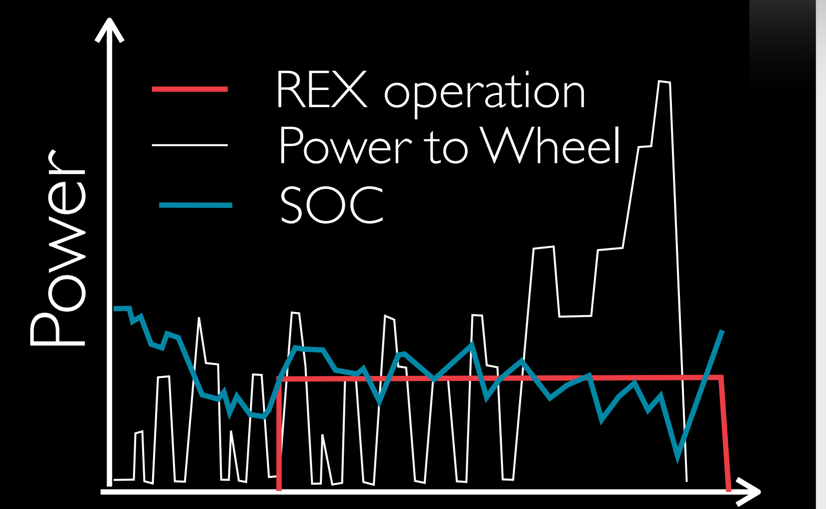
100 l gasoline/hab/year

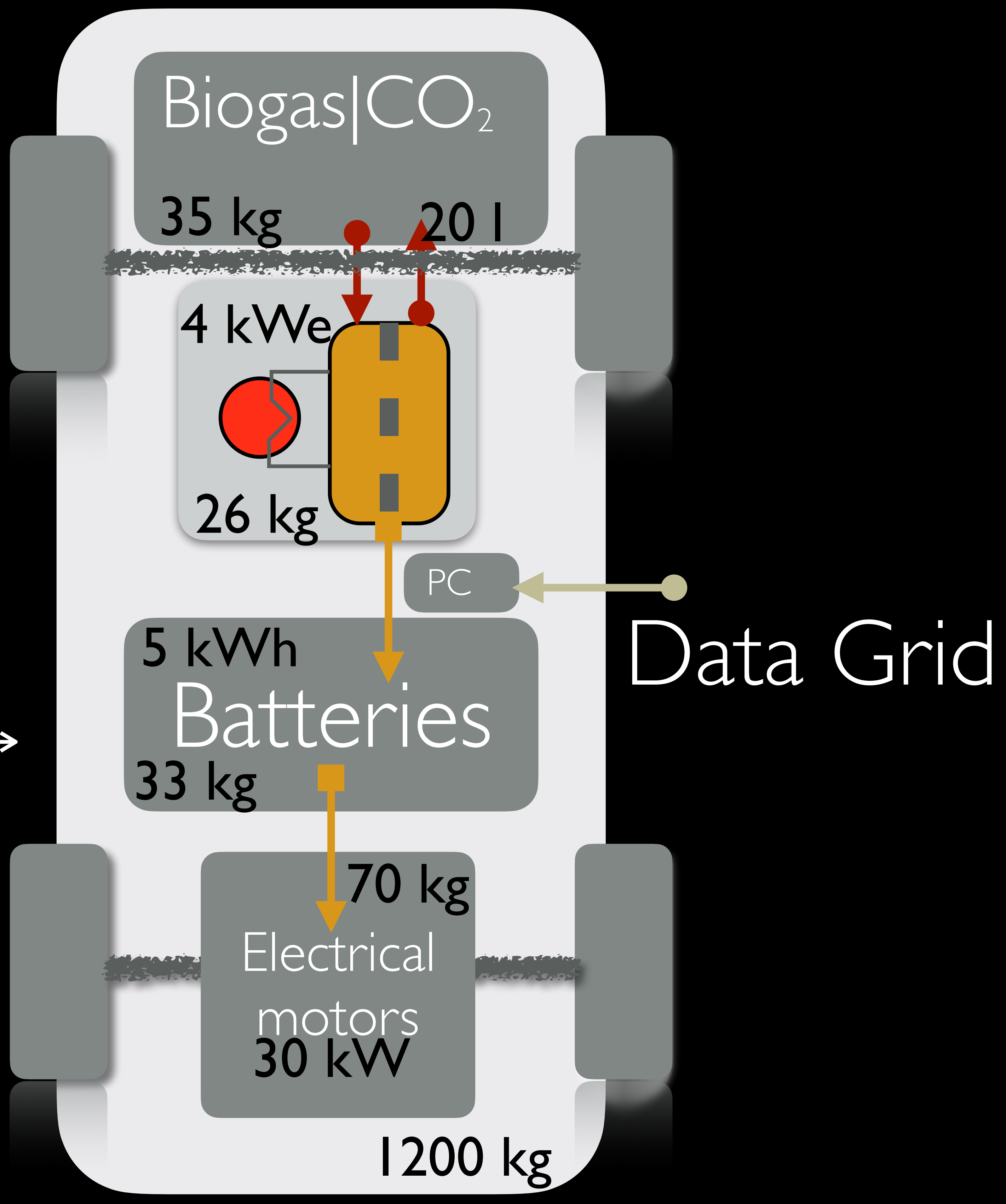
# “RANGE EXTENDERS” VEHICULES

## Driving mode

Autonomy : 950 km
Cons : 1.1l/100 km



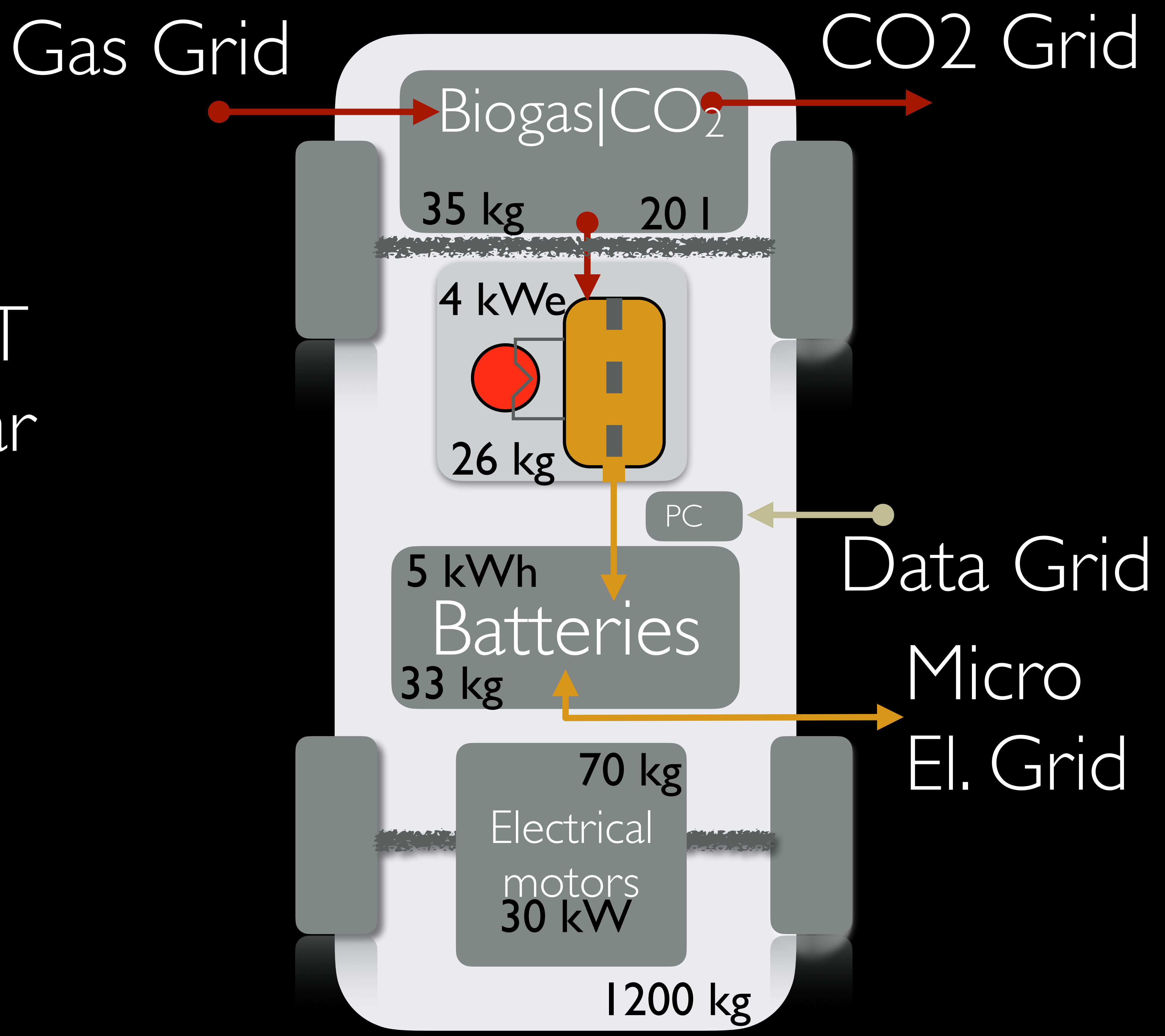




SOFC-GT
Hybrid car

## Parking mode

Power plant : 3.5 kWe (eff. >70%)
Battery : 5 kWh




Dimitrova, Zlatina, and François Maréchal. "Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender." *Renewable Energy* 112 (2017): 124-142

PhD PSA

EPFL

# CAPTURER LE CO2 SUR LES CAMIONS

www.qaptis.com

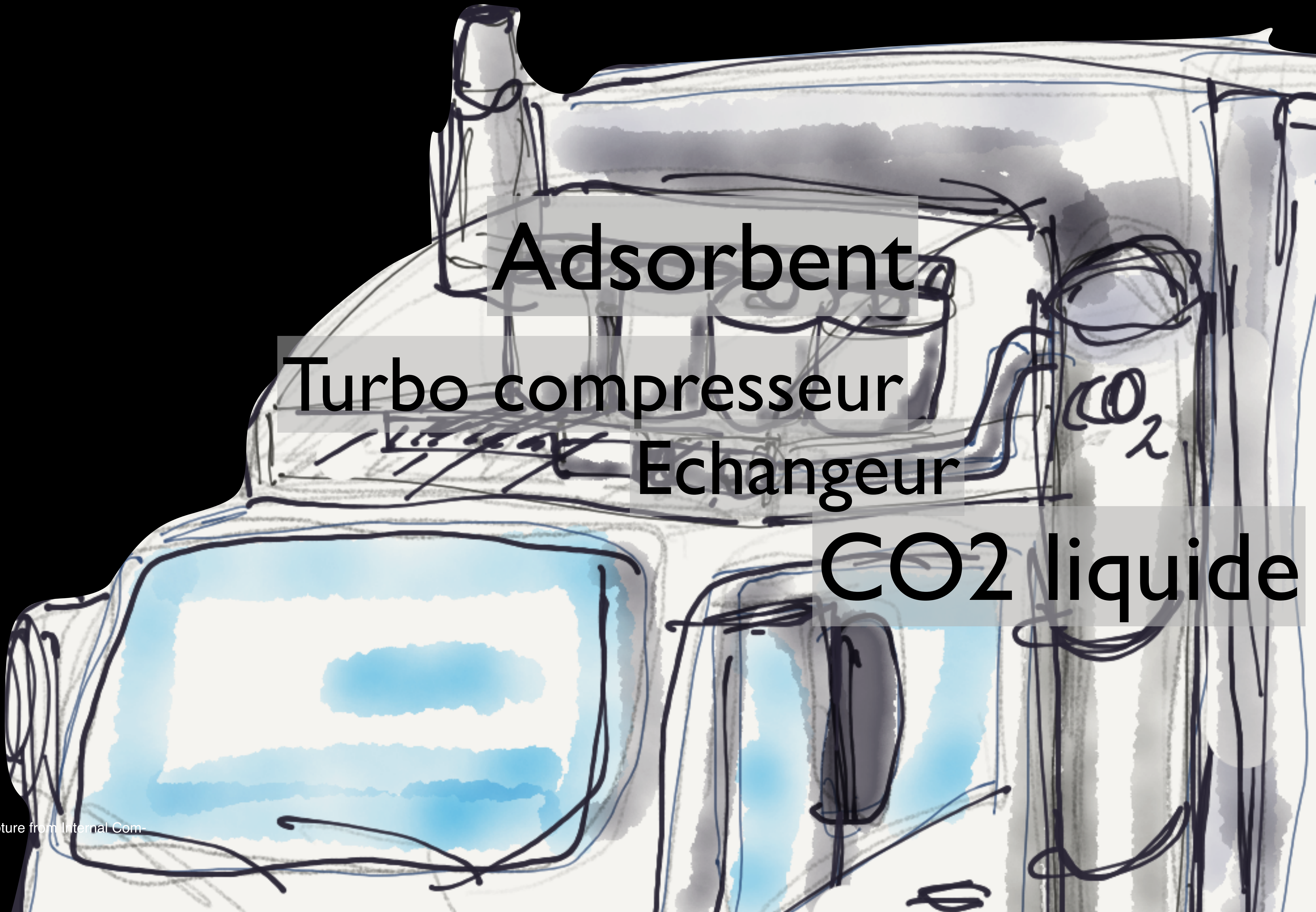
90% CO2 capture

3

l $CO_2$/l fuel

5%

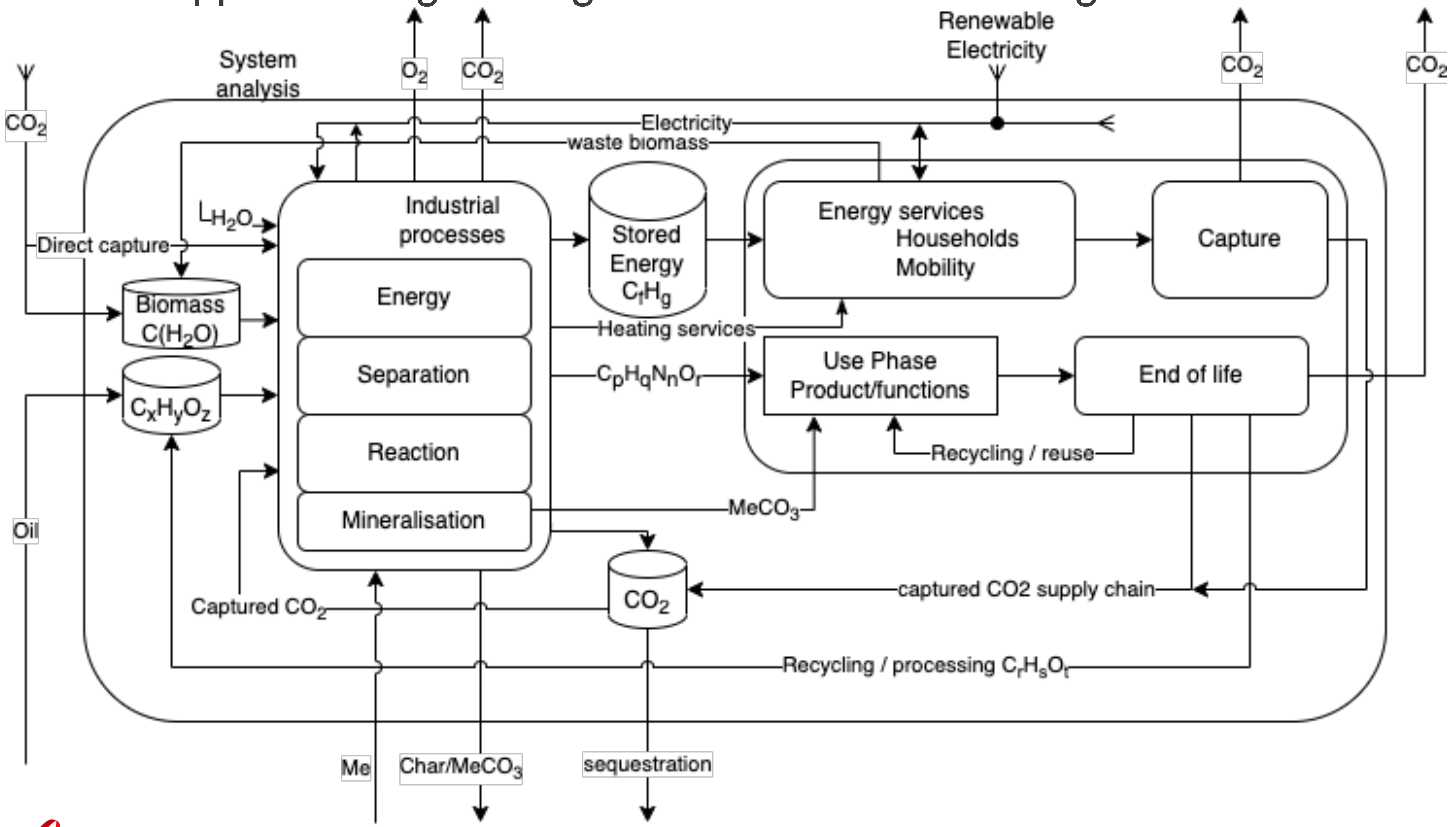
kg $CO_2$/kg payload



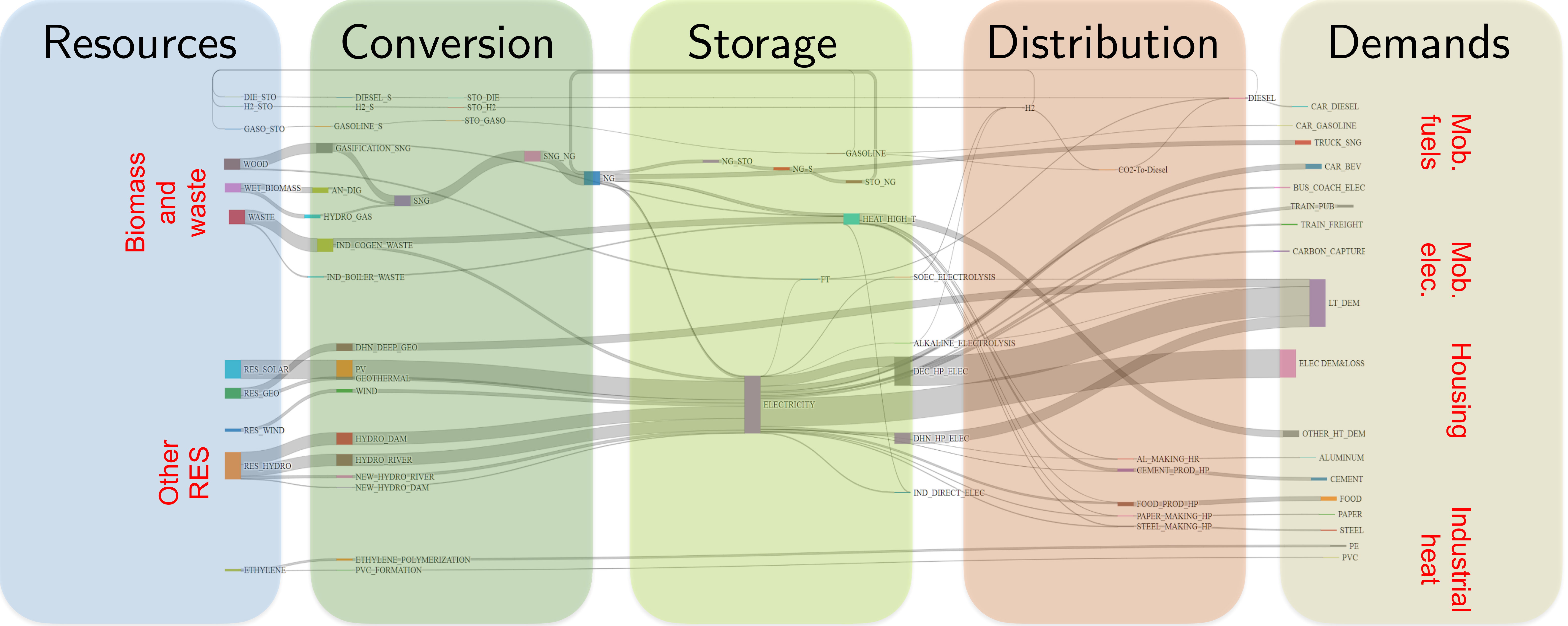

Sharma, Shivom, and François M.A. Marechal. 2019. "Carbon Dioxide Capture from Internal Combustion Engine Exhaust Using Temperature Swing Adsorption." Frontiers in Energy Research accepted doi:10.3389/fenrg.2019.00143.

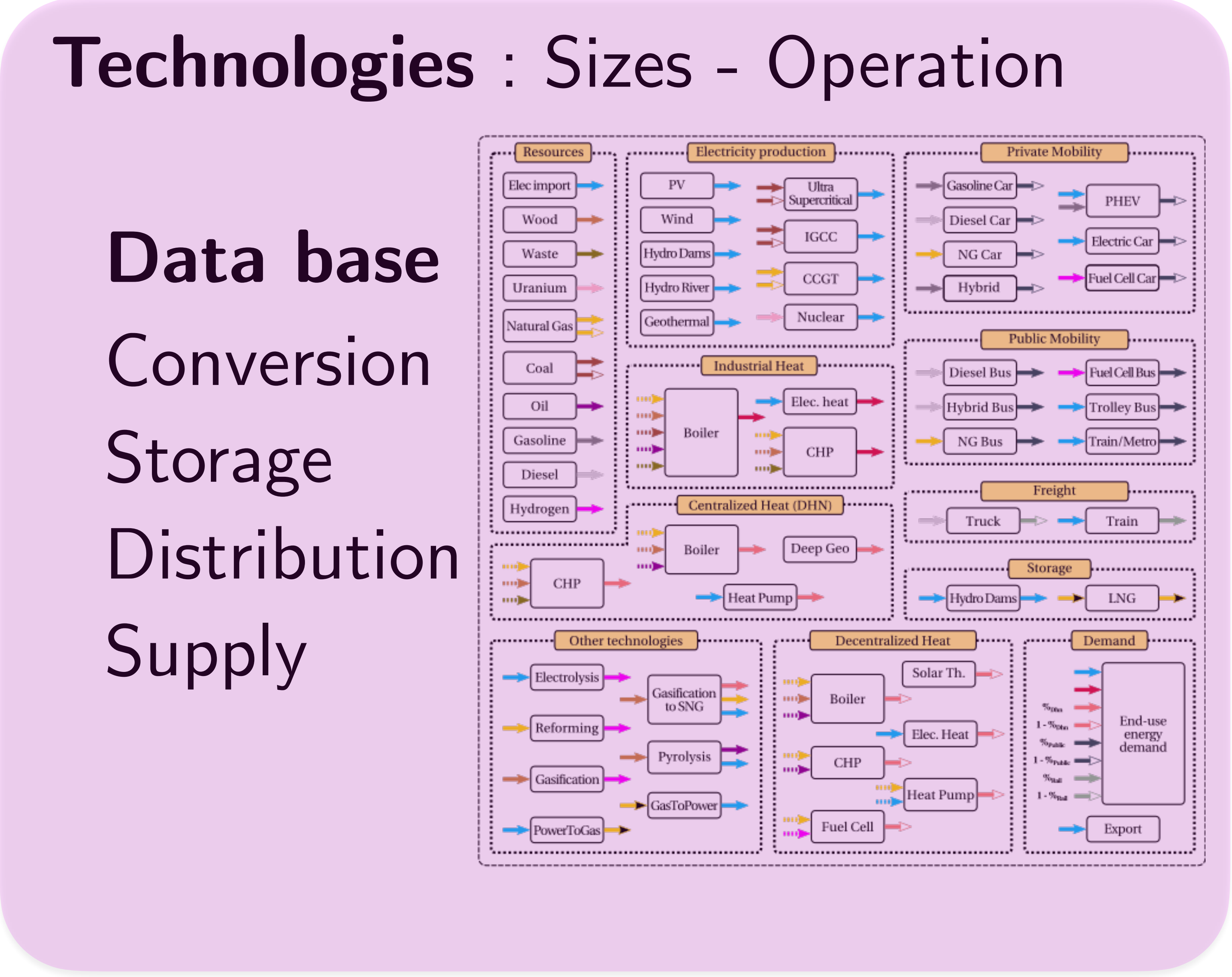
# Carbon flows in the society

## Decision support for engineering the Carbon Flows management in the society

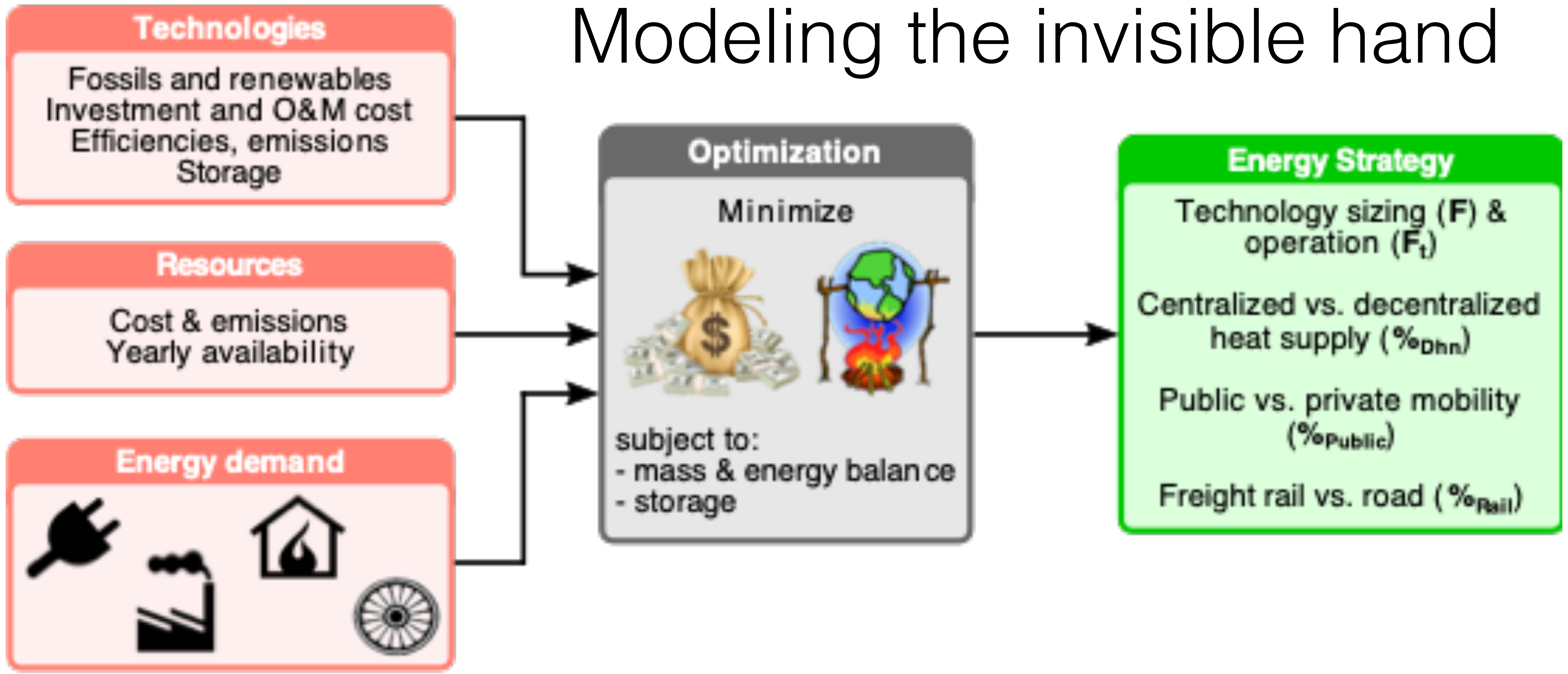


# Decarbonization of the Swiss Energy System : Energy system model

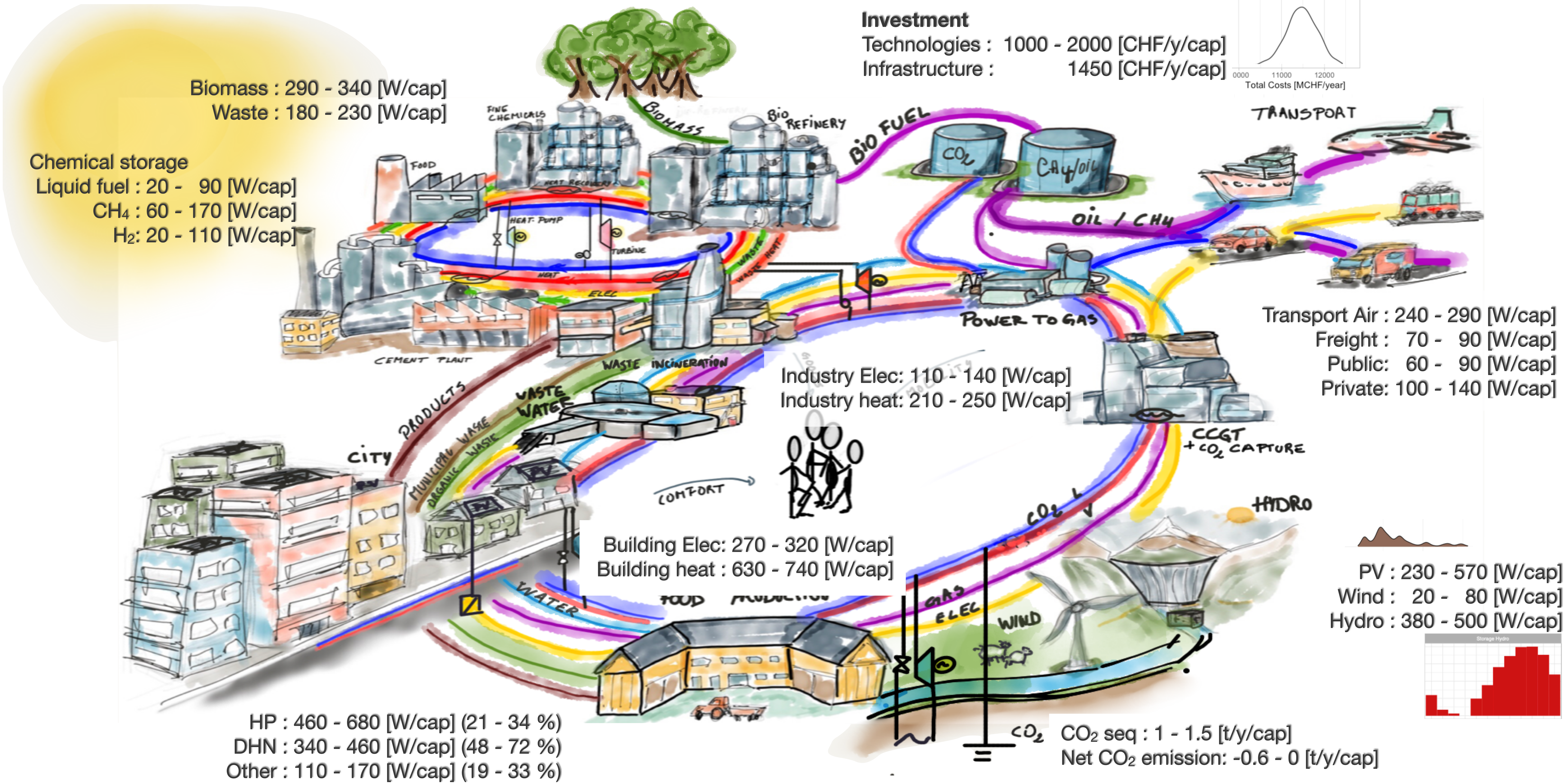



## Modeling the invisible hand



# energyscope.ch : Systemic vision of independent and neutral Switzerland




IPESE
Industrial Process
and Energy Systems
Engineering

# ON THE ROLE OF PROCESS SYSTEM ENGINEERING FOR THE ENERGY TRANSITION

- Efficiency in conversion
  - Process design
  - Process integration
- Model predictive control
  - Tanks & units sizes
- System integration
  - CO2 capture
  - Power2tanks2Power for energy grids
  - District heating and cooling
- Multi-scale integration
  - Systems in systems
  - Multi-states & security of supply
  - Uncertainty analysis
- Multi-objective optimisation
  - SDG metrics
  - System's configuration generations

=> Data base of shared blueprint models ?

=> Data base of shared models ?

=> solving methods

=> KPIs multi-criteria decision methods

# ACKNOWLEDGMENTS

- **Sun** : for the energy supply
- **Mother Nature** : to show us the way to store energy
- **Carnot** : to show us the importance of ambiance and efficiency
- **Research** : to develop the methods and the knowledge to develop new technologies
- **Industry** : to give us the technologies
- PS **Engineers** : to assemble and use the technologies in the right way at the right time
- **Authorities** : to develop education system and the infrastructure
- **Finance** : to ethically use (our) money for the right goals
- **Citizen** : to adopt responsible ways to consume

EPFL

- Thanks to my team … and their amazing contributions