Ecole Polytechnique
Fédérale de Lausanne

TOWARDS ZERO EMISSIONS : A SYSTEMS ENGINEERING PERSPECTIVE

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THE SWISS ENERGY SYSTEM

80
CHF/month/cap

15
kg CO2/day/cap

47%
Z Z Z Z Z Z
Z Z Z Z Z
N Z

36%
Z Z Z Z Z Z Z Z Z Z

17%
Z Z N Z

products 2%

80-140
CHF/month/cap
24
kg CO2/day/cap

Import
N Z

Mix
50-90
gCO2/kWhe

Export

Subsidies from our children
250
CHF/month/cap

Fosil fuel
1 unit = our food energy needs
100 l gasoline/year/hab

Electricity

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CO2 emissions : Cost of repair

Polluters-pay principles ?

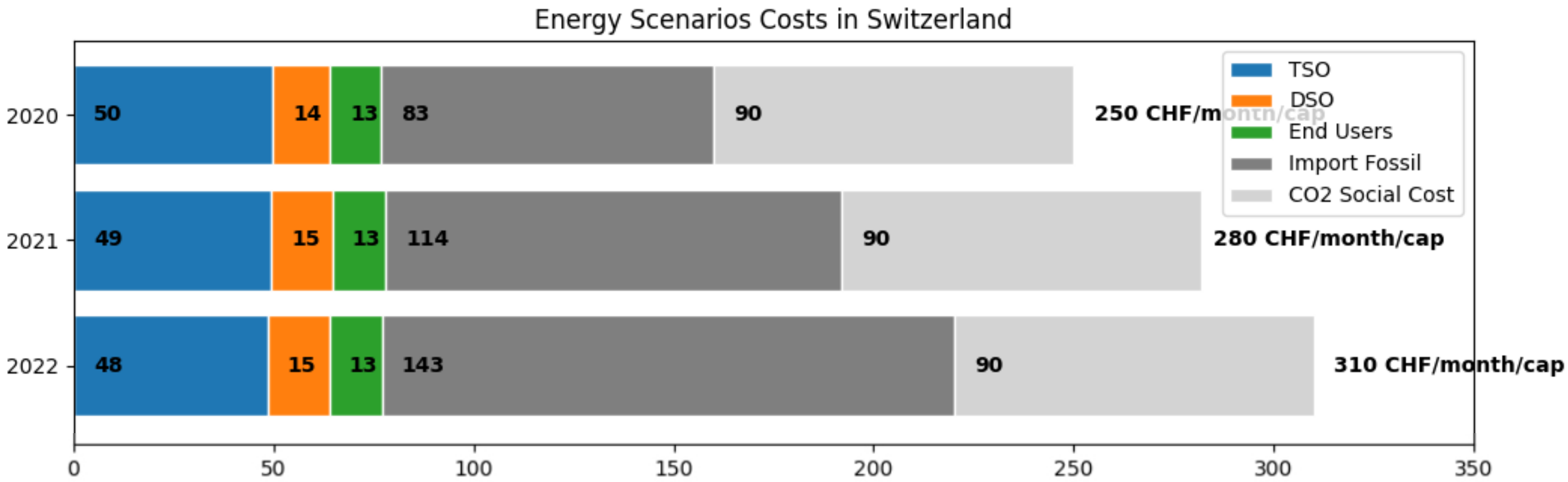
In case of CO_2: “Let the children pay …”

200 - 600* USD/ton CO2

12 $ton_{CO_2}/year/cap$ => 200-600 CHF/month/cap

*EPA (2023)

Swiss energy system: today



Investment : 80 CHF/month/cap: infrastructure and conversion

Import : 80 - 140 CHF/month/cap: Energy imports, variations by V. Poutine

Russia receives 30 CHF/month/cap

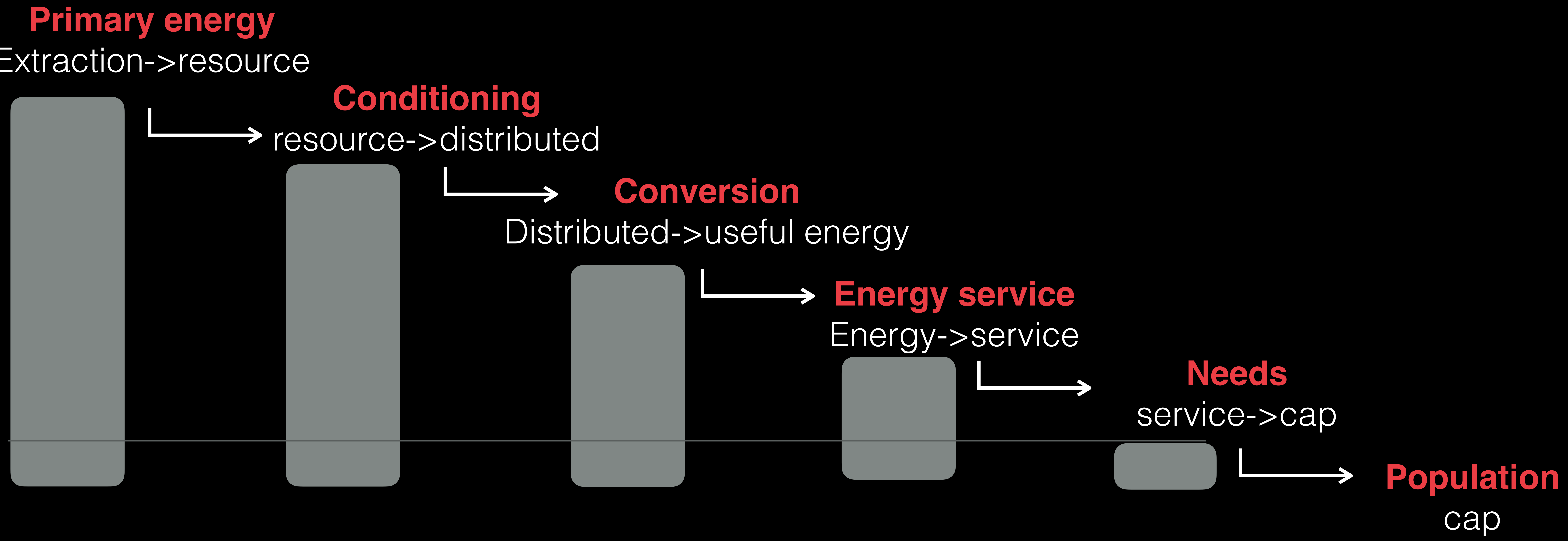
Cost of repair : 90 CHF/month/cap

-> Our children will have to pay to repair

*10 CHF/month/cap = 1 Billion CHF/year

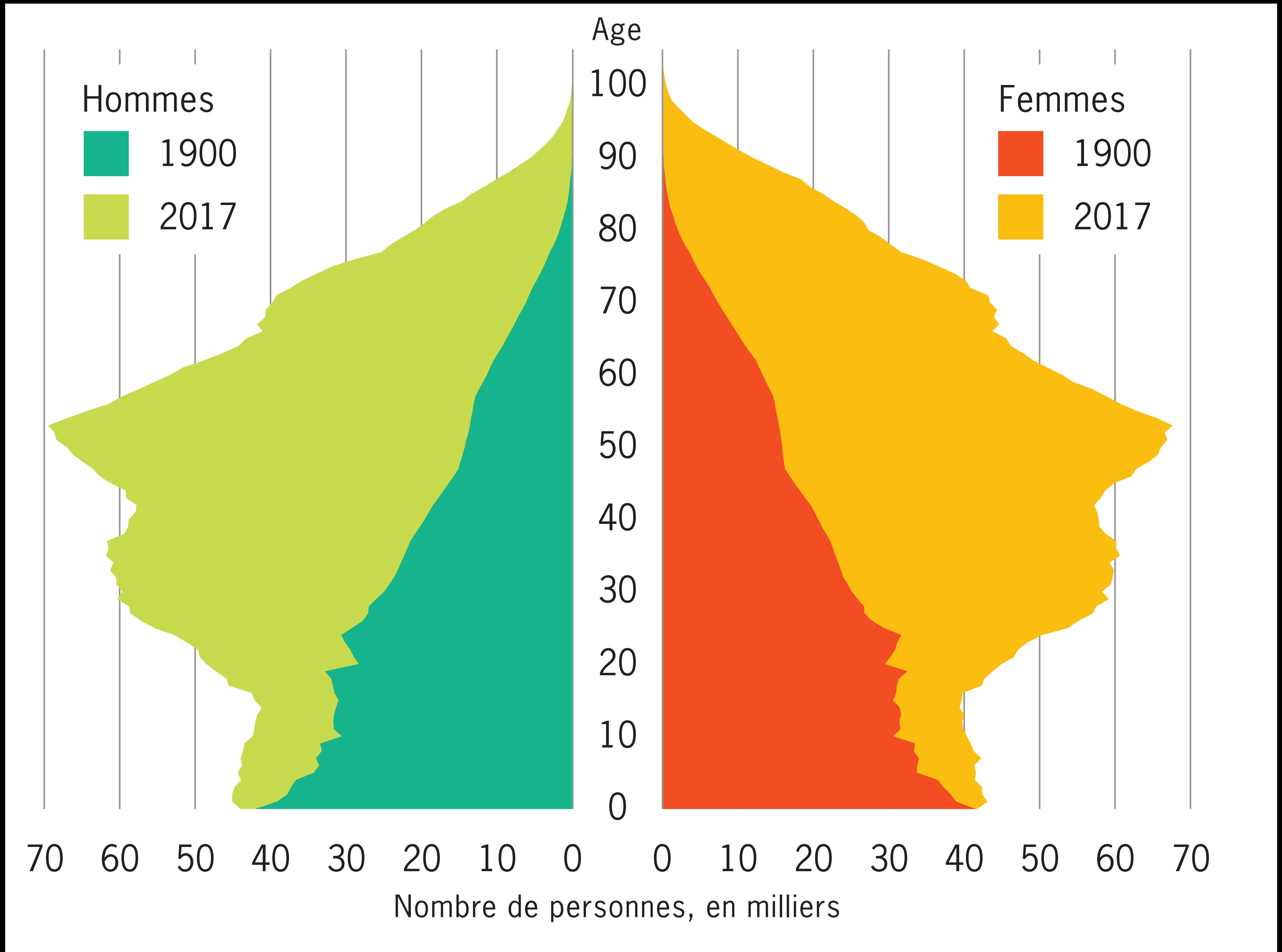
THE CHALLENGE OF THE COMPLETE CONVERSION CHAIN

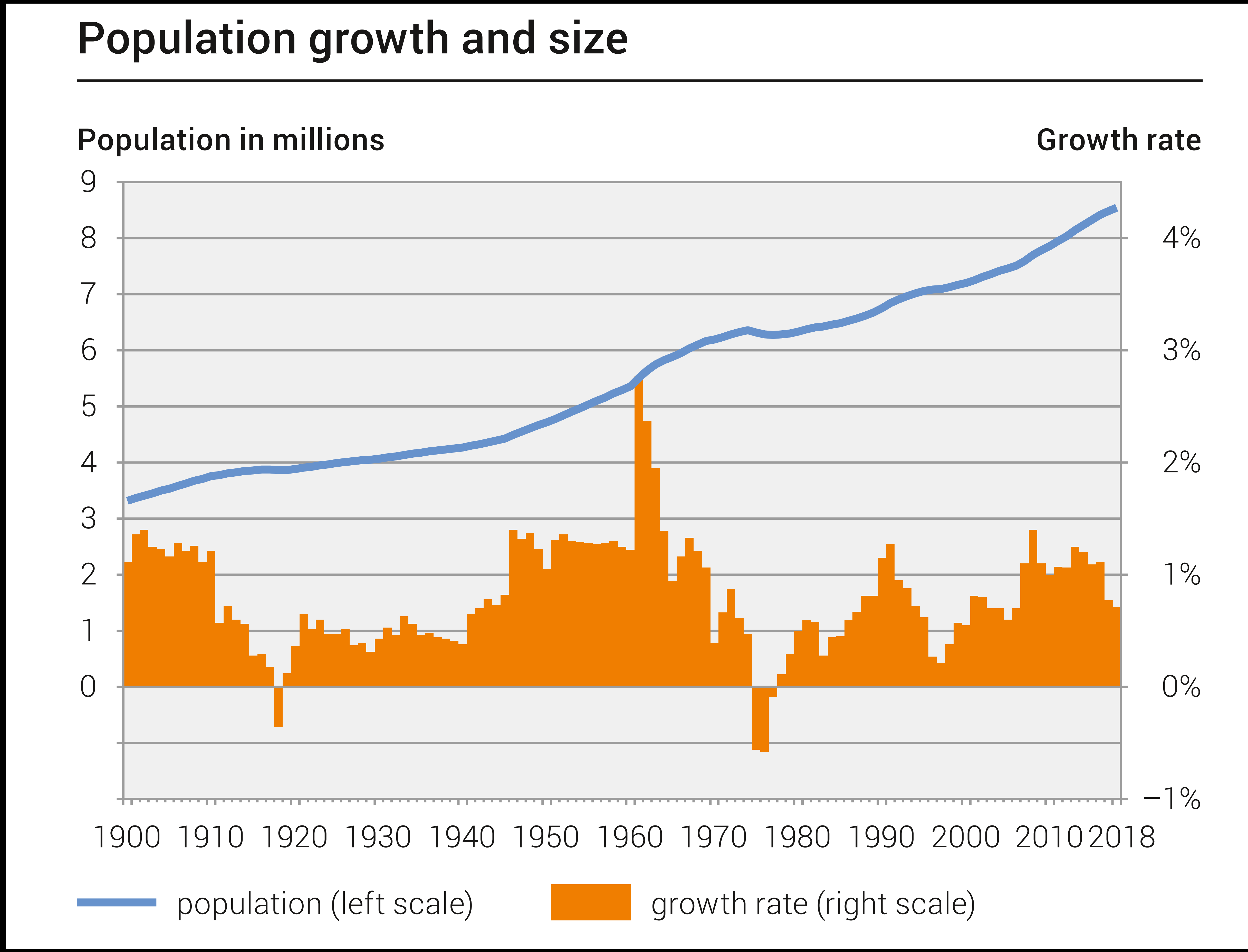
$$[kJ_p/hab/an] = \eta_e[kJ_p/kJ_e] \cdot \eta_s[kJ_e/kJ_s] \cdot e_d[kJ_s/an/m^2] \cdot d_{hab}[m^2/hab] \cdot hab[hab]$$



EVOLUTION OF POPULATION

Structure par âge de la population





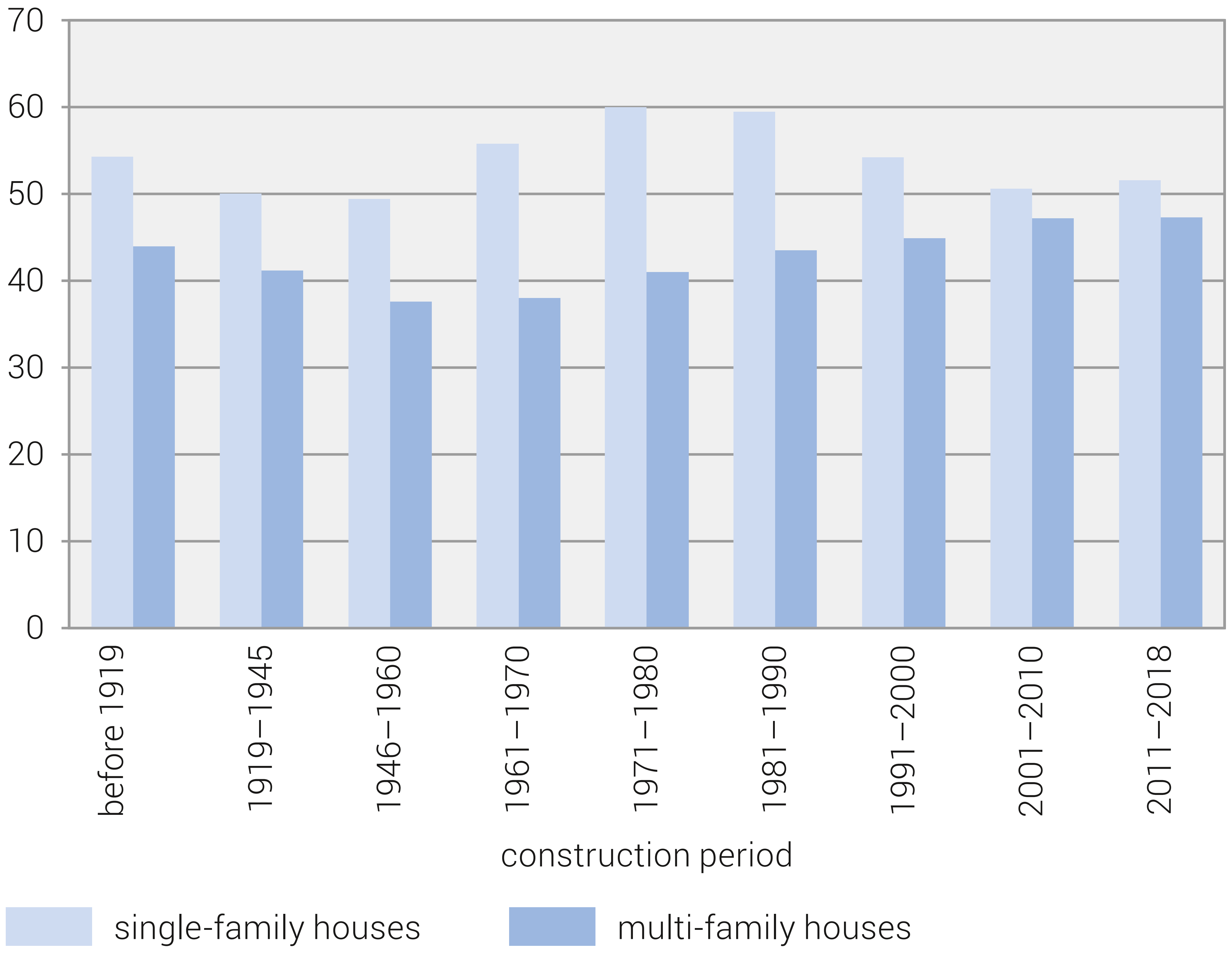
Sources: FSO – Population census, ESPOP, STATPOP

8’500’000 hab. (life time exp : 83 years)

Growth rate : 1.0 %/year

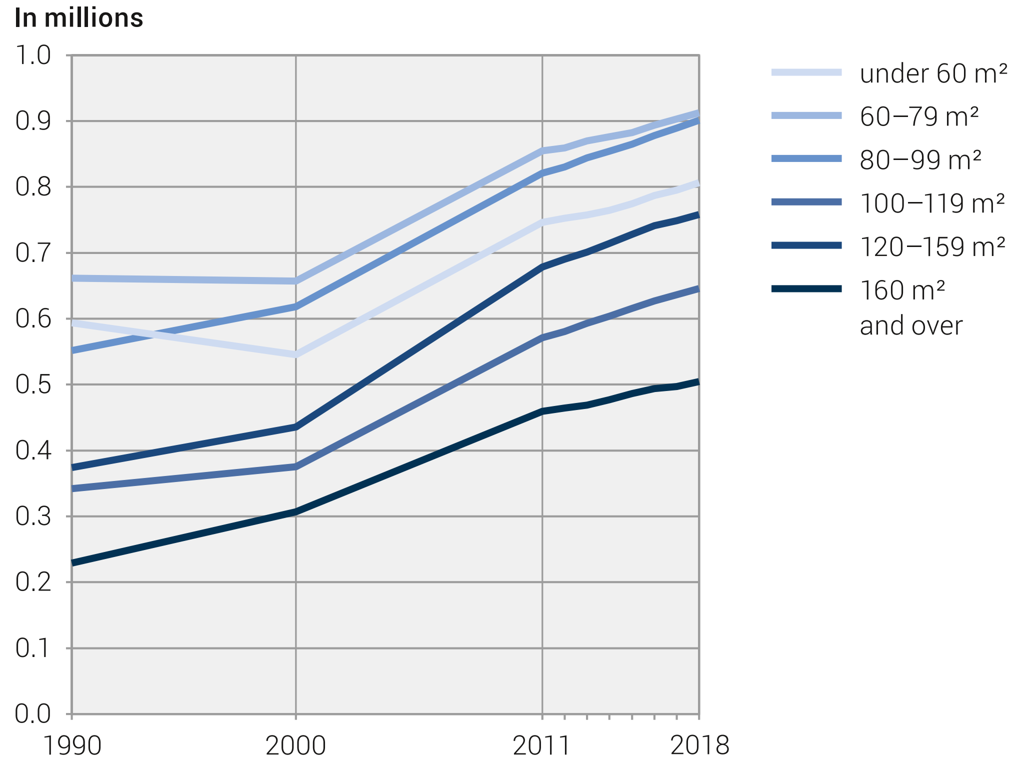
EVOLUTION OF THE NEEDS

Average living space per occupant by building category and period of construction, 2018



Source: FSO – Buildings and dwellings statistics © FSO 2019

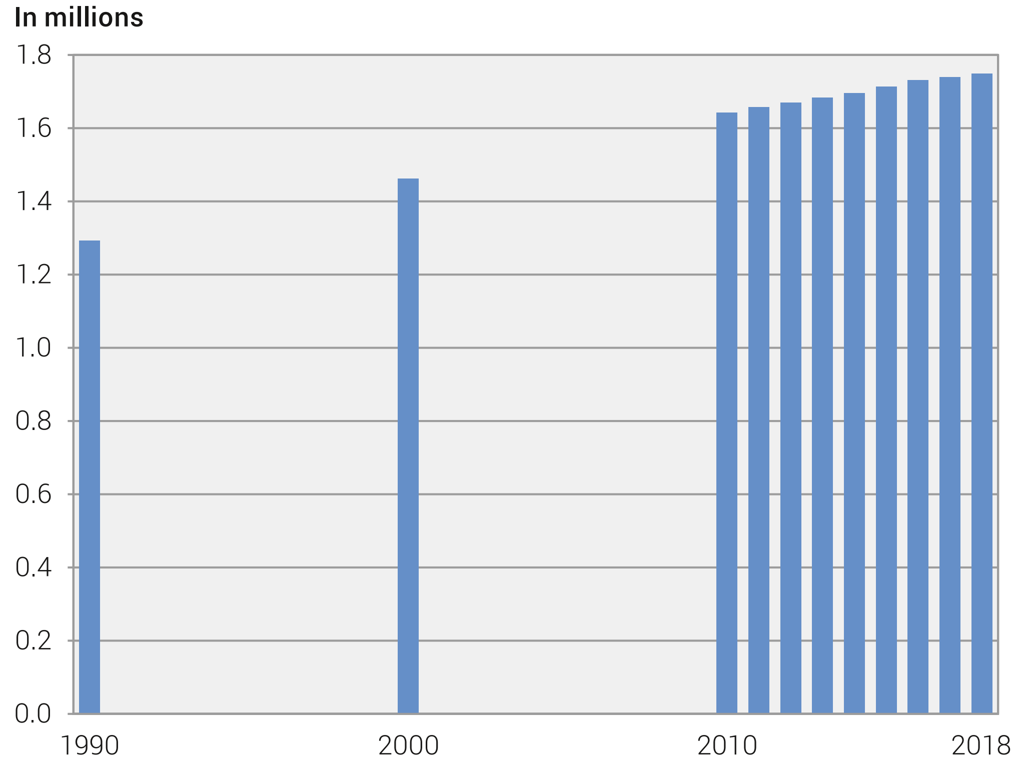
Dwellings by size group



Sources: FSO – Federal population censuses, Buildings and dwellings statistics © FSO 2019

50-70 m2/hab

Residential buildings in Switzerland

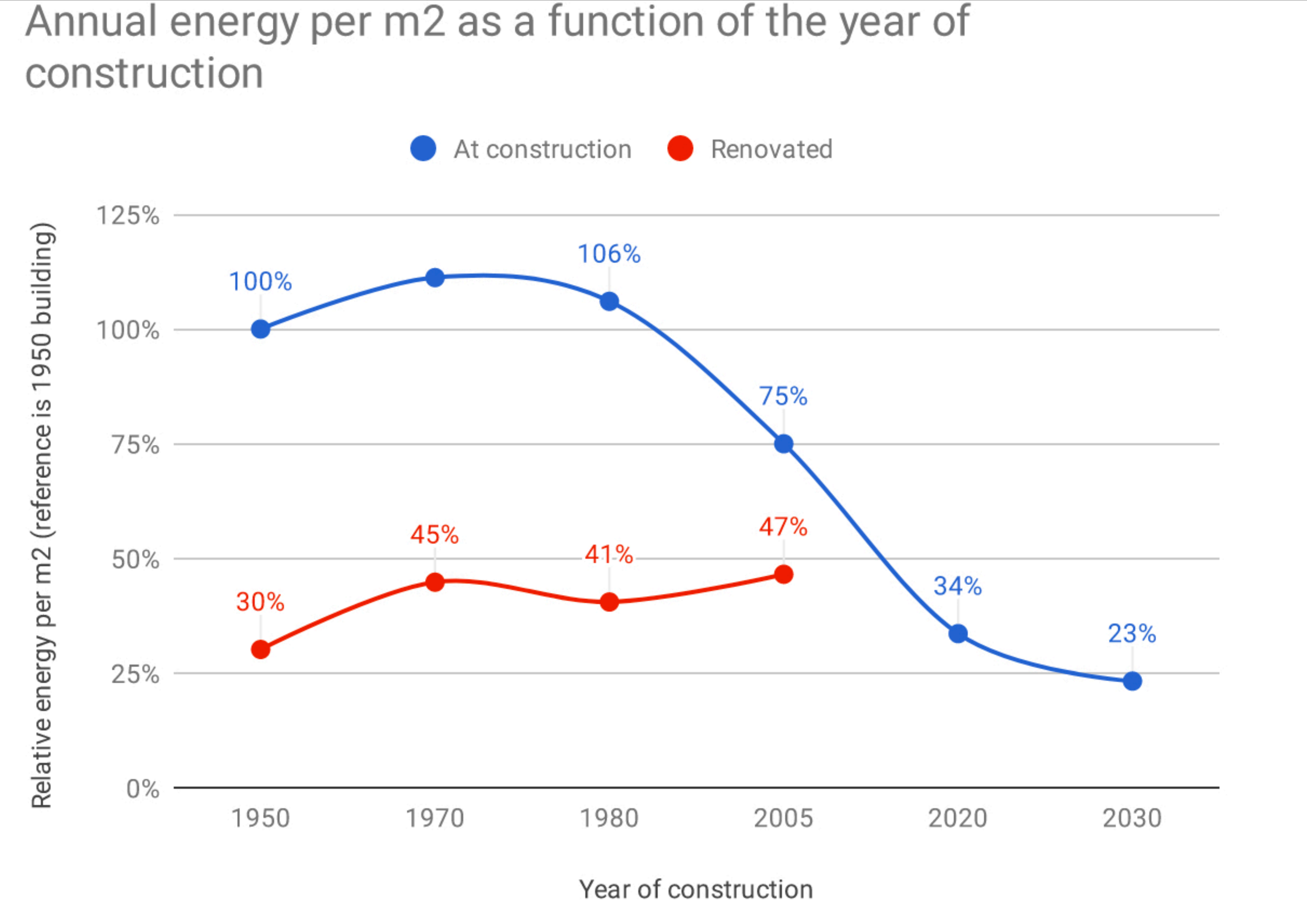


Sources: FSO – Federal population censuses, Buildings and dwellings statistics © FSO 2019

1,748,477

Buildings

ENERGY EFFICIENCY OF HEATING HOUSES



Reference : 750 MJ/m2/an (1950)

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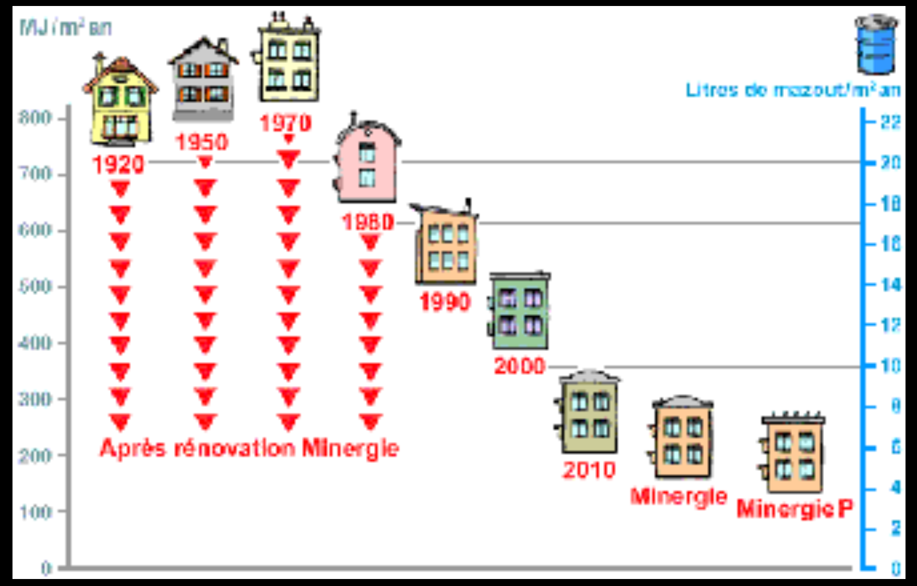
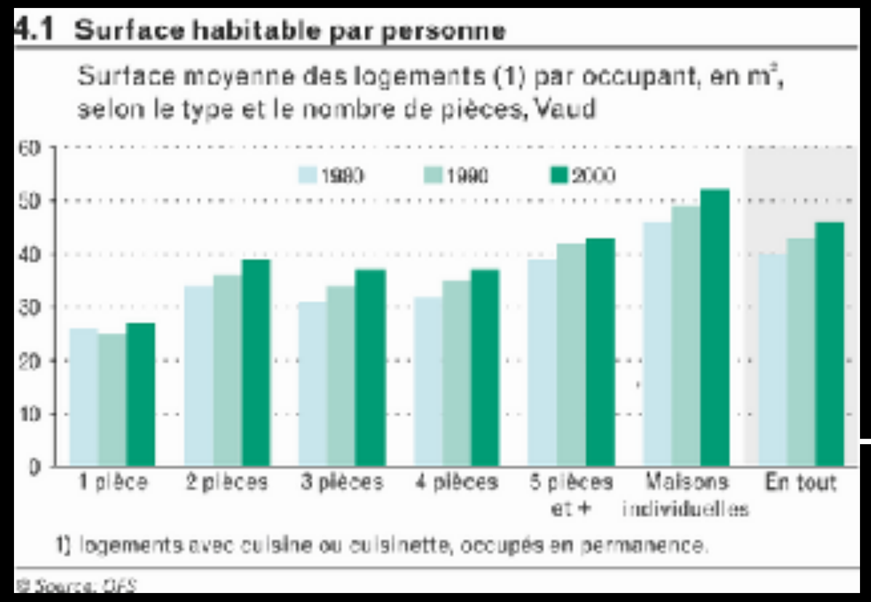
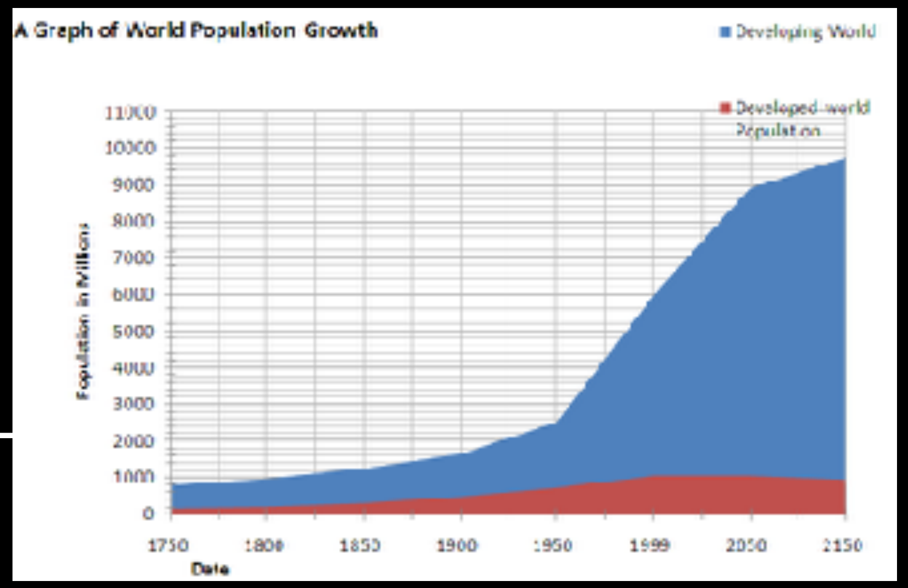
THE NEEDS

Soberty Energy->m2 heated **X** **Comfort** m2->hab **X** **Population** hab **=** Service service/hab







	Renovation	**New buildinds**	**Population**
2020	-		8.6 M hab
2050	30 %	+56 %	9.9 M hab

http://worldpopulationreview.com/countries/switzerland-population/

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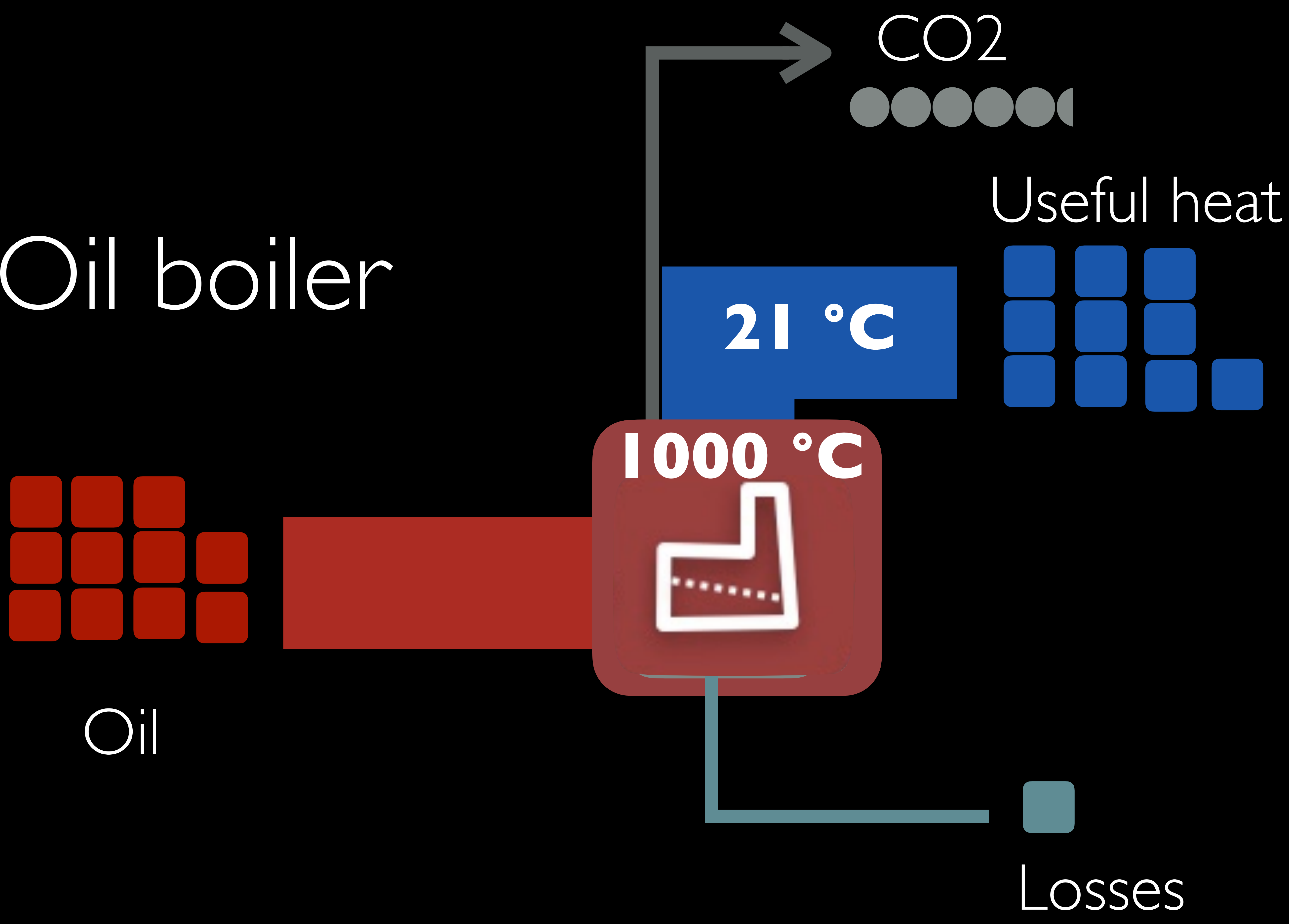
HOW DO WE SATISFY THE ENERGY NEEDS IN A BUILDING ?

"Good" Oil boiler



HEATING BUILDING IS 50% OF COUNTRY ENERGY CONSUMPTION

120-190

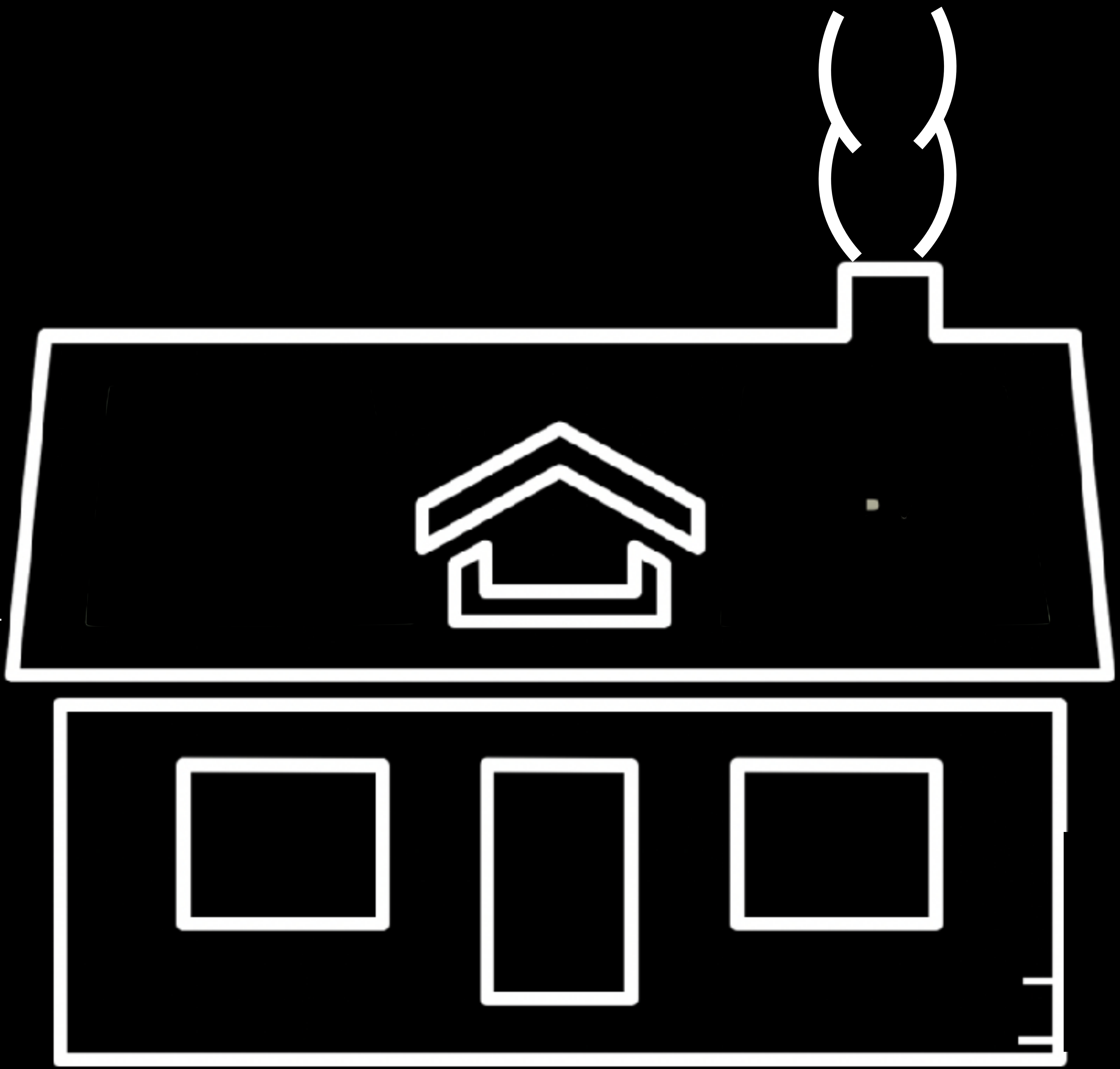
CHF/month/100 m²

Energy (Oil)

110-180 CHF/month/100 m²
in which 85-155 CHF/month/100 m² import

Boiler

10 CHF/month/100 m²



3.78

tons **CO_2** /year/100 m²

63

$CHF_{children}$/month/100 m²

(1830) CARNOT : THE MAGIC FORMULA

Nicolas Léonard Sadi CARNOT (F)

1796 - 1832

Electricity

your soberty

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

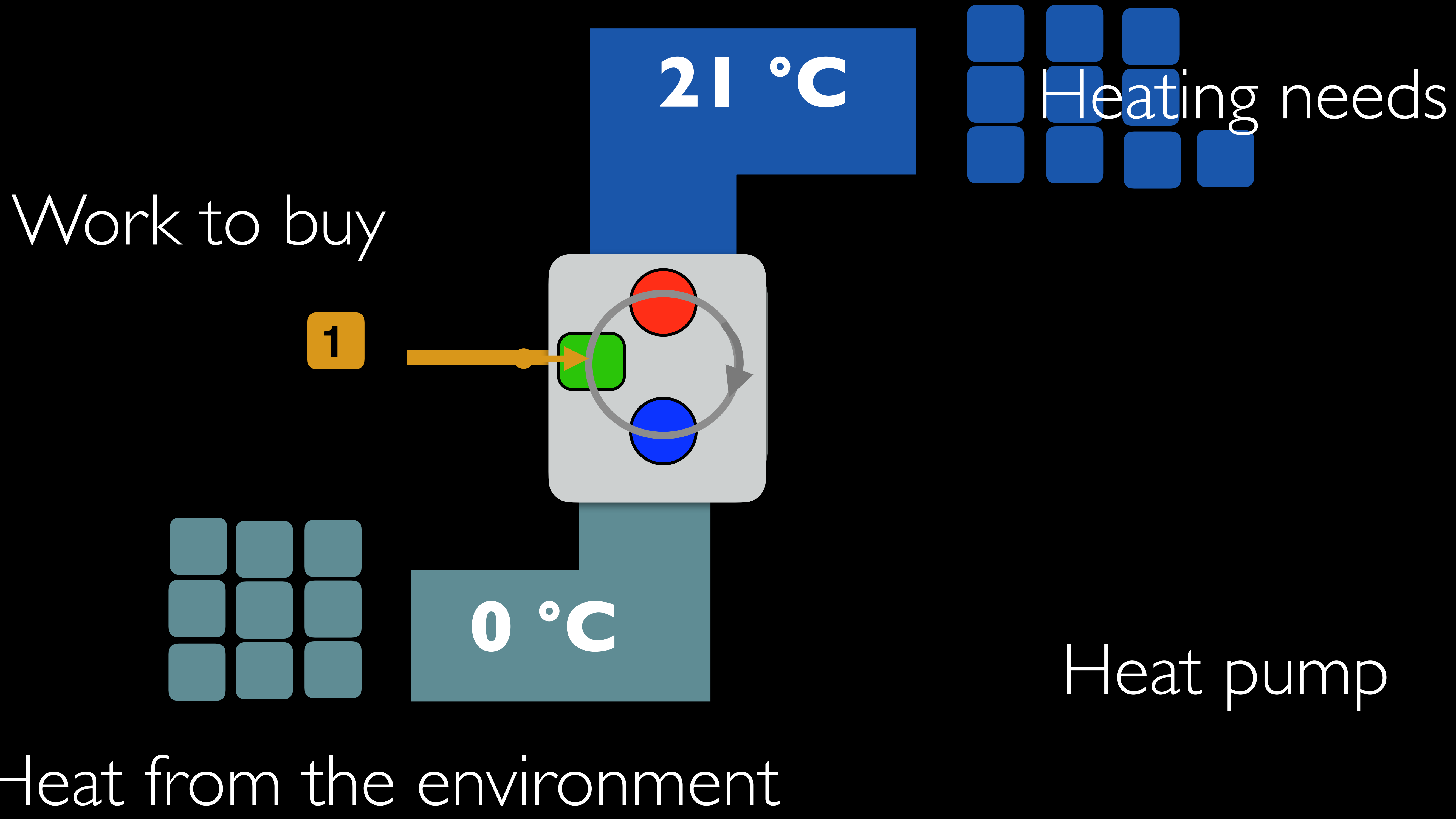
Fraction of heat from the environment

(1830) CARNOT : THE MAGIC FORMULA APPLIED

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

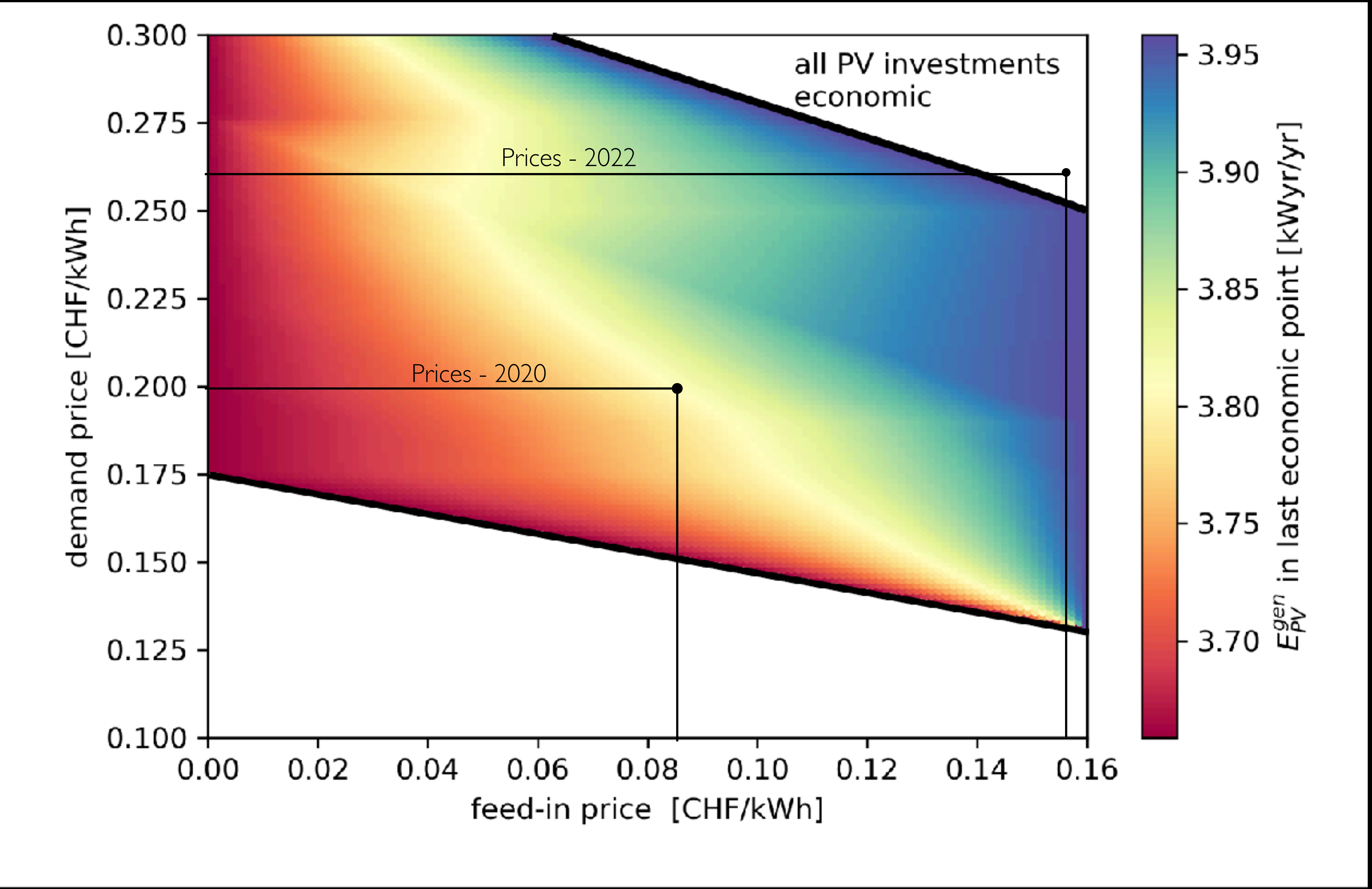
For 10 units of heat, 9 come from the environment and 1 as electricity

Nicolas Léonard Sadi CARNOT (F)
1796 - 1832



RENEWABLE ENERGY HUB

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

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YOU HAVE ALSO A FREE BATTERY FOR THE ENERGY SYSTEM

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

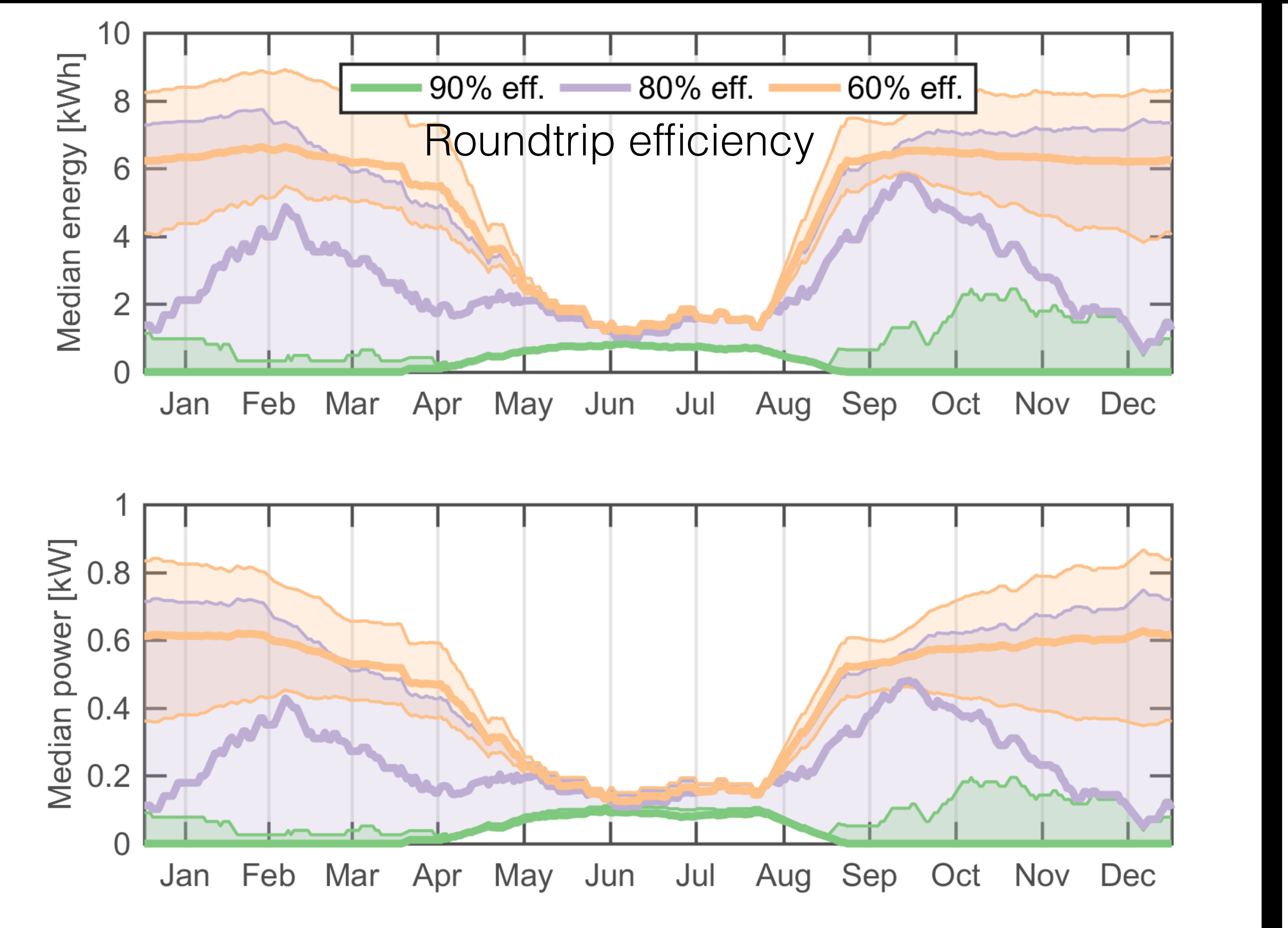
Building performance (solution I)

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

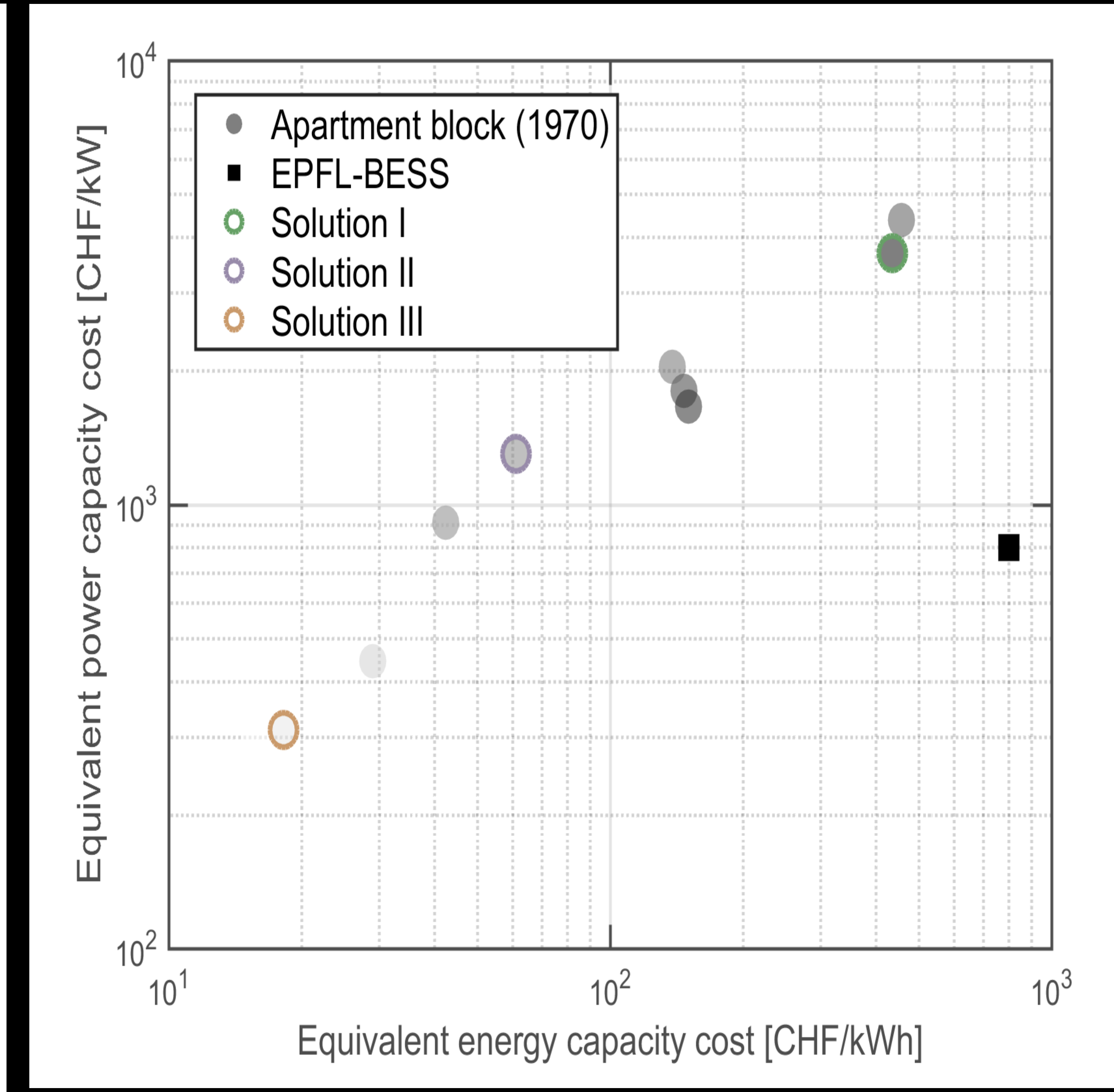
Building energy system design (solution I)

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



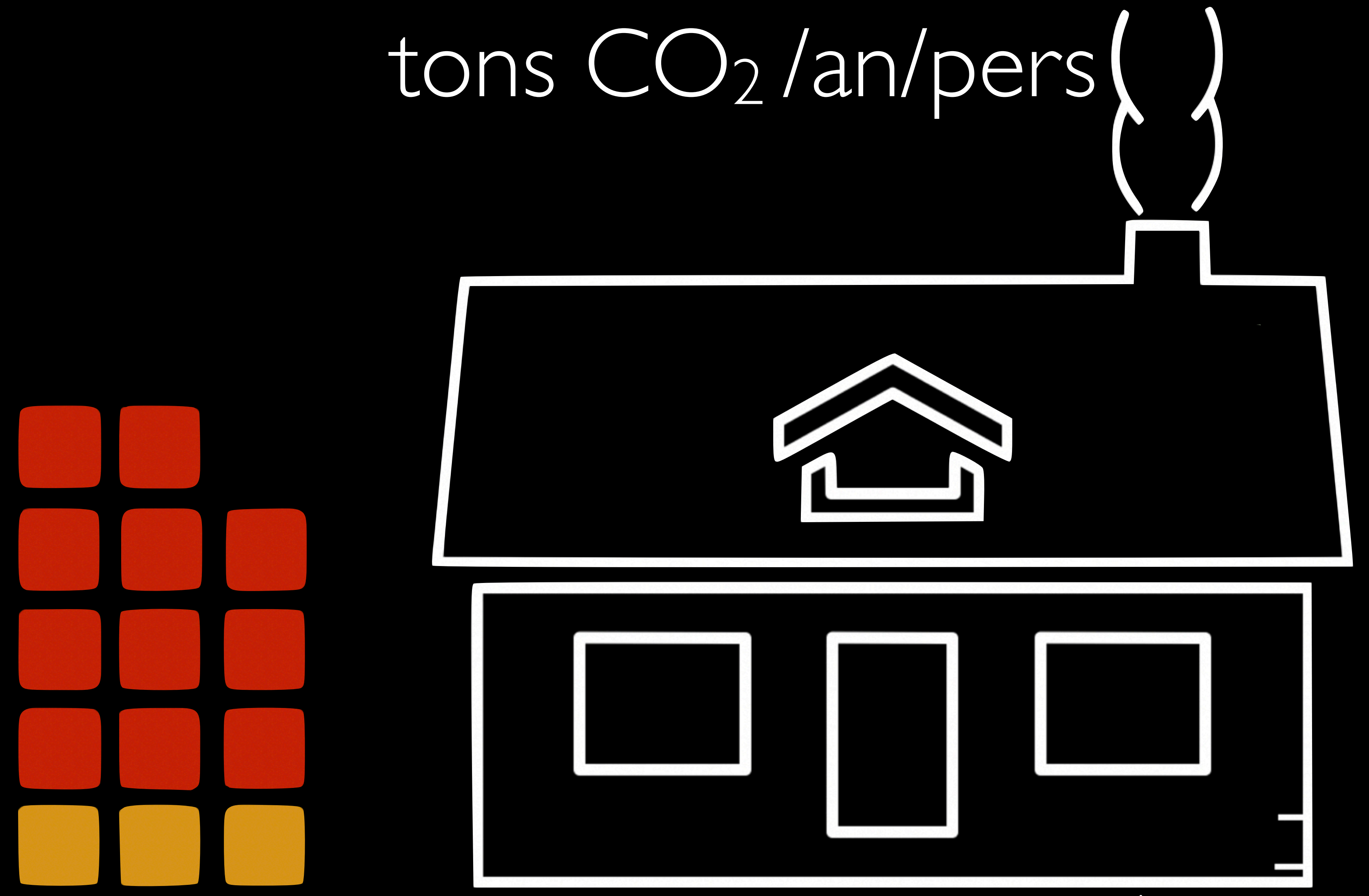
Annual equivalent battery performance



BUILDINGS : RENEWABLE ENERGY HUB
90+ % CO2 EMISSIONS REDUCTION

2.20

tons CO_2 /an/pers



Oil: 6 cts/kWh
Electricity: 18 cts/kWh

572

CHF/y/cap

Energy : **542** CHF/y/cap
Investment : **30** CHF/y/cap

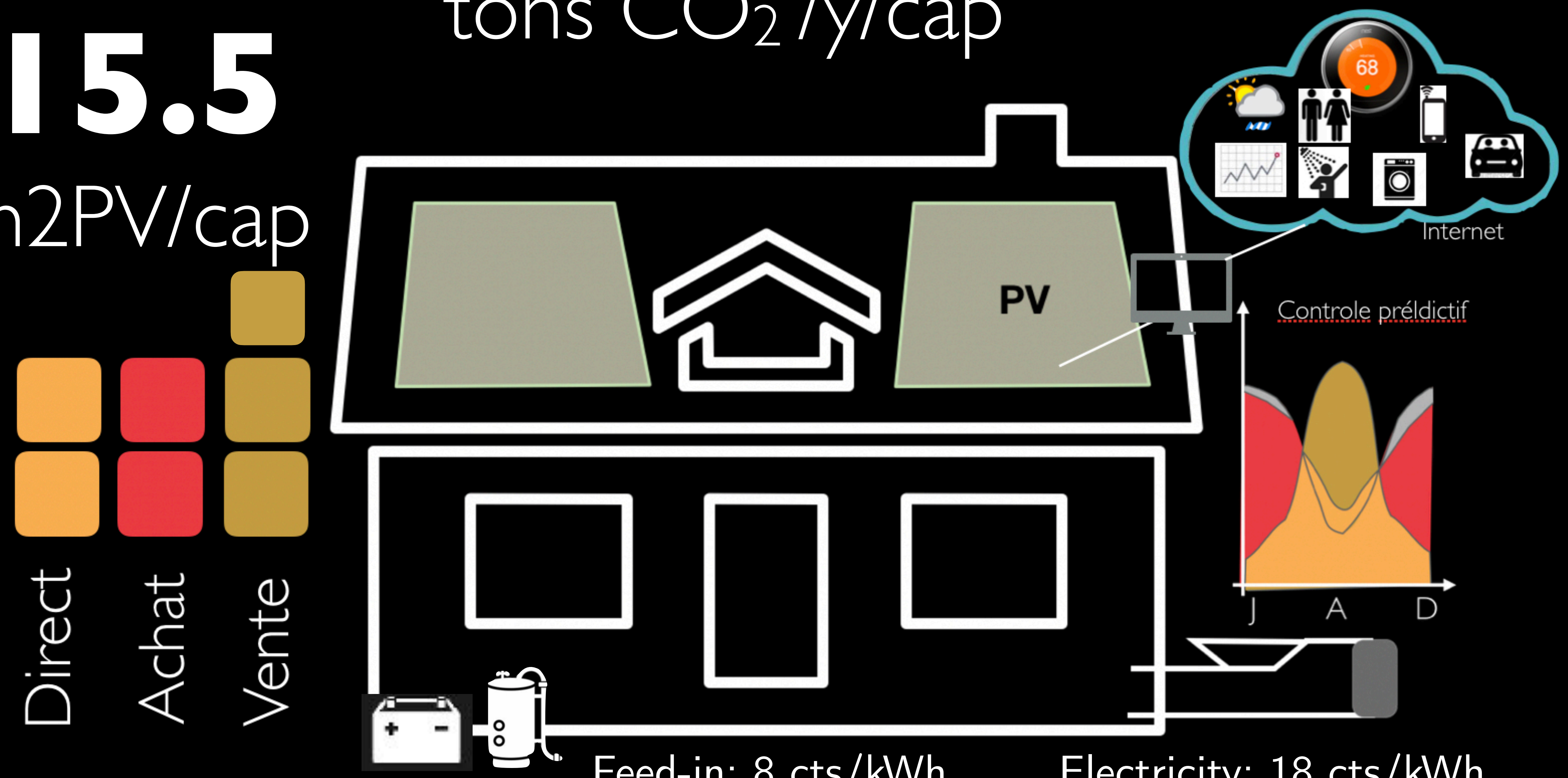
2021

0.25 - 0.04

tons CO_2 /y/cap

15.5

m2PV/cap



Feed-in: 8 cts/kWh
Electricity: 18 cts/kWh

209

CHF/y/cap

PV feed-in : **-139** CHF/y/cap
Energy : **118** CHF/y/cap
Investment : **230** CHF/y/cap

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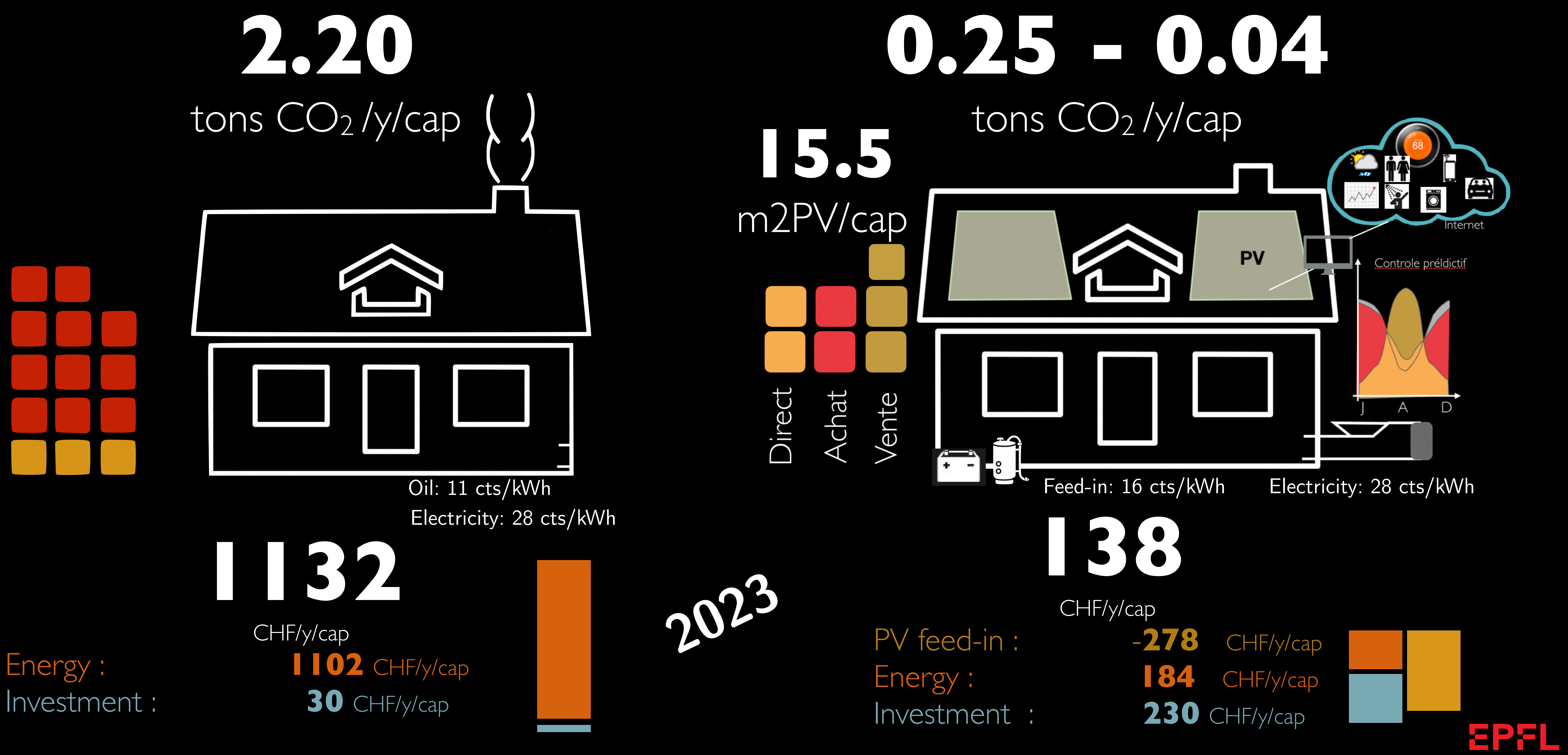
BUILDINGS : RENEWABLE ENERGY HUB
90+ % CO2 EMISSIONS REDUCTION



RENEWABLE ENERGY HUB AND E-VEHICULES

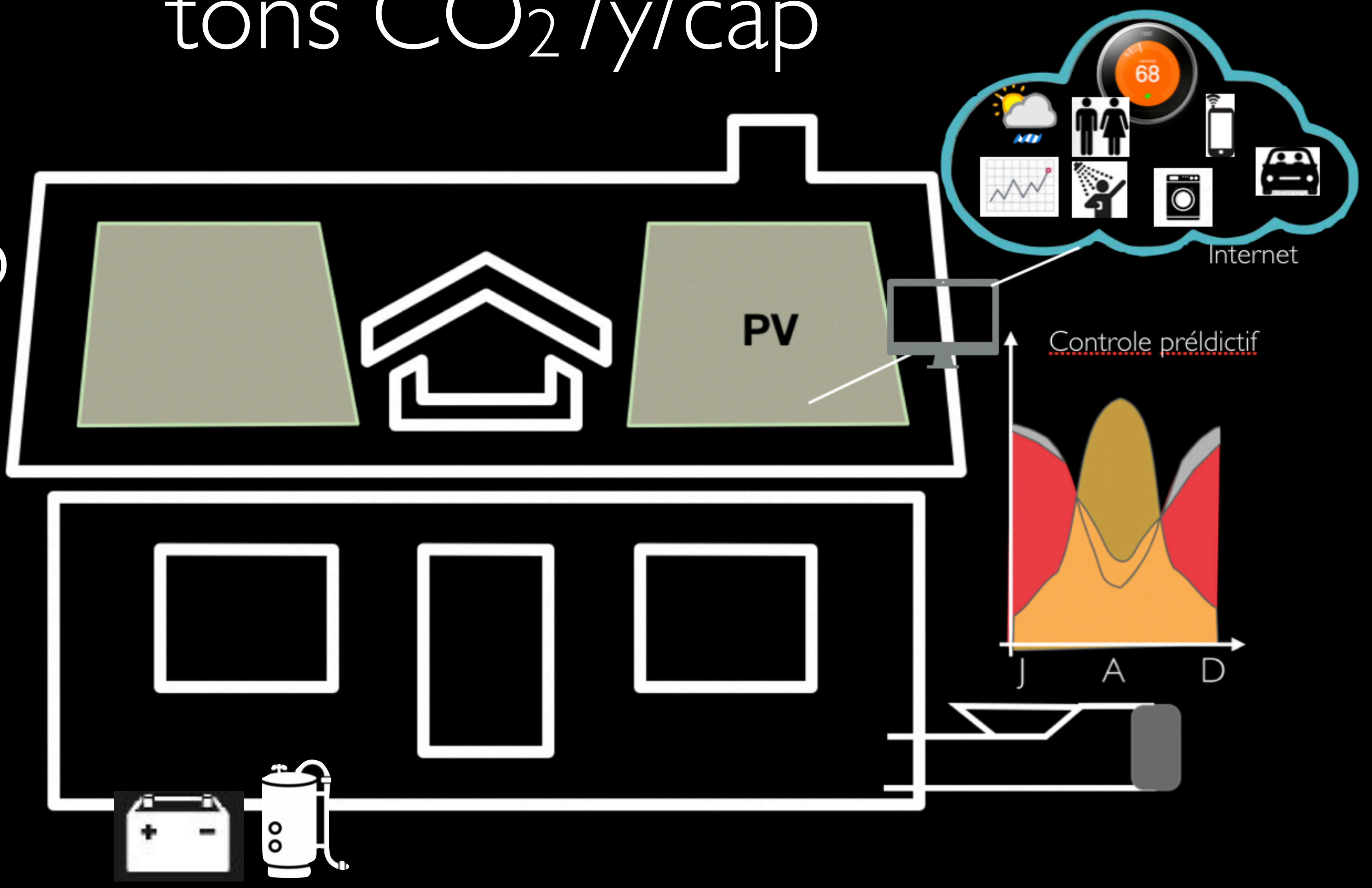
2.00 **(0.25 + 1.74)**

tons CO_2 /y/cap

15.5

m2PV/cap

Direct Achat Vente



1109 **(138 + 881)**

CHF/y/cap

PV feed-in : **-278** CHF/y/cap

Energy : **184** CHF/y/cap

Investment : **230** CHF/y/cap

Building

Gasoline car

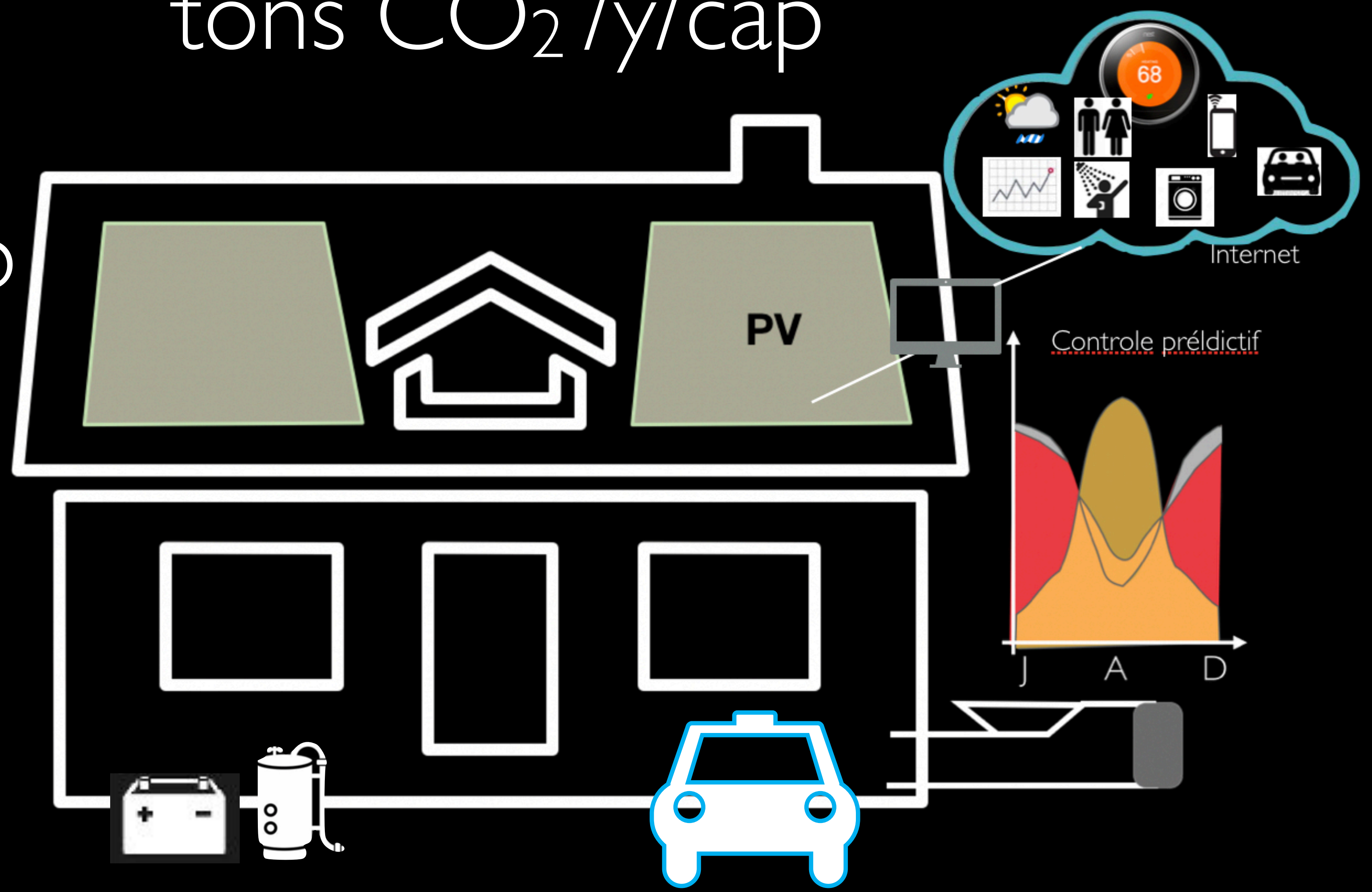
0.32 **(-83%)**

tons CO_2 /y/cap

15.5

m2PV/cap

Direct Achat Vente



208 **(-79%)**

CHF/y/cap

PV feed-in : **-226** CHF/y/cap

Energy : **204** CHF/y/cap

Investment : **230** CHF/y/cap

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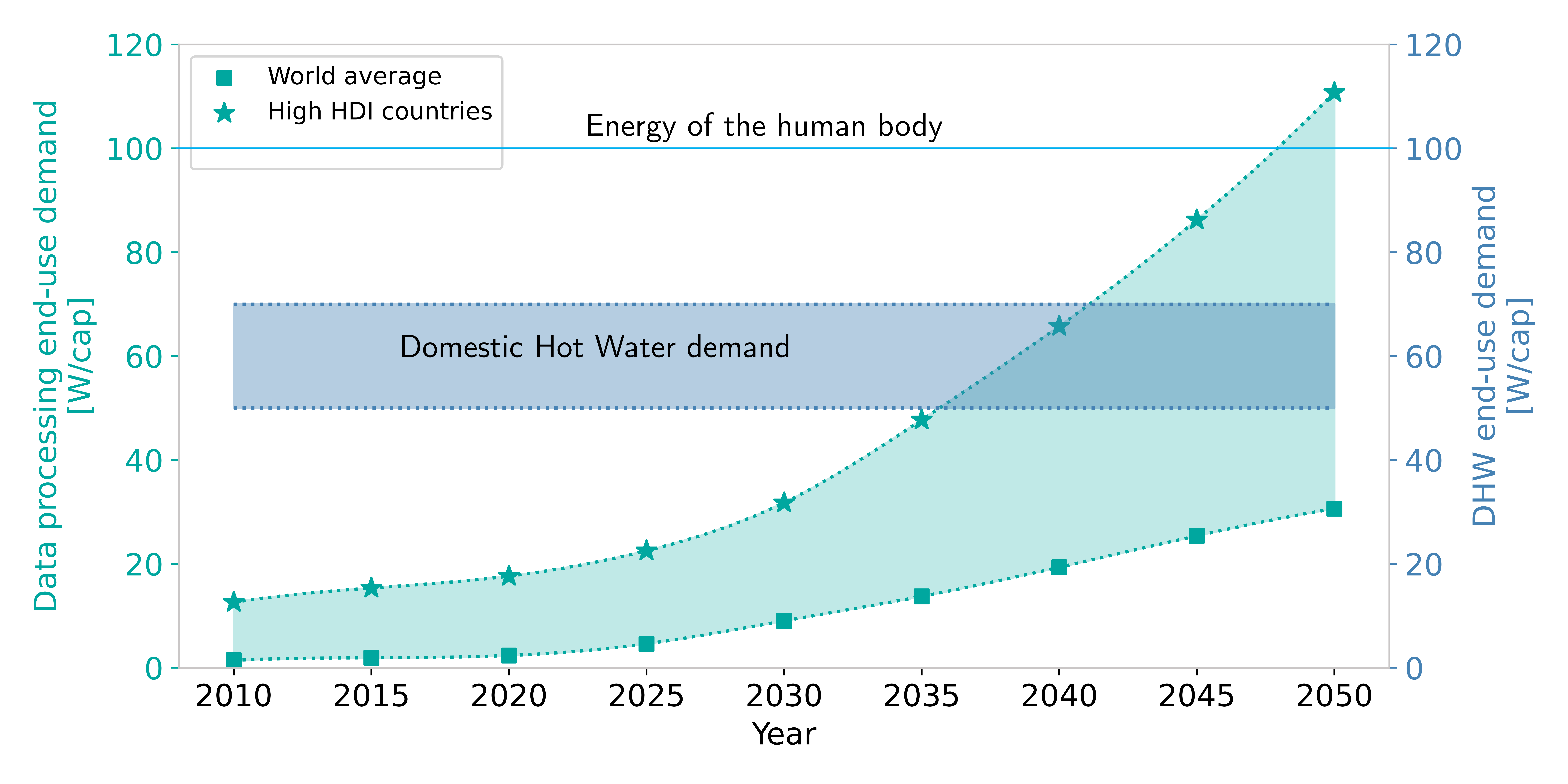
DATA PRODUCTION AND ENERGY SYSTEM



Lepour et al., (2022) ECOS 2022 proceedings

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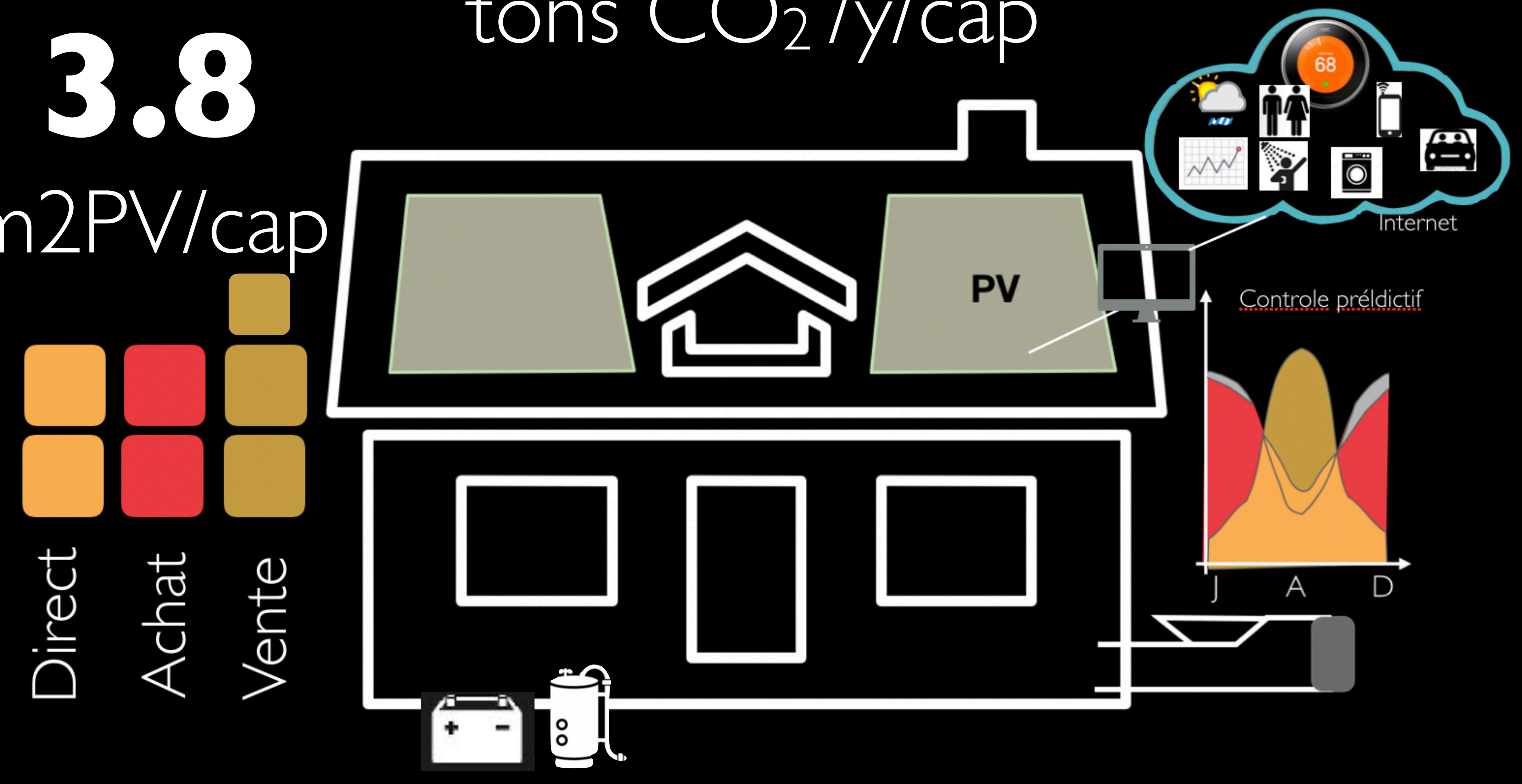
RENEWABLE ENERGY HUB AND DATA PRODUCTION

0.25 + 0.24

tons CO_2 /y/cap

3.8

m2PV/cap

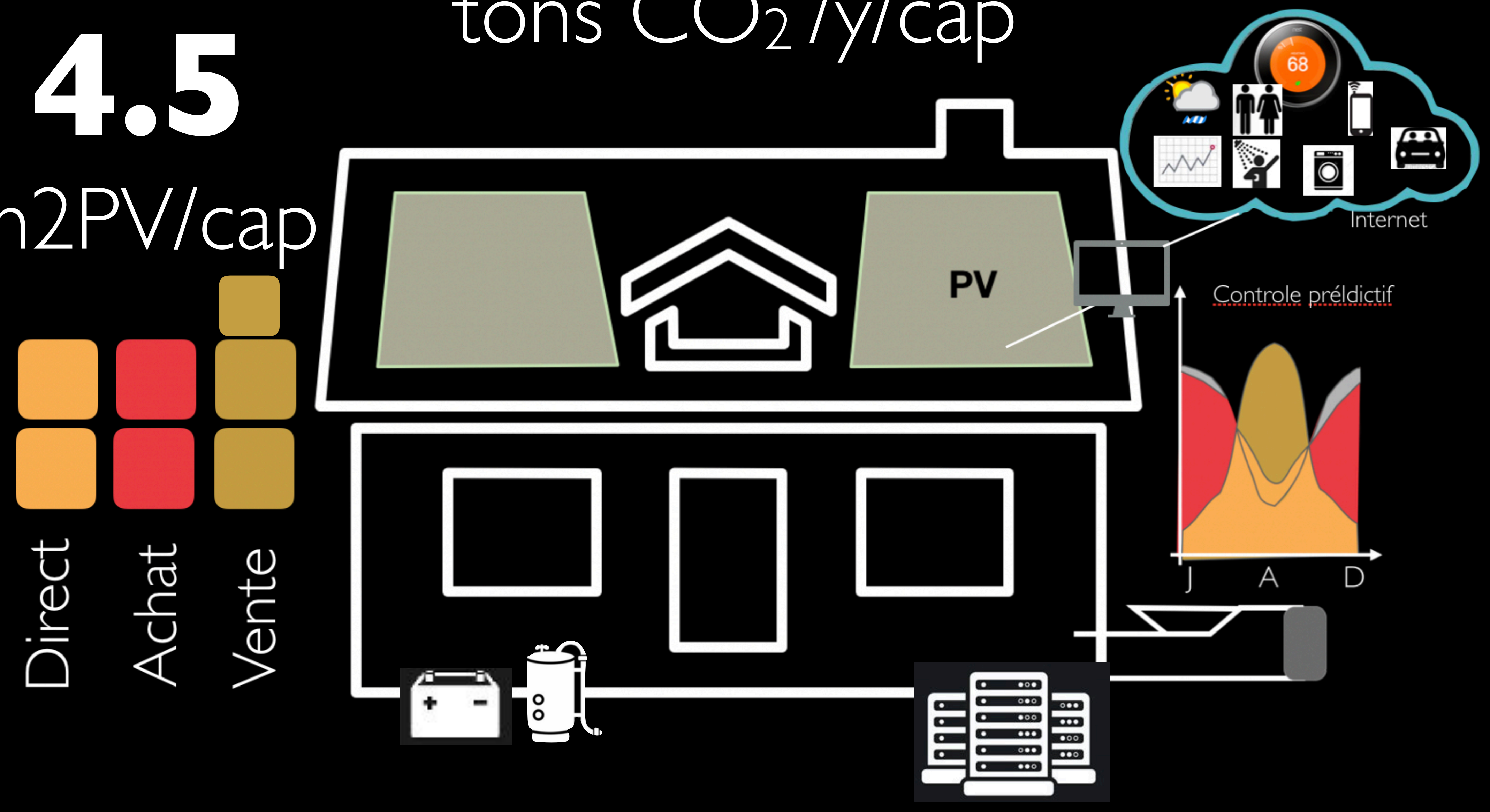


0.32 (-34%)

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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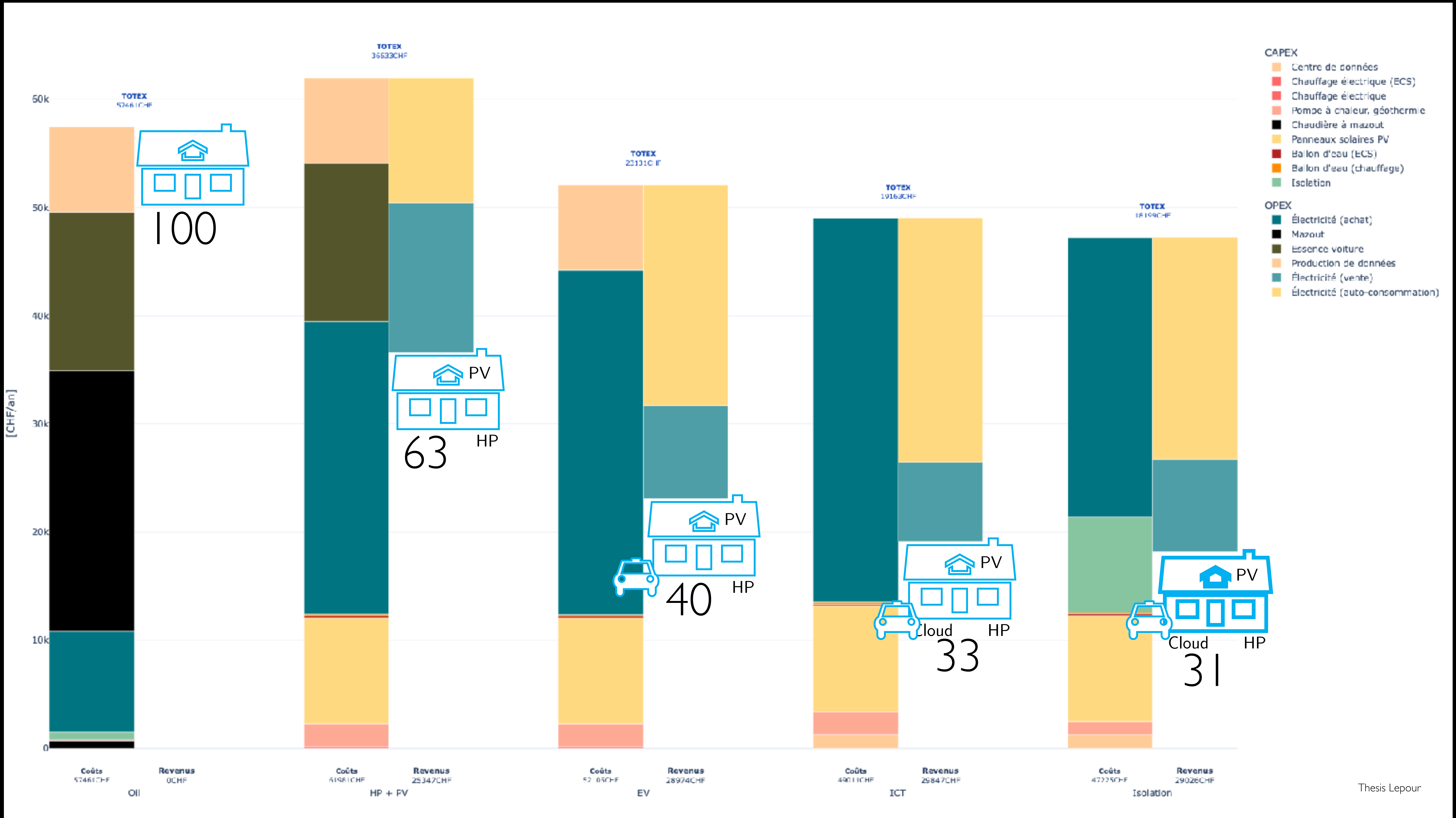
PV - HEAT PUMP - ELECTRIC CARS - DATA - RENOVATION



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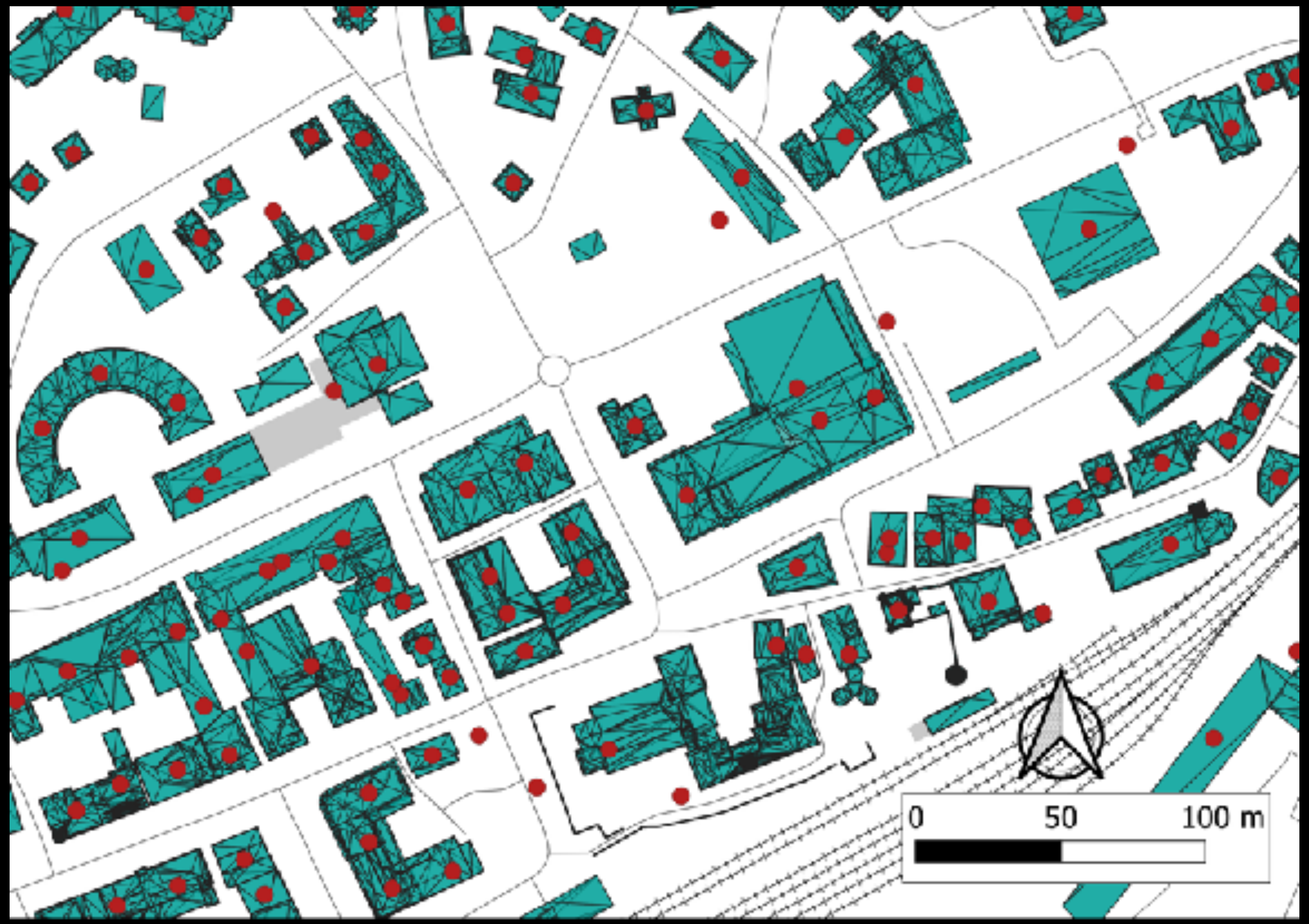
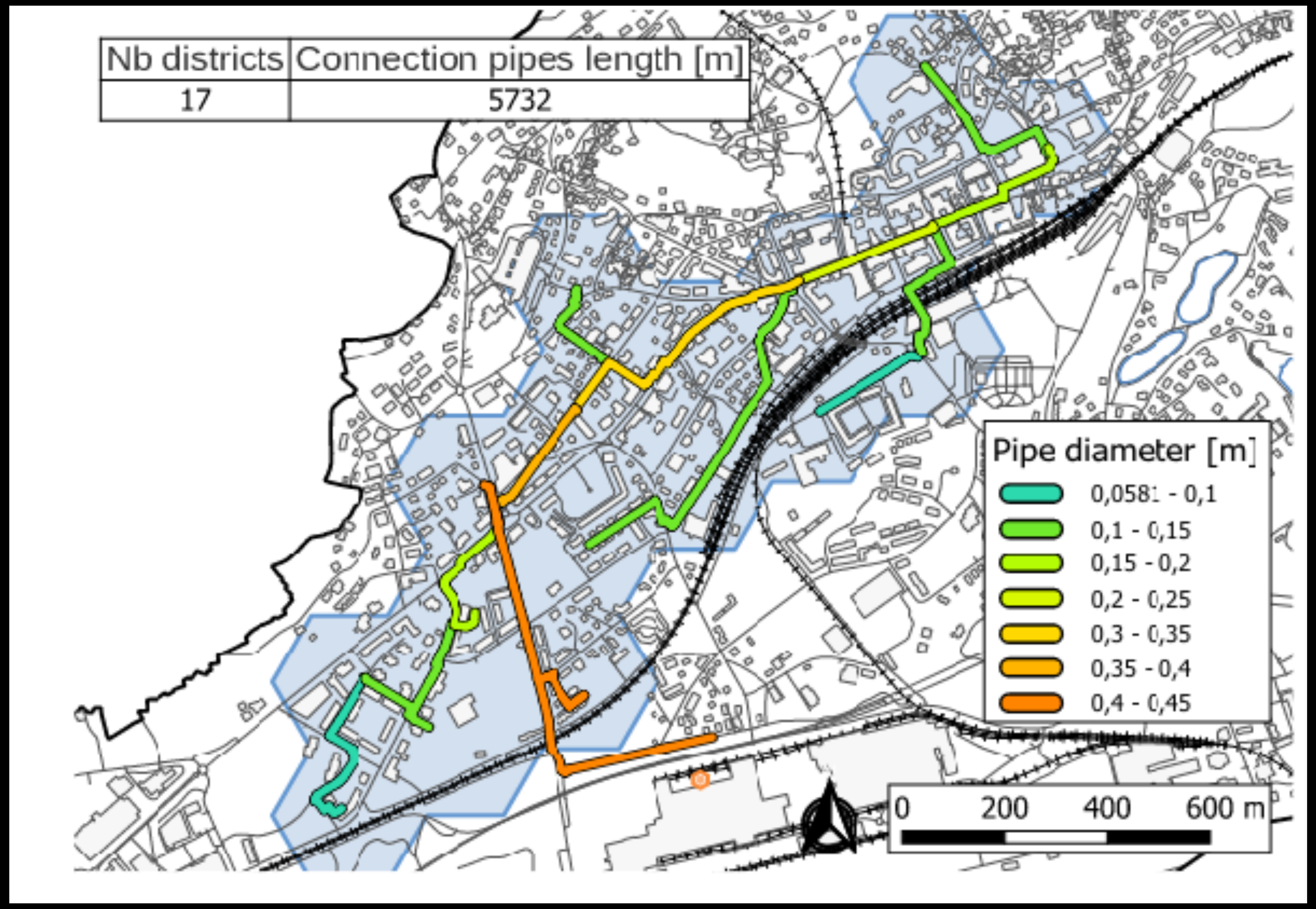
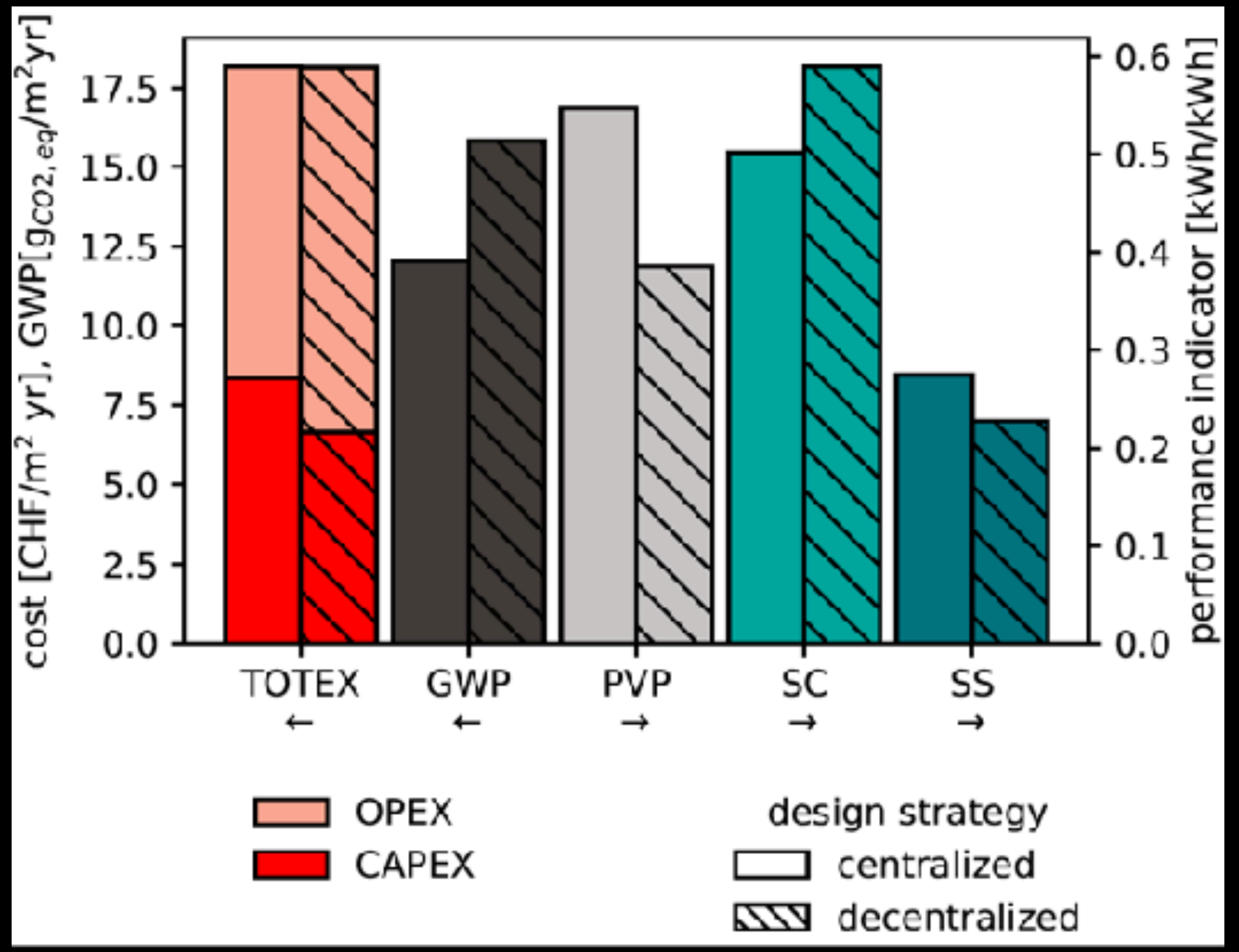
INTEGRATING RENEWABLE ENERGY HUBS : SYSTEMS IN SYSTEMS

- District scale => interactions between buildings

building vs community







For the same feed-in/feed-out prices

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

→Operating costs: -9%
→Self-consumption: +34%

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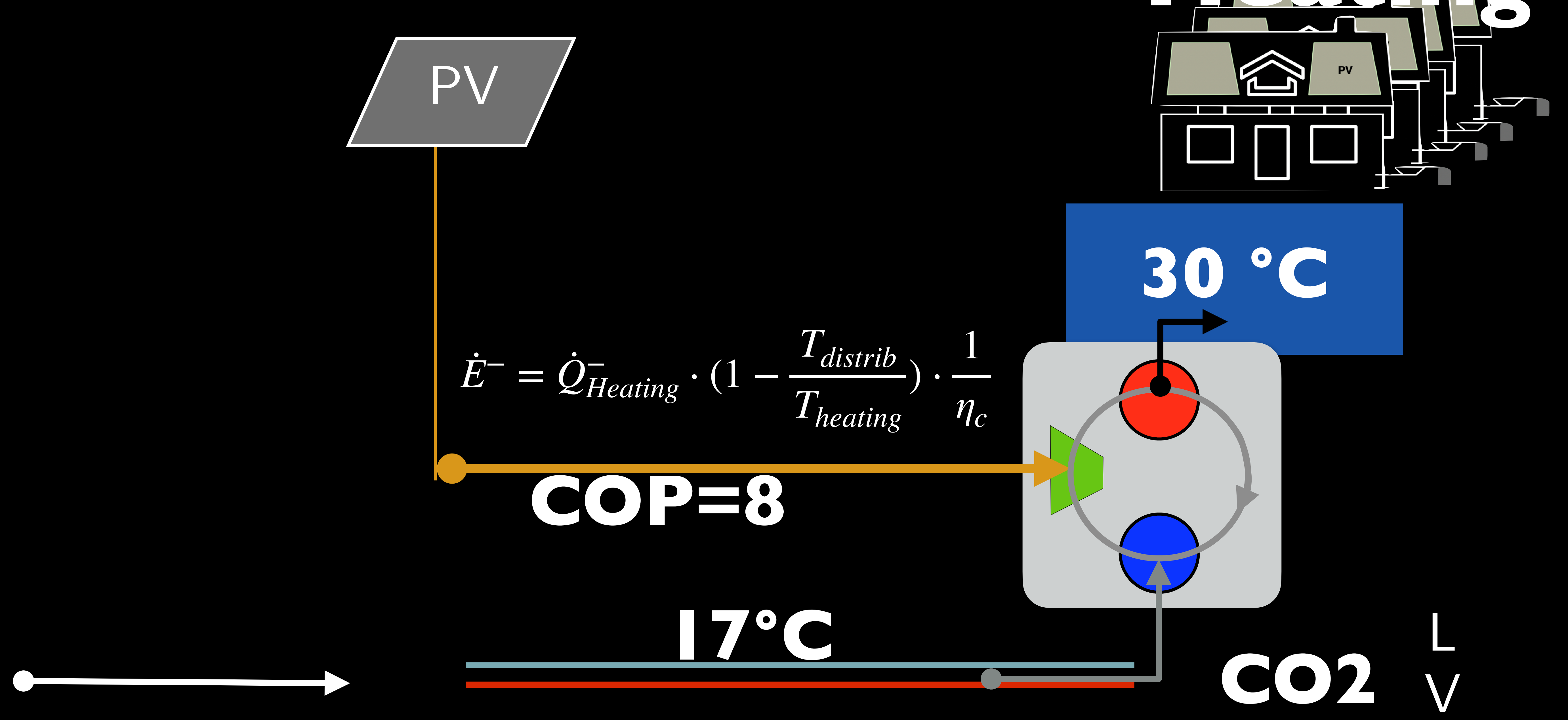
CHASING HEAT SOURCES IN THE CITY

Users ($T_{heating}$)

Heat sources (T_{source})

Heating



Data center : **30**°C

WWTP : **17-22** °C

Distribution

HEAT SOURCES IN THE CITY

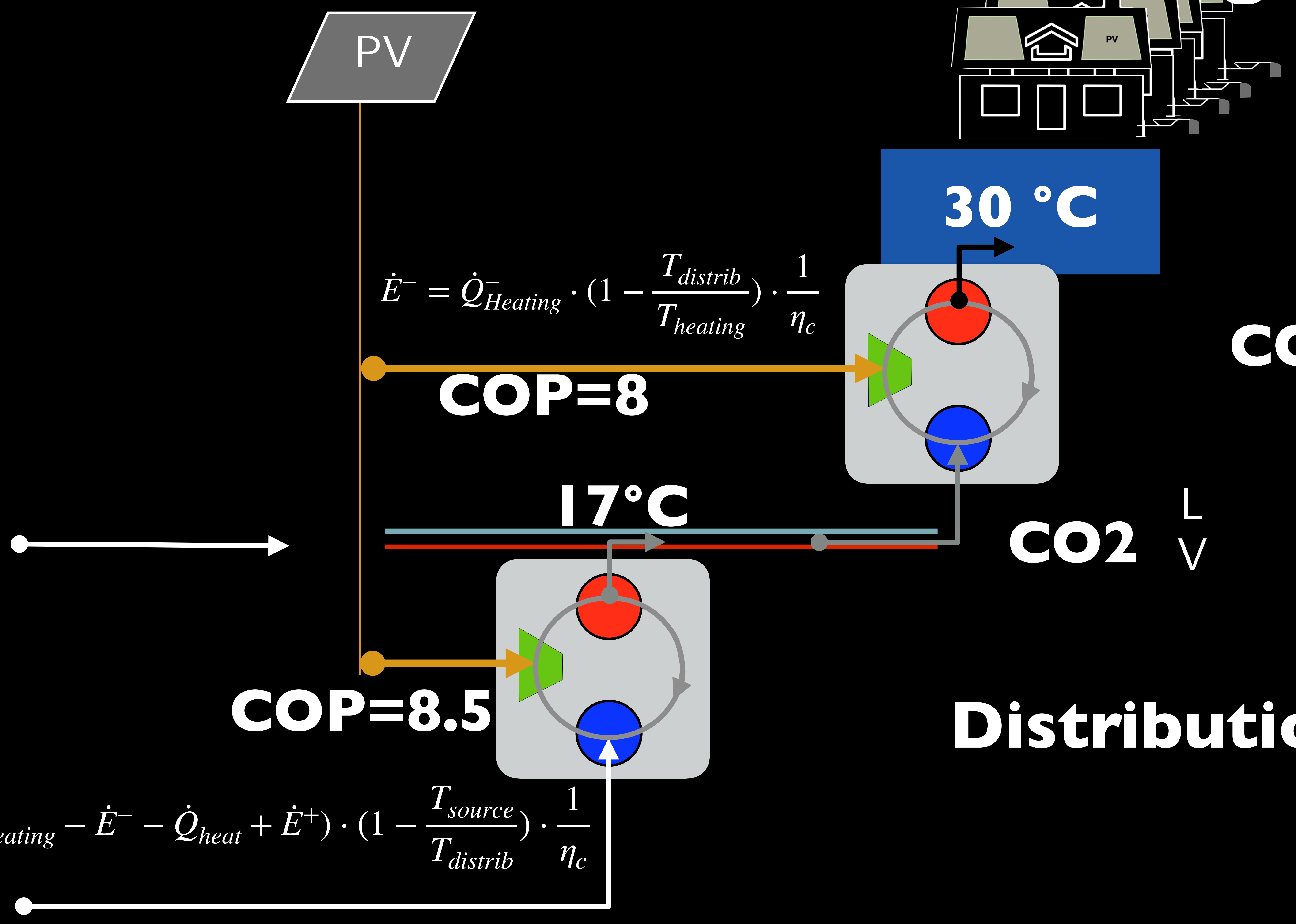
Heart sources (T_{source})

Users ($T_{heating}$)

Heating

Data center : **30**°C
STEPS : **13-20** °C

Aquifers : **10** °C
Rivers/Lakes : **7**°C
Geothermy : >**10** °C
Refrigeration : **< 0**°C



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

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

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APPLYING THE MAGIC FORMULA IN THE CITY

Heat sources (T_{source})

Industry: **>80**°C

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

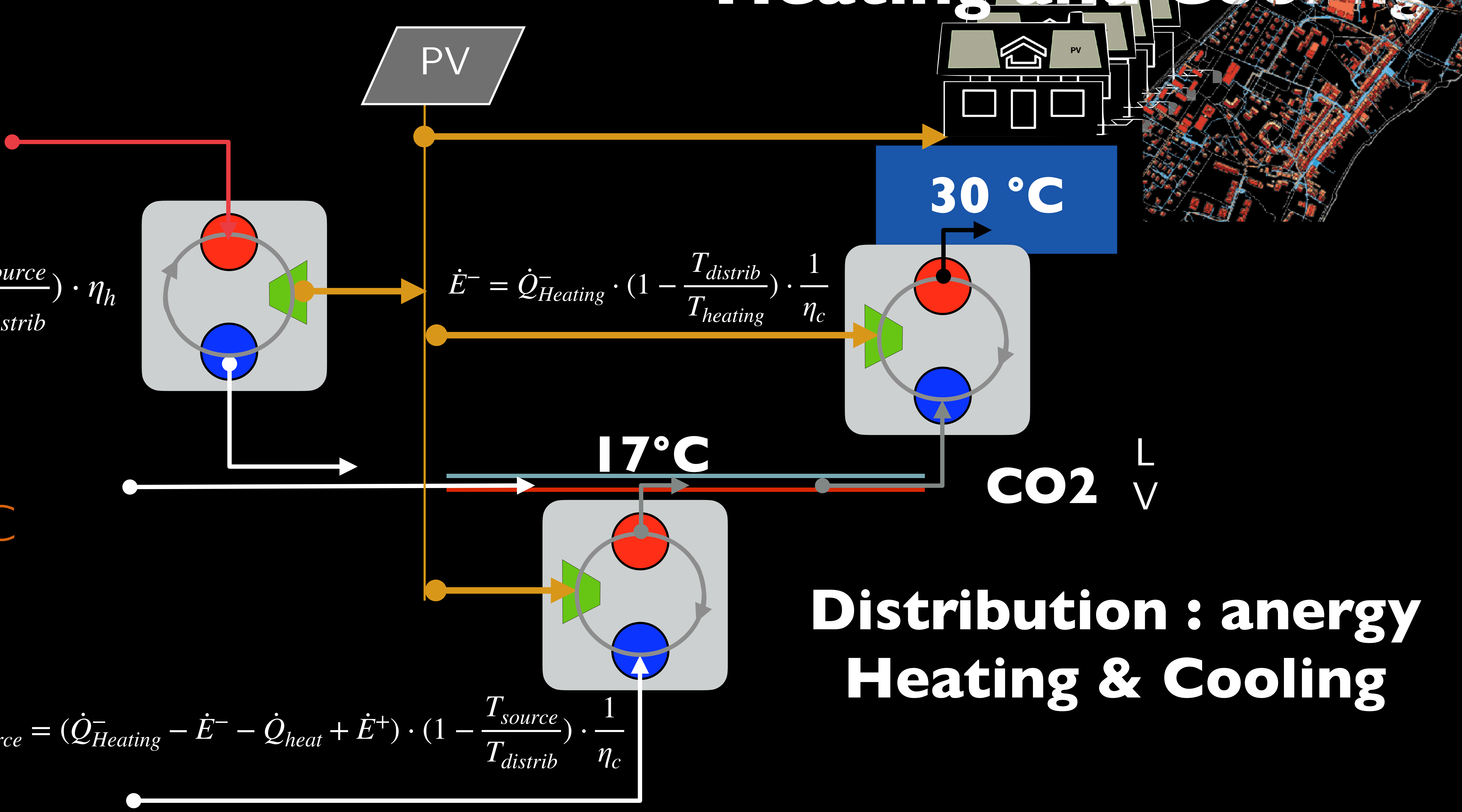
Aquifers : **10** °C
Rivers/Lake : **7**°C
Geothermal : >**10** °C
Refrigeration : **< 0**°C

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

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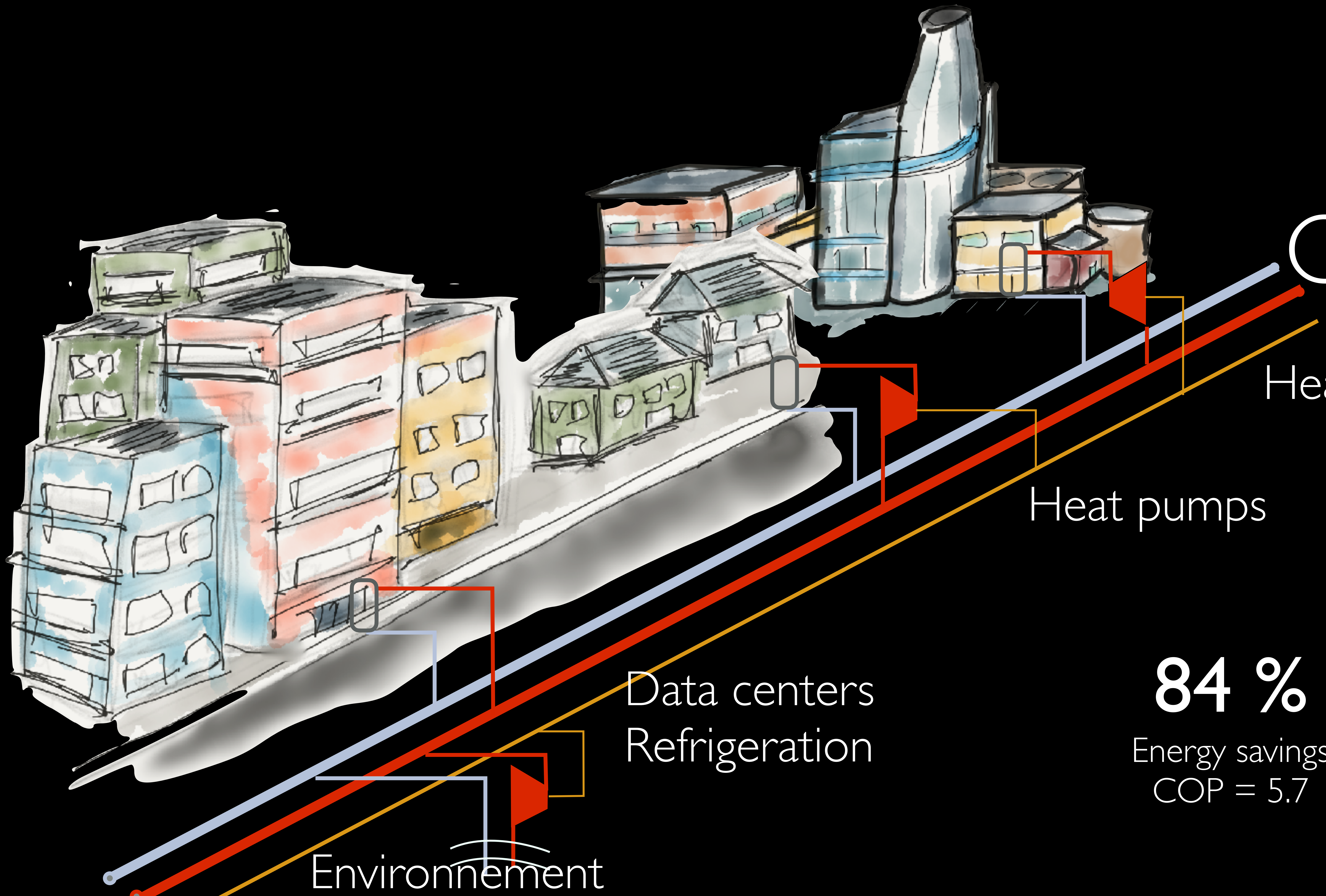
URBAN SYSTEMS

www.exergo.ch



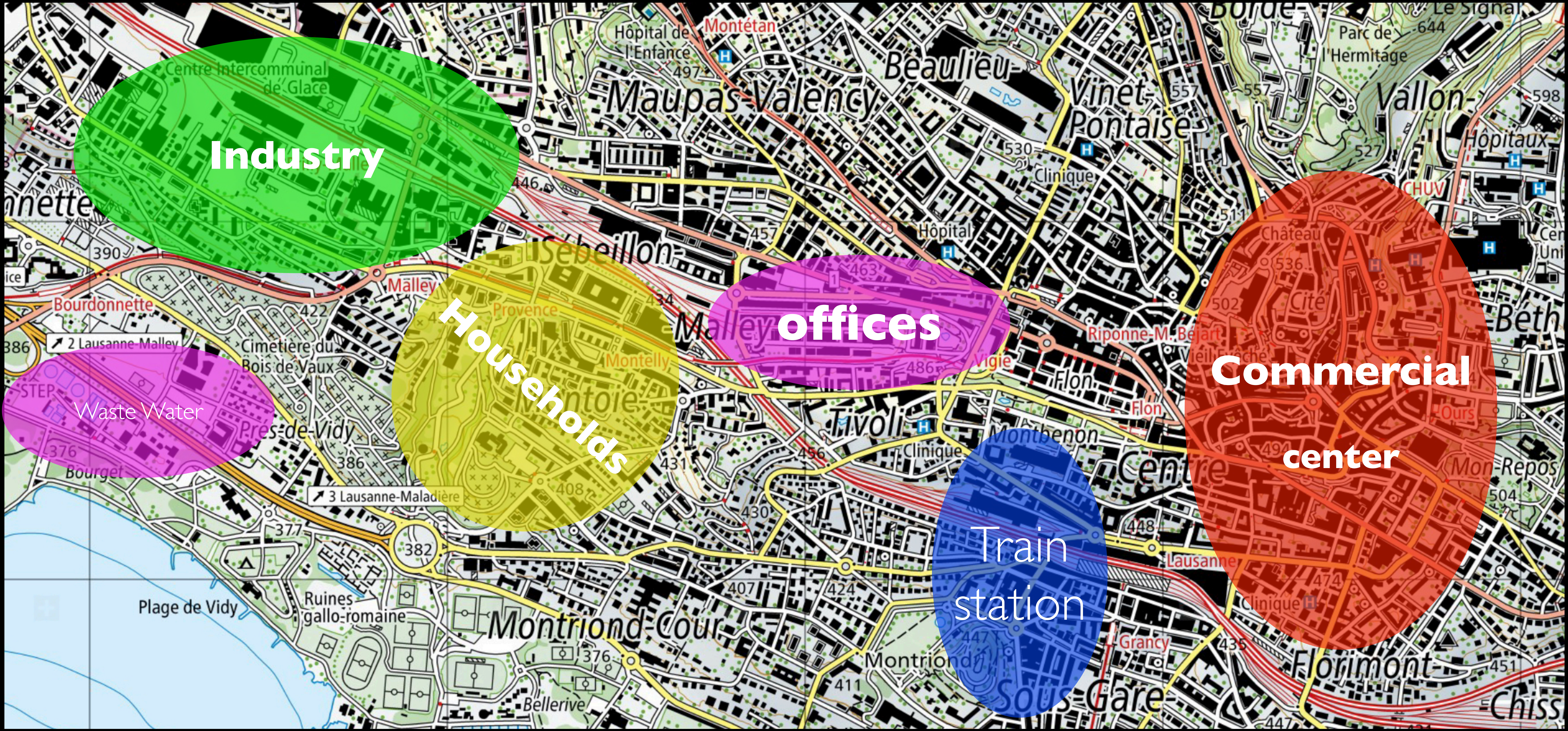
City center

84 %
Energy savings
COP = 5.7

6
years
return

Thèse EPFL : Samuel Henchoz (2017)

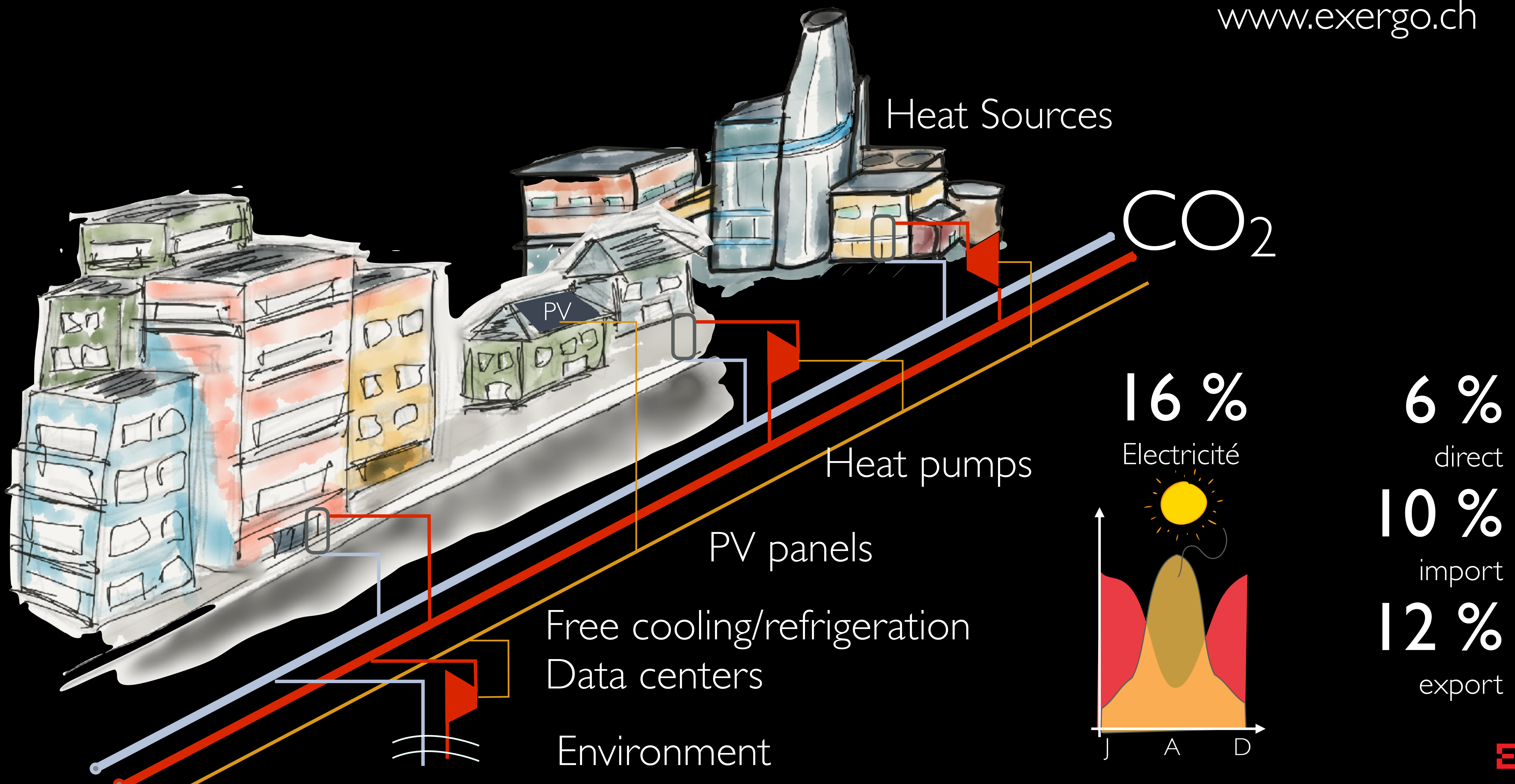
DISTRICT ENERGY HUBS



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

DISTRICT RENEWABLE ENERGY HUBS

www.exergo.ch



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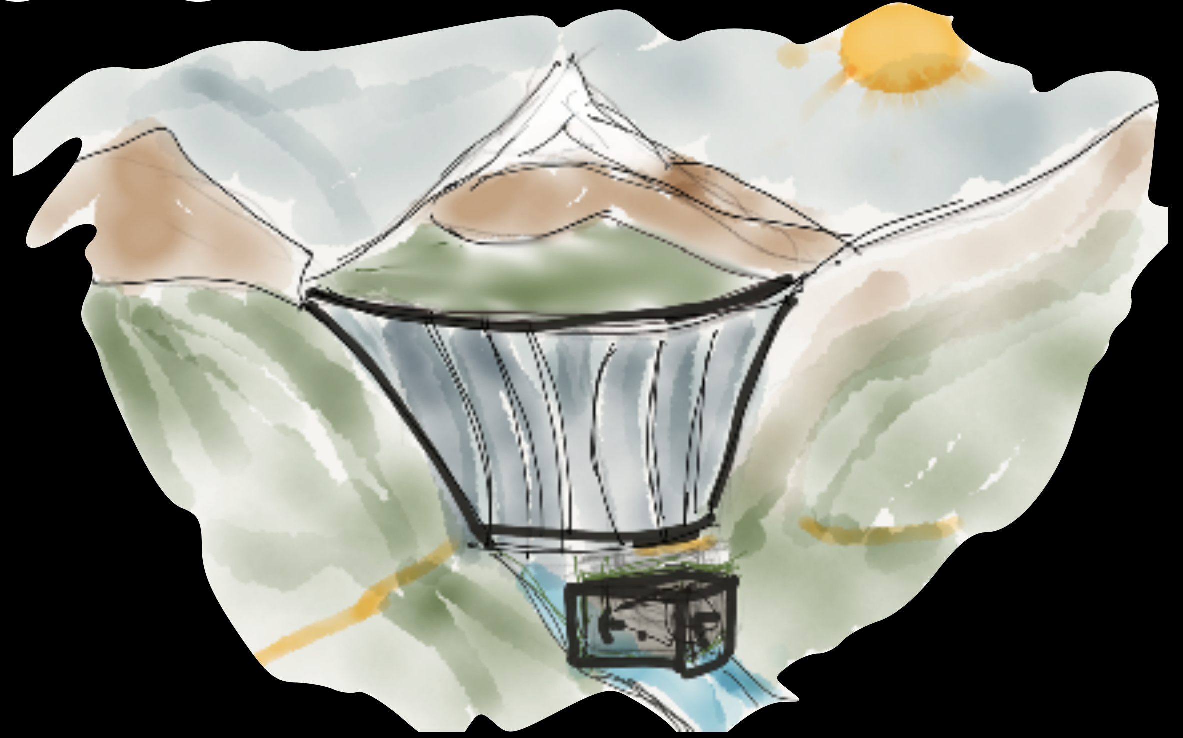
HOW TO PRODUCE THE IMPORT ?

Hydro



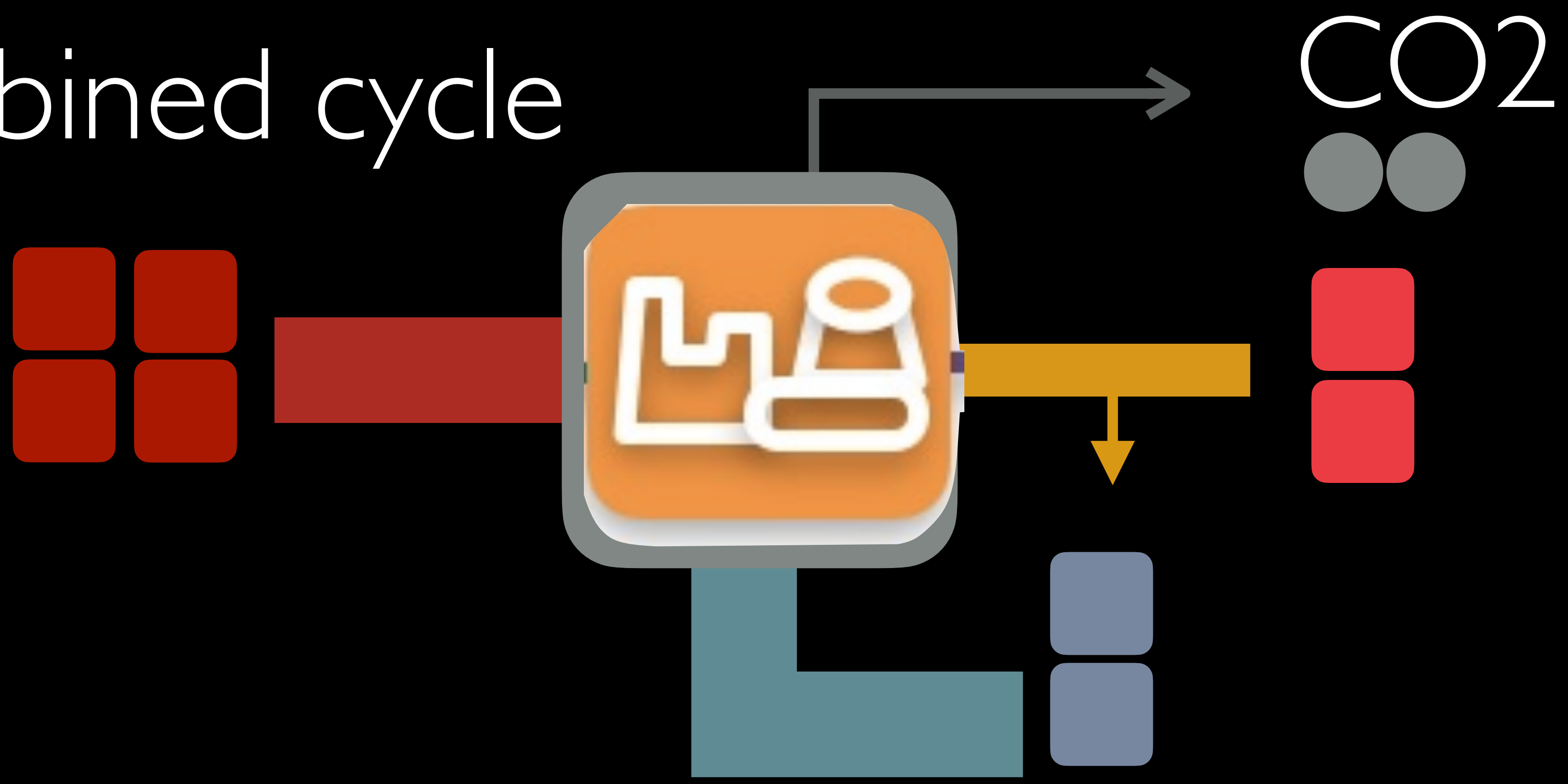
Also stores energy

Wind

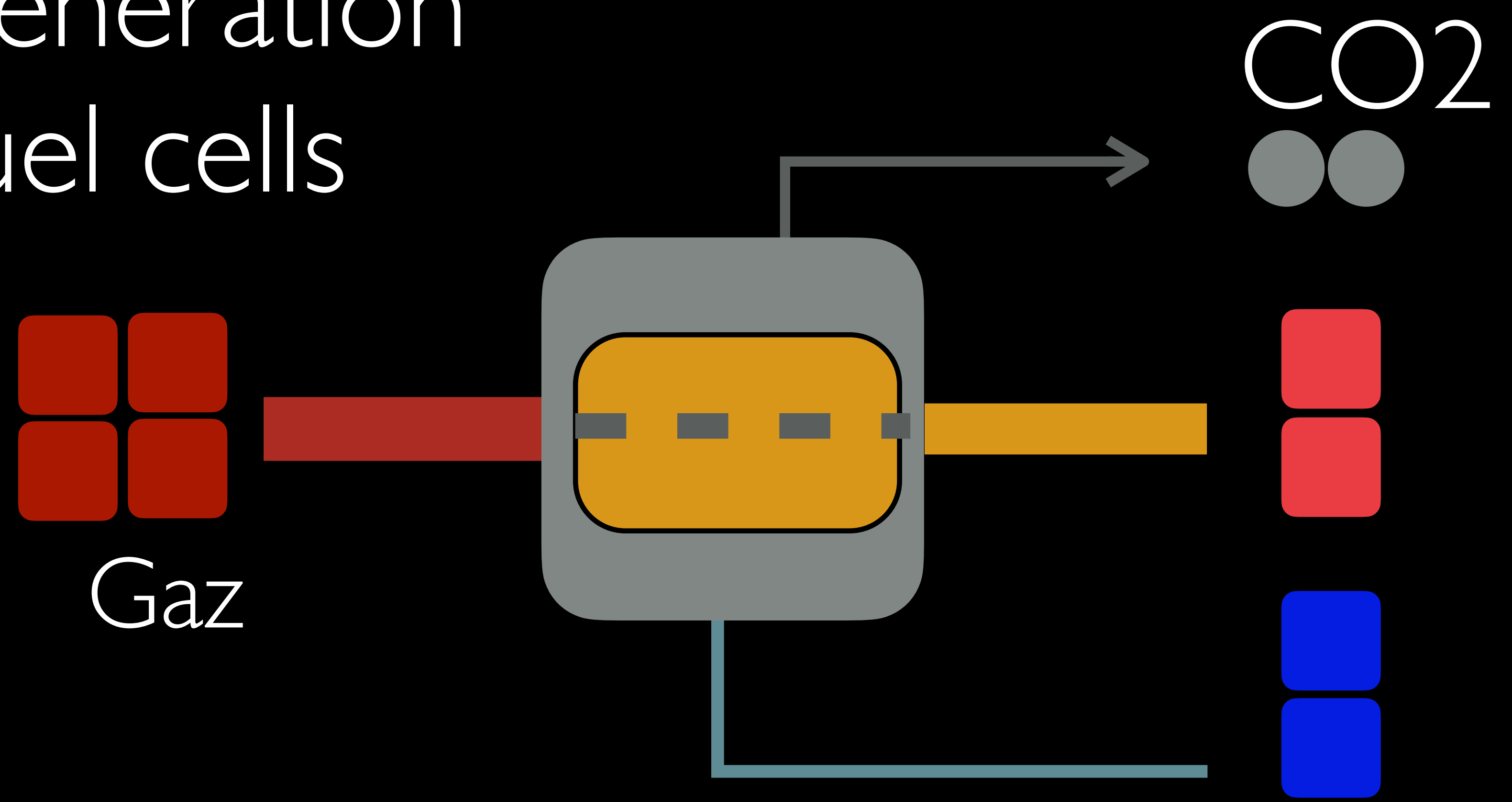
Intermittent !

Gas

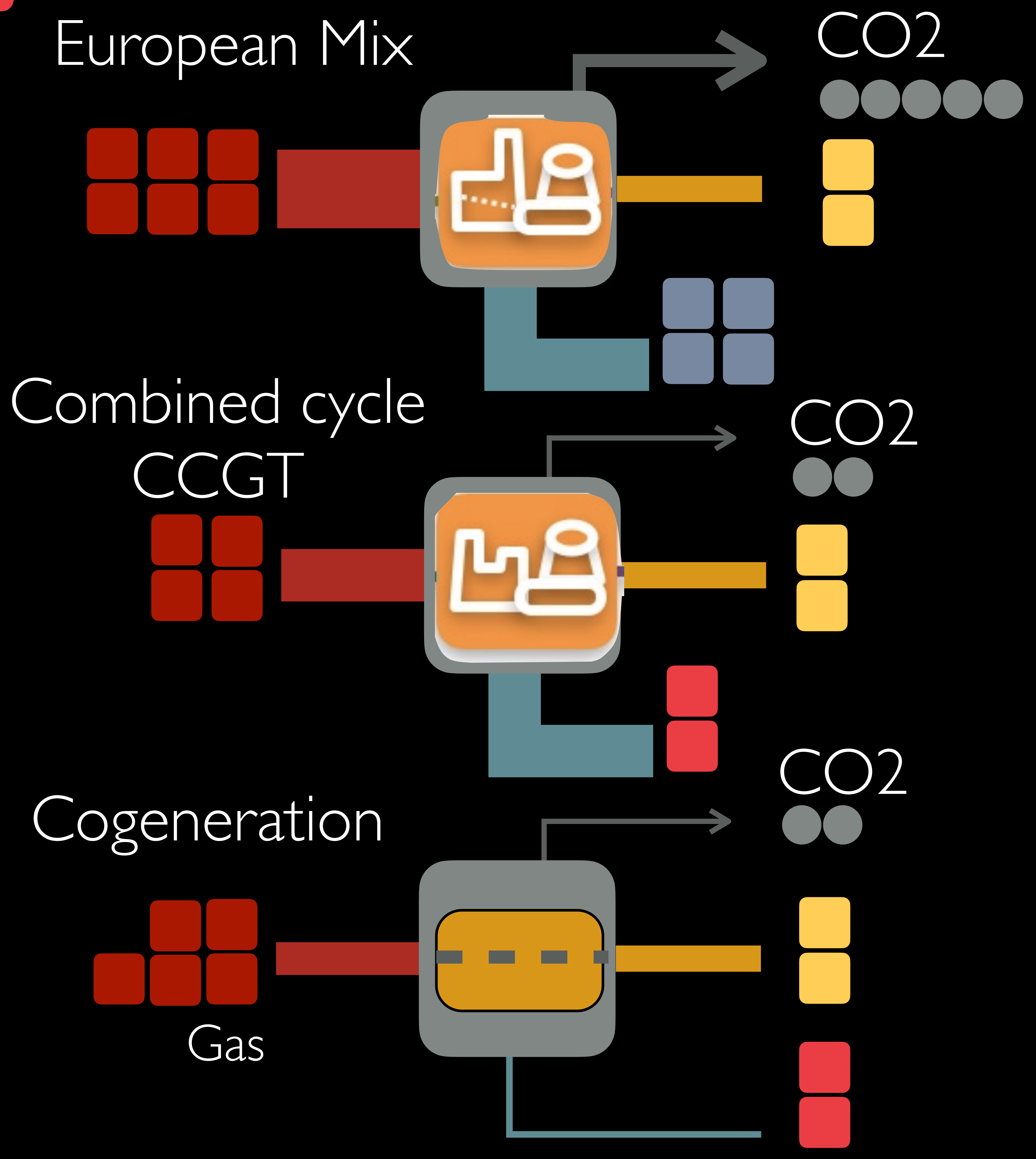
Combined cycle

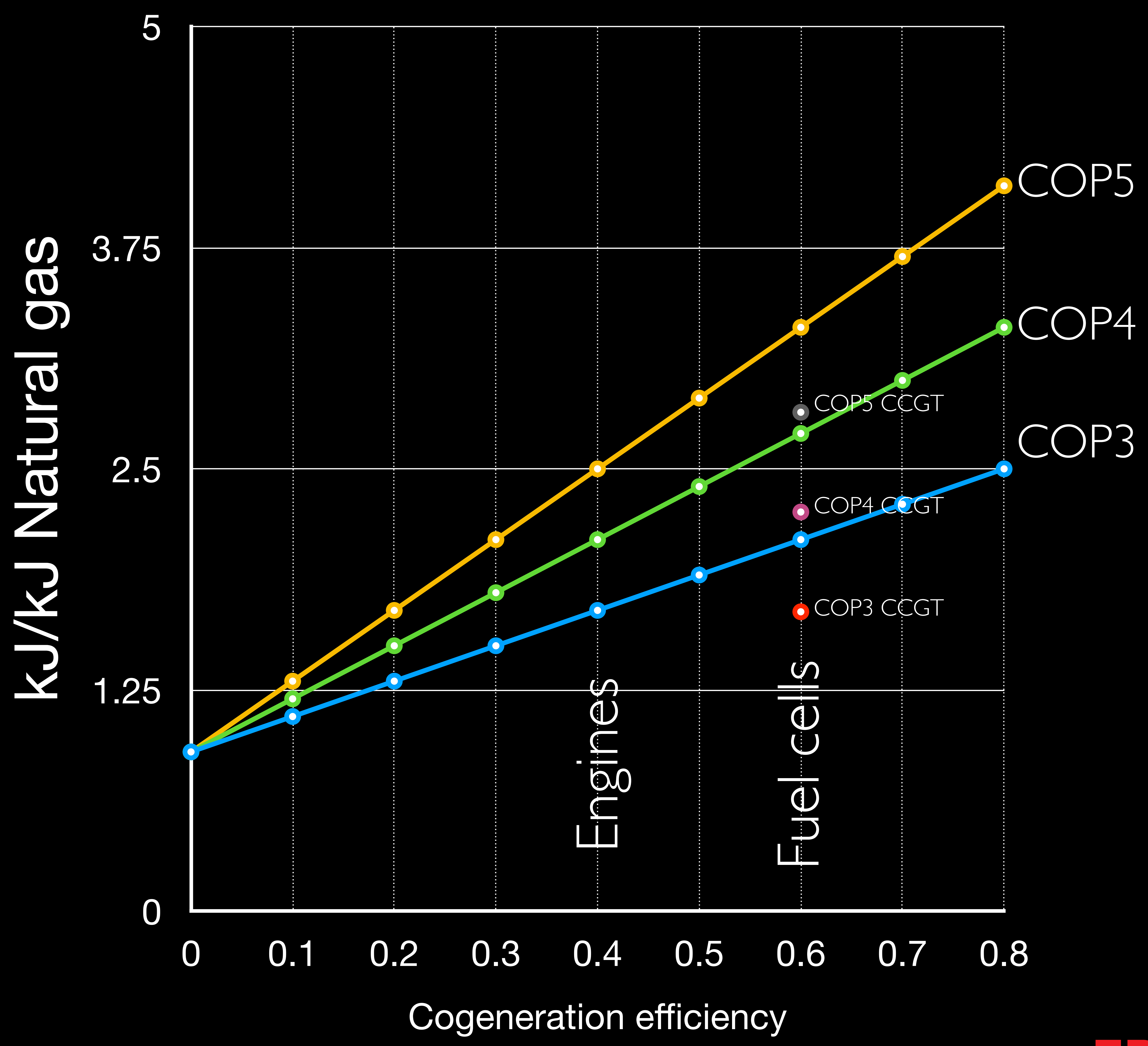


Cogeneration
Fuel cells



PRODUCING THE ELECTRICITY DEFICIT





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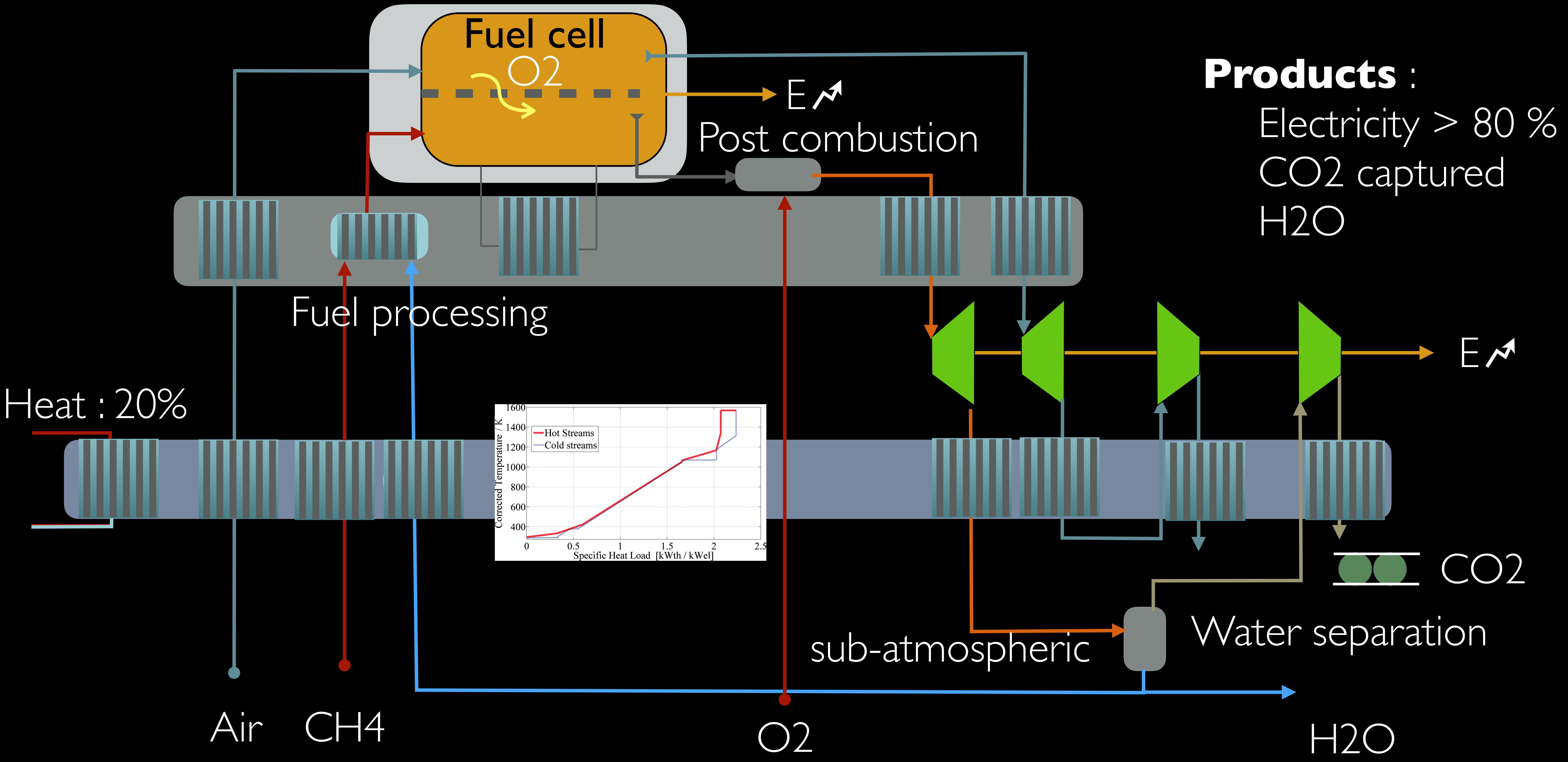
PRODUCING ELECTRICITY WITH ADVANCED FUEL CELL SYSTEM



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

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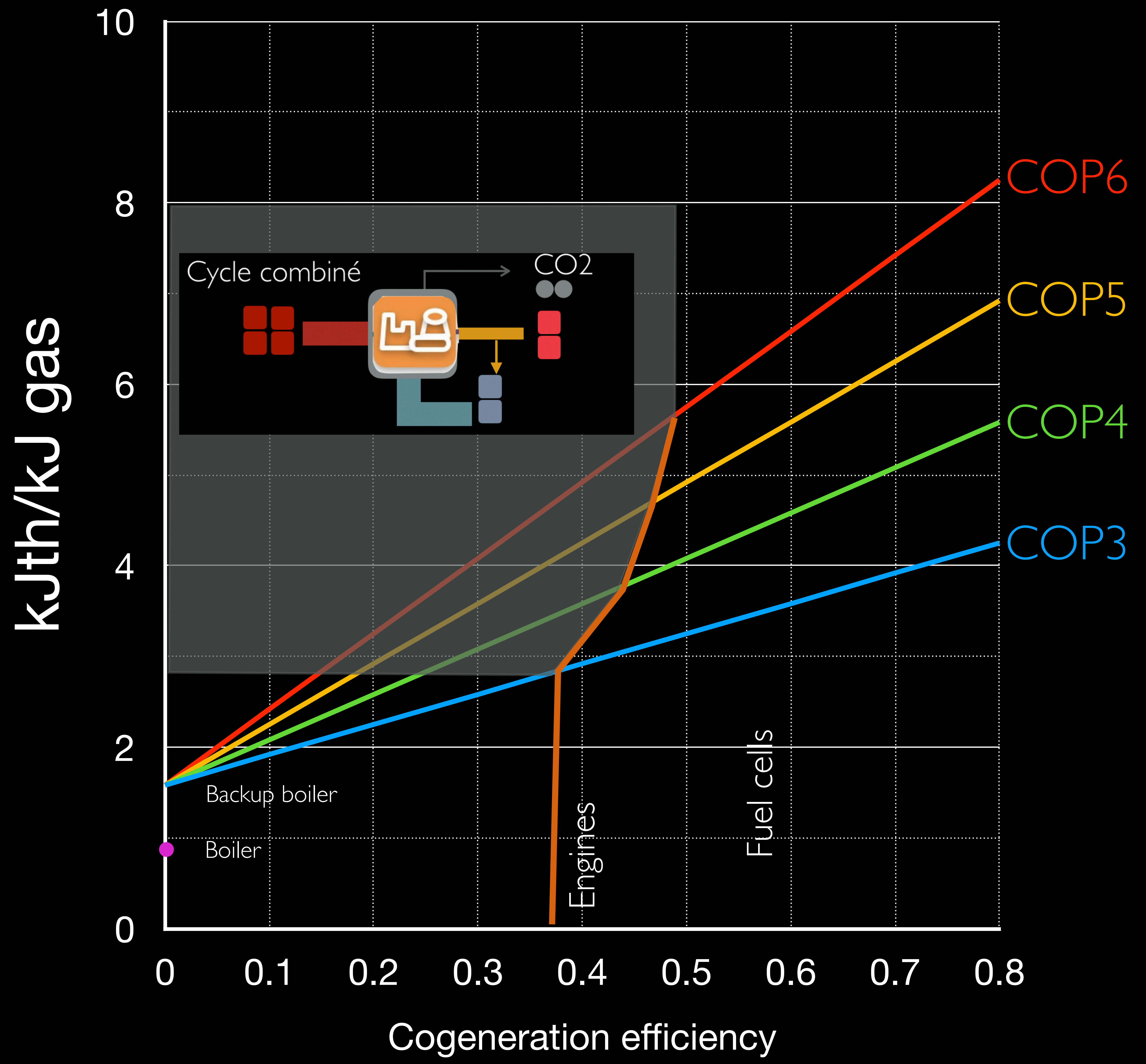
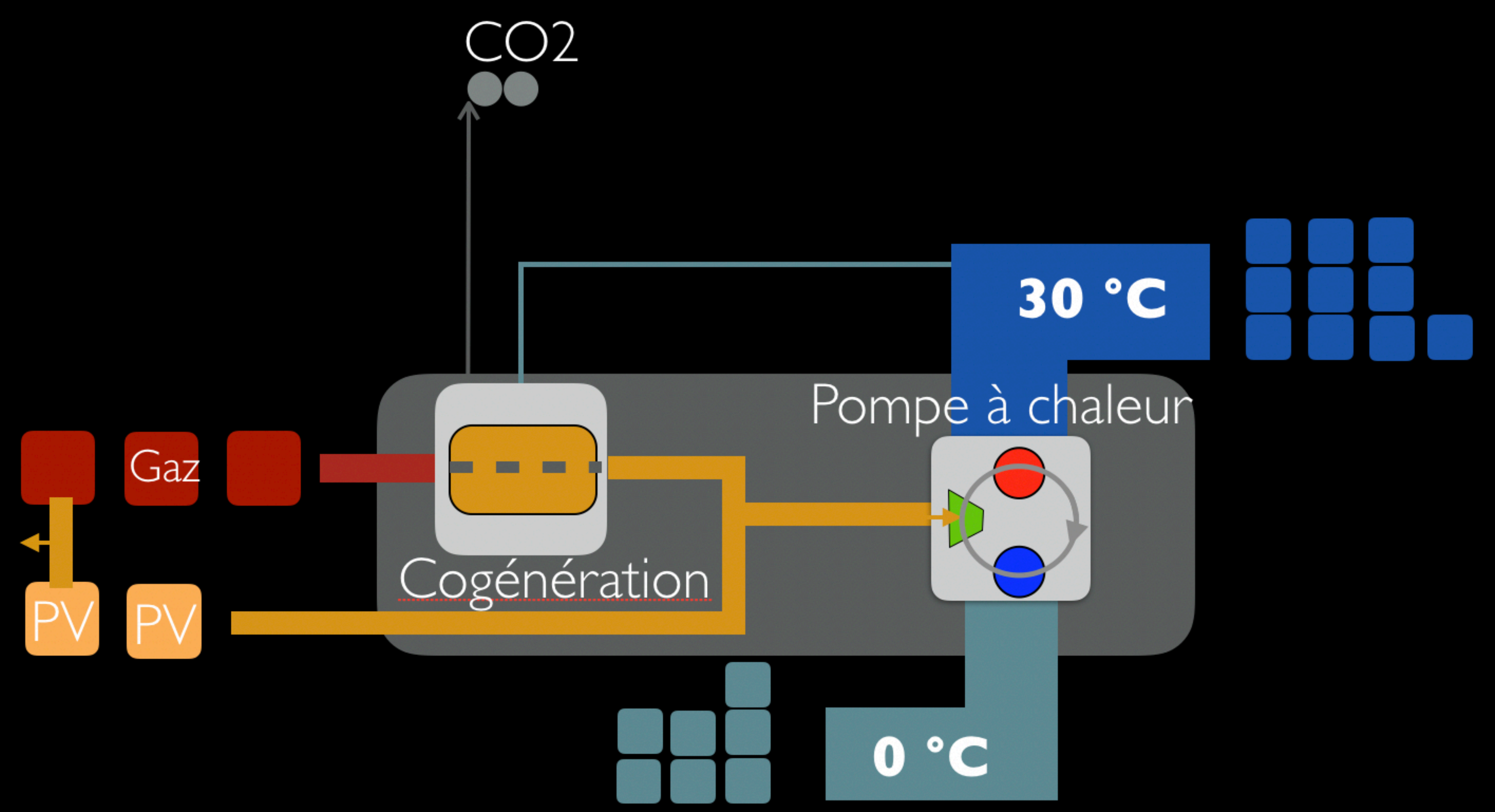
EFFICIENT USE OF NATURAL GAS



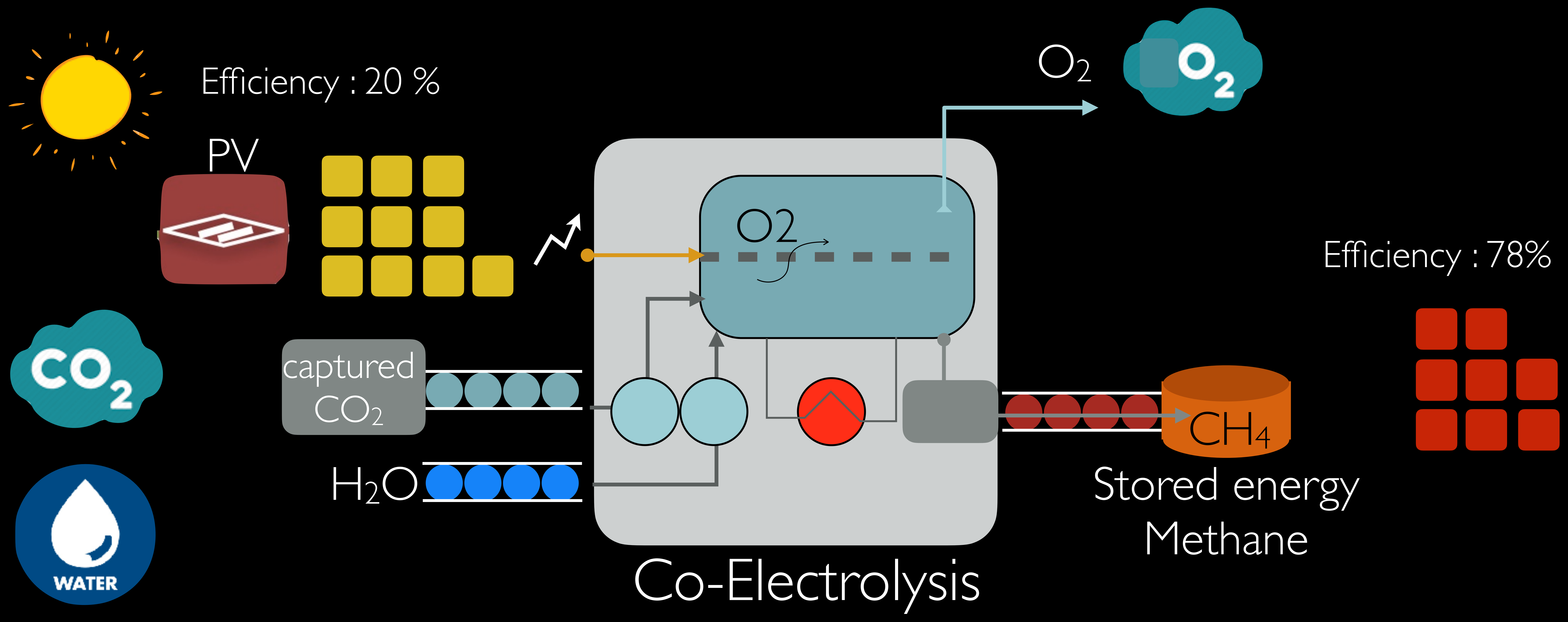


Decentralized solution

+20% per unit of gas

PV
PV

STORING EXCESS OF ELECTRICITY



Artificial photosynthesis : 13-16 % Solar efficiency

L. Wang, et. al. Optimal design of solid-oxide electrolyzer based power-to-methane systems: A comprehensive comparison between steam electrolysis and co-electrolysis. Applied Energy (211), 2018, 1060-1079.

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.

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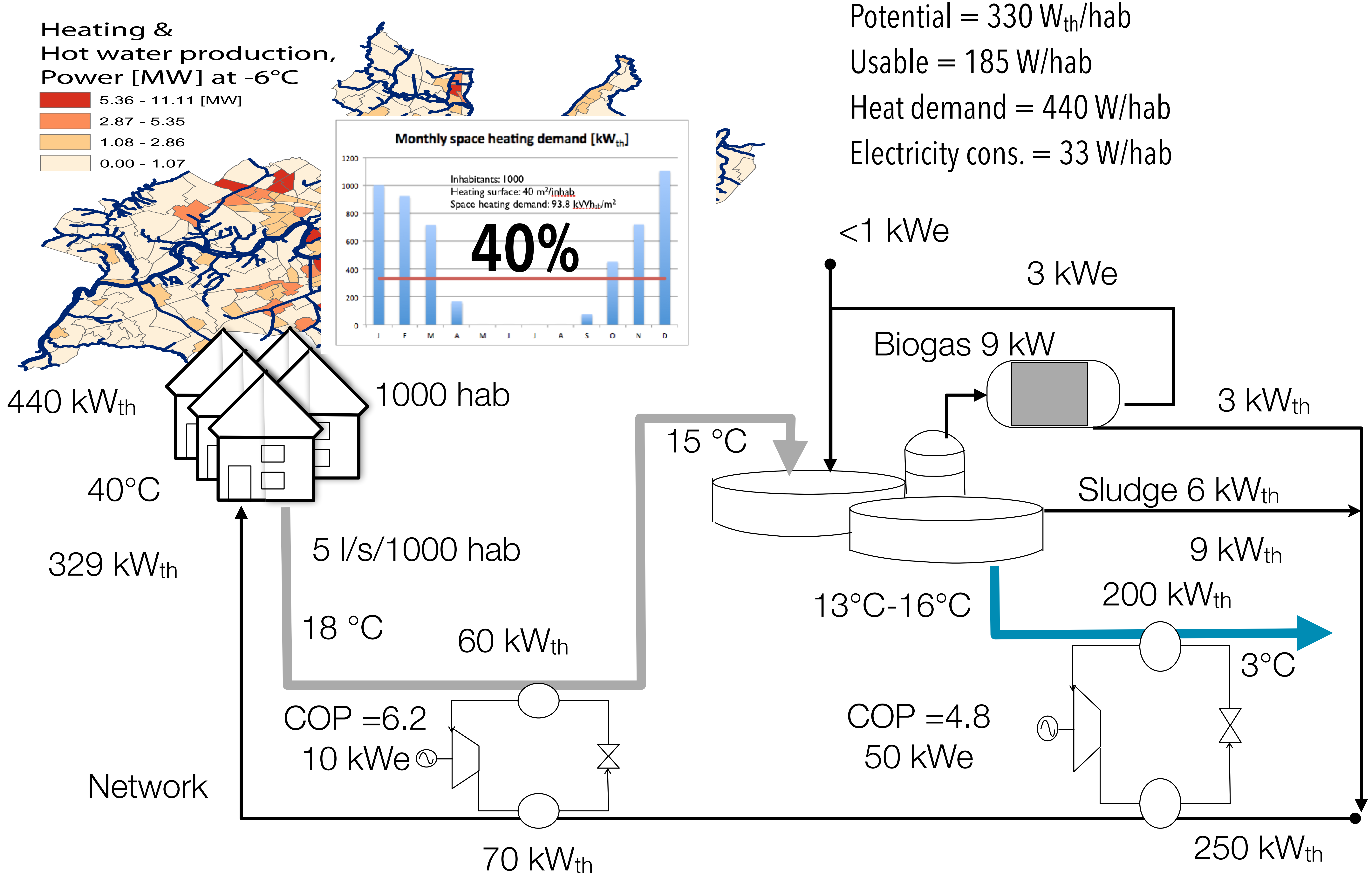
Waste water management : chase the heat sources

Potential = 330 W_{th}/hab
Usable = 185 W/hab
Heat demand = 440 W/hab
Electricity cons. = 33 W/hab



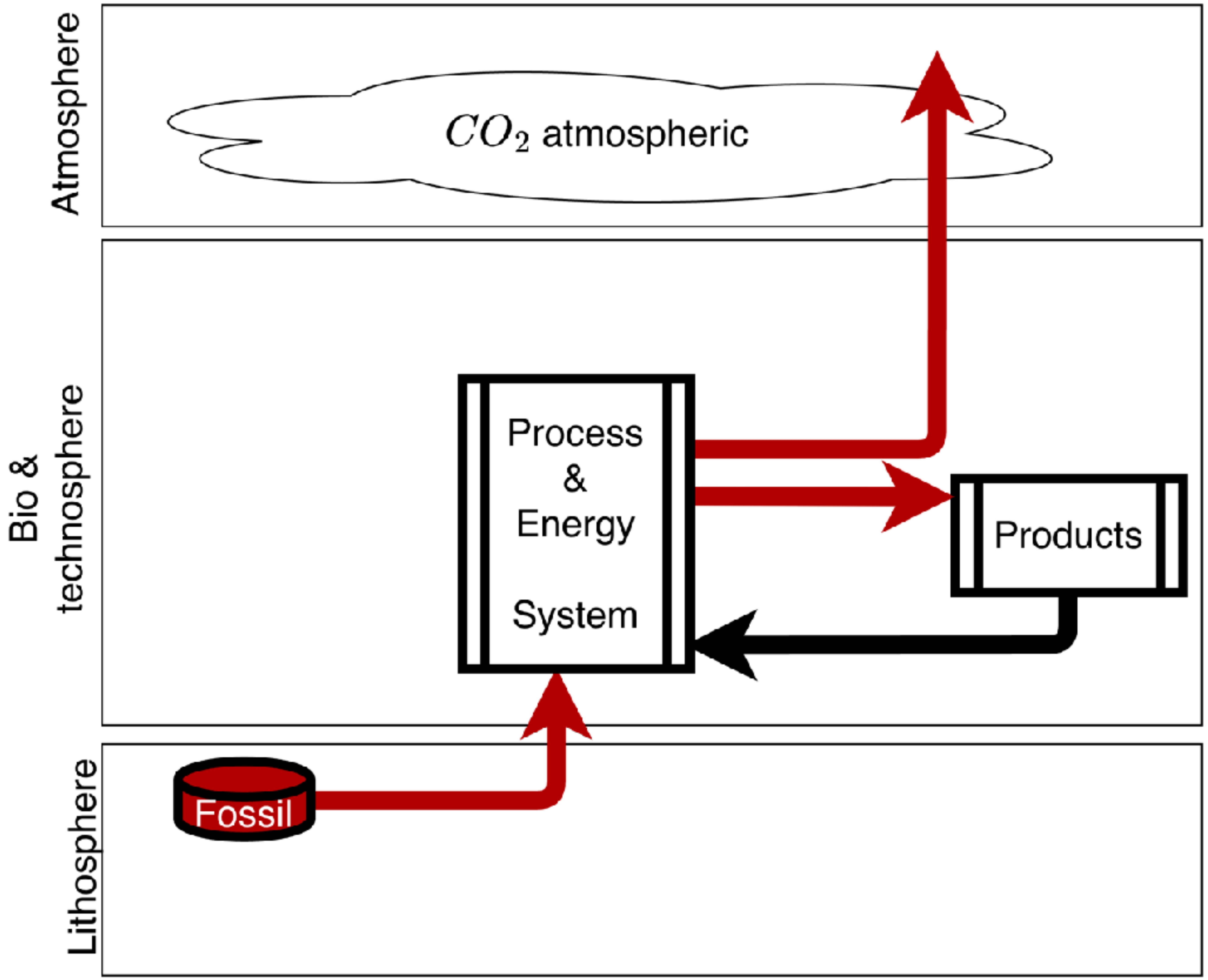
Biomass resource

Heat pump resource

Girardin et al., ENERGIS, A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, Energy, 2010

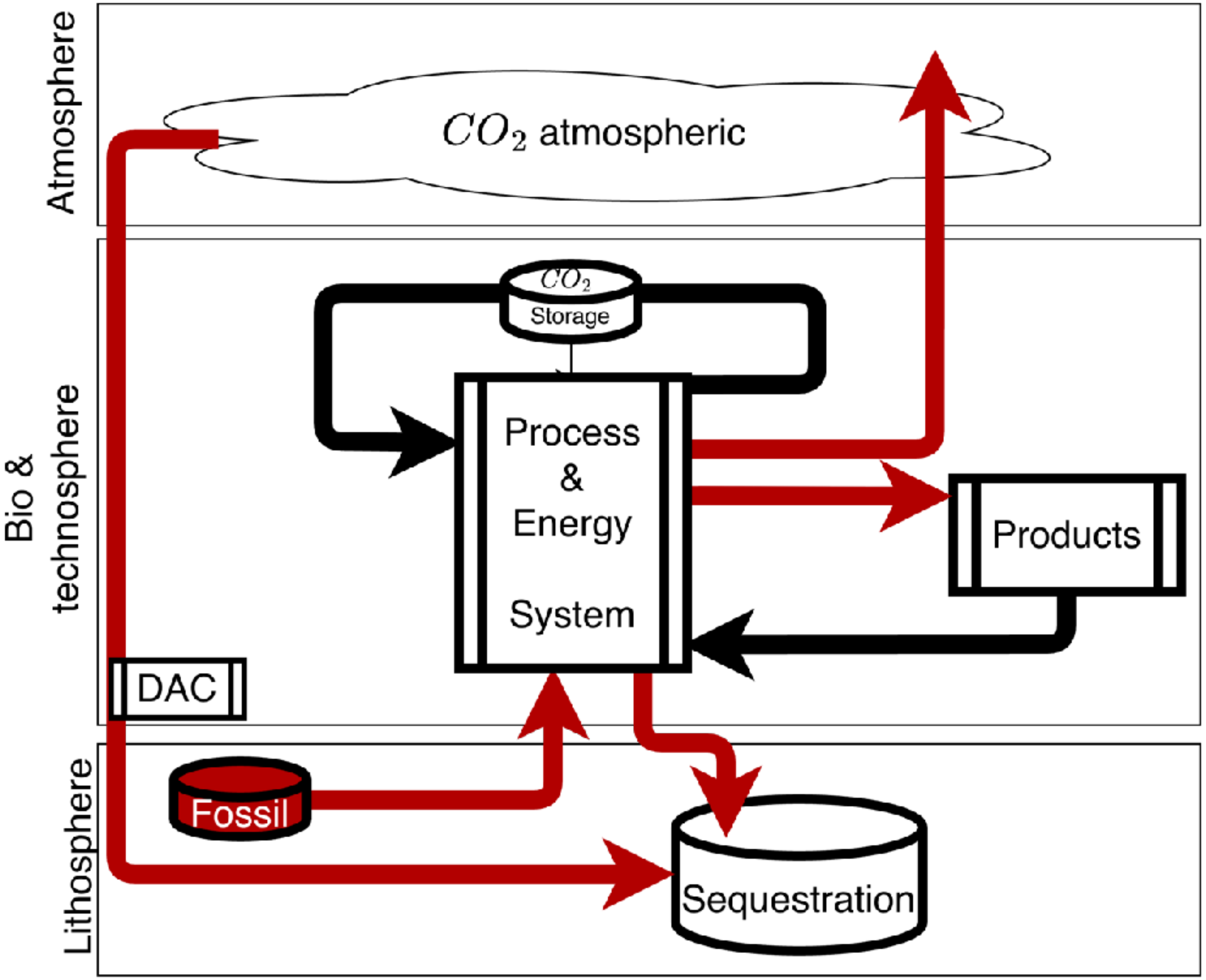
Fossil system

- From 327 ppm to 427 ppm (+30%) in 60 years



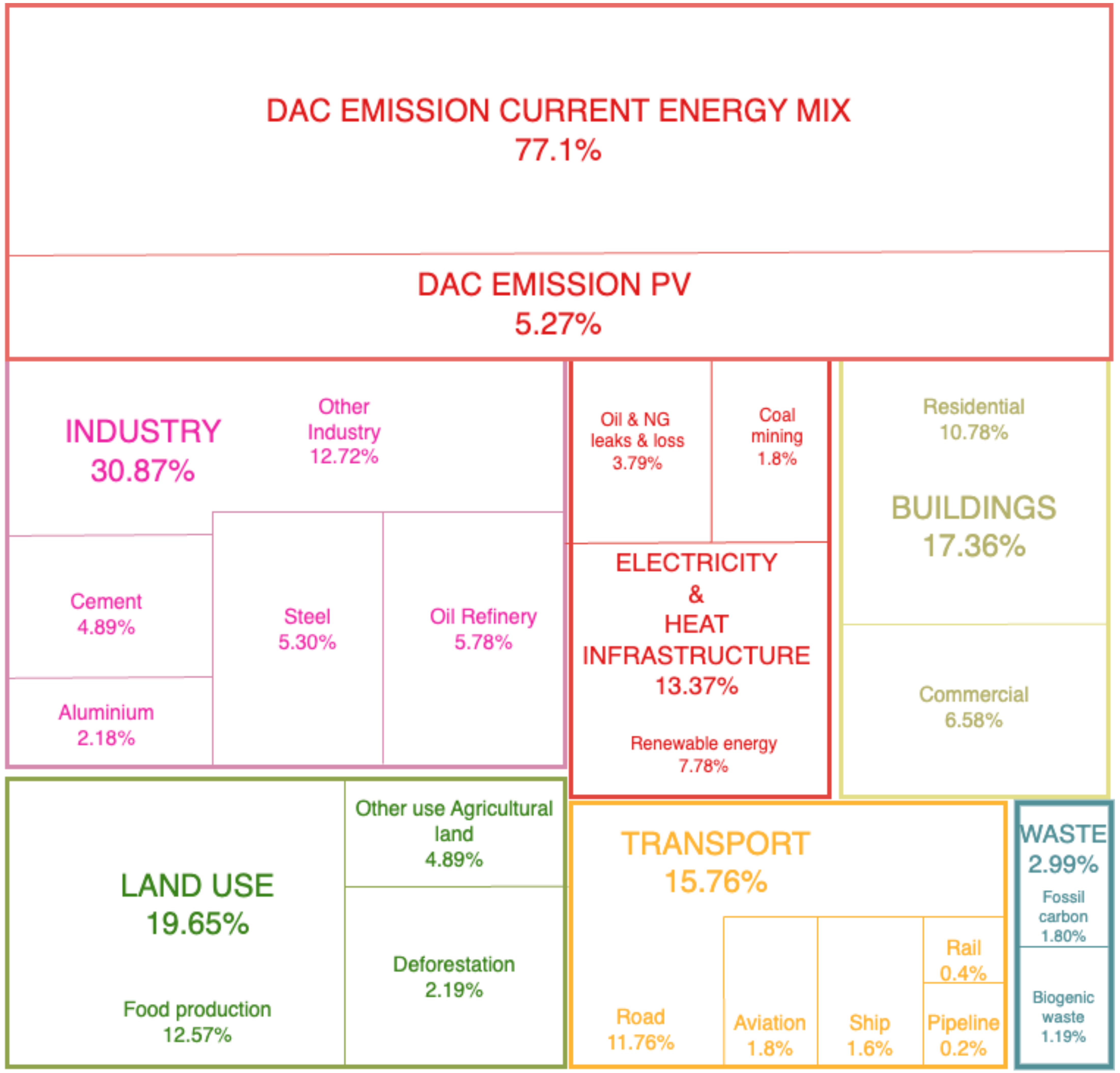
Fossil system illusion

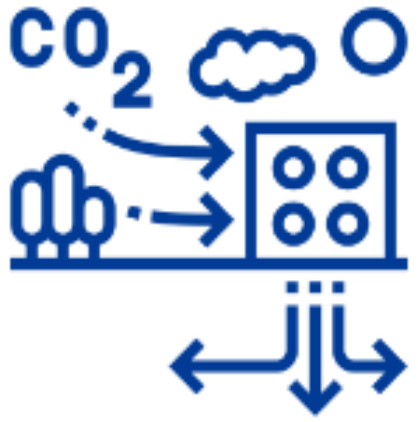
- From 327 ppm to 427 ppm (+33%) in 60 years



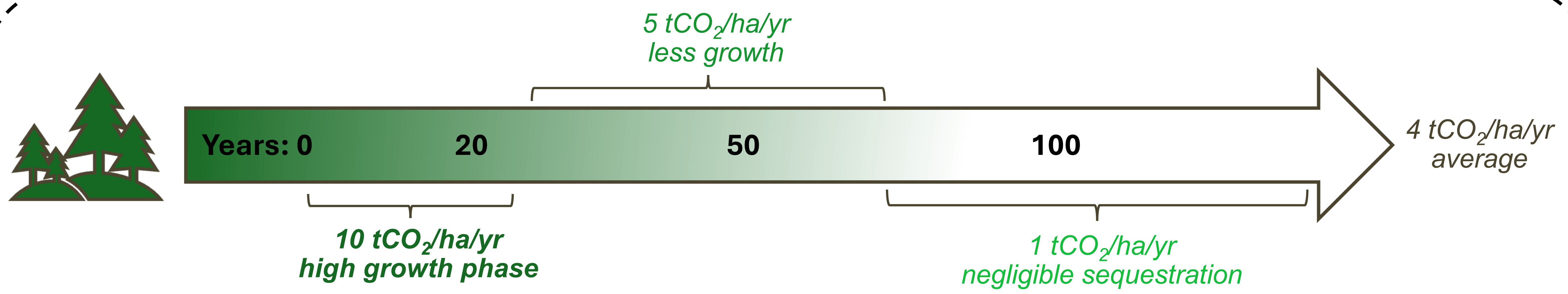
Direct Air Capture illusion

-3500 kJ/kg CO2
374 €/ton CO2
6.4 m3/ton CO2



		
Current energy mix	DAC	PV
82901 TWh/year	Electricity consumption (TWh/year) Current world consumption is- 28660 TWh/year	51186 TWh/year
547.8 km^3/year	Volume of carbon dioxide to be stored (km^3/year) 6 X the leman lake	338.4 km^3/year
2.2 times EU Economy 32’000 Milliards/an	Cost of capturing CO2 (EU Economy/year) EU Economy - $14500000000000	1.36 times EU Economy 20’000 Milliards/an

Direct Air Capture by Nature: Biomass



Carbon flows over 100 years	Absorbed (tCO_2)	Lost (tCO_2)	Net Stored (tCO_2)
1 hectare Conifer Trees Plantation in Switzerland	400	120 (~30% from harvest) 40 (~10% from decay/risks)	240

0.1-0.2 % photosynthesis efficiency

Direct air capture by nature

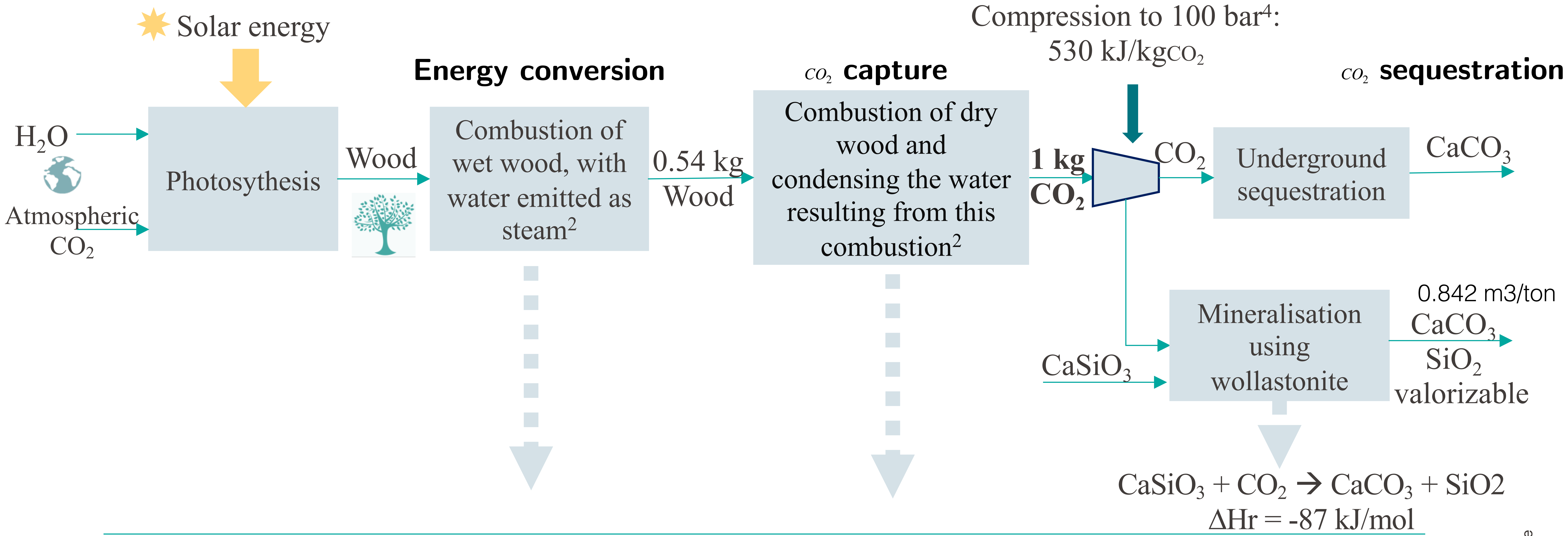
- $0.52 \quad [kg_{dry}/kg_{CO2}]$
- $\dot{E}^{-}_{LHV} = +10.4 \quad [MJ/kg_{CO_2}]$
- $\dot{E}^{-}_{LHV} = +41.6 \quad [GJ/ha/year]$
  or $1300 \quad [W/ha]$

compare with Direct Air Capture

- $\dot{Q}^{-}_{th} = -(4.4 - 5.4) \quad [MJ/kg_{CO_2}]$
- $\dot{E}^{-} = -(0.36 - 1.0) \quad [MJ/kg_{CO_2}]$

Dardor D, Flórez-Orrego D, Ribeiro Domingos ME, Germanier R, Margni M, Maréchal F. CO2 Capture and Management Strategies for Decarbonizing Secondary Aluminium Production. ESCAPE 2024 - 34th European Symposium on Computer Aided Process Engineering [Internet]. Florence, Italy; 2024. https://infoscience.epfl.ch/record/311522?&ln=en

Direct Air Capture by Nature => real negative emissions



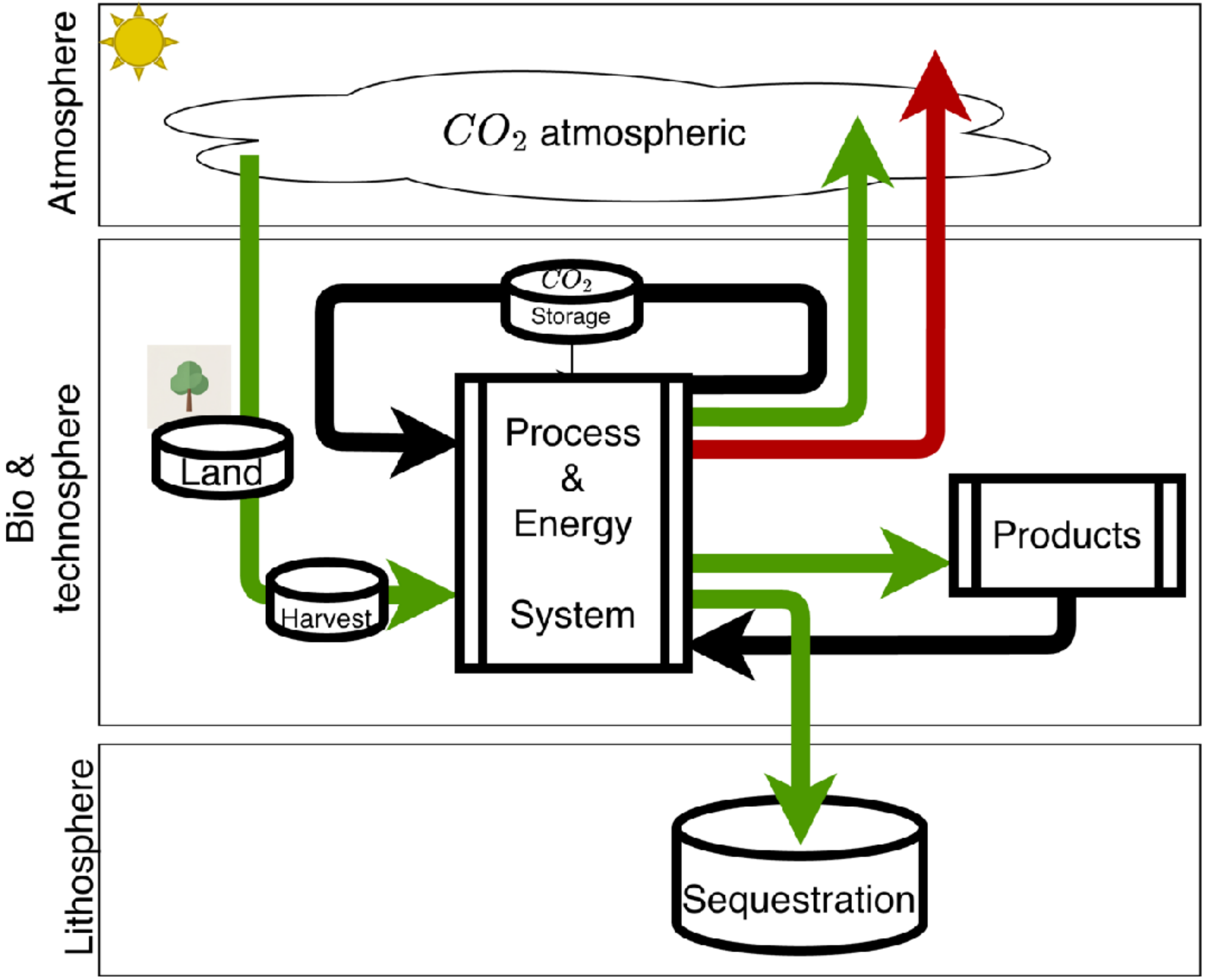
Recoverable energy[1]	**5 480 kJ/kgCO_2**	**10 720 kJ/kgCO_2**		**12 700 kJ/kgCO_2**
v.s. Biomass boiler	x1.0	x1.9	x1.8	x2.3

[1] Xavier Déglise. Les conversions thermochimiques du bois. *Revue forestière française*, 1982, 34 (4), pp.249-270. ⟨10.4267/2042/21577⟩. ⟨hal-03423398⟩
[2] Techniques de l'ingénieur Bois et papiers, 2005/04/10, ref. article : be8747", 10.51257/a-v1-be8747
[3] Techniques de l'ingénieur Ressources énergétiques et stockage, 2020/10/10, ref. article : be8535, 10.51257
[4] isentropic compressor modelled on Aspen plus V14, efficiency of 80%
[5] Lackner, KS., Wendt CH, Butt, DP, Joyce, EL, Sharp, DH (1995) Carbon dioxide disposal in carbonate minerals, Energy, 20 (11), 1153-1170

François Maréchal, Soline Corre

The biogenic based system

- **Biogenic carbon**
  - Harvested on Land
    - $\dot{E}^{-}_{LHV} = +41.6 - 140.0 \quad [GJ/ha/year]$
  - Bio-Carbon => products
    - $0.52 \quad [kg_C/kg_{CO2}]$
  - Bio-Energy
    - $\dot{E}^{-}_{LHV} = 10.4 \quad [MJ/kg_{CO_2}]$
  - Negative emissions
    - $0.1 \quad [kg_{CO_2}/MJ]$
    - $4 - 16 \quad [t_{CO_2}/ha/year]$

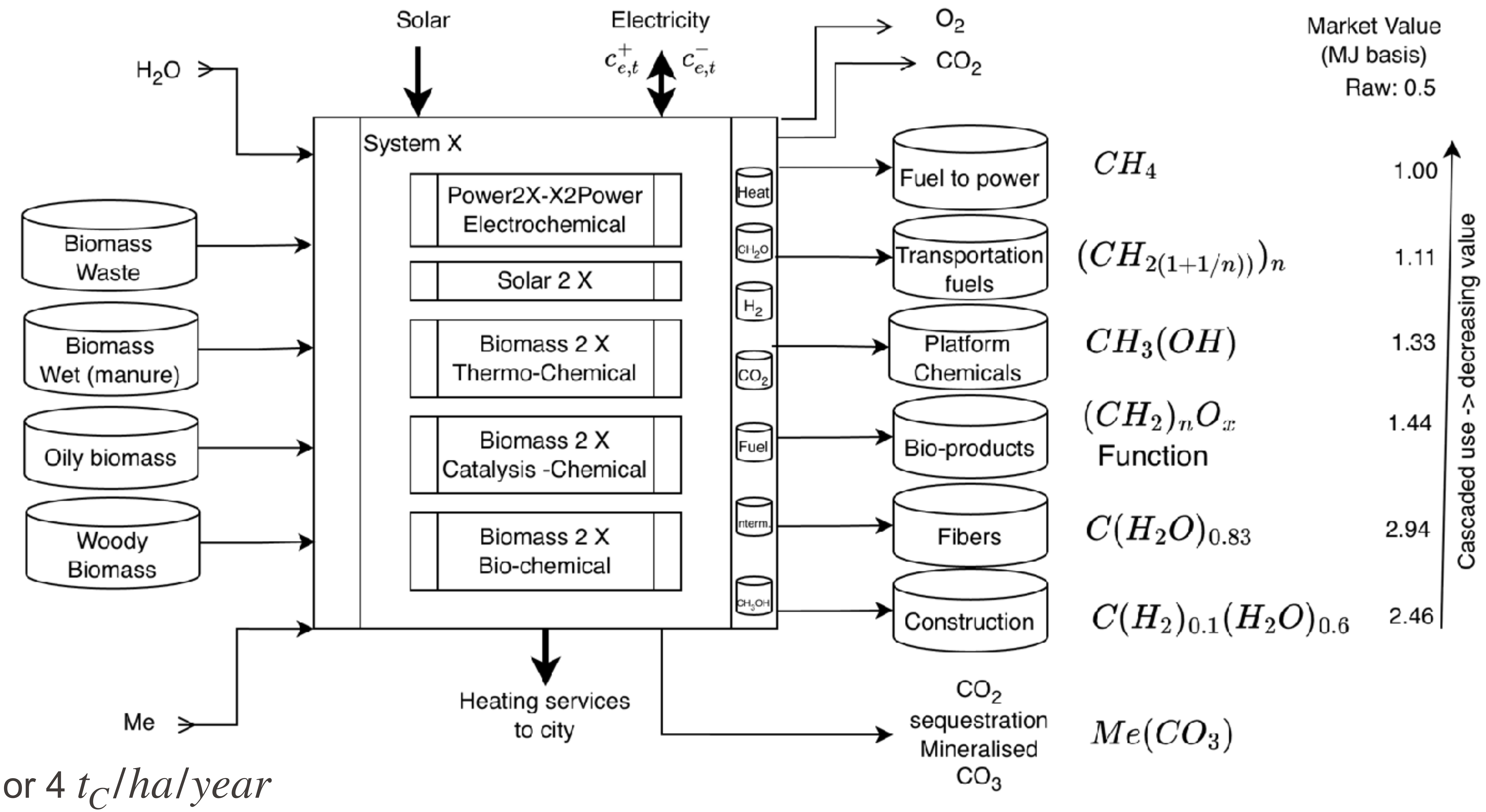


Biomass cascaded use

Conversion chalenges

$$(C(H_2)_{0.1}(H_2O)_{0.6}) \cdot (H_2O)$$

- Hydrogen balance
  - + H_2O
- Oxygen Balance
  - - O_2
  - - CO_2
  - - $MeCO_3$
- Energy Balance
  - Photon : embedded
  - +H / -O : endothermic
- Carbon balance
  - LULUCF : 150-300 $[t_C/ha]$ or 4 $t_C/ha/year$



Mass and energy values of carbon based chemicals

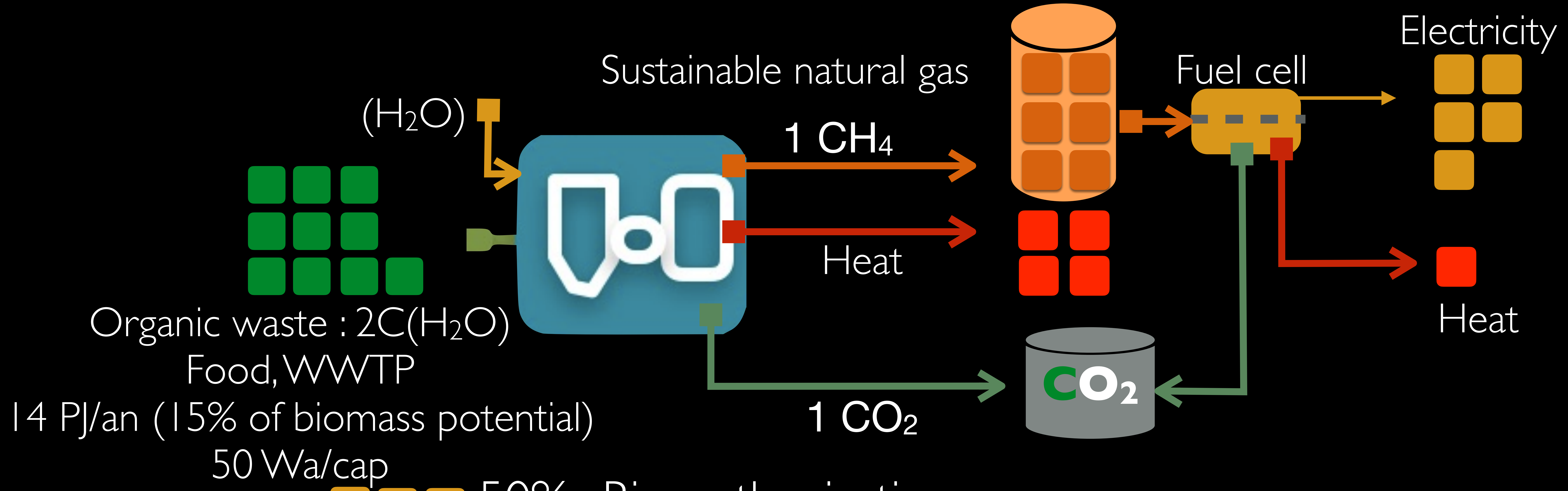
Harvested wood$((CH_{1.4}O_{0.6}).(H_2O))$: $9-10[MJ/kg]$ $5.6-9.0[MJ/l]$

Max Carbon efficiency: $CH_{1.4}O_{0.6} + 1.3H_2O \overset{e^+}{\rightarrow} CH_4 + 0.95O_2$

Max Energy efficiency: $CH_{1.4}O_{0.6} + 0.35H_2O \overset{\dot{Q}^-}{\rightarrow} 0.525CH_4 + 0.475CO_2$

	Material	Chemical Formula	LHV (MJ/kg)	LHV (MJ/l)	LHV (MJ/mol C)	
Power	Methane	$C(H_2)_2$	50.0	0.035 (1bar)	600	Targets
Products	Ethylene	$C(H_2)_1$	47.2	59.1	566.4	
Fuel	Kerozene	$C(H_2)_{1.08}$	43-46	35.0-37.0	516–552	
	Ethanol	$C(H_2)_1(H_2O)_{0.5}$	26.8	21.15	321.6	
	Palm Oil	$C(H_2)_{0.8}(H_2O)_{0.1}$	37–39	34.0–35.9	421–452	
	Methanol	$C(H_2)_{0.5}(H_2O)$	20.0	15.84	240	
	Pyrolysis Oil	$C(H_2)_{0.2}(H_2O)_{0.4}$	17–19	20.4–22.8	204–228	
	$Wood_{dry}$	$C(H_2)_{0.1}(H_2O)_{0.6}$	18–20	9.0–10.0	216–240	
	Cellulose	$C(H_2O)_{0.83}$	16–17	24.0–25.5	192–204	
	Glucose	$C(H_2O)_1$	15.6	24.02	187.2	

ORGANIC WASTE TO CLOSE THE ENERGY BALANCE



50% : Biomethanisation

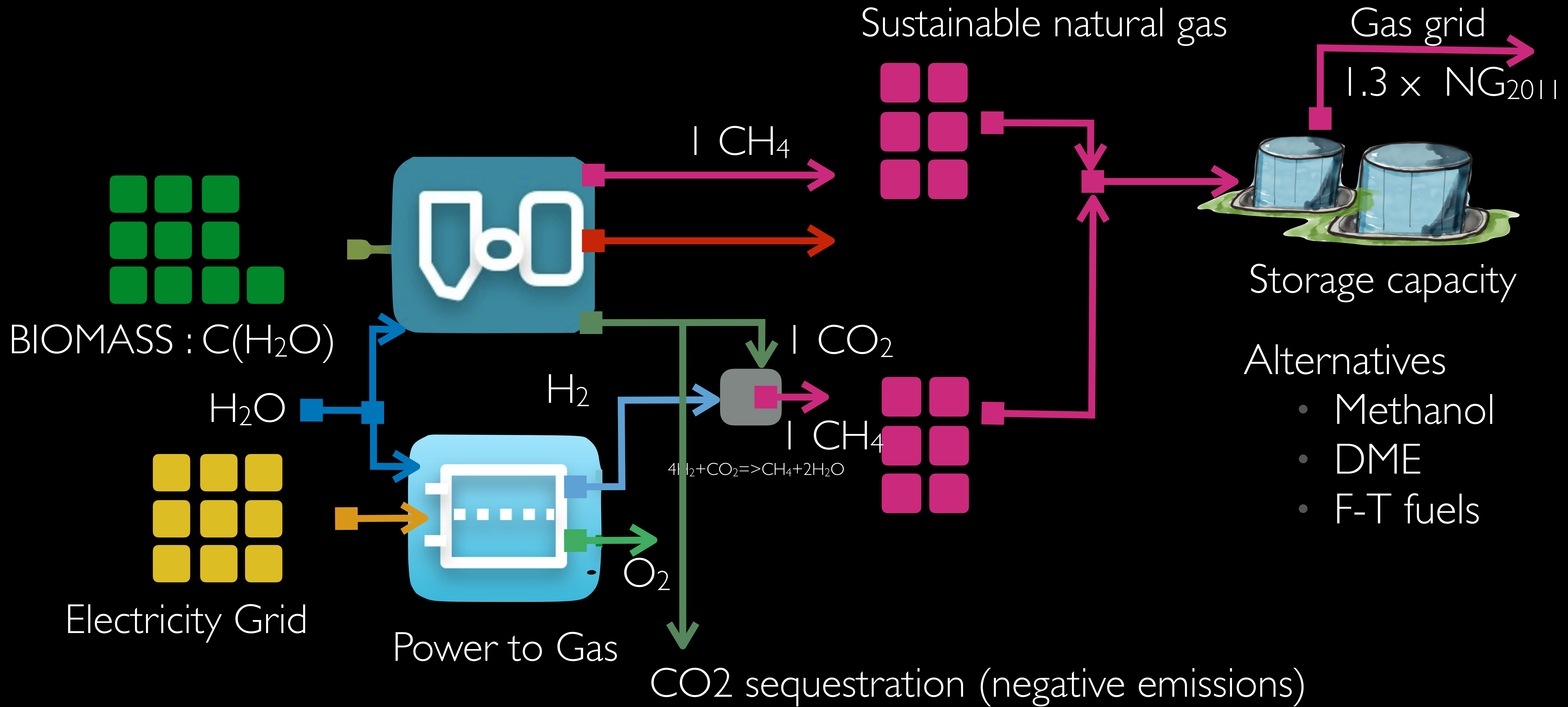
70% : Hydrothermal gasification (http://trea-tech.com)

70% : Synthetic Natural Gas

Gassner et al.,, Energy & Environmental Science 4, no. 5 (2011): 1742.

Gassner et al., Energy and Environmental Science 5, no. 2 (2012):

COMBINING BIOMASS CONVERSION AND ELECTROLYSIS



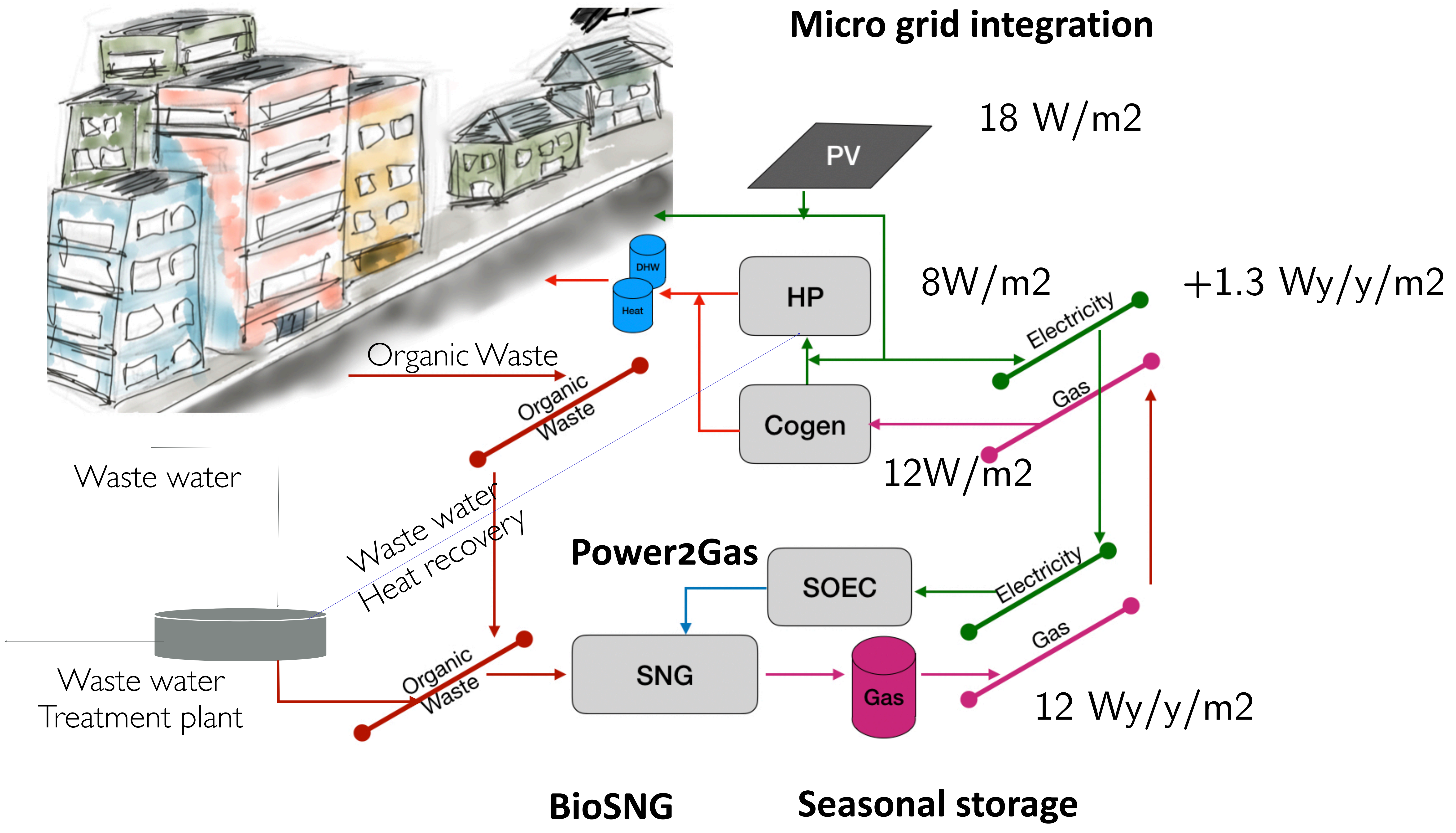
Alternatives

- 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.

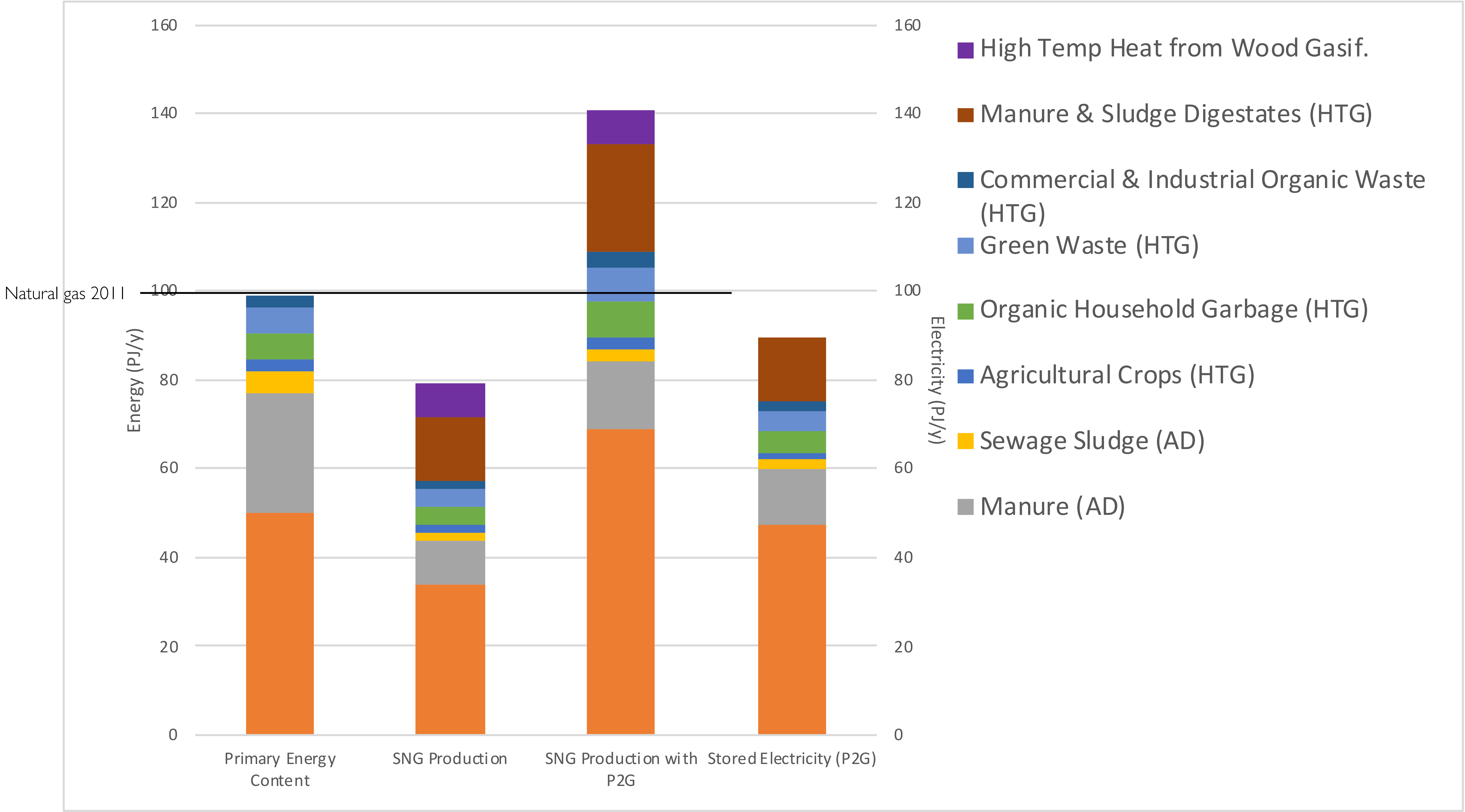
Integrating Renewable Energy Sources : Biogas + PV+ Power2gas

- District scale => Exploring options



m2 = heated surface

SNG from biomass potential in Switzerland



NEGATIVE EMISSION CITIES

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.

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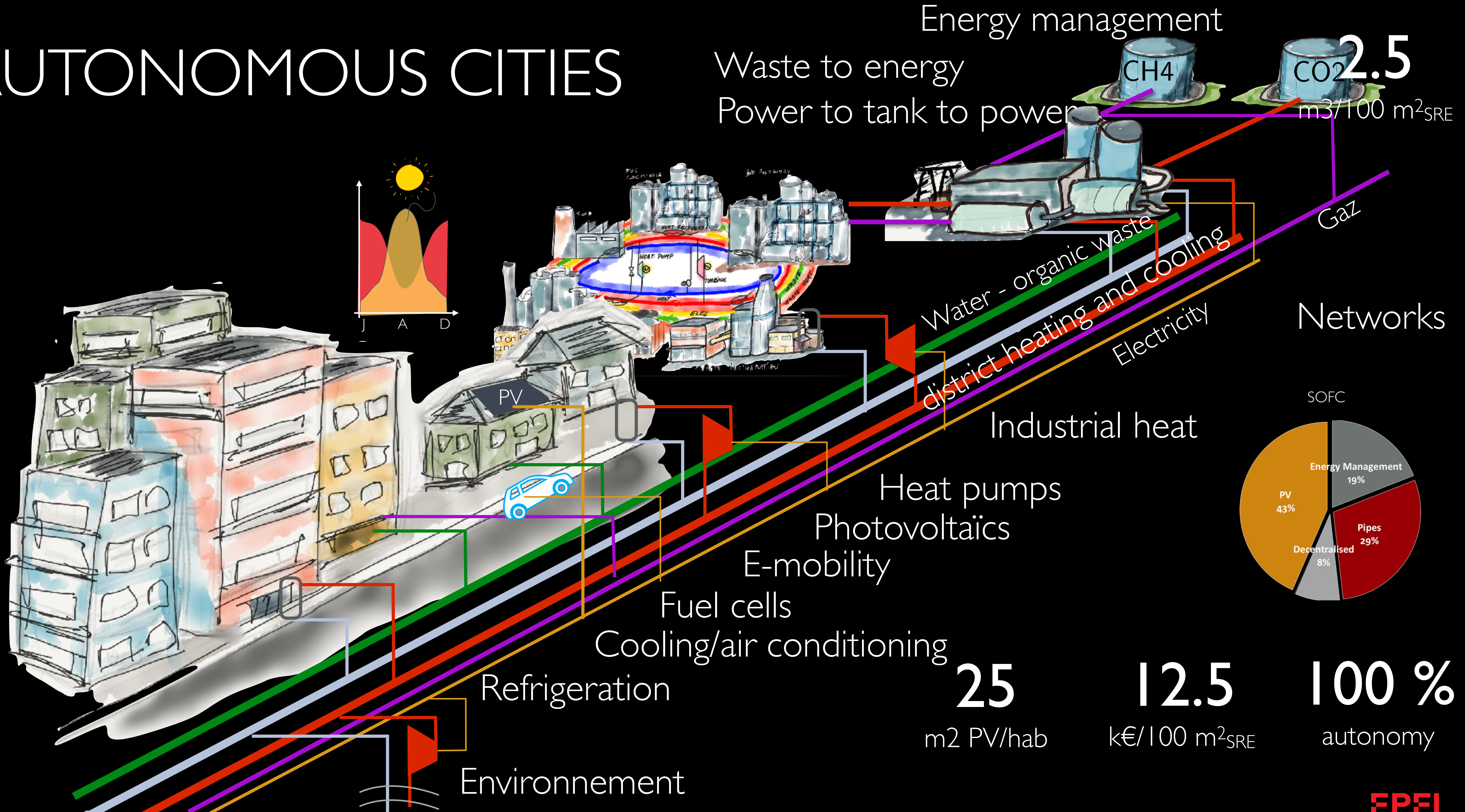
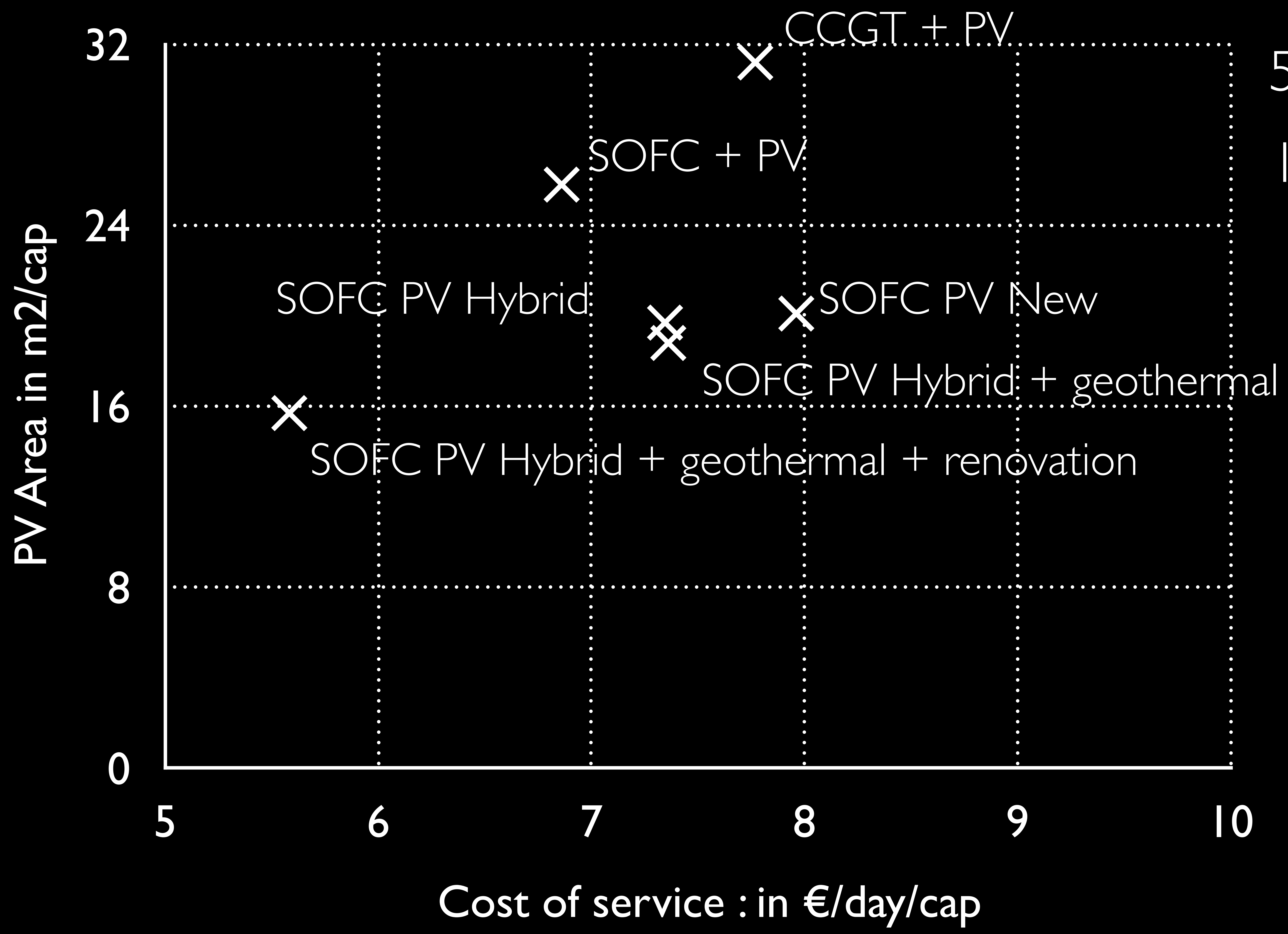
AUTONOMOUS CITIES



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]

EFFICIENCY VS COSTS



5.5 - 8 €/day/cap

16 - 32 m2 PV/cap

- Advanced Cogeneration
- Perovskite PV
- Hybrid PV
- Geothermal storage
- Buildings renovation

PV cost 300 €/m2

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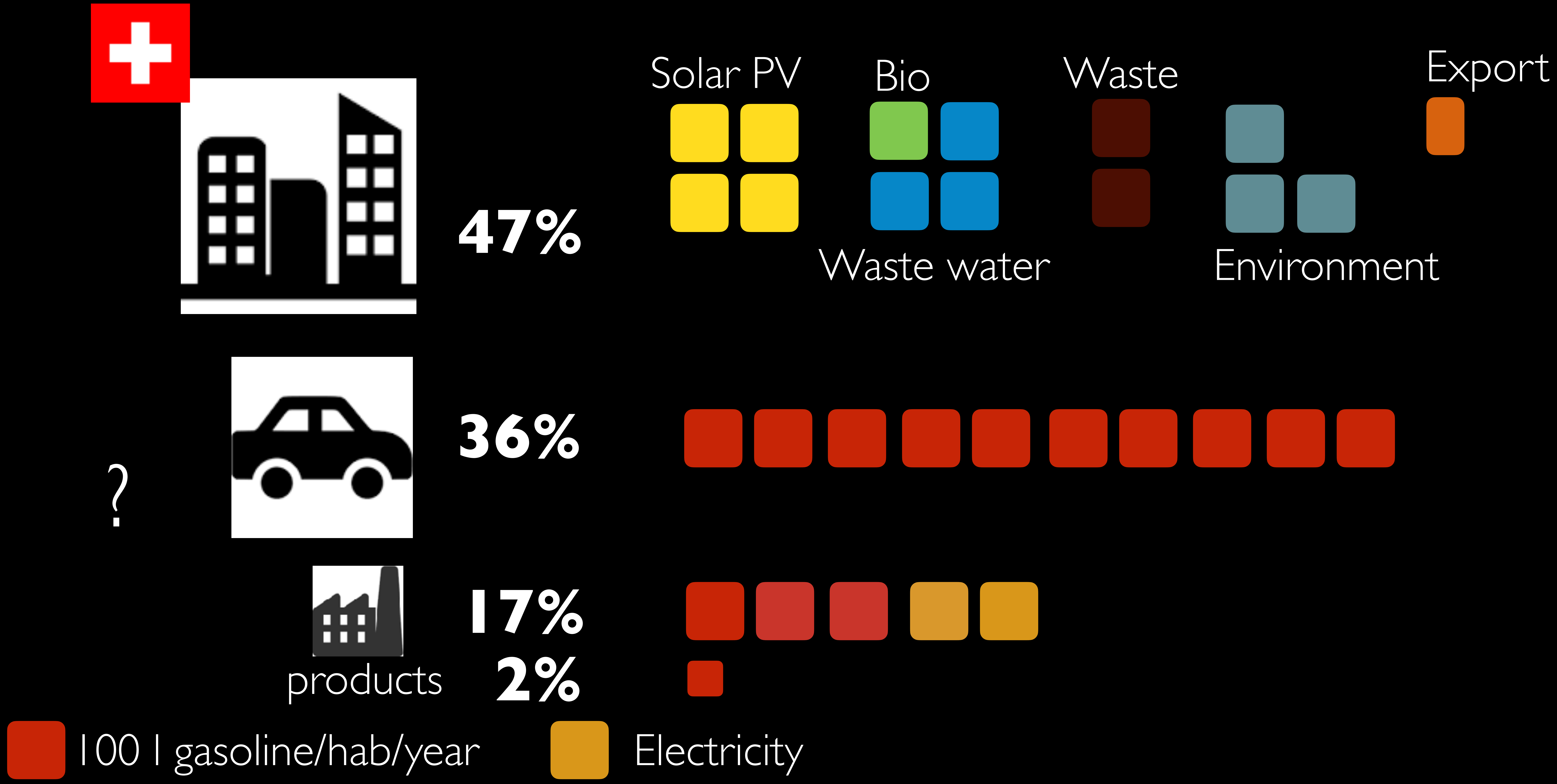
THE ENERGY SYSTEM



Industrial clusters : industry in the territory

Efficacy

Efficiency
Mass & Heat
Recovery

Waste Heat
Heat pumps
Heat2Power

Conversion

Energy vectors
Renewables
COmbined heat and power
CO2 Capture

Soberty

Technology innovation
Smart operation
New technologies

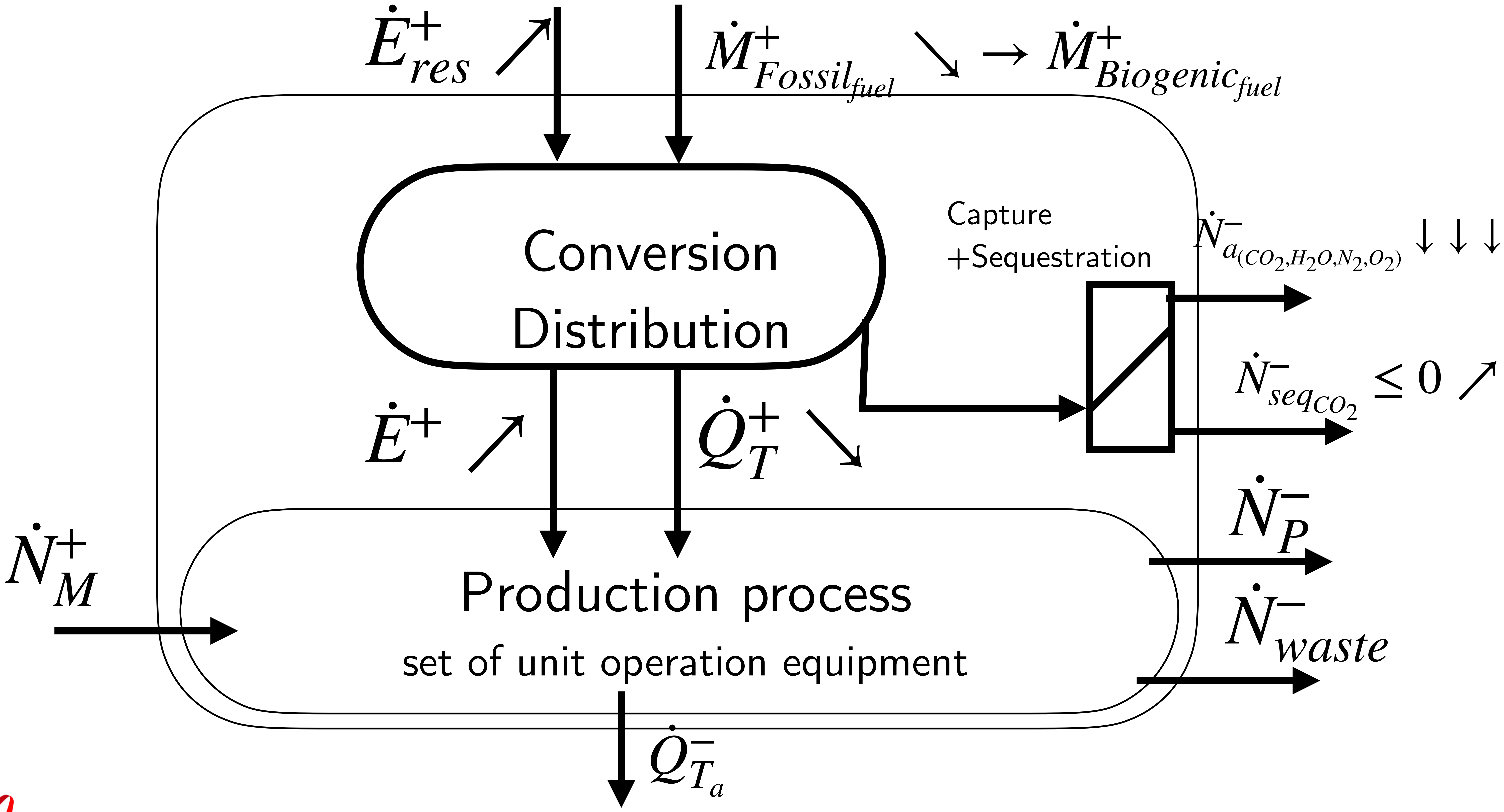
Why ?
Monitoring
Losses

System integration

Multi-energy systems
Grid : Elec-gas-waste
Storage : Power2Tanks2Power
Flexibility services

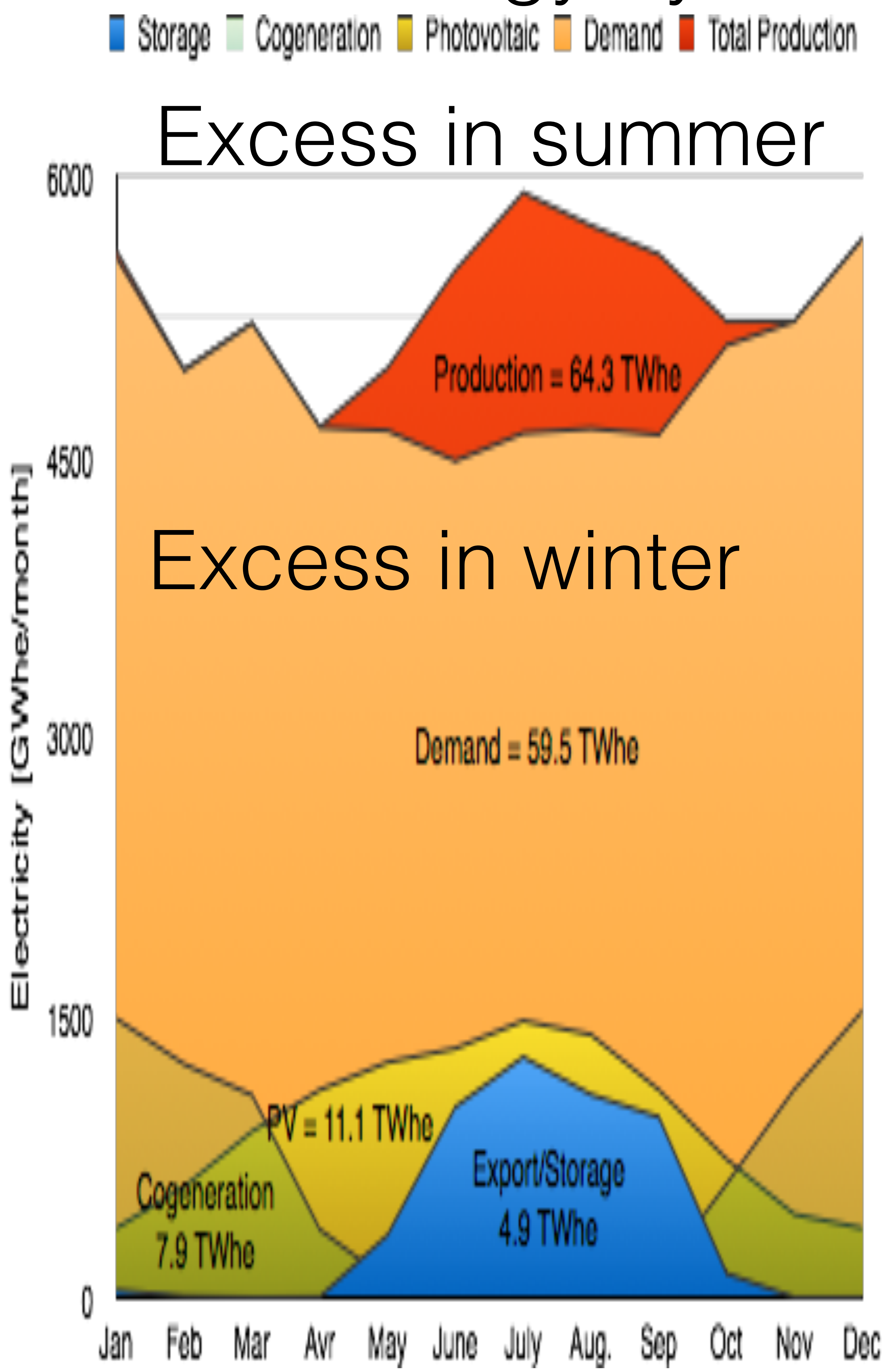
Systemic integration
District heating
Industrial Symbiosis
Circular economy

Reducing emissions In Industrial processes

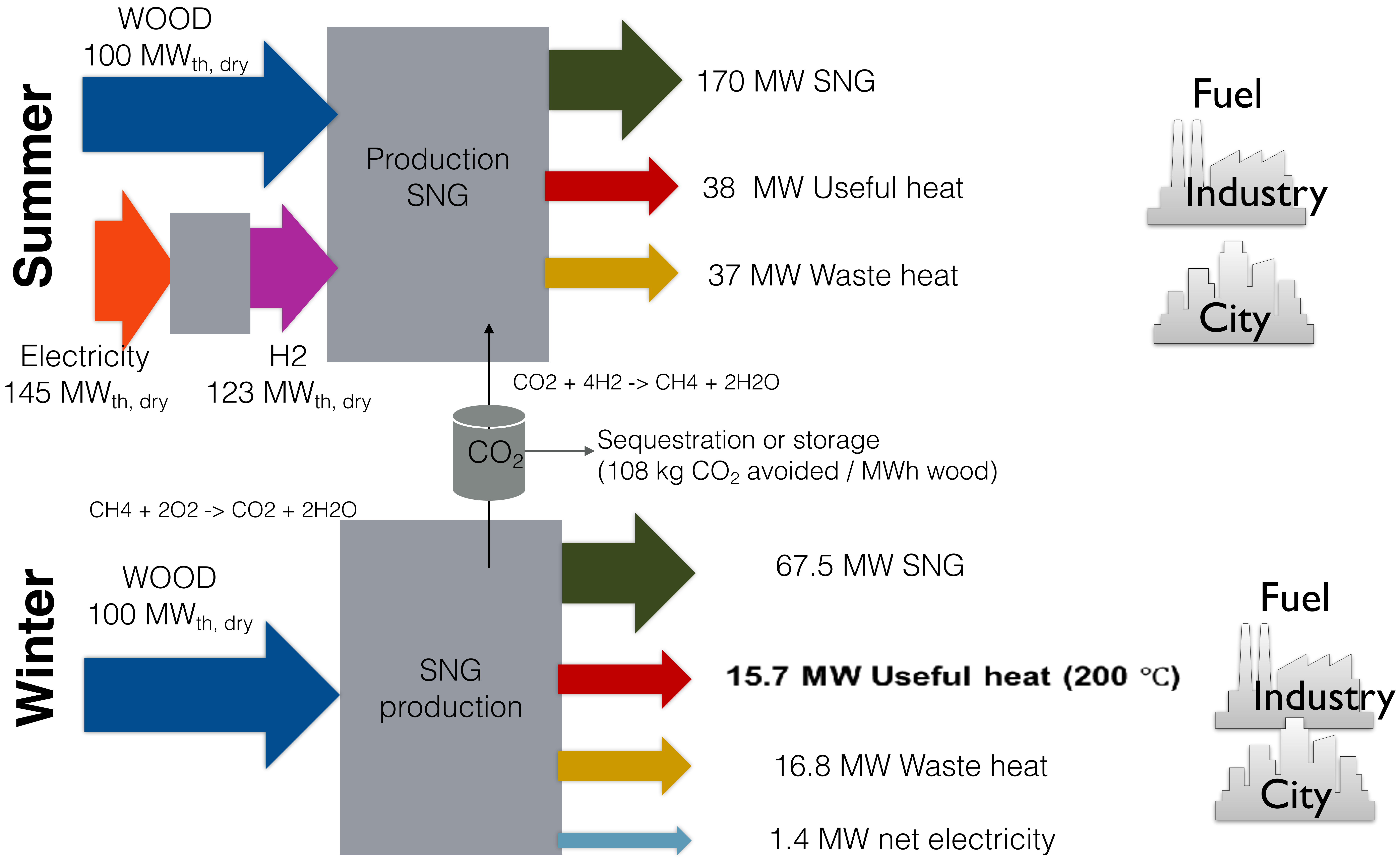


Integrating with the energy system : Combined heat and fuel production

Swiss Energy System



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



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

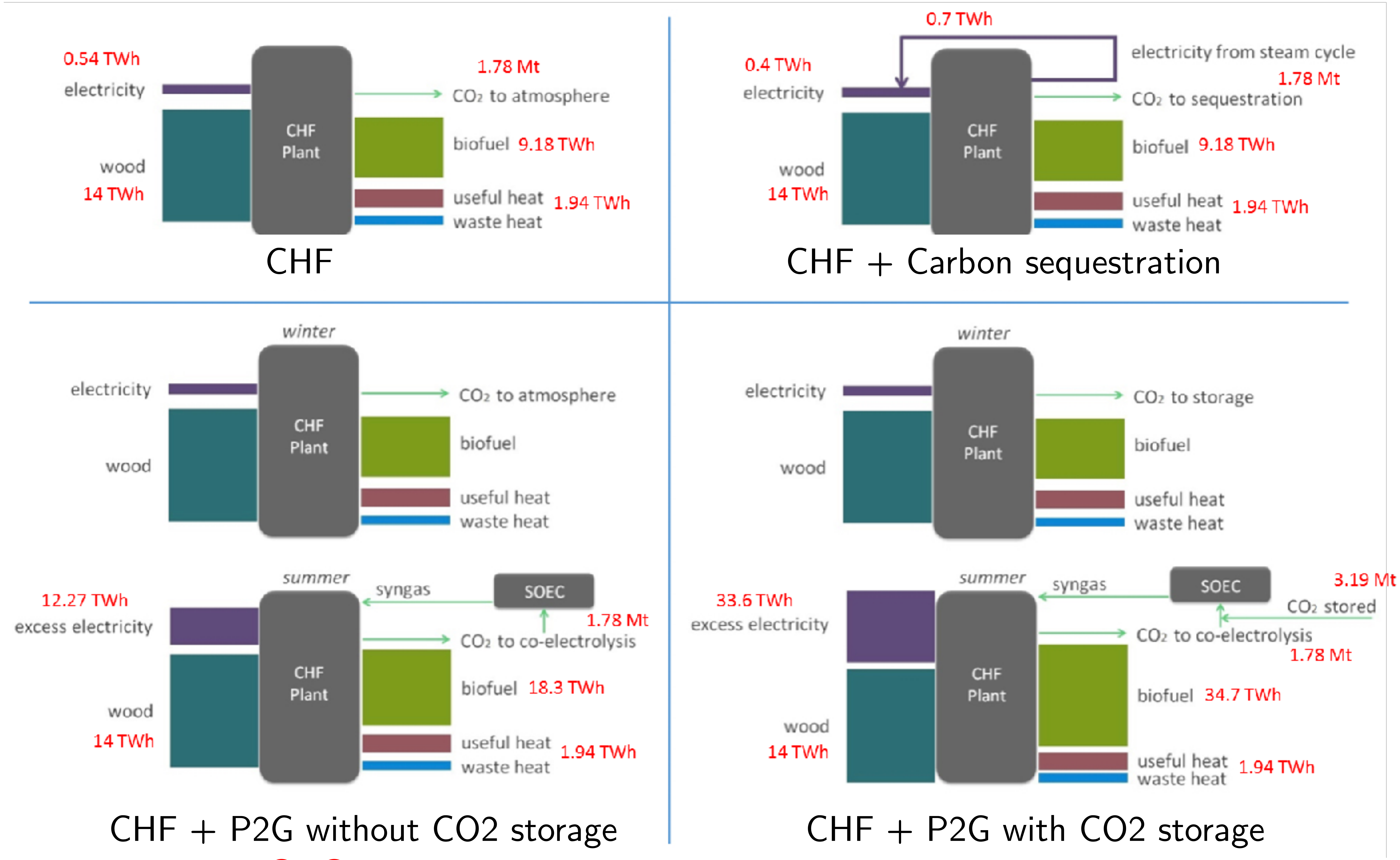
New boiler : Combined Heat and Fuel (CHF) production
Substituted fossil carbon per unit of biogenic carbon in wood (kg/kg)

0.48

0.84

0.63

1.0

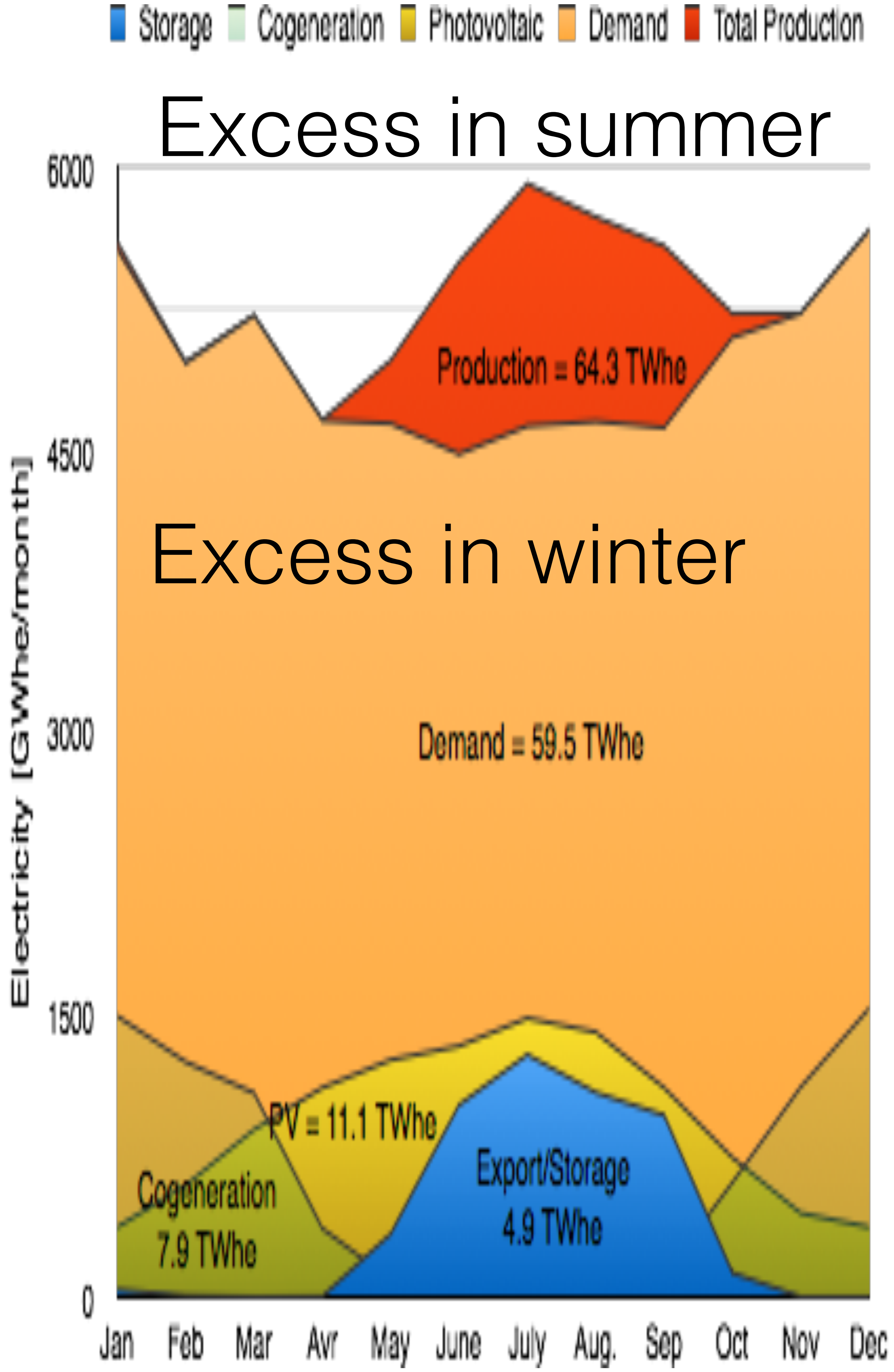


For wood boiler (WB) 0.3 kg of fossil carbon are substituted per kg of biogenic carbon

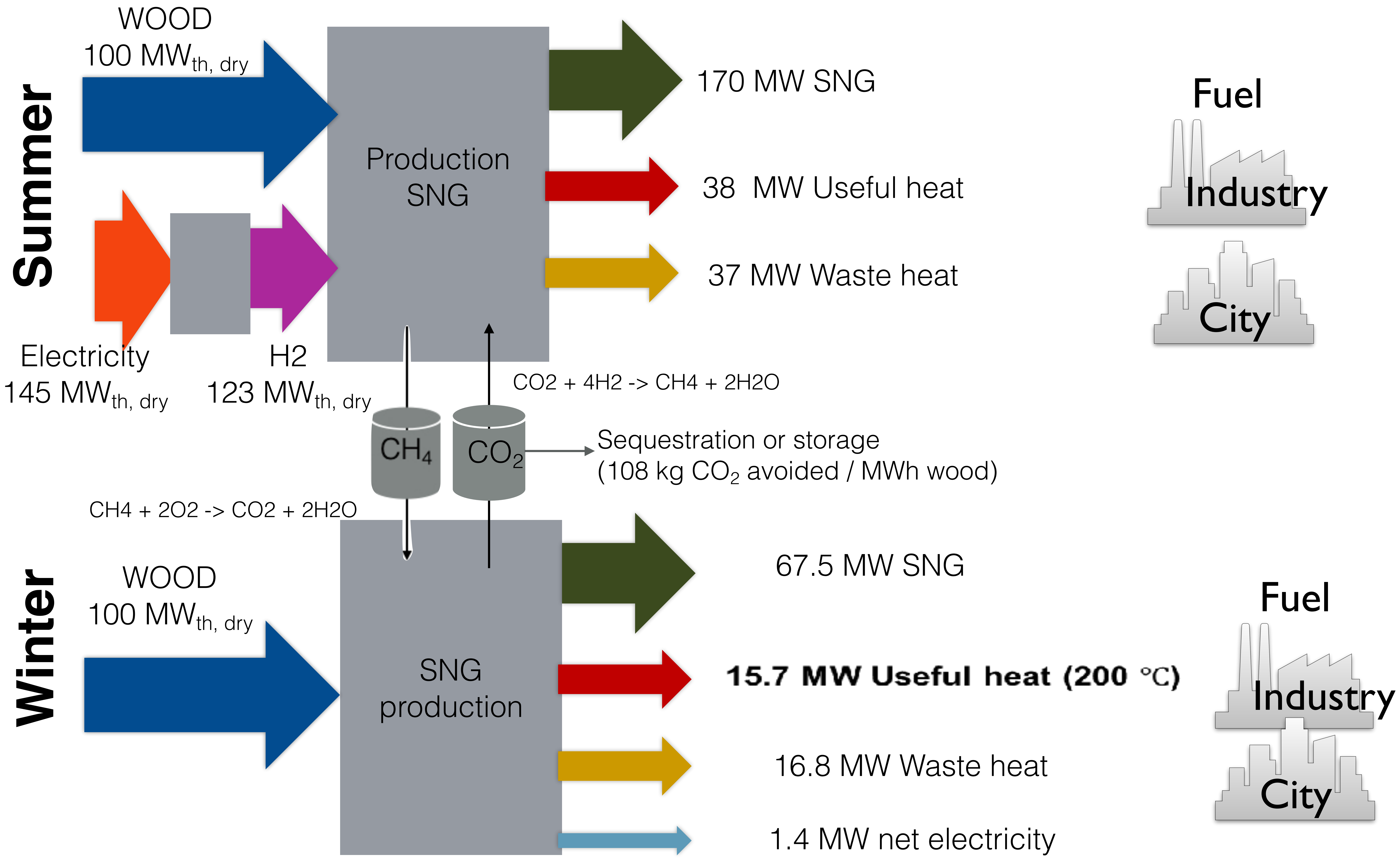
Celebi, et al. *Chemical Engineering Science* 204 (2019): 59-75.

New boiler : Combined Heat and Fuel production

Swiss Energy System

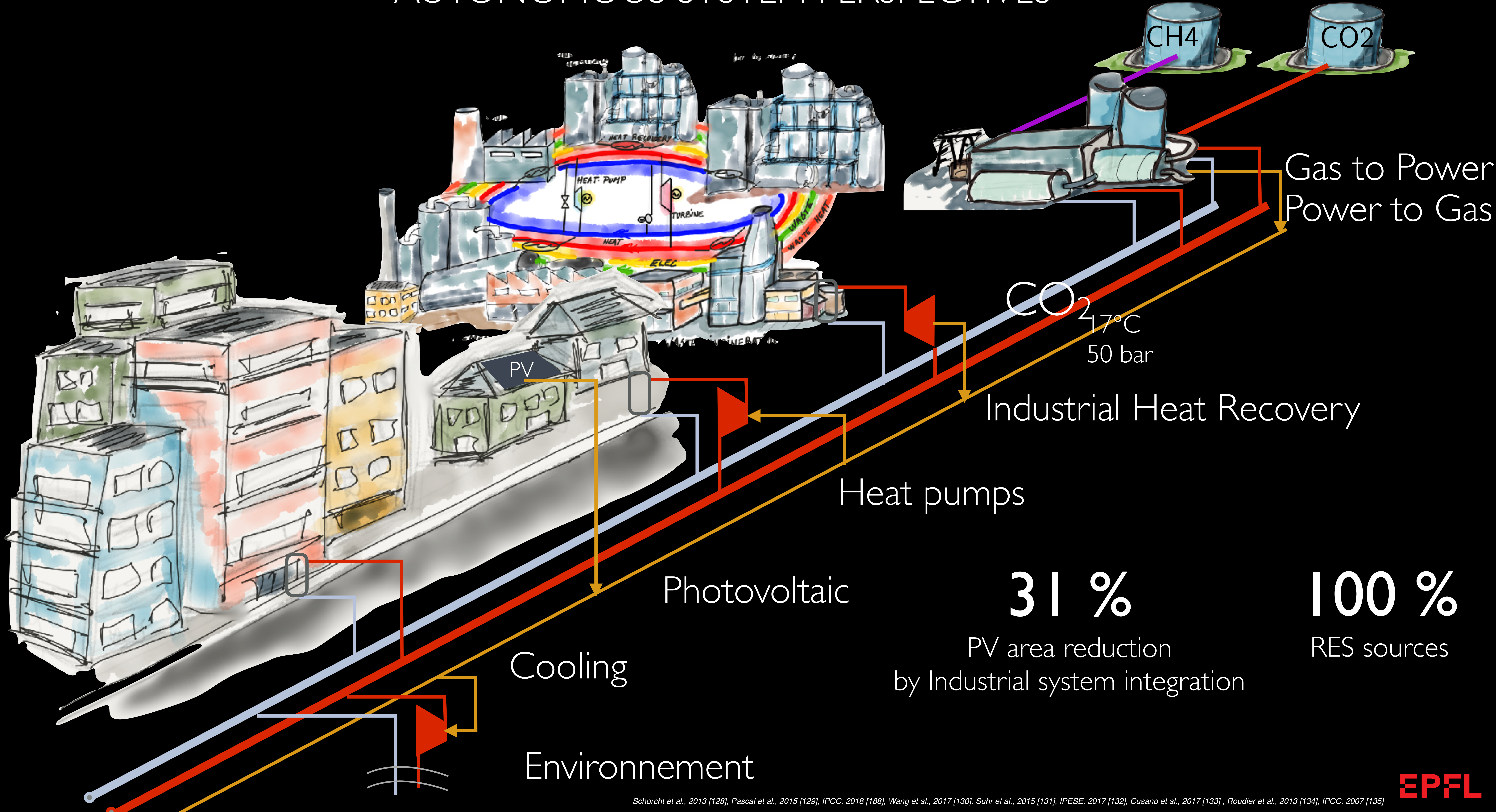


$$2C(H_2O) + 4H_2 \rightarrow 2CH_4 + 2H_2O$$



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

AUTONOMOUS SYSTEM PERSPECTIVES



31 %
PV area reduction
by Industrial system integration

100 %
RES sources

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]

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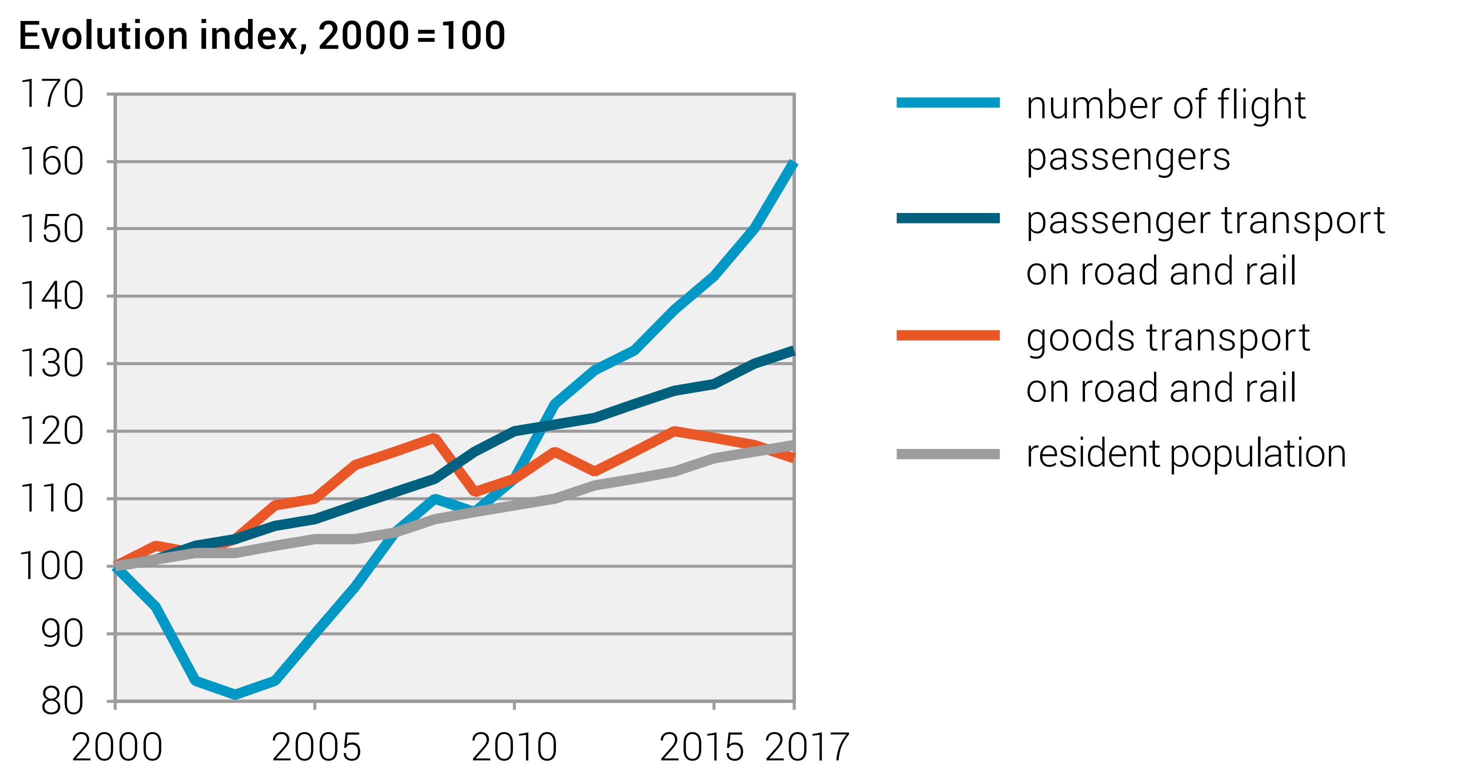
MOBILITY

36%

Key figures on mobility and transport

	Value	Year	Change from 2000
Total costs[1] of transport	CHF 89.7 billion	2016	...
National road network length	1 859 km	2018	+13%
Stock of passenger cars	4 602 688	2018	+30%
Average daily distance per person[2]	36.8 km	2015	+5%
Passenger transport performance[3]	134.6 billion person-km	2017	+32%
Public transport share	19%	2017	+3 pp
Goods transport performance[4]	27.9 billion tonnes-km	2018	+19%
Rail share	37%	2018	–5 pp
Persons killed in road traffic	233	2018	–61%
Transport's[5] share of CO_2 emissions	39%	2017	+3 pp

Passenger transport is growing faster than the population



Note: base passenger transport = person-km, base goods transport = tonne-km

1) Road, rail and air transport, without human-powered mobility (on foot, by bike). Including non-material costs due to damage to environment and health as well as accidents
2) Distances inside Switzerland
3) Rail and road incl. human-powered mobility
4) Rail and road. In combined transport calculated without the tare weight of the loaded road vehicles, containers and swap bodies (i.e. for rail: net tonne-kilometres)
5) Excl. international aviation
pp = percentage points

Sources: FSO – Goods transport statistics (GTS), Costs and funding of transport (CFT), Passenger transport performance (PV-L); FSO, ARE – Mobility and transport microcensus (MTMC); FSO, FEDRO – Stock of road motor vehicles (MFZ); FEDRO, FSO – Road accidents (SVU); FEDRO – Length of Swiss motorway network; FOEN – Greenhouse gas inventory

100 l gasoline/hab/year

MOBILITY

36%

Efficacité

Soft Mobility

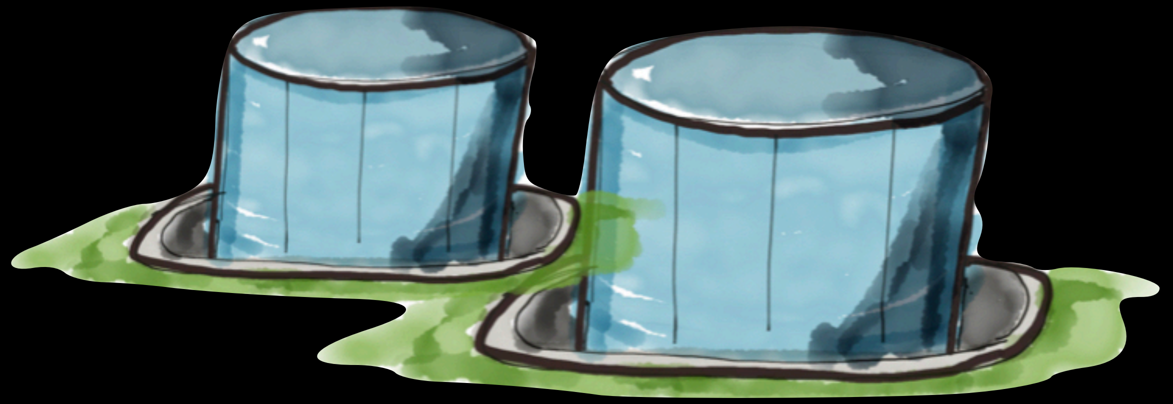
Public transport : electric/hybrid (mobilitylab.ch)

Electric vehicles : 400-500 km

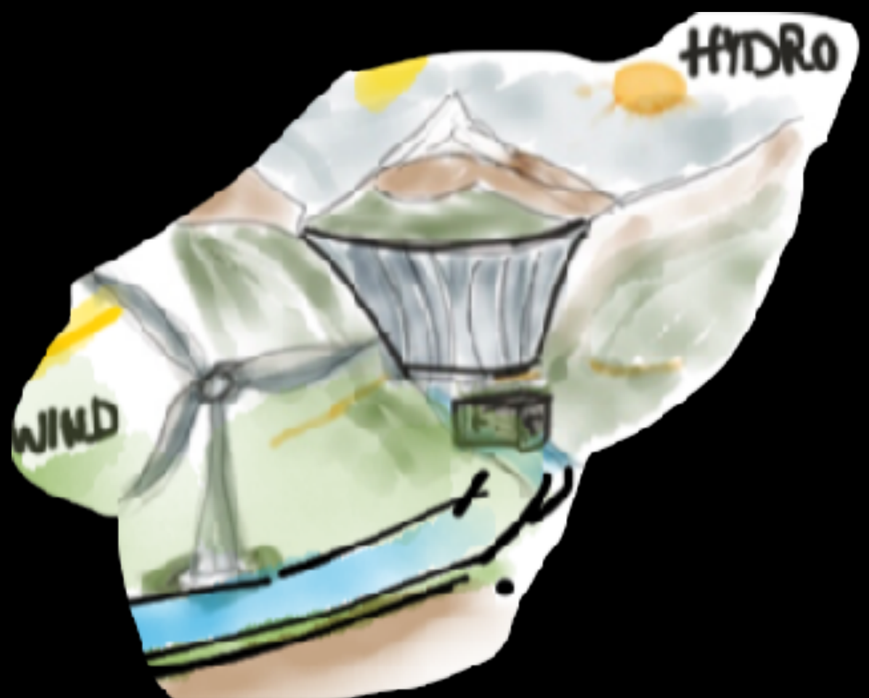
Fast charge

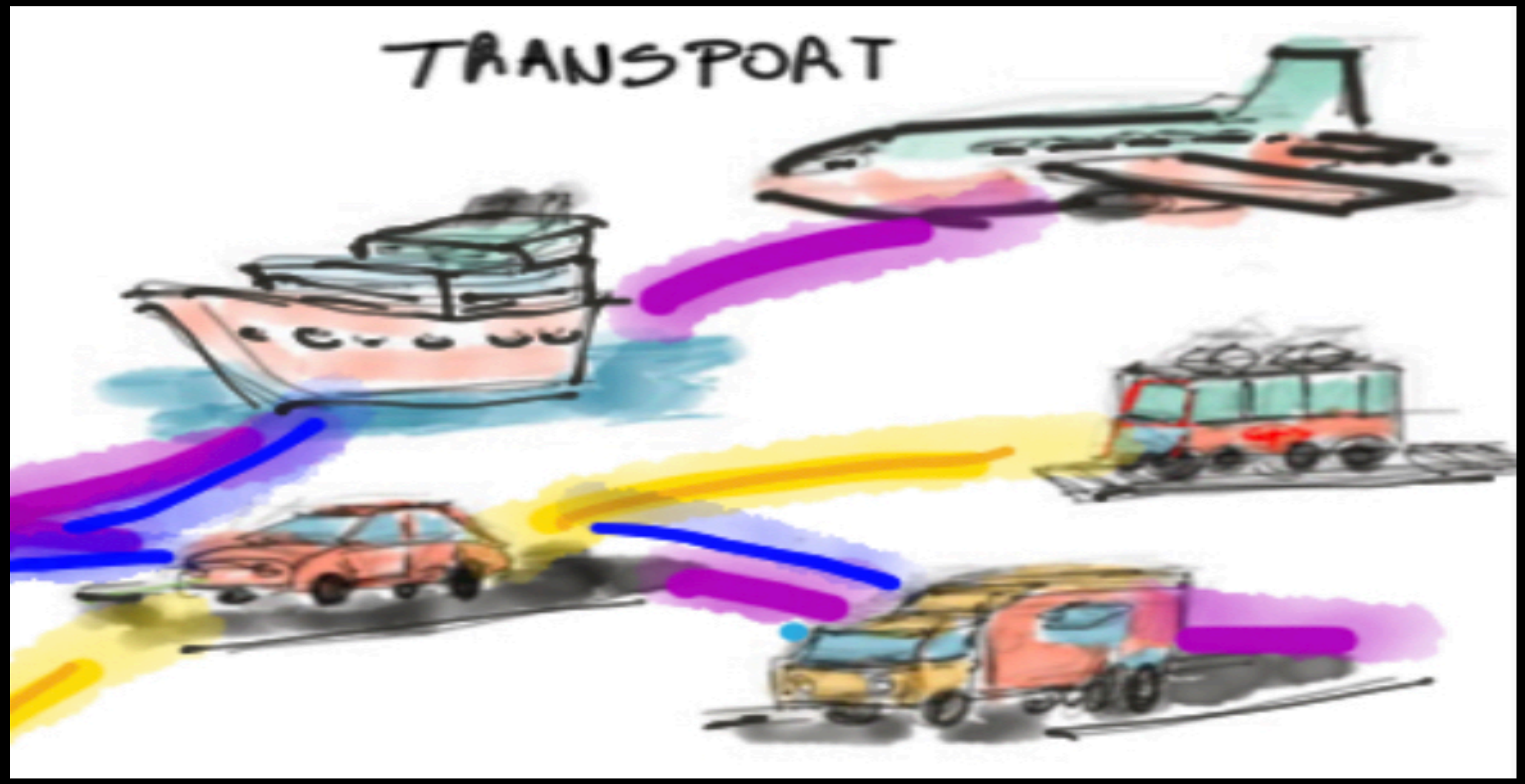
Range extenders vehicules (H2, CH4)

CO2 capture on board



Bio-Fuel





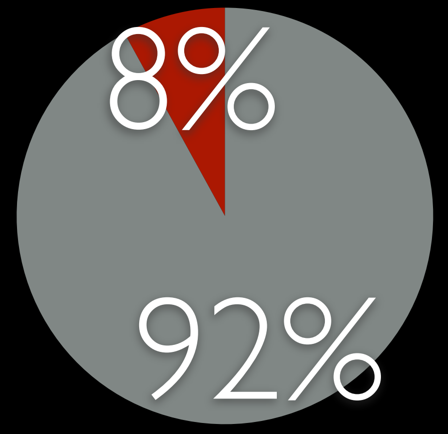
Wind and Hydro

100 l gasoline/hab/year

"RANGE EXTENDERS" VEHICULES

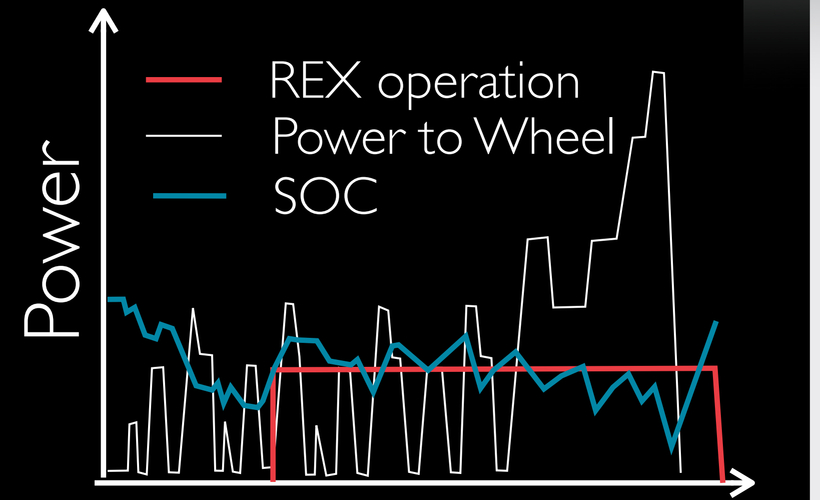
Driving mode

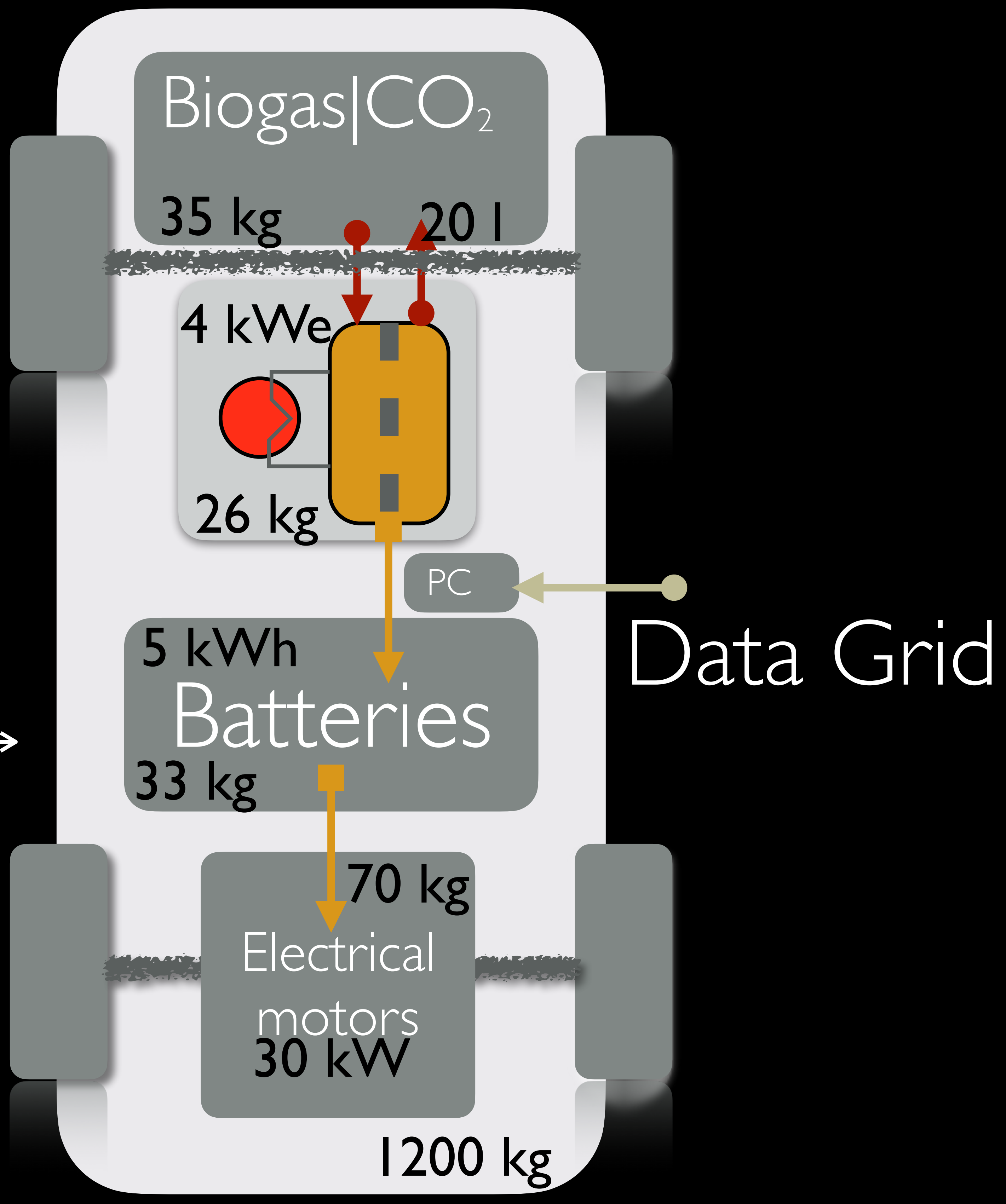
Autonomy : 950 km
Cons : 1.1l/100 km



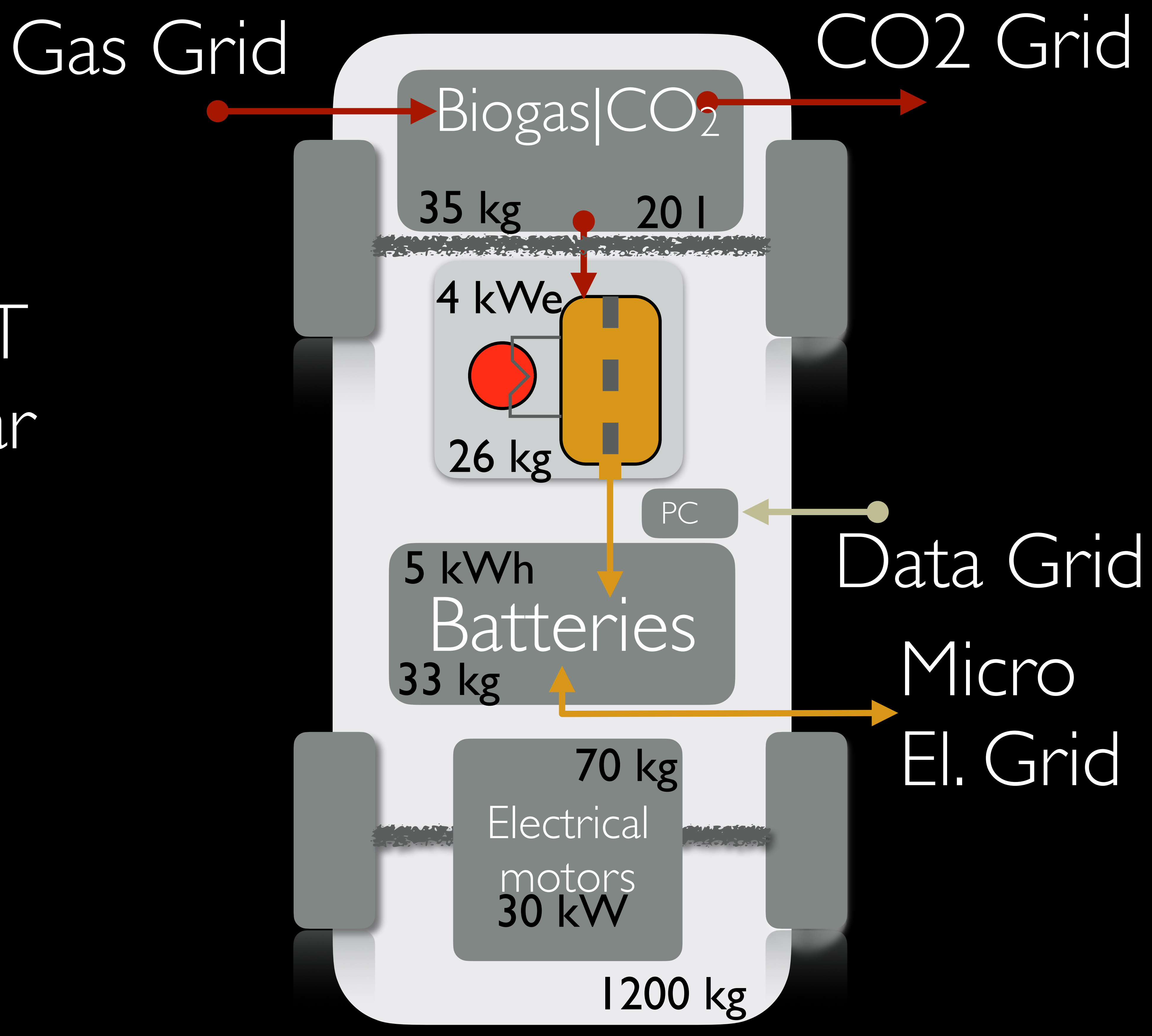
Parking mode

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





SOFC-GT
Hybrid car



PhD PSA

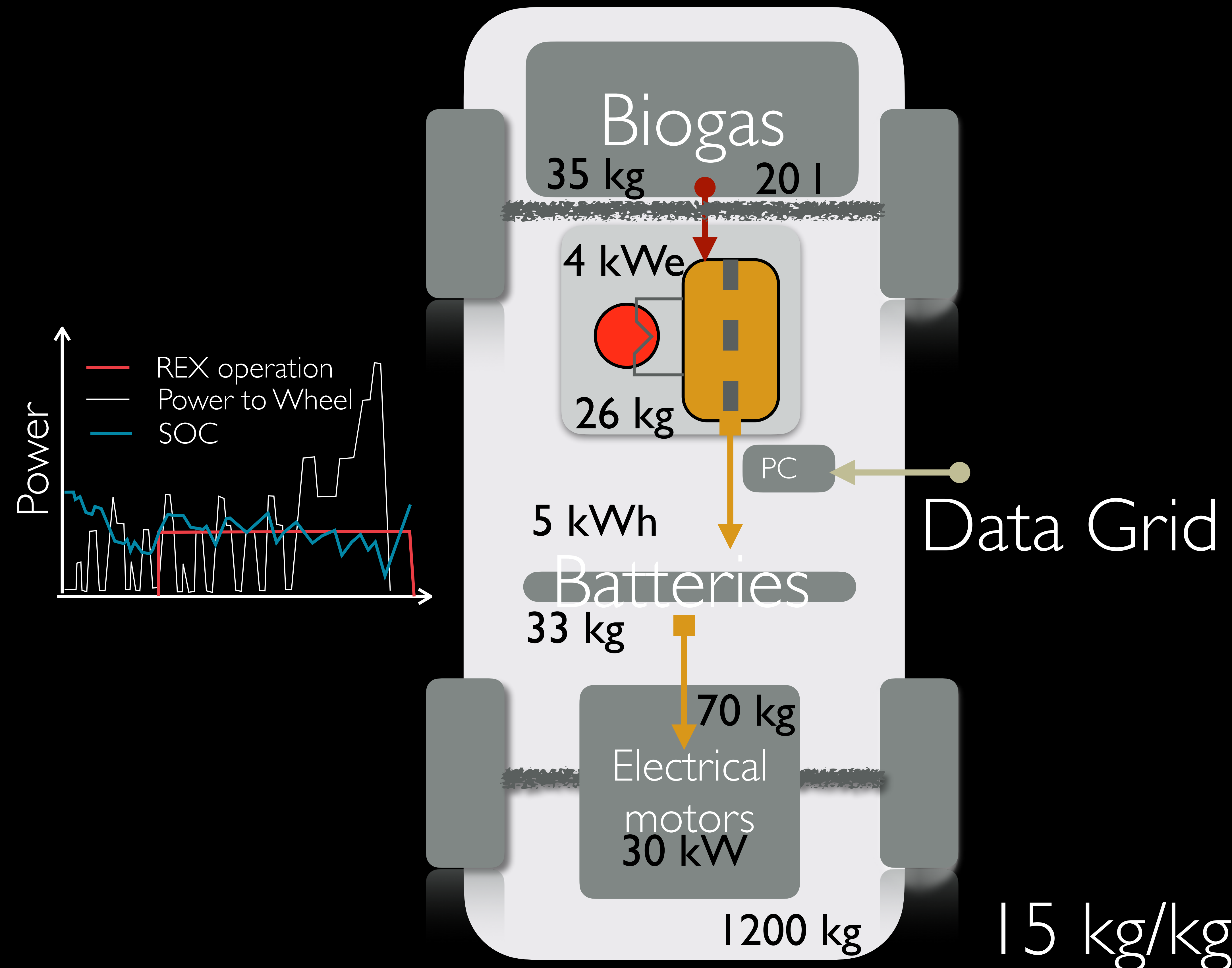
Dimitrova, Zlatina, and François Maréchal. "Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender." *Renewable Energy* 112 (2017): 124-142

SMART CARS

12 m2 PV/car (hybrid SOFC-GT)

Autonomy : 950 km

Cons : 1.1l/100 km



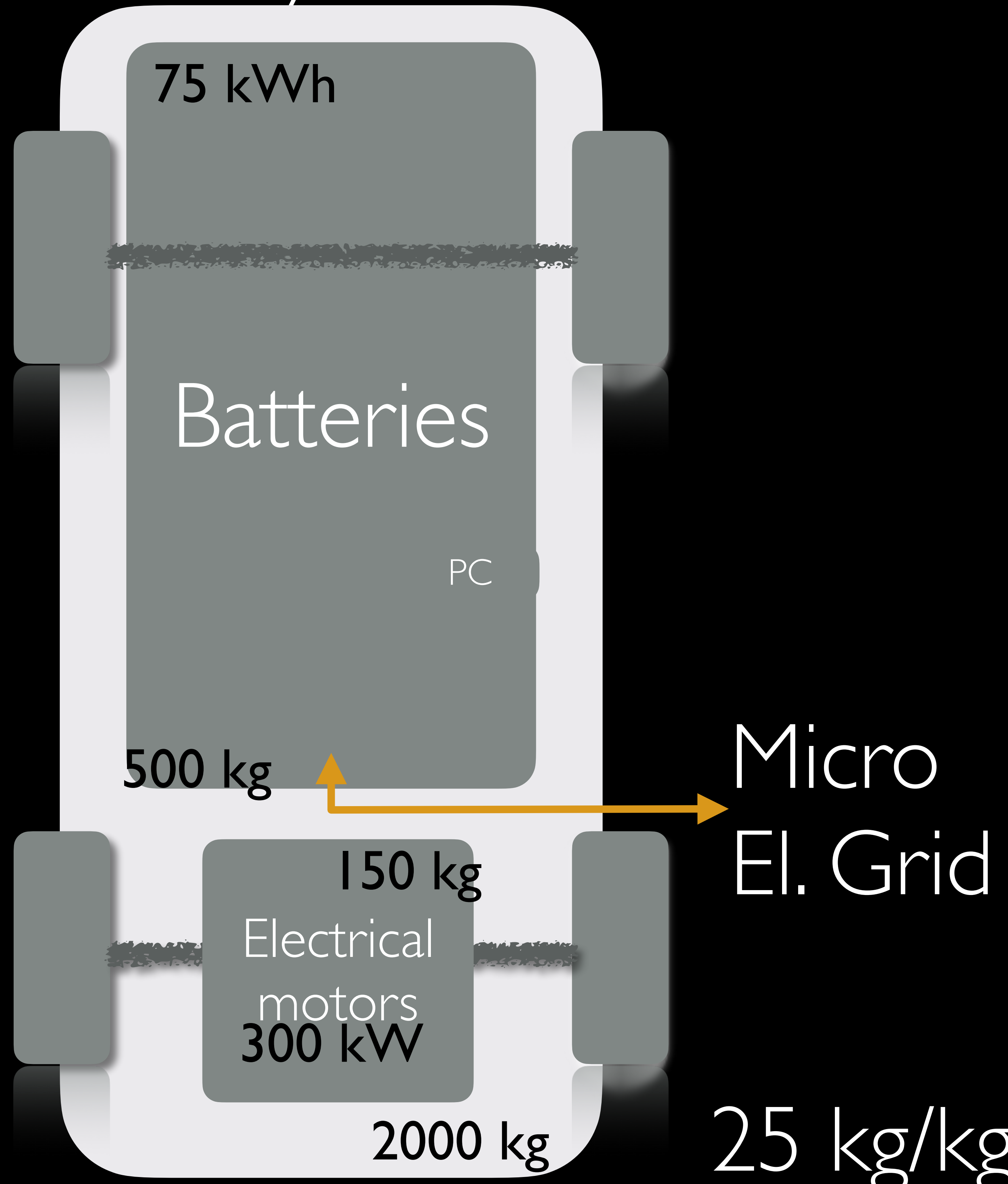
15 kg/kg

24m2 PV/car (Tesla)

Autonomy : 800 km

Cons : 2.0 l/100 km

Battery :75 kWh

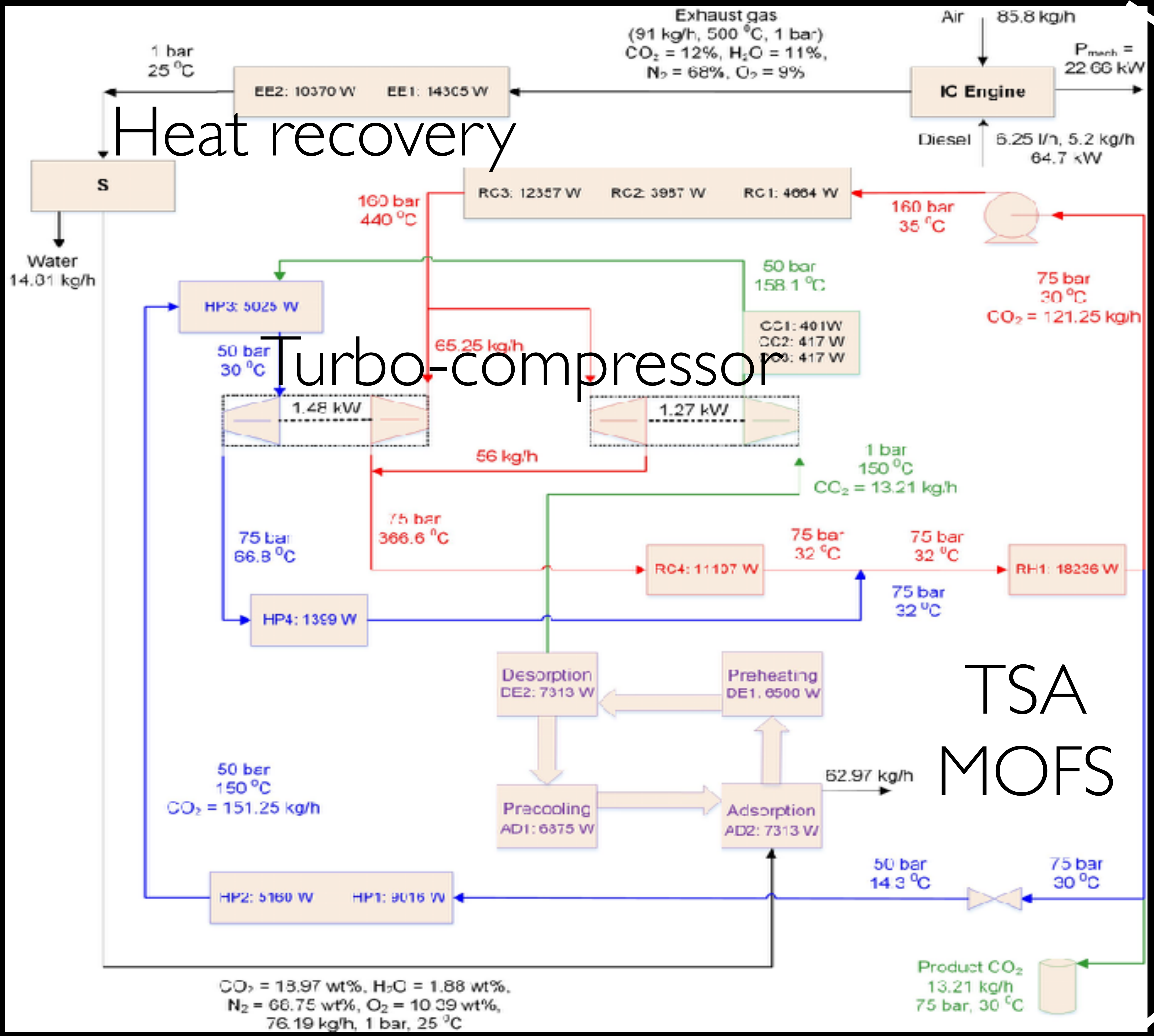


25 kg/kg

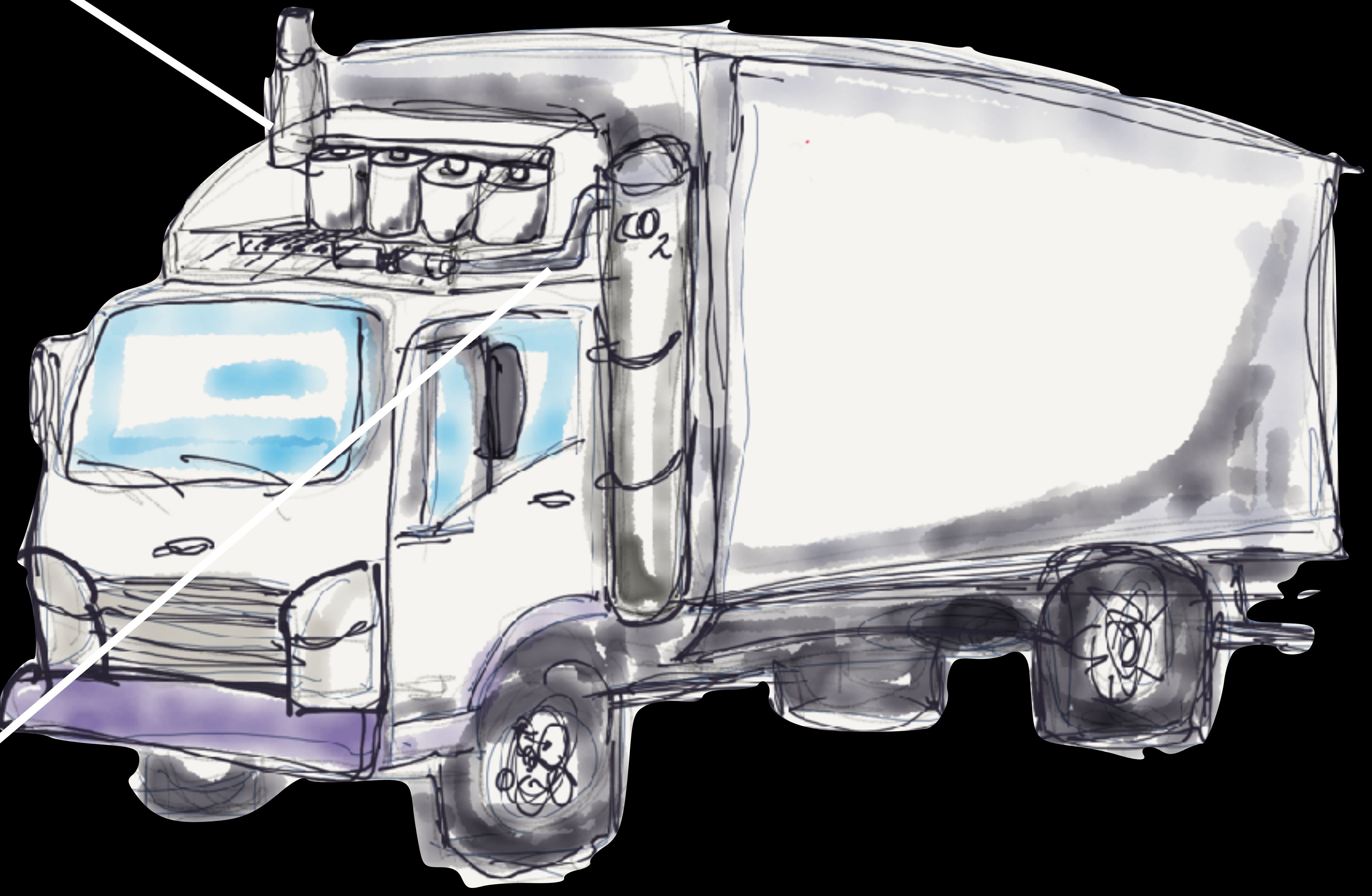
Dimitrova, Zlatina, and François Maréchal. "Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender." *Renewable Energy* 112 (2017): 124-142

EPFL

CAPTURING CO2 FROM TRUCKS



90% CO2 capture



3
liter CO_2/liter fuel

0.05 - 0.1
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.

EPFL

CARBON NEUTRAL TRANSPORTATION SYSTEM

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.

CARBON SINK ?

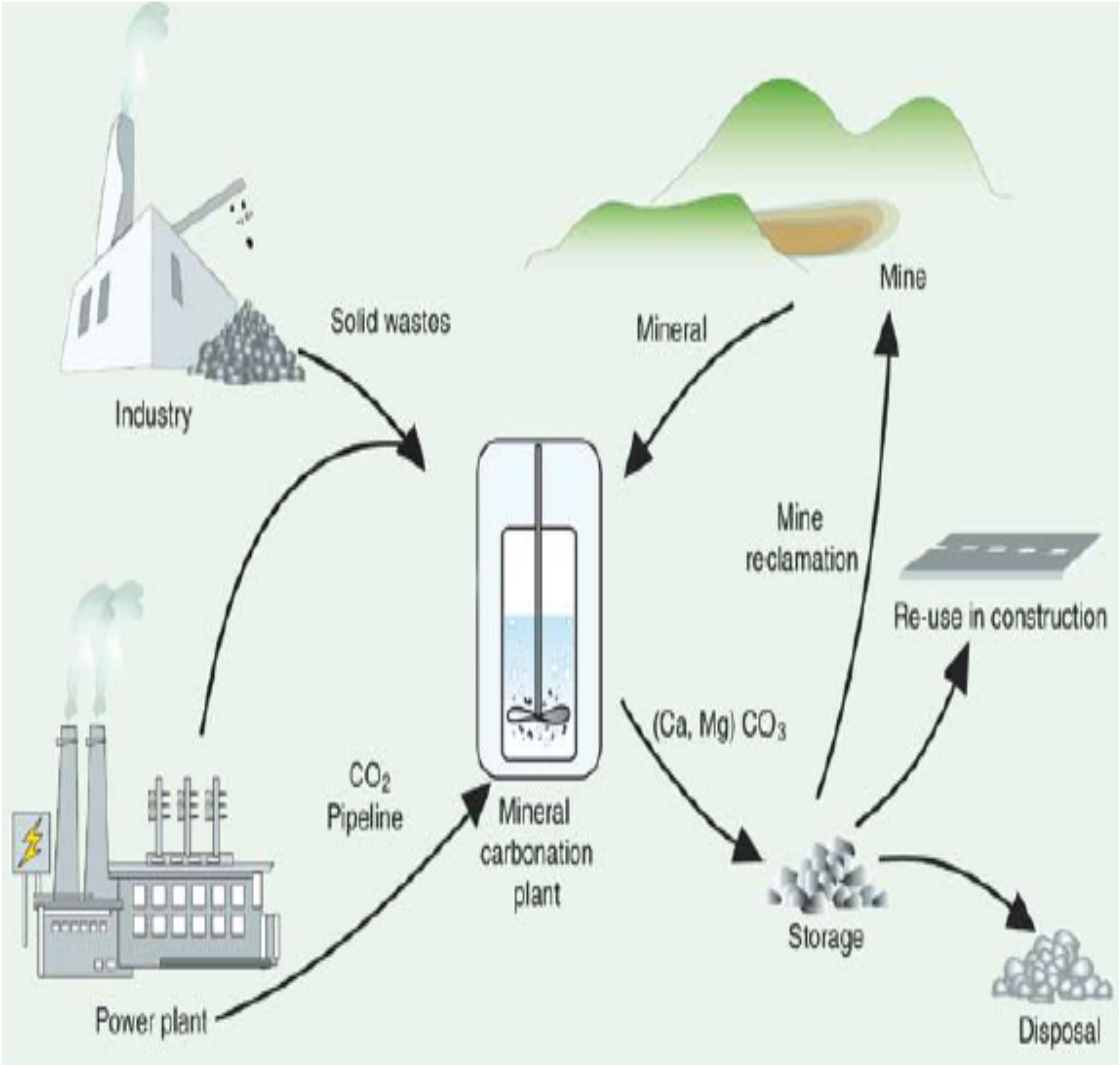

CO2
WATER
CH4
CH4
HT Heat
LT-Heat
78.4 MJ/kgC
54.4 MJ/kgC
4.4 MJ/kgC
0 MJ/kgC
BIOMASS : C(H2O)
H2O
CO2
Serpentine 1/3 Mg3(OH)4(Si2O5)
Mg3Si2O5(OH)4 + 3 CO2 => 3MgCO3 + 2SiO2 + 2H2O
Mineral Carbon (product)
MgCO3 + 2/3 SiO2 + 2/3 H2O
-3.3 kgCO2/day/cap

CO_2 storage by Mineral carbonation

- CO2 conversion to solid inorganic carbonates by chemical reaction

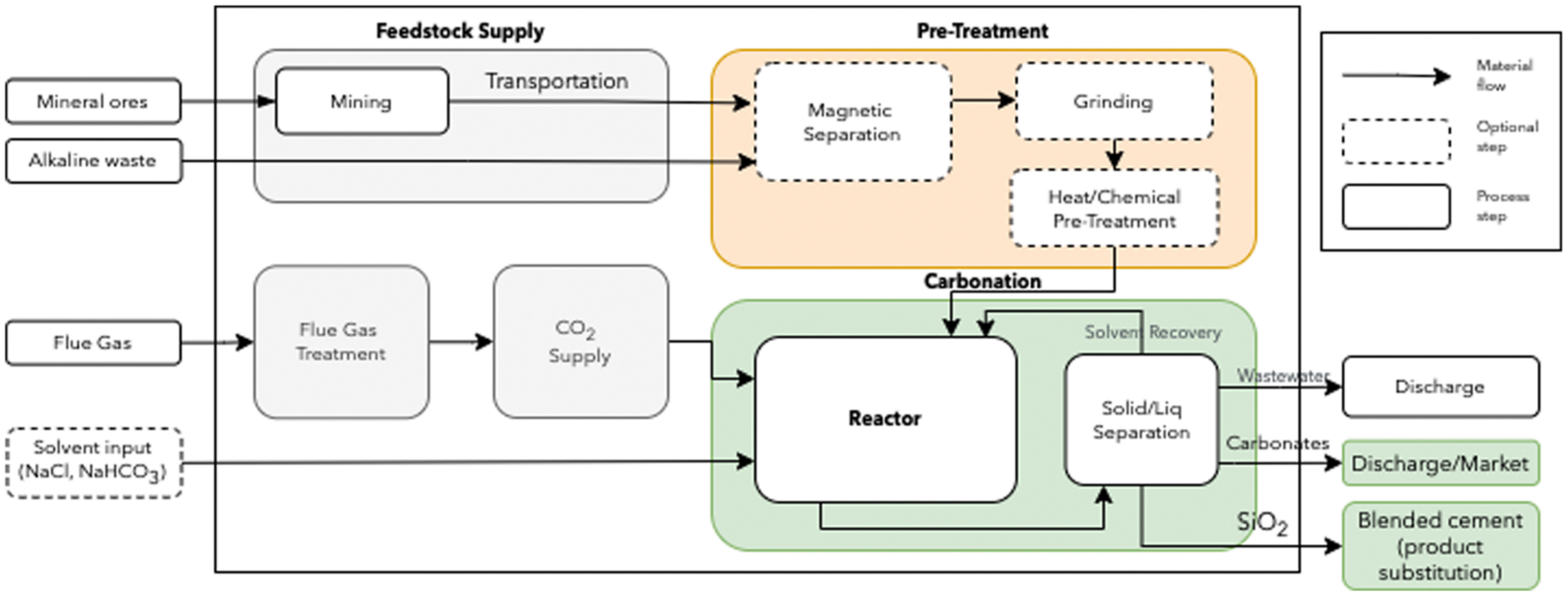
$$1t/CO_2 + [2-3t] \quad MO \rightarrow [3-4t] \quad MCO_3 + heat$$

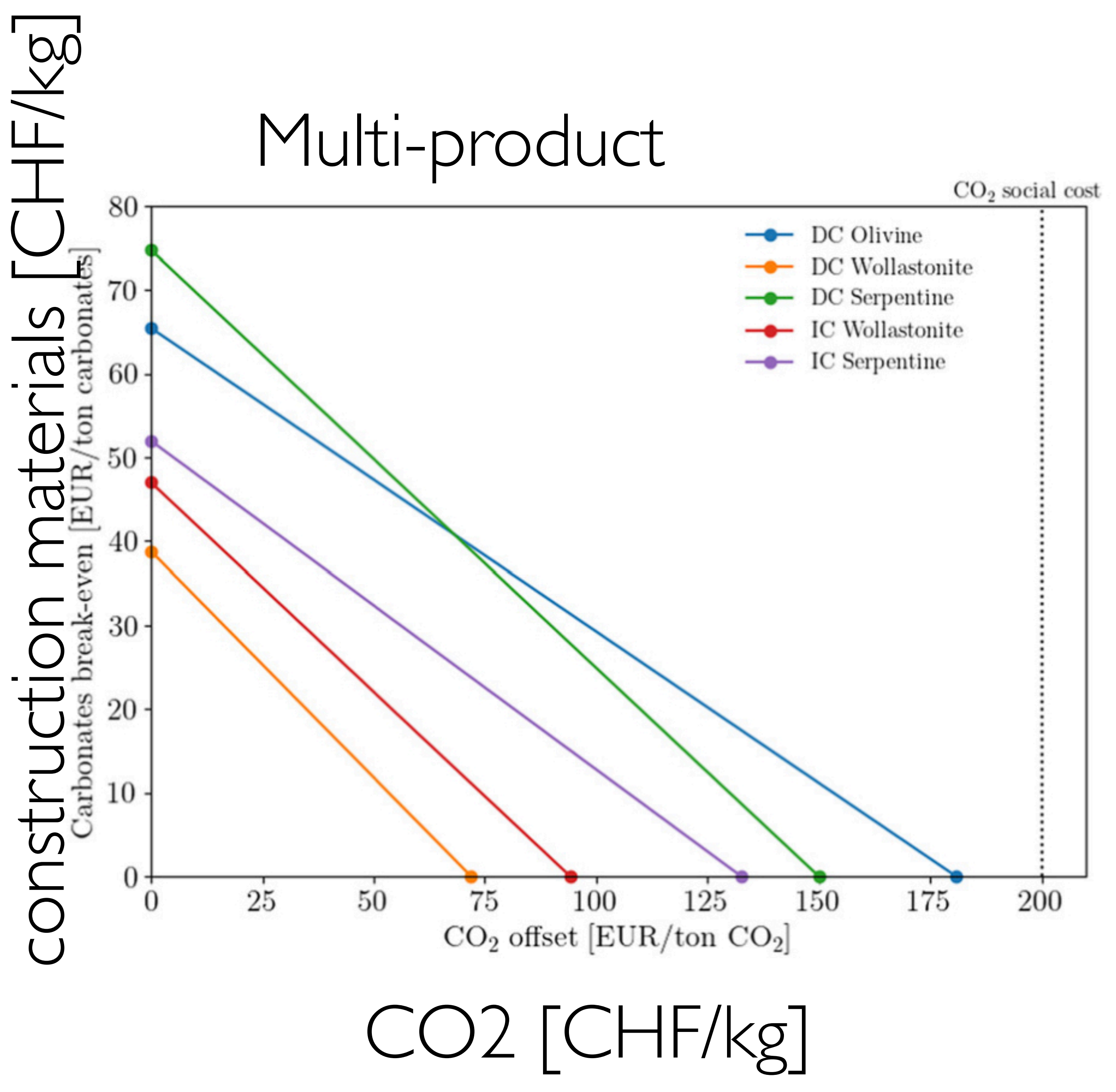
- MO= Metal oxide (MgO, CaO) or CaSiO3, Mg2SiO4, Mg3Si2O5(OH)4
- Magnesium carbonate (MgCO3) or calcium carbonate (CaCO3 limestone) => Salt of Type II not soluble in Water
- =accelerated or assisted natural "weathering"
- Available silicate rocks are larger than needed to fix all fossil-derived CO2, however limited to technically exploitable reserves
- Heat ≈ 60 kJ/mol CO2 (to compare with 400 kJ/mol CO2 for combustion)
- Cost: 50-100$/tCO2 mineralized
- Impact mining & disposal

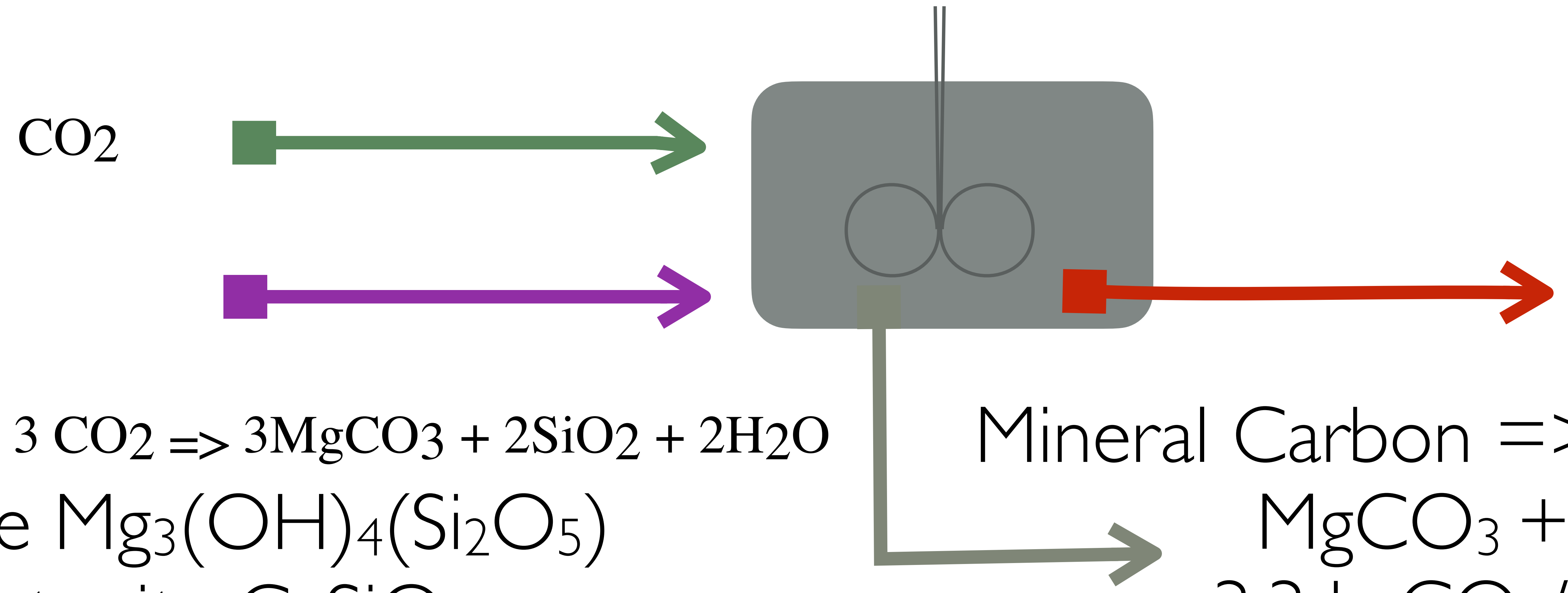


IPCC2005 CCS report

Carbon mineralisation







$Mg_3Si_2O_5(OH)_4 + 3\ CO_2 \Rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$

Serpentine $Mg_3(OH)_4(Si_2O_5)$

Wolastonite $CaSiO_3$

Mineral Carbon => construction

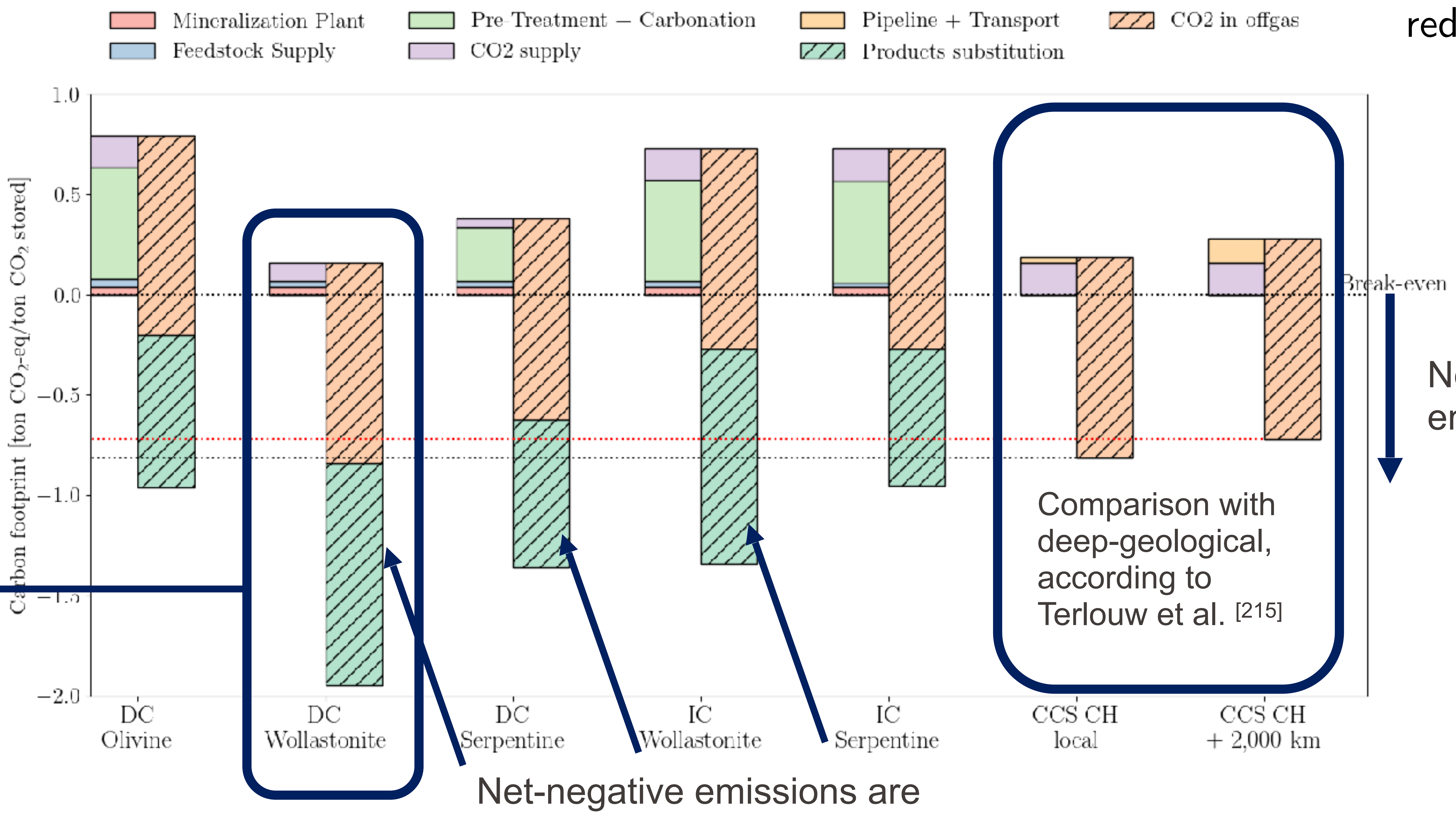
$MgCO_3 + SiO_2$

$-3.3\ kgCO_2/day/cap$

Results: carbon footprint in the waste sector

Process integration leads to 35% cost reduction

Comparison of different sources of mineralization



Net-negative emissions

Wollastonite outperforms due to a simpler process

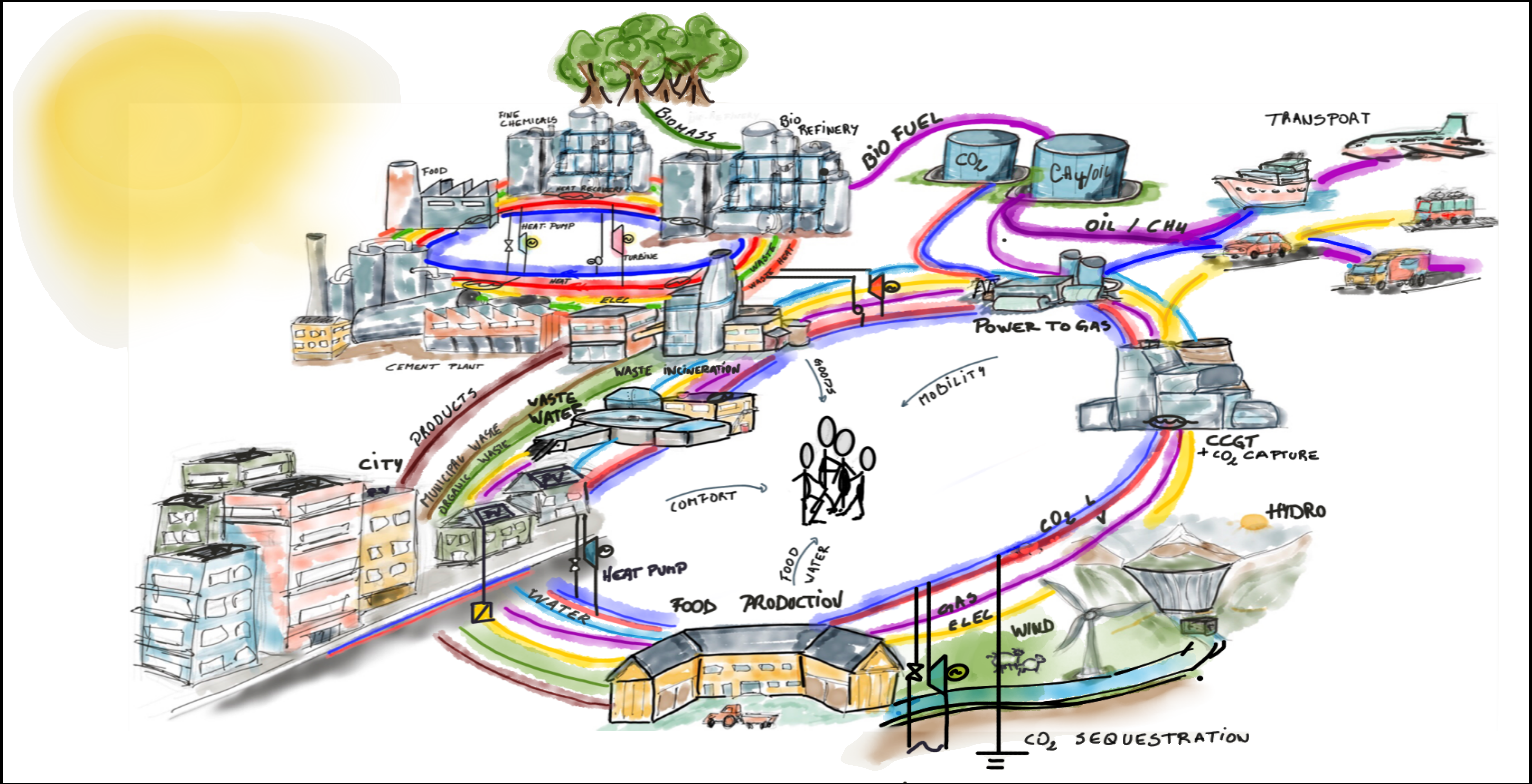
Net-negative emissions are possible, but are mostly dependent on the products **substitution credit**

Circular Renewable/Bio energy hub

CIRCULAR ECONOMY-EFFICIENCY AND INTEGRATION

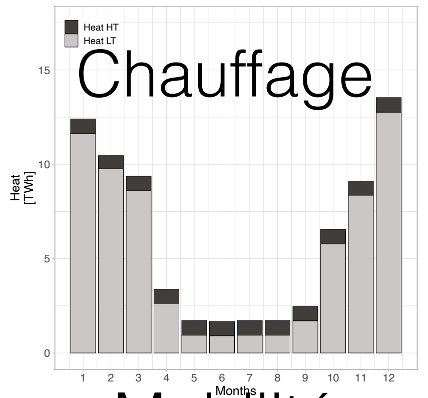
EPFL

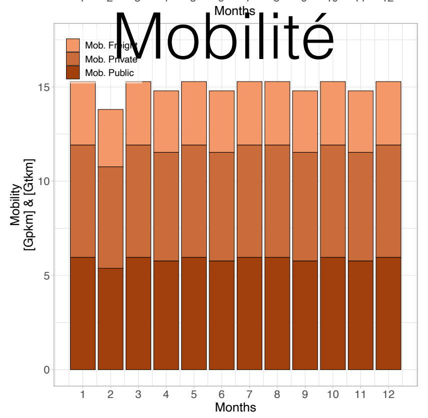
ENERGY SYSTEM INTEGRATION

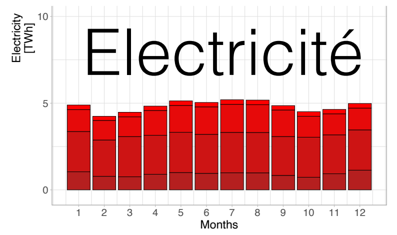


Deciding the energy transition

Ether



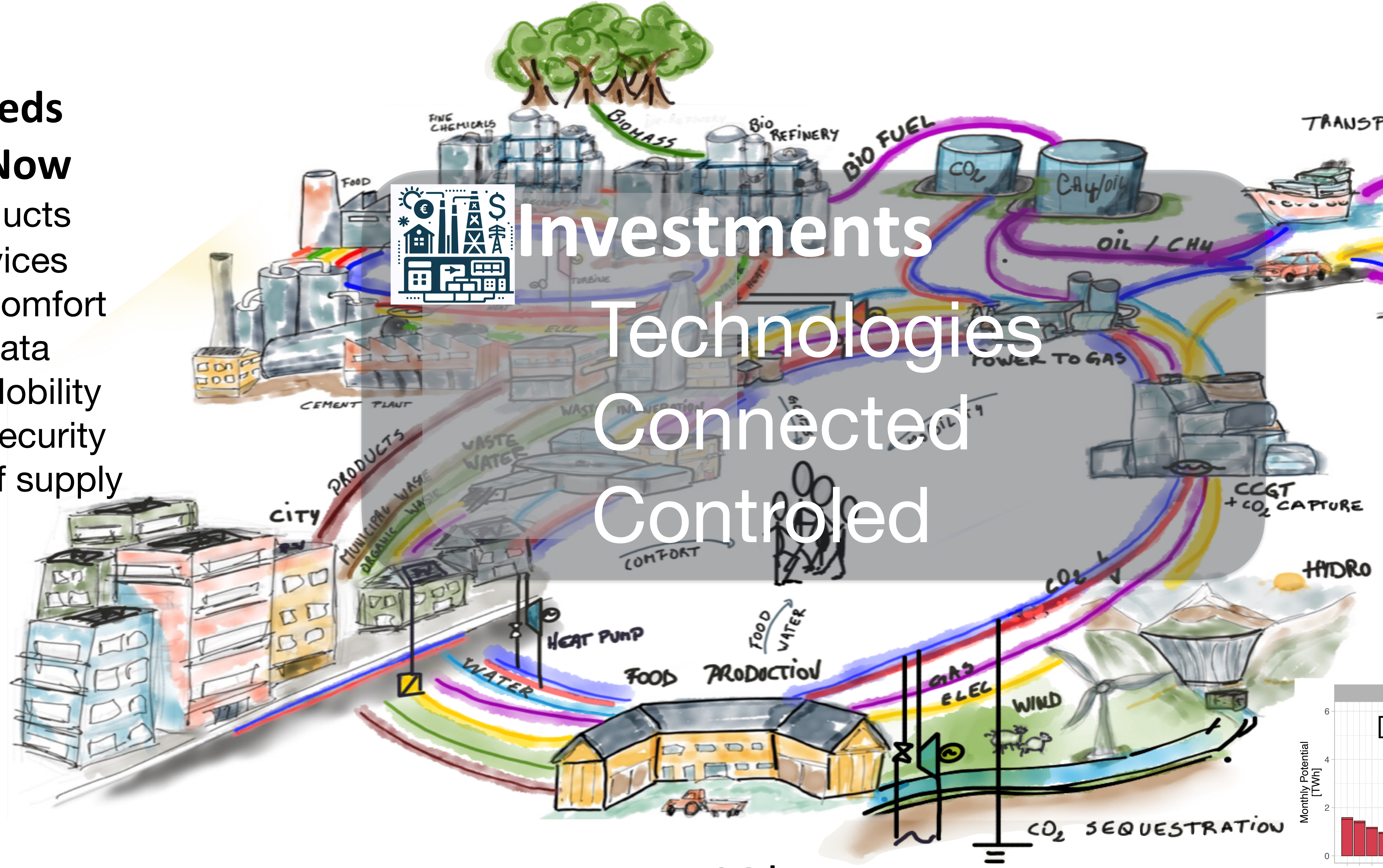




My needs

… Now

- Products
- Services
  - Comfort
  - Data
  - Mobility
  - Security of supply



Investments

Technologies

Connected

Controled

Air

Cooling source
Climate change
Quality

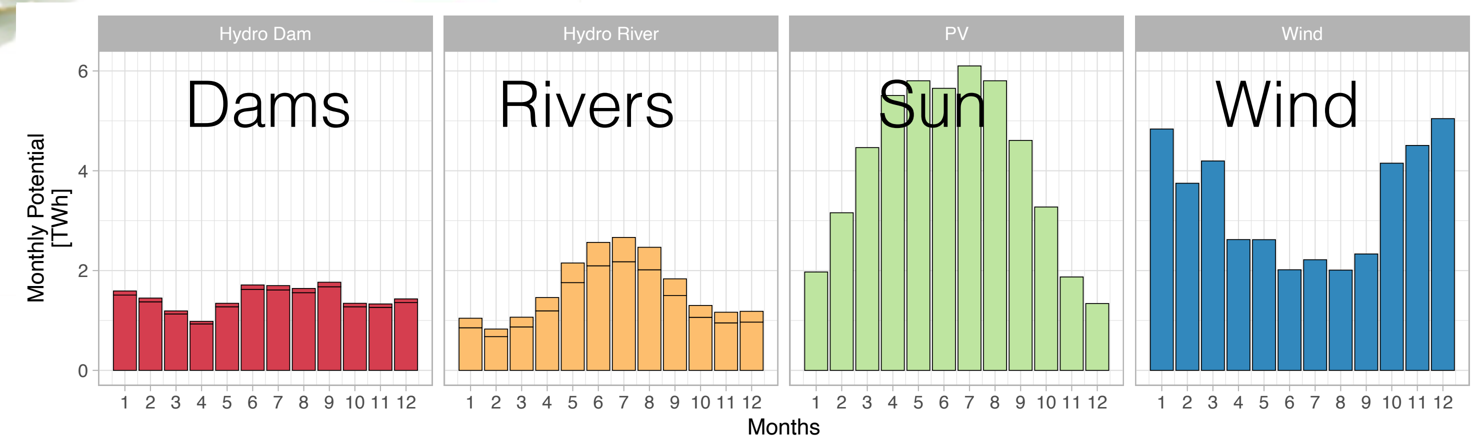
Water

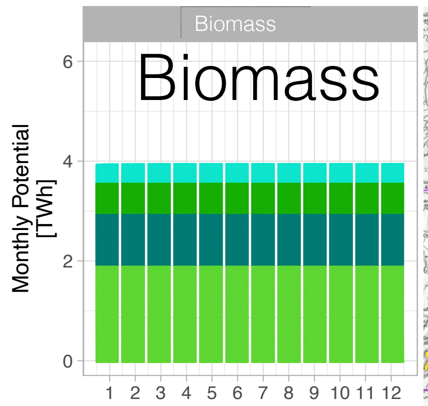
Potable
Used
Irrigation
Cooling
Floods

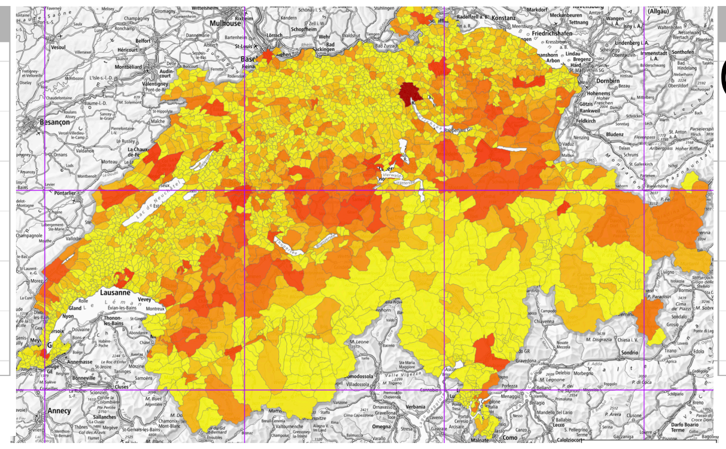
Earth

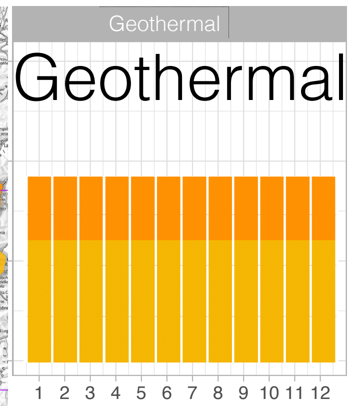
Urbanism
Forest
Landscape
Food
Wildlife
Flora

Fire









My Waste

Recycling
Valorising

ESG* Impact

Future Generations

Environment

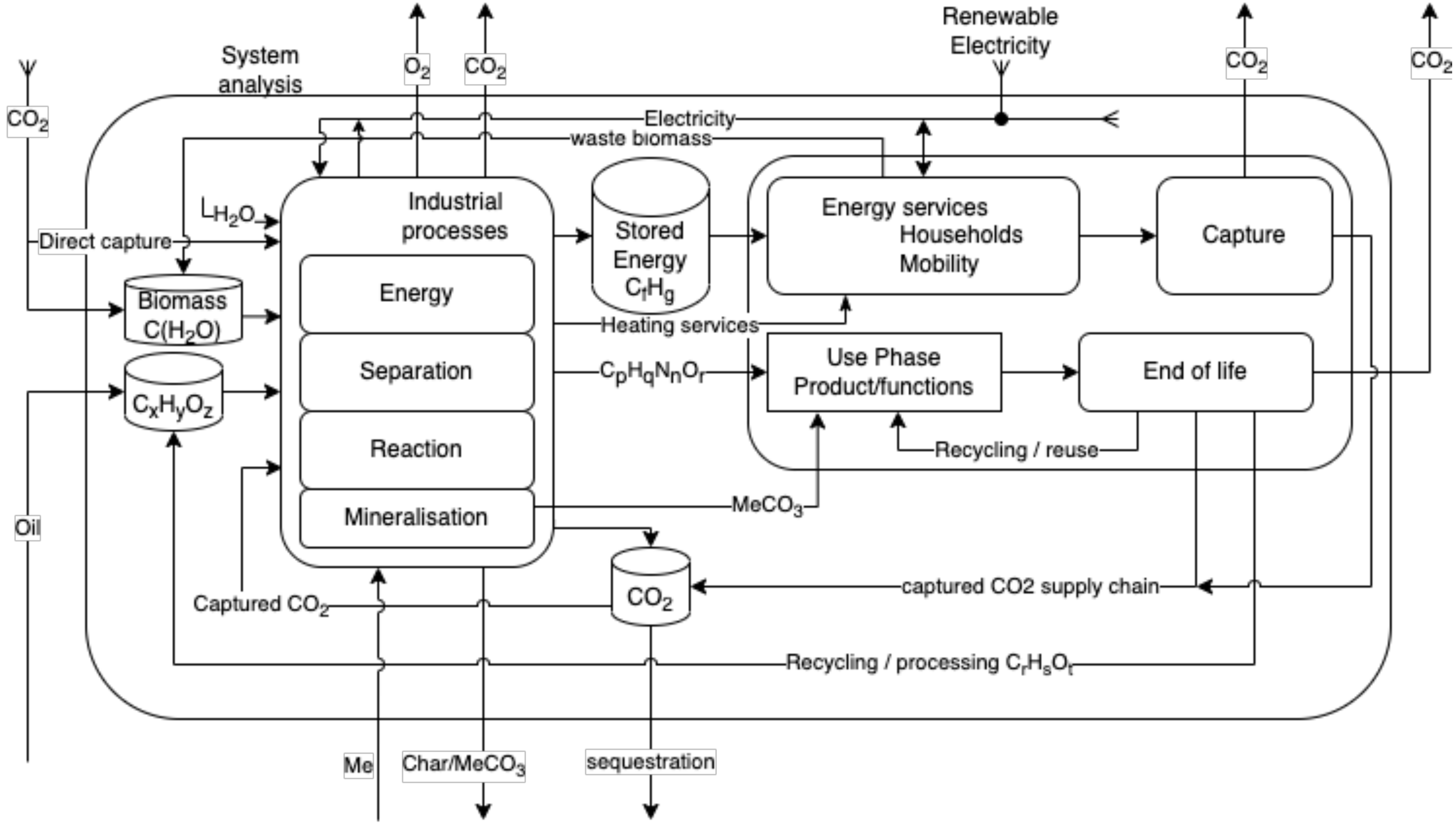
Well-being

Economy

*ESG : Environment - Social - Gouvernance : règles des PFI

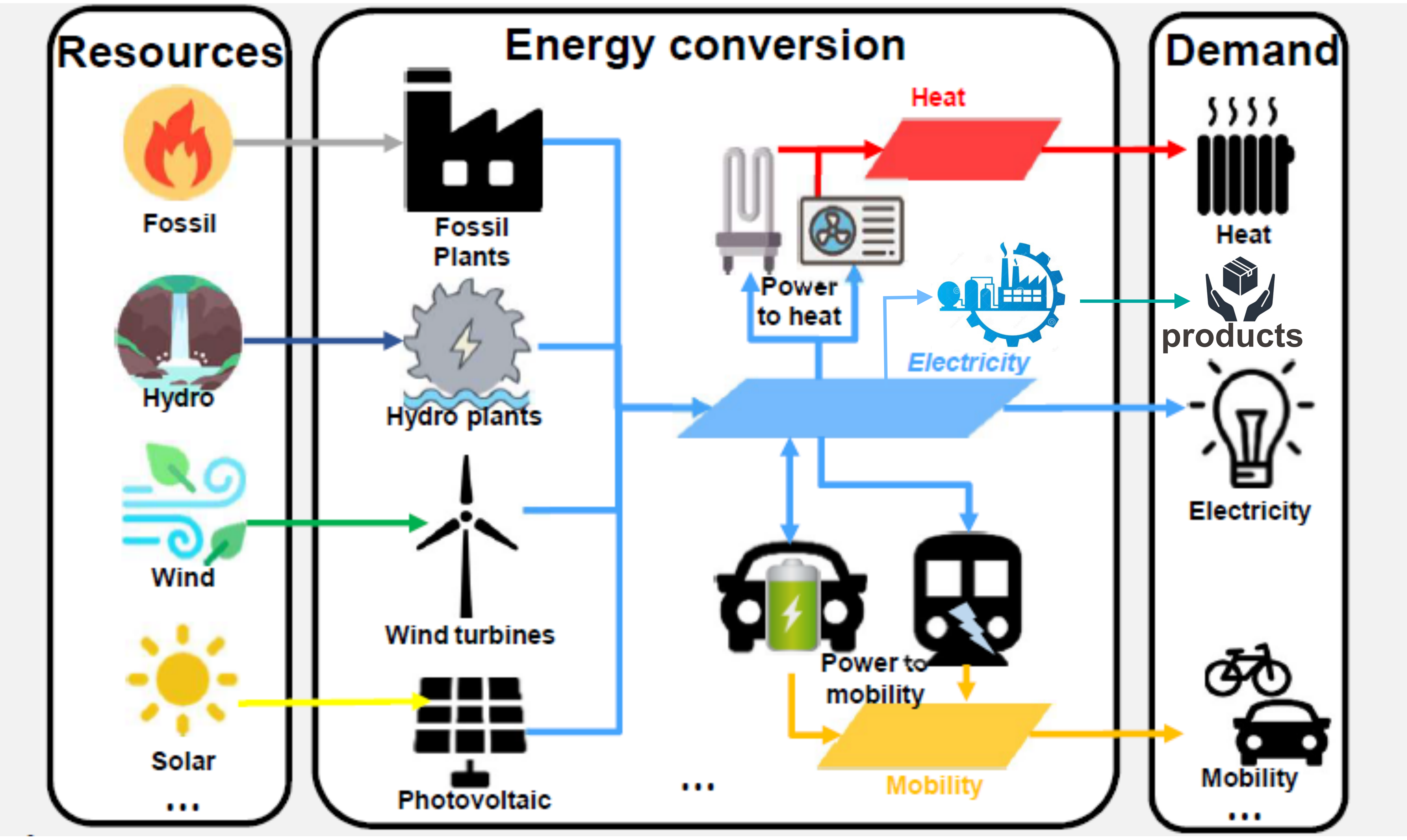
Carbon flows management system

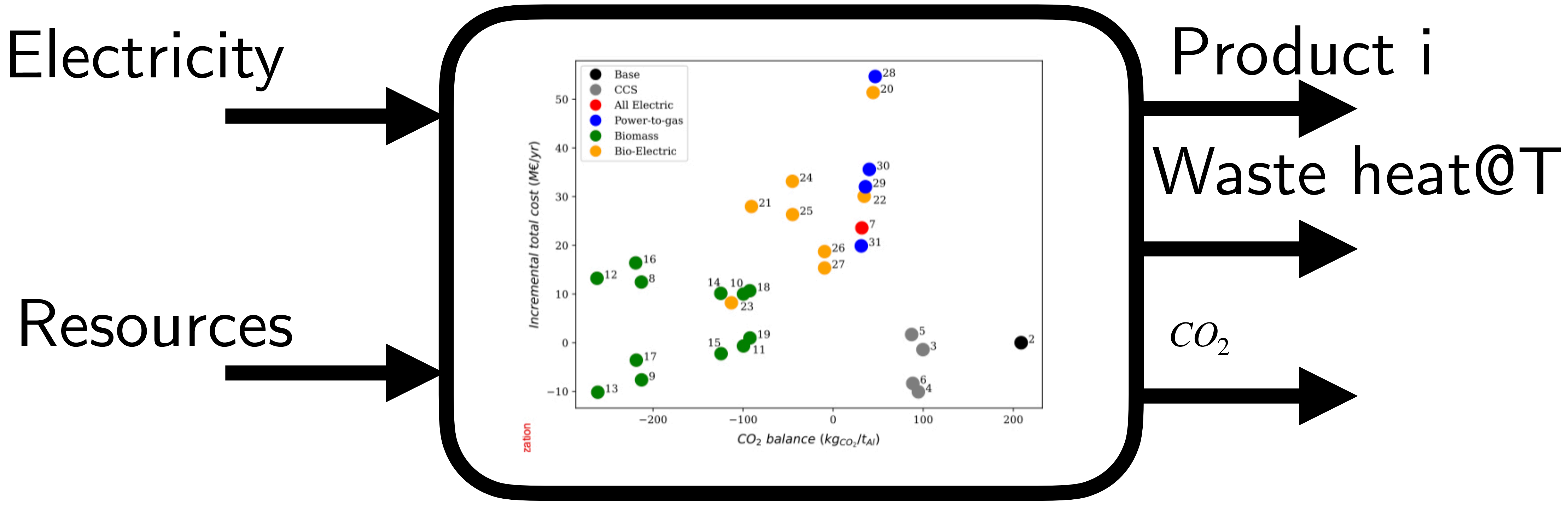
Decision support for engineering the Carbon Flows management in the society

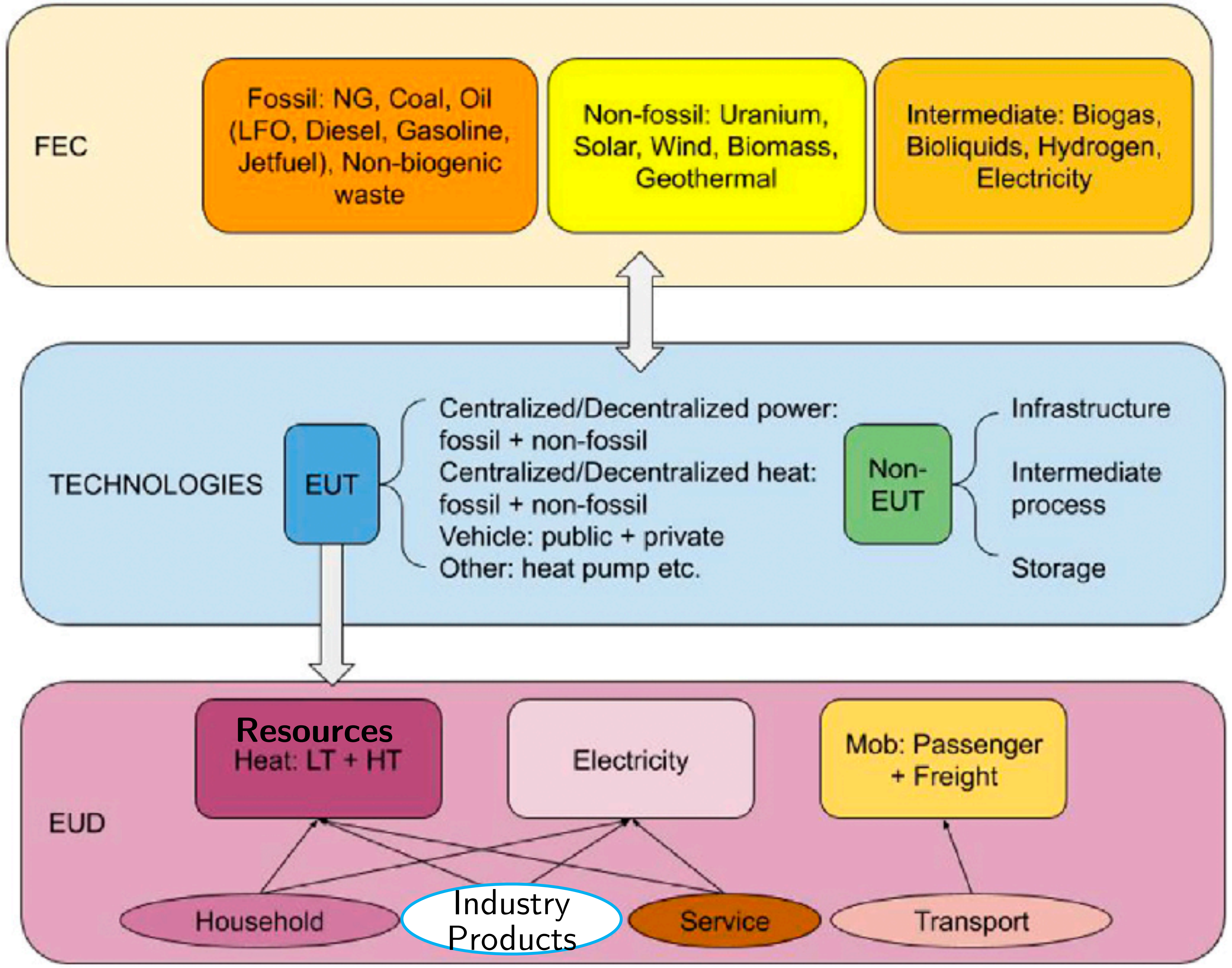


Integration in an energy system in transition

- Feedback loop between process and energy system models (e.g. energyscope)

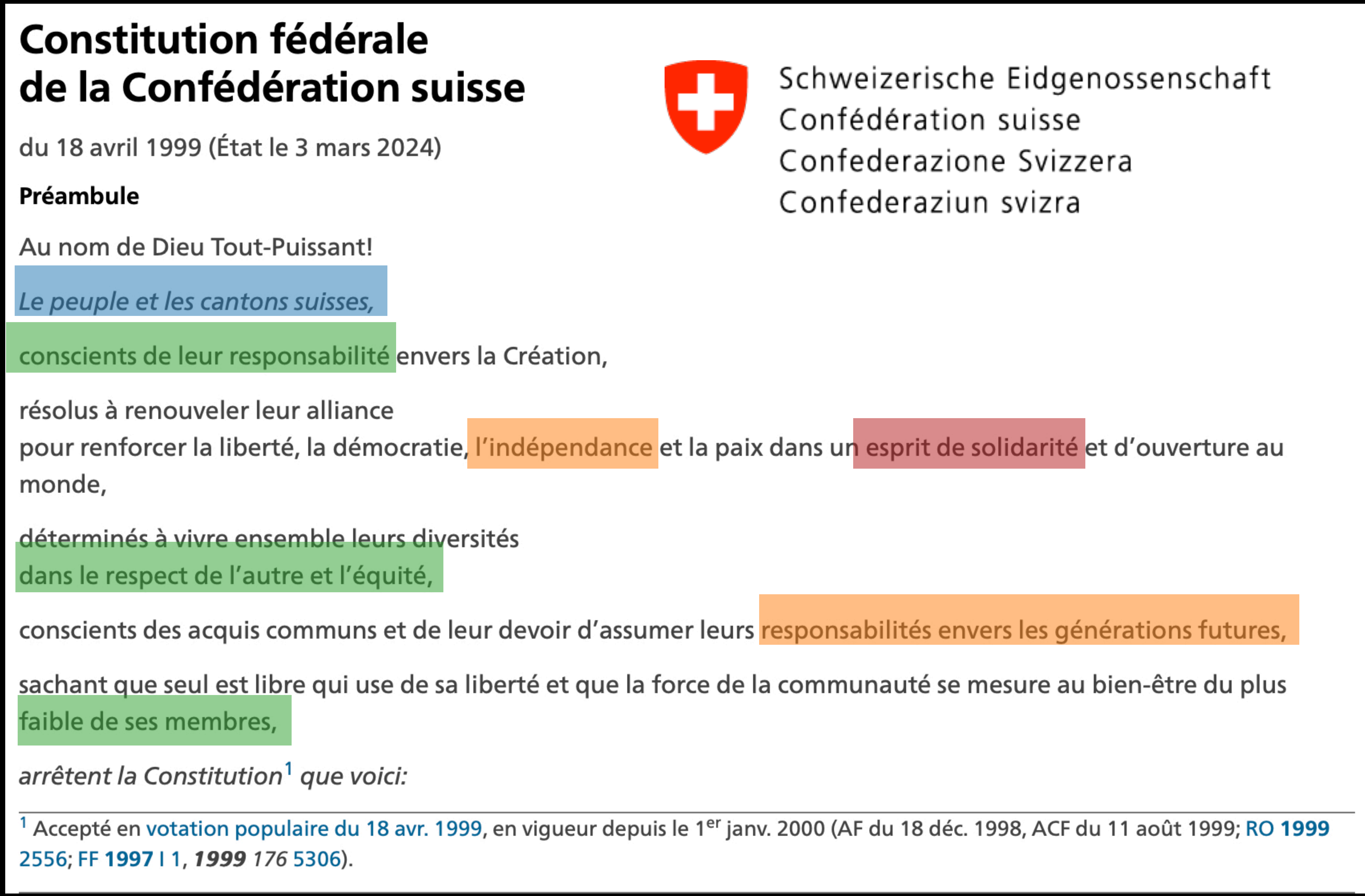






MODELING THE DECISION IN THE SOCIETY

- Constraints
  - security of supply
  - Independence
  - Net-zero CO_2
- What is the goal ?
  - Minimise the cost for the society
- Criteria of comparison ?
  - Environmental Impact
  - Social welfare
  - Fair



Constitution fédérale de la Confédération suisse

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

du 18 avril 1999 (État le 3 mars 2024)

Préambule

Au nom de Dieu Tout-Puissant!

Le peuple et les cantons suisses,

conscients de leur responsabilité envers la Création,

résolus à renouveler leur alliance
pour renforcer la liberté, la démocratie, l'indépendance et la paix dans un esprit de solidarité et d'ouverture au monde,

déterminés à vivre ensemble leurs diversités
dans le respect de l'autre et l'équité,

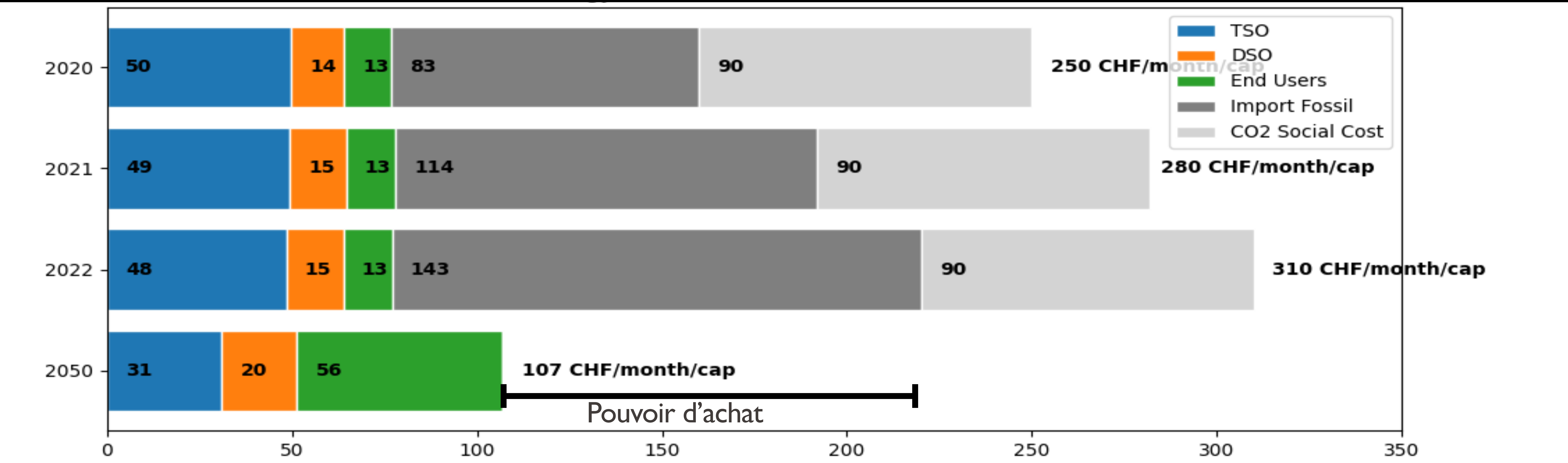
conscients des acquis communs et de leur devoir d'assumer leurs responsabilités envers les générations futures,

sachant que seul est libre qui use de sa liberté et que la force de la communauté se mesure au bien-être du plus faible de ses membres,

arrêtent la Constitution[1] *que voici:*

[1] Accepté en votation populaire du 18 avr. 1999, en vigueur depuis le 1er janv. 2000 (AF du 18 déc. 1998, ACF du 11 août 1999; RO **1999** 2556; FF **1997** I 1, ***1999*** *176* 5306).

THE FUTURE SWISS ENERGY SYSTEM



x 5 : Investments in districts **(communautés d'énergie locales)**

Replace **66%** of the fossil purchases

x 1.8 Investments increase by the distribution operator (**DSO)**

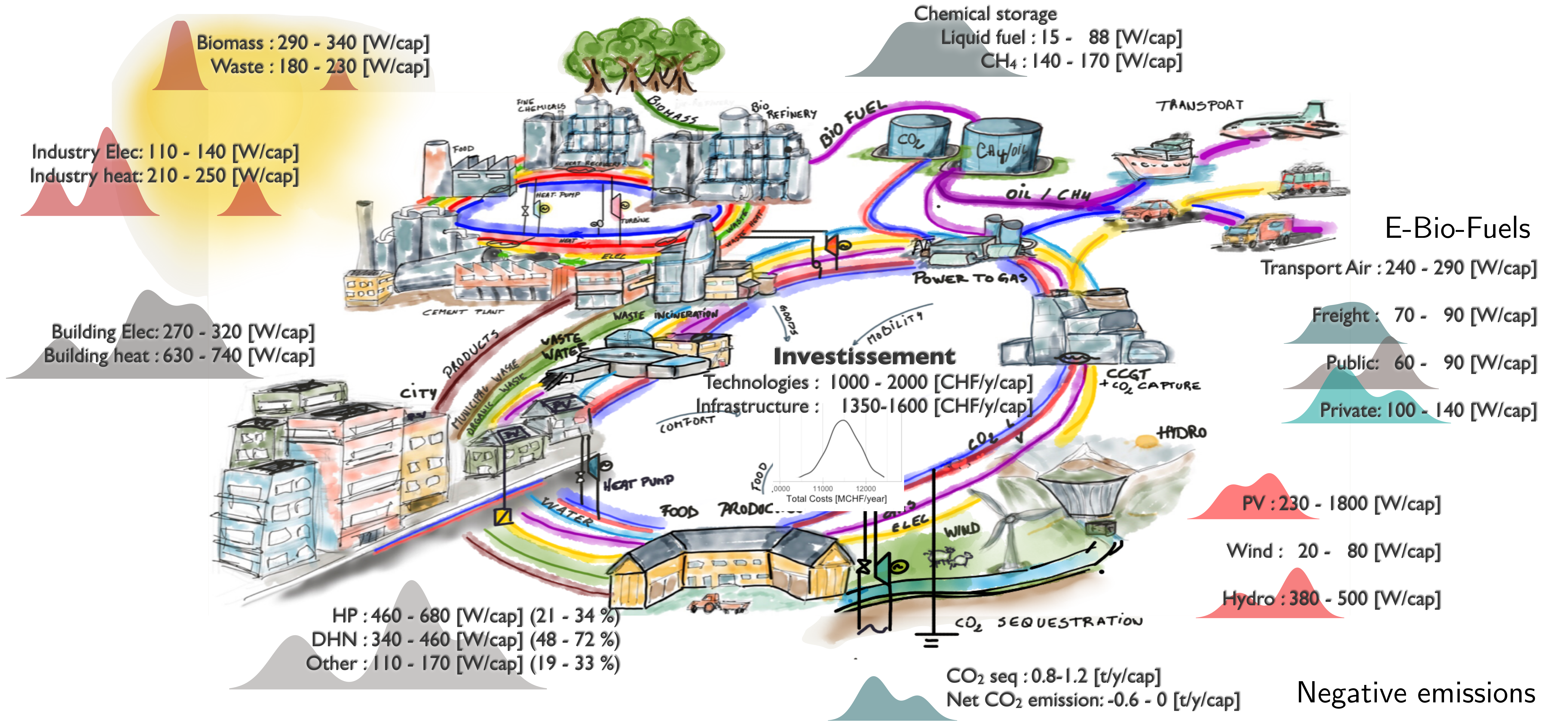
-40% : decrease of the investments in transmission **(TSO)**

33% to 50% : increase of purchase power by private

✓ **Debt constraint:** no additional debt to the future generation due to CO2 emissions

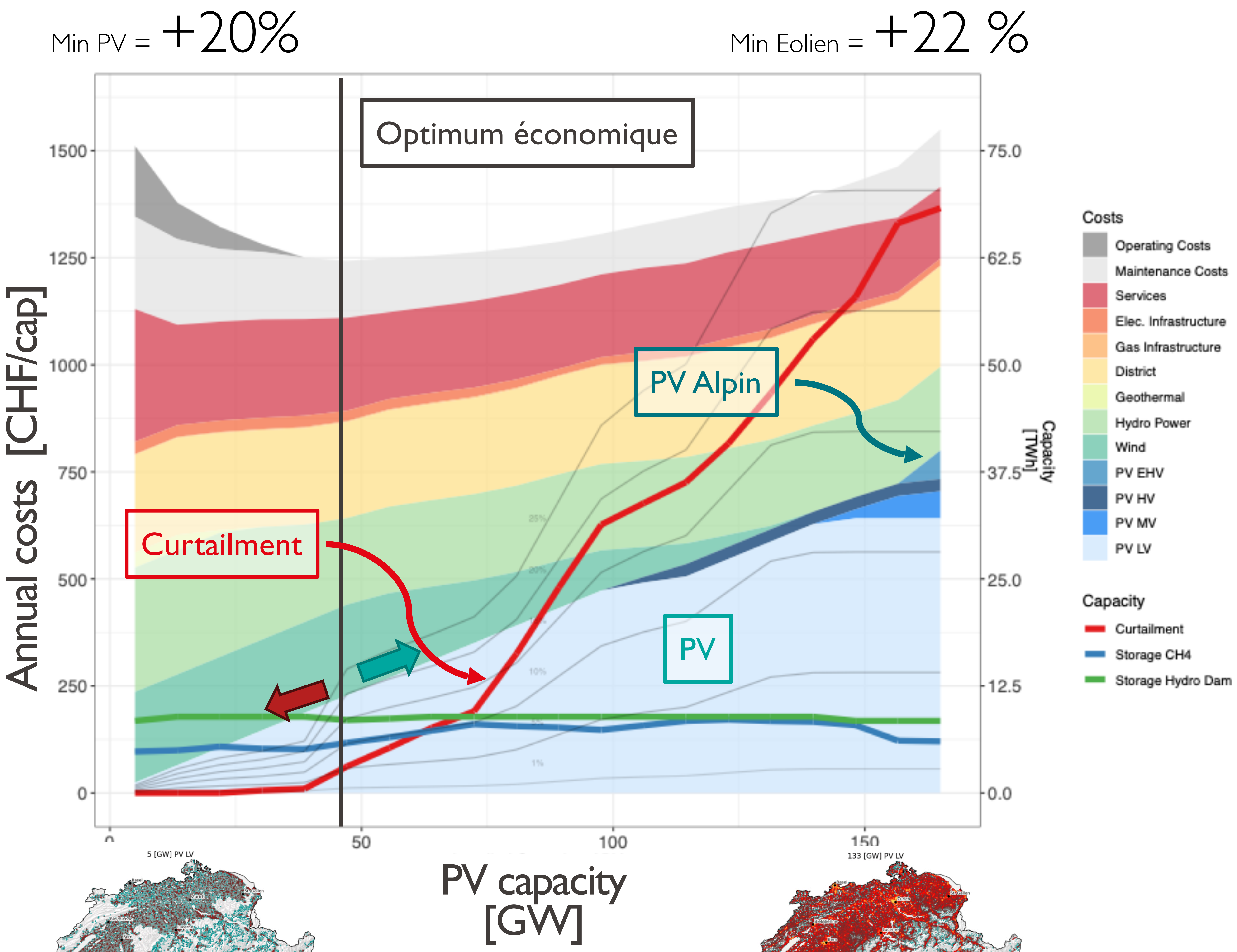
✓ **Stability:** no more market mechanism just reimburse the investment

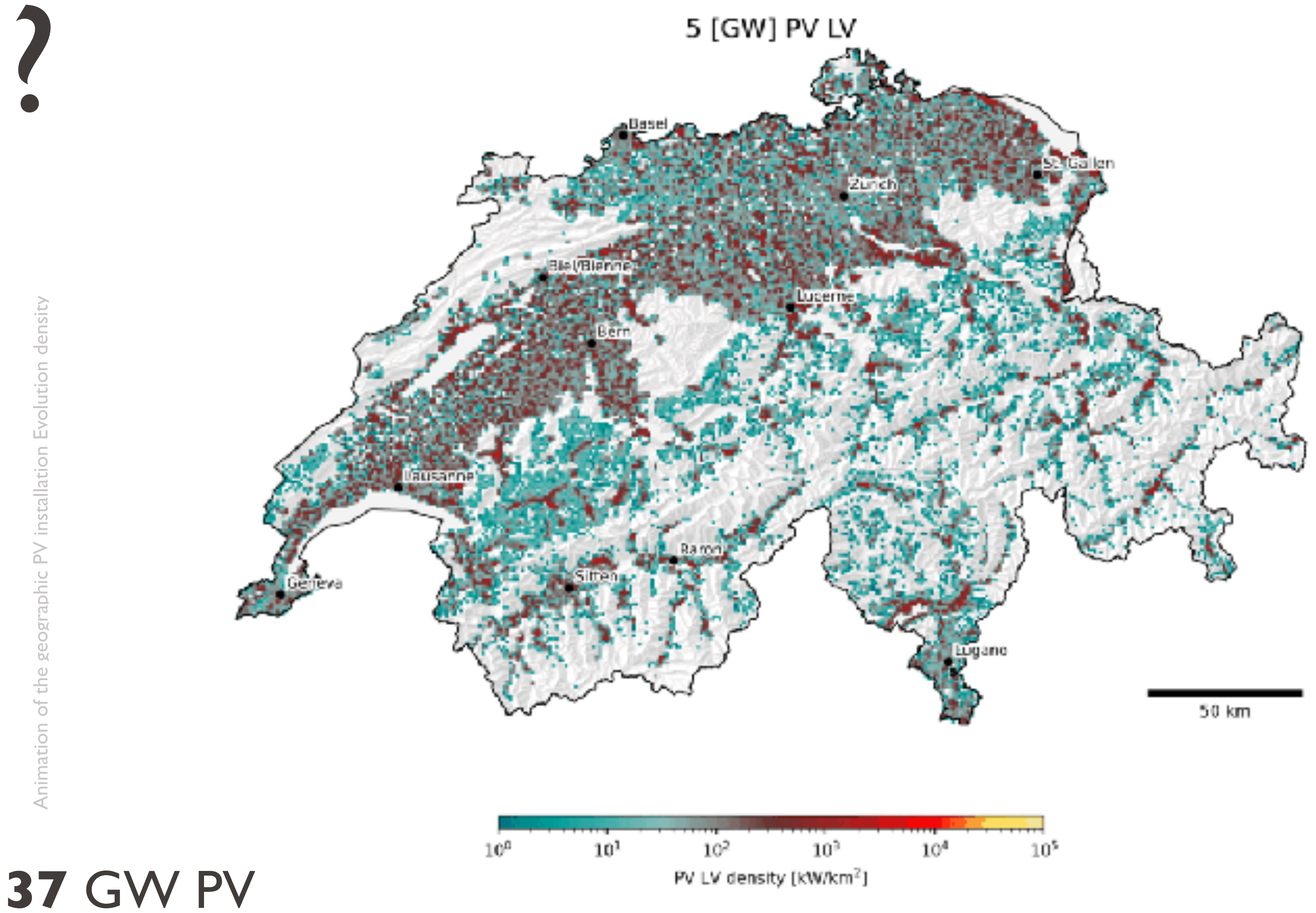
THE ENERGY SYSTEMS CONFIGURATIONS

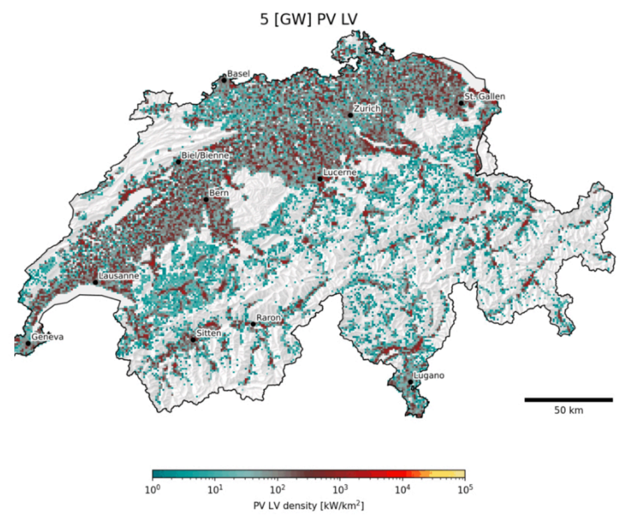


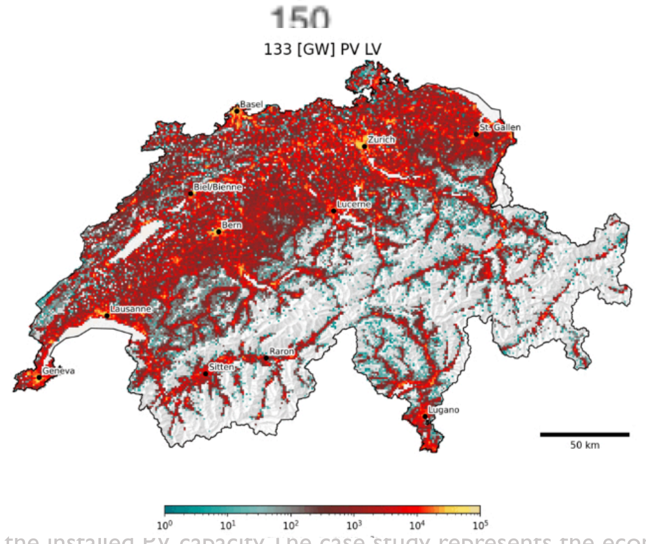
Schnidrig, Jonas, et al. "On the role of energy infrastructure in the energy transition. Case study of an energy independent and CO2 neutral energy system for Switzerland." *Frontiers in Energy Research* 11 (2023): 1164813.

Your Question: Wind vs Photovoltaic ?









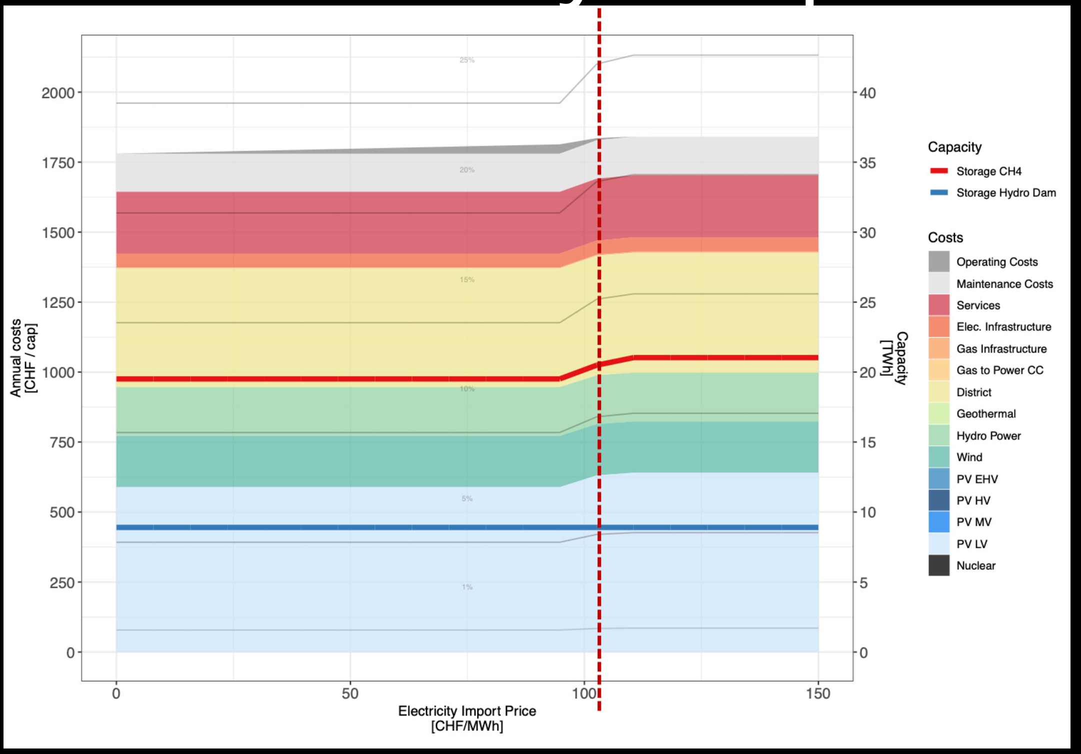
- **Best mix**
  20 GW Wind & **37** GW PV
  - PV: LT grid limits
  - Max potential of wind
- PV ↘
  - Wind to maximum
  - Biomass compensates
    0-15% biomass potential
  - Power2tank2Power via biogenic methane (4.3 —> 6.1 TWh)
- PV ↗
  - Wind is reduced
  - more seasonal storage
  - Power2tank2Power via biogenic methane (6.1 —> 8.8 TWh)

The transparent lines represent the annual PV production fractions, allowing us to compare them with the curtailment depending on the installed PV capacity. The case study represents the economic optimization of a neutral (no net emission) and independent (no import) Swiss energy system in 2050 for a population of 10 Million.

Schnidrig et al. 2024, *Power to the People: Envisioning Decentralized Energy Landscapes - Synergies of Centralized and Decentralized Energy Models through Unveiling the Role of Districts and Self Consumption, Energies*

SMART TRANSITION ?

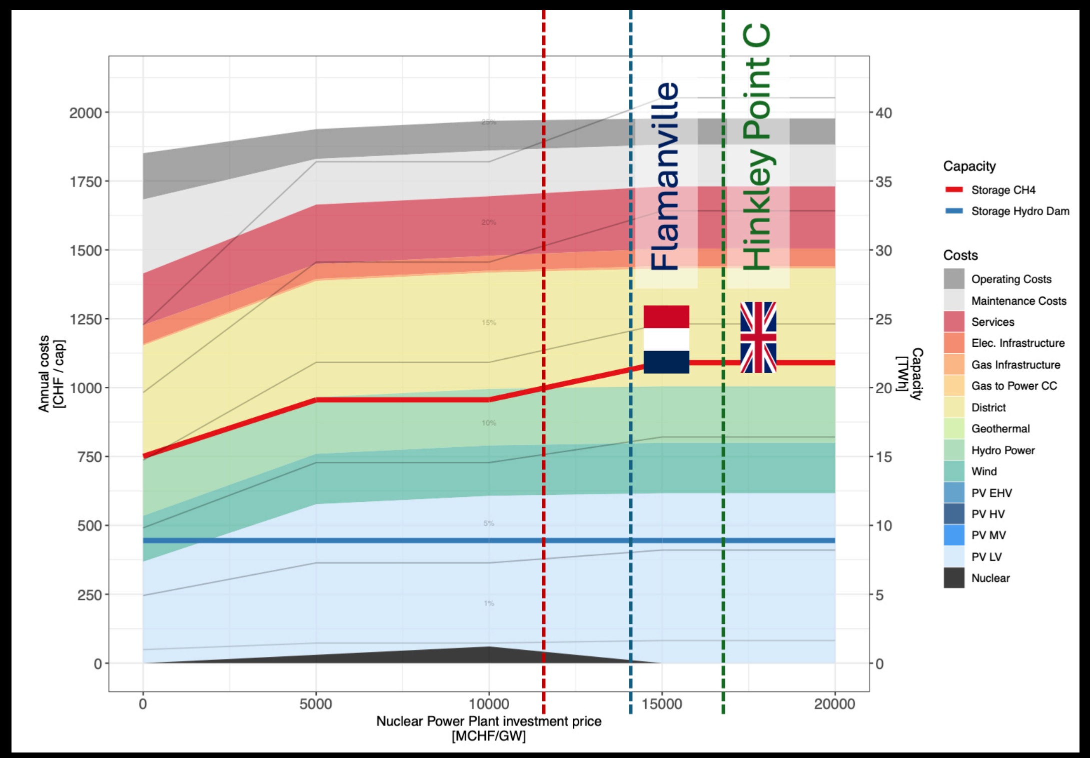
Electricity import



Flexibility services
New markets rules

if <105 CHF/MWh

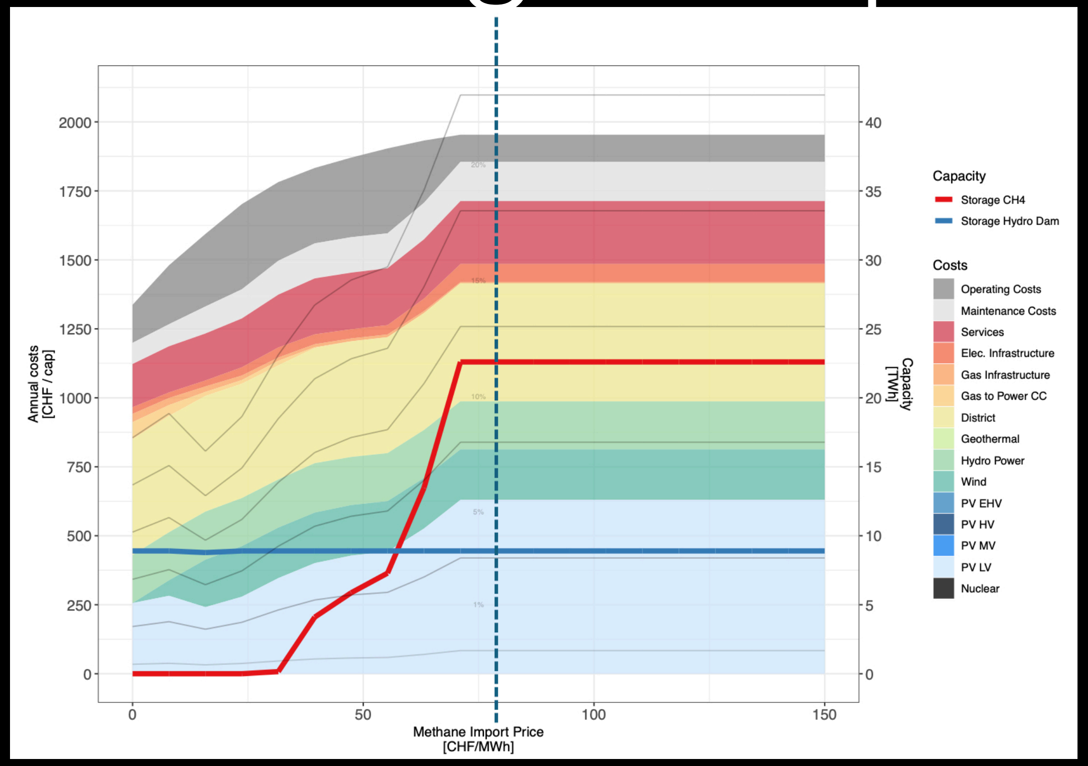
Nuclear



Construction time
>15 ans
CO2 budget in the meantime ?
Substitutes PV
not wind

if investment + waste < 12000 MCHF/GW

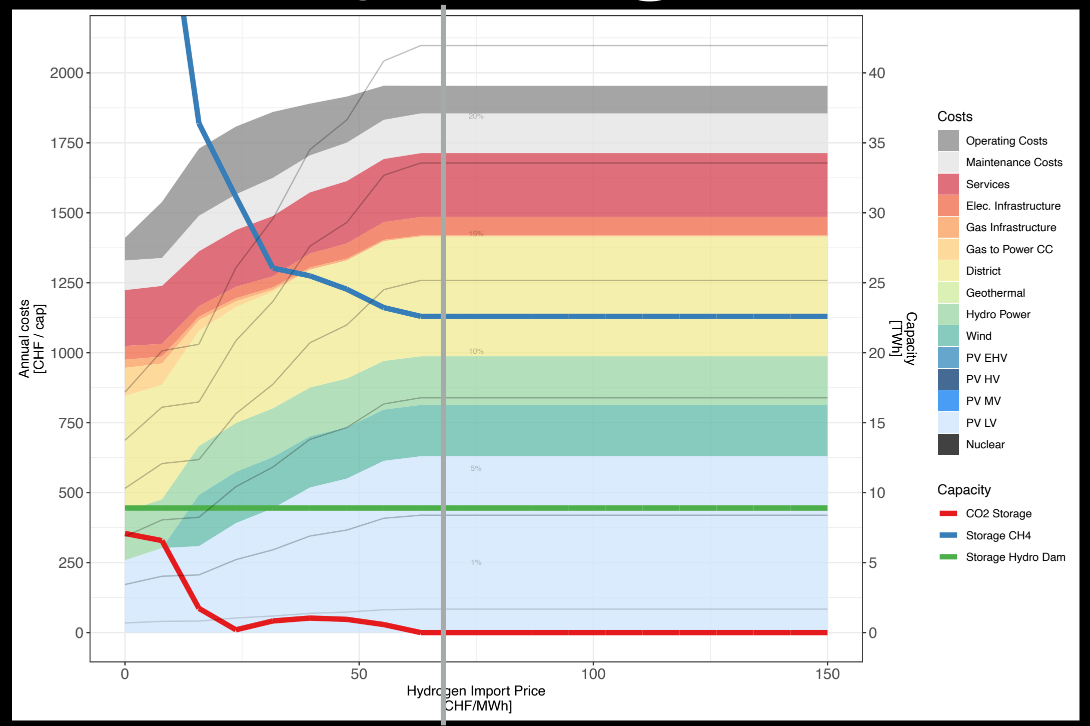
Natural gas import



Scope 2
CO2 Emissions
to compensate

if < 75 CHF/MWh

Hydrogen



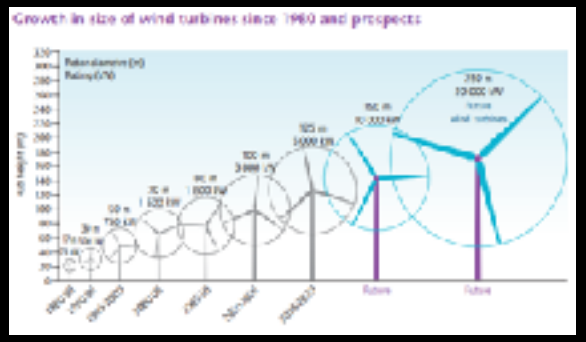
New infrastructure
No need of H2 molecules

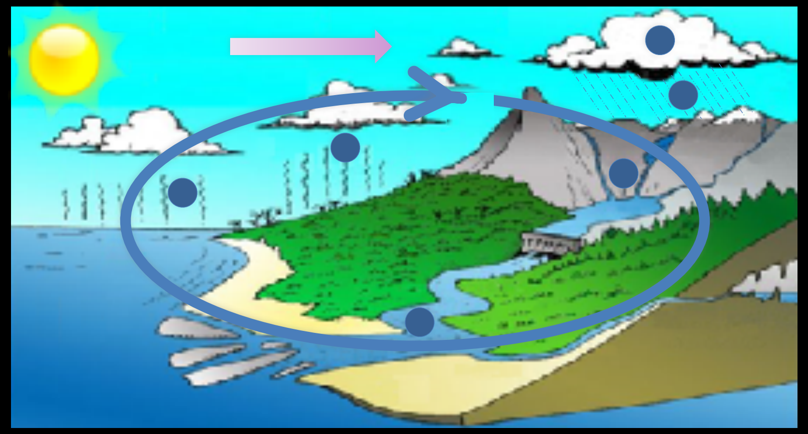
if < 60 CHF/MWh => elec < 4 cts/kWh !

CONCLUSION

$$[kJ_p/hab/an] = \eta_e[kJ_p/kJ_e] \cdot \eta_s[kJ_e/kJ_s] \cdot e_d[kJ_s/an/m^2] \cdot d_{hab}[m^2/hab] \cdot hab[hab]$$

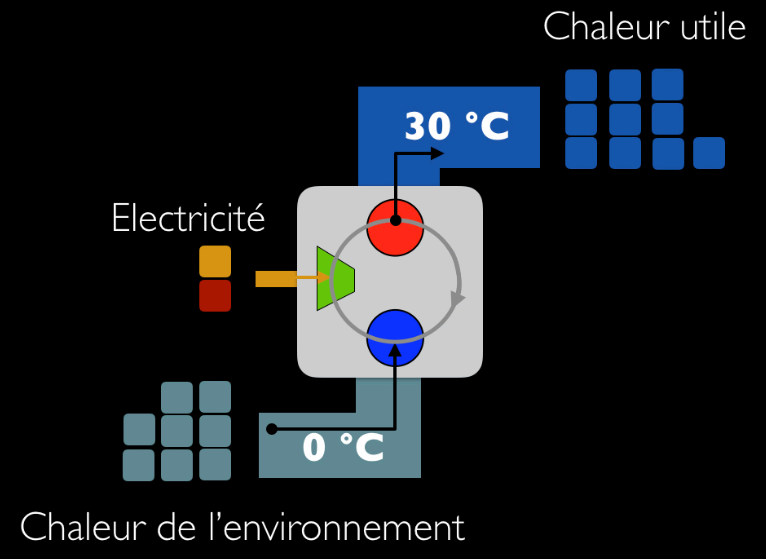
Primary energy
Extraction->resource



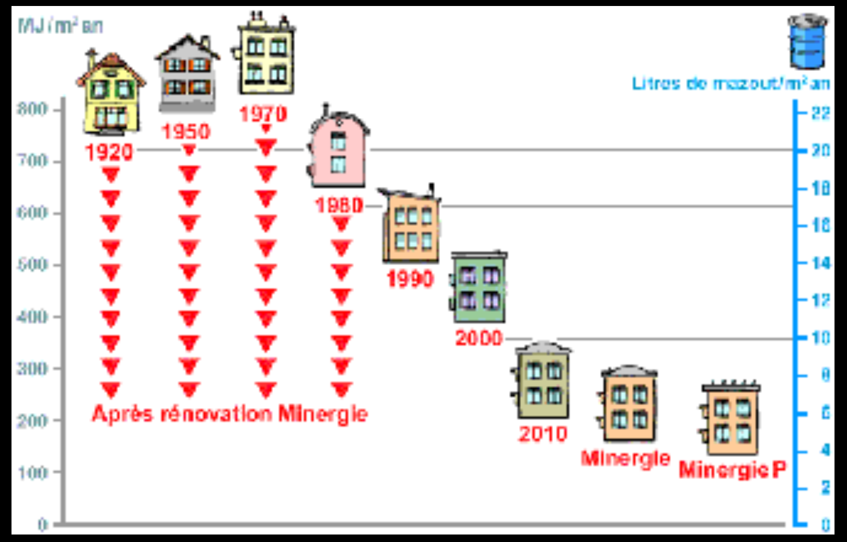


Conditioning
resource->distributed

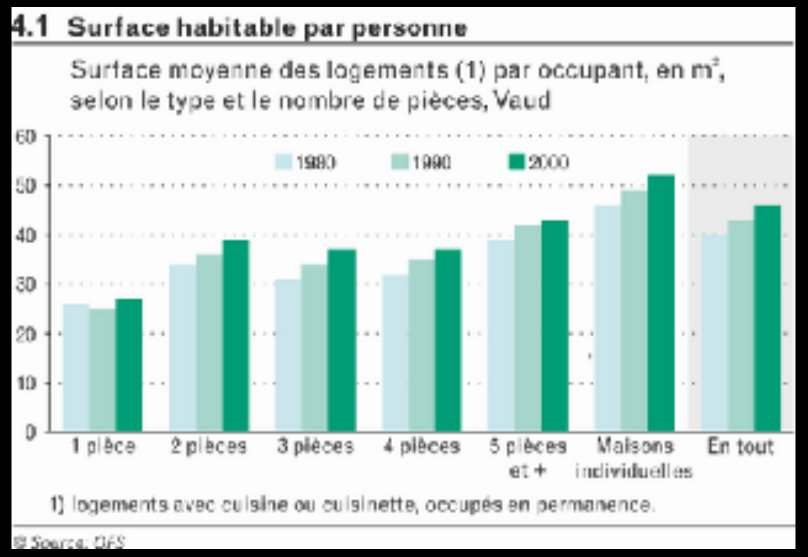
Conversion
Distributed->useful energy

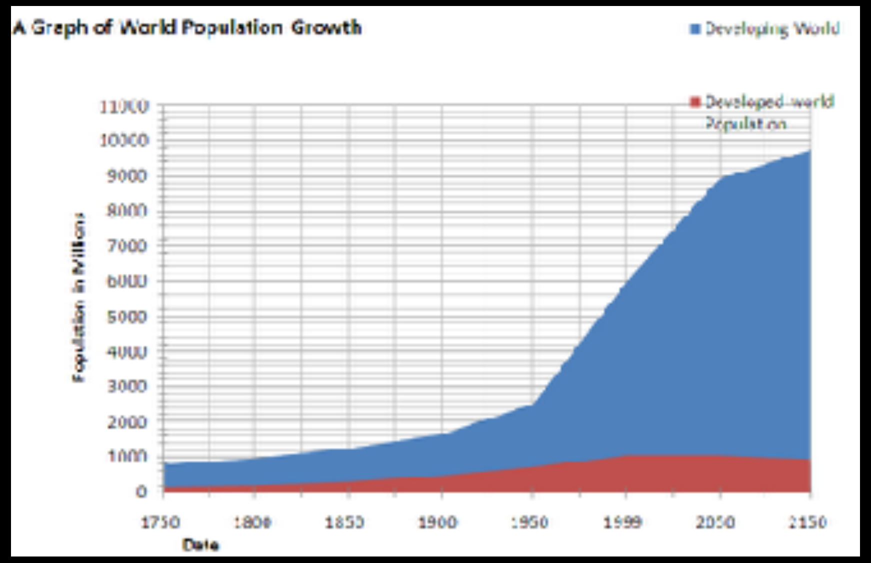


Energy service
Energy->service



Needs
service->cap





Population
cap

ACKNOWLEDGMENTS

- **Sun** : for the energy supply
- **Mother Nature** : to show us the way to store energy
- **Citizen** : to adopt responsible ways to consume
- **Carnot** : to show us the importance of ambiance and efficiency
- **Research** : to develop the methods and the knowledge to develop new technologies
- **Engineers** : to assemble and use the technologies in the right way at the right time
- **Industry** : to give us the technologies and develop circular economy
- **Authorities** : to develop education system and the infrastructure
- **Finance** : to ethically use (our) money for the right goals
- **Tuong-Van, Arthur, Naveen, Pullah, Linda, Tom, Anaëlle, Margaux** for their contribution to this course