Ecole Polytechnique
Fédérale de Lausanne

# DEFOSSILIZE SWITZERLAND : YES WE CAN

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# Industrial Process and Energy Systems Engineering


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EPFL Valais-Wallis
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25 amazing researchers to make our country 100% renewable

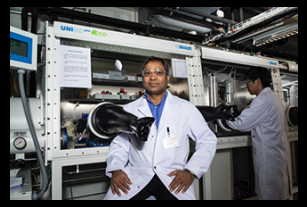
# EPFL VALAIS-WALLIS : A HOLISTIC RESEARCH FRAMEWORK

## CO2 capture

**Prof Berend Smit**
Molecular Simulation

**Prof Raffaela Buonsanti**
Nanochemistry for Energy
**Catalysts for CO2 reduction**

**Prof François Marechal**
Energy system engineering
**System integration**

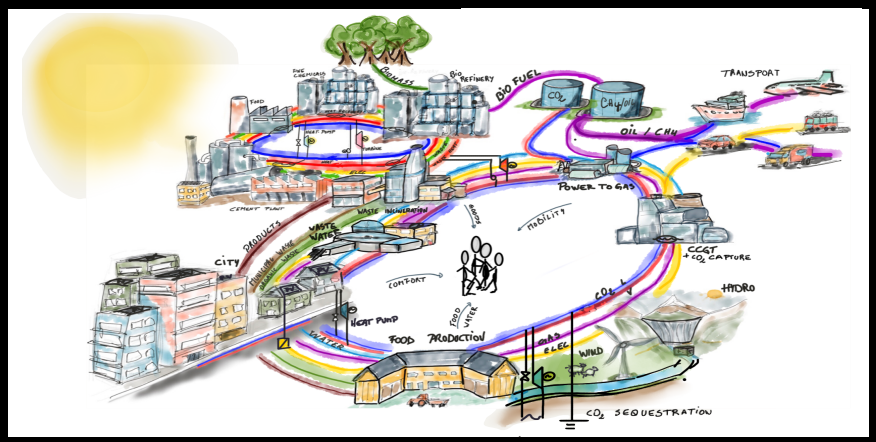


**Prof K. Nazeeruddin**
Molecular Engineering of Functional Materials
**Perovskite solar cells**

**Prof Hubert Girault**
Physical and Analytical Electrochemistry
**Hydrogen stations**

**Prof Wendy Queen**
Functional Inorganic Materials
**MOFS for CO2 capture**

**Prof K. Agrawal**
**Gaznat Chair for Advanced Separations**
**Membranes for gas separation**




Building our fossil CO2 free energy future

**Prof Andréas Züttel**
Materials for Renewable Energy
**Hydrogen and methane production**

**MER Jan Vanherle**
Energy and Materials
**SOFC/SOEC fuel cells**

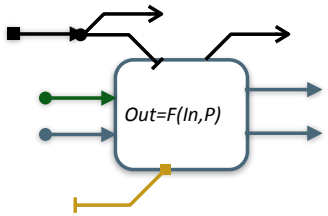
# Developing methods for designing process and energy systems

**Energy services**
**Resources**
**Context & Constraints**

System Boundaries

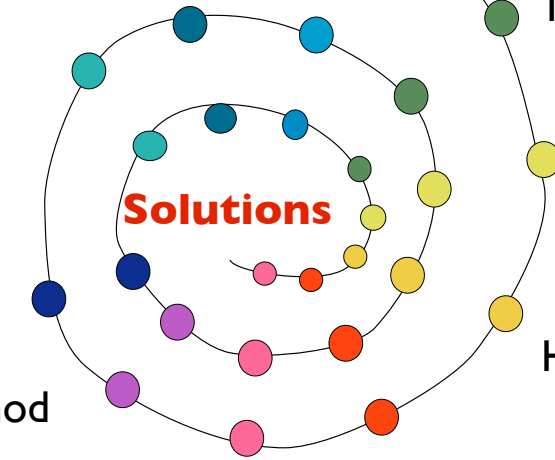
Models
data base

Technology options

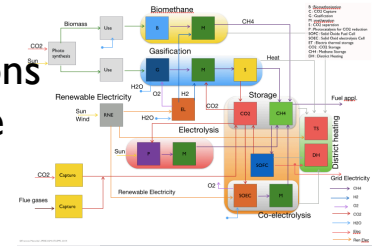



Models

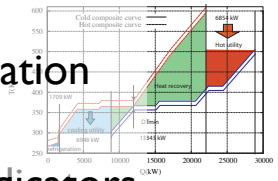
Results analysis
- Exergy analysis
- Composite curves
- Sensitivity analysis
- Multi-criteria




Interconnections
superstructure



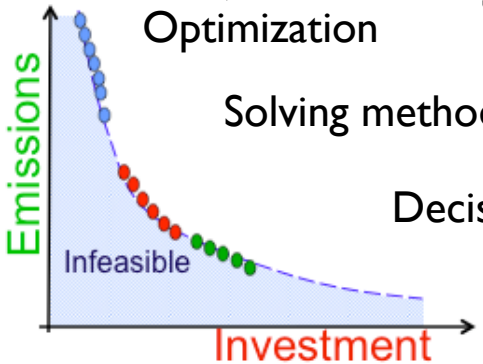
Heat &
Mass integration



Multi-objective
Optimization

Solving method

Decision variables




Thermo-economic Pareto

System performances indicators
- Economic
- Thermodynamic
- Life cycle environmental impact

# Domains of application

## Energy efficiency

Industrial Symbiosis
- From audits to implementation
- Large scale integration
- Grids flexibility services

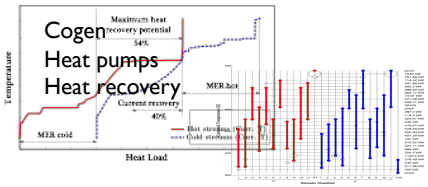
Energy and resources Audits

New technologies
Process Optimisation

Processes

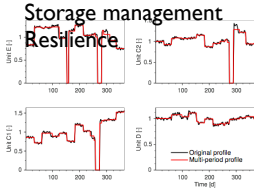
Heat recovery and energy conversion

Cogen
Heat pumps
Heat recovery




Operation

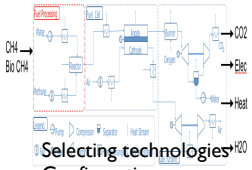
Scheduling
Storage management
Resilience




## Process system design

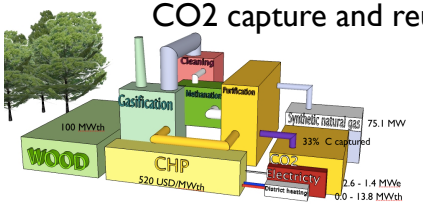
Fuel cell based systems
Bio-refineries & Bio-energy
CO2 capture and reuse
Long term electricity storage

Fuel cell



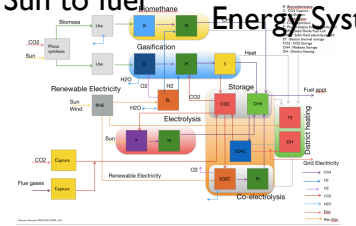

Selecting technologies
Configuration
Size
operation

Biofuel & Bio-refineries




CO2 capture and reuse

Sun to fuel

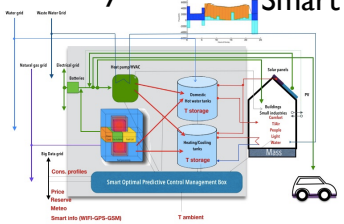



Energy Systems

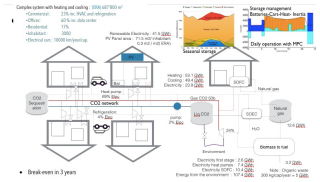
## Energy system design

Smart systems
- Design of MPC piloted systems
- Multi-energy micro grids
- CO2 network

Smart systems

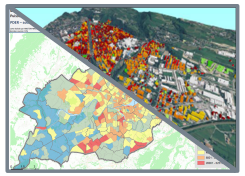



Smart grids/district networks



Industrial symbiosis

Energy System



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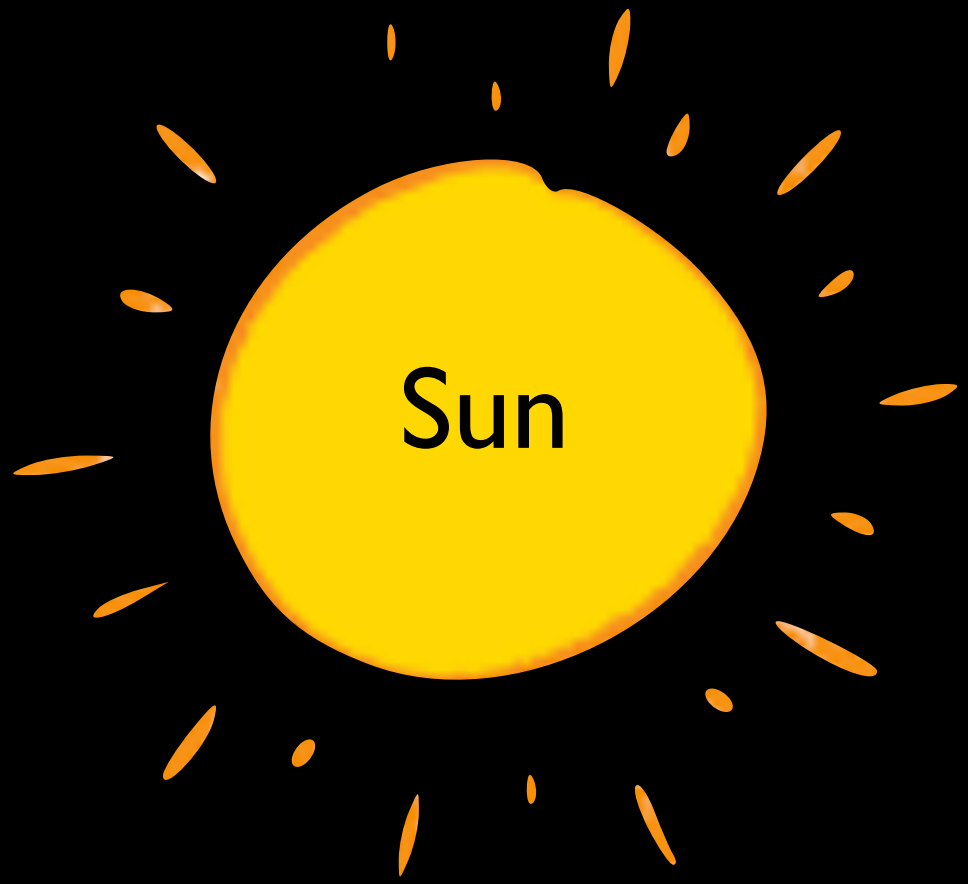
# DO WE HAVE REALY A PROBLEM OF ENERGY ?




1.5 hours

time needed to supply our yearly needs

6500 years

number of years we can survive if we store
1 year of solar energy received

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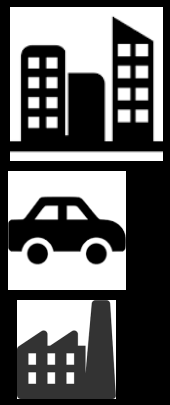
# OUR ENERGY NEEDS


FOOD
0.25 l oil eq./day
100 l oil eq./year

100 l gasoline/hab/year

Oil
5.5 l/day

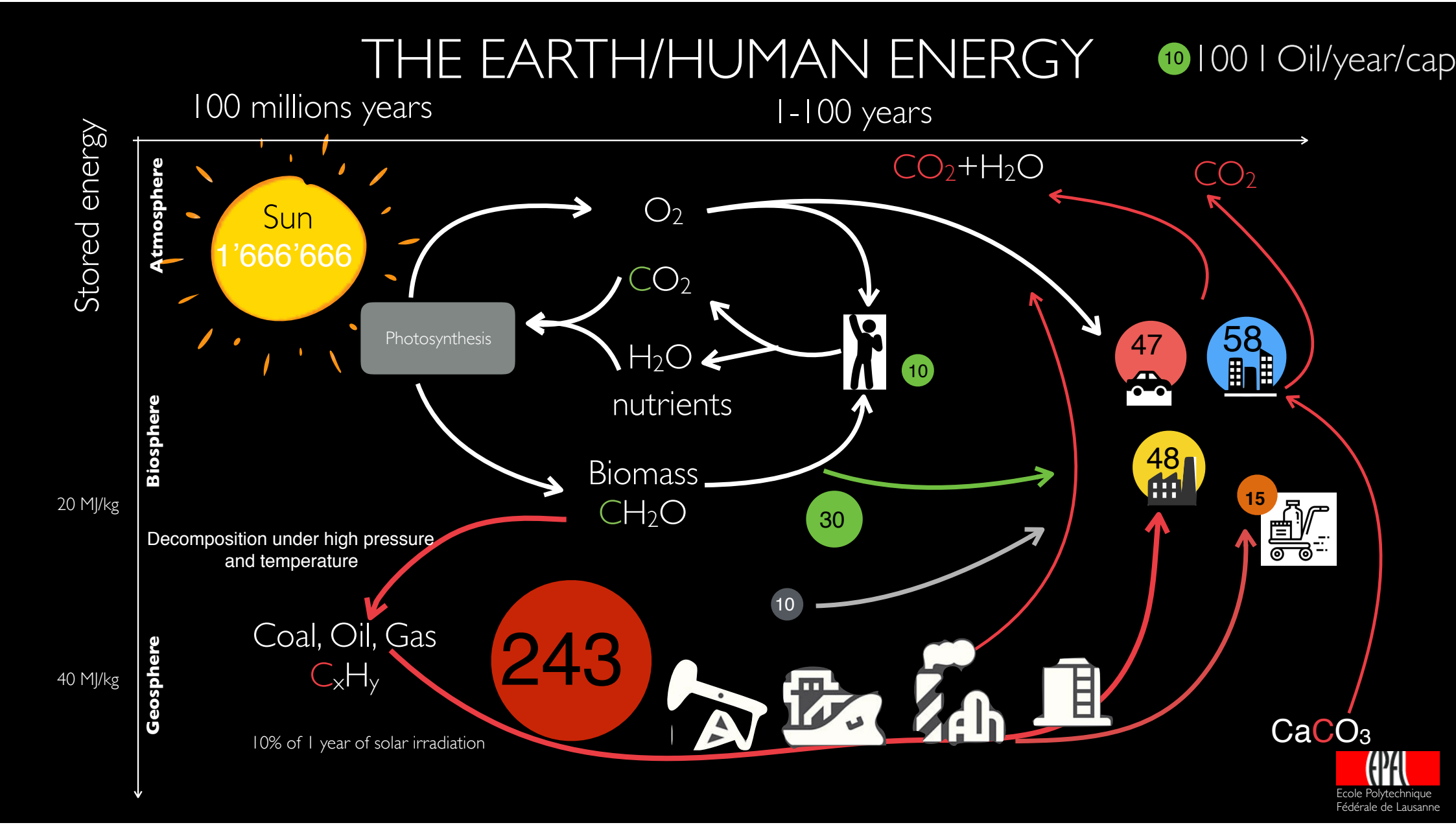



CO2 :14 kg/day



Waste : 1.3 kg/day
Bio-waste : 0.7 kg/day

Per capita consumption per day in Oil eq.


THE EARTH/HUMAN ENERGY
10 100 l Oil/year/cap
100 millions years
1-100 years
Stored energy
Atmosphere
Biosphere
Geosphere
Sun
1'666'666
Photosynthesis
$O_2$
$CO_2$
$H_2O$
nutrients
10
$CO_2+H_2O$
$CO_2$
47
58
48
15
Biomass
$CH_2O$
30
10
20 MJ/kg
Decomposition under high pressure
and temperature
Coal, Oil, Gas
$C_xH_y$
243
40 MJ/kg
10% of 1 year of solar irradiation
$CaCO_3$
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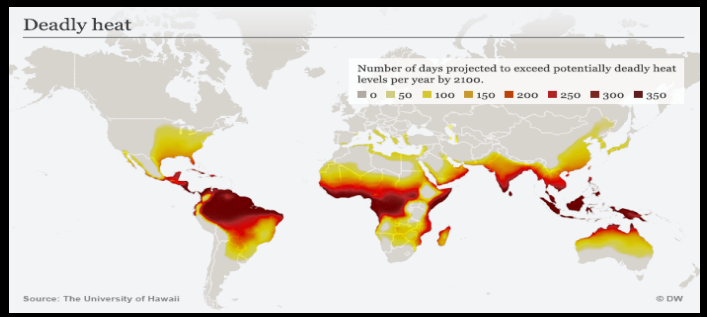
# GLOBAL WARMING


The
ENGLISH WINE
Collection

# IMPORTANT ALERTS

Floodings/slow hurricanes

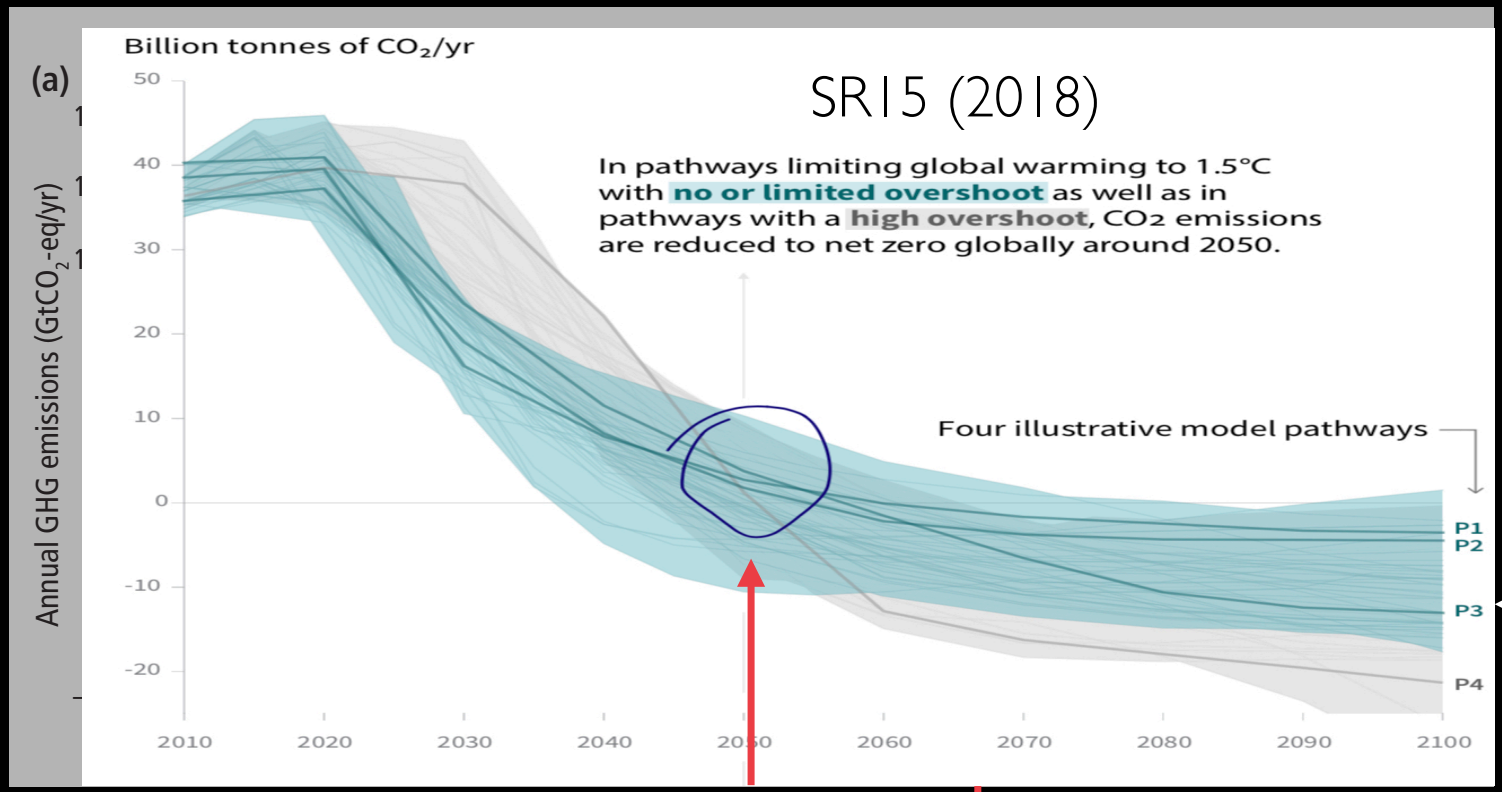

Heat waves


Fire/drought


Temperatures higher then dry bulb for human body ?

# FOSSIL CARBON EMISSIONS




COP 21 target

0 net Fossil carbon emissions in 2050

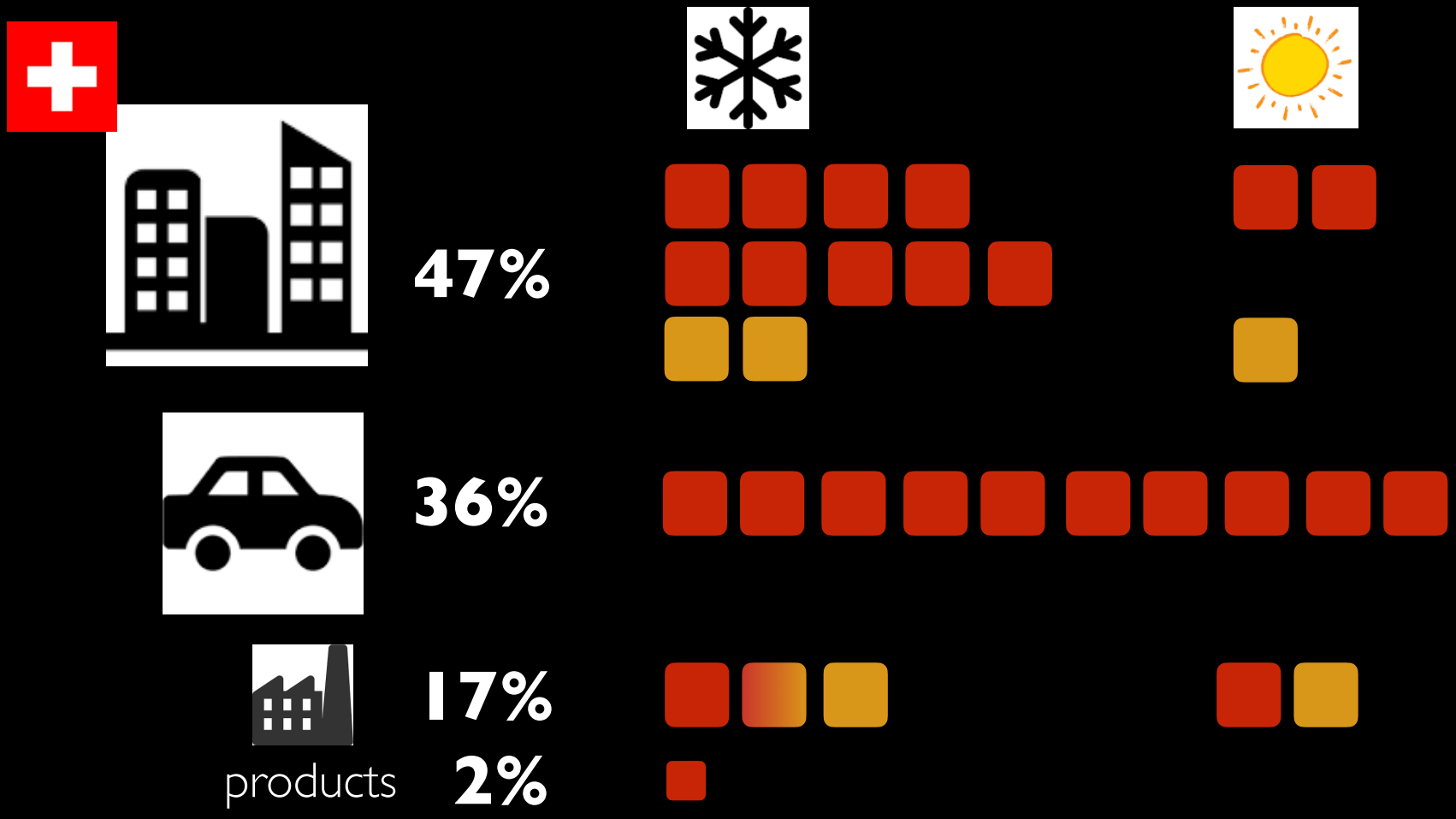
0 net Fossil carbon emissions in 2070

IPCC AR5 (2015)

# IS IT POSSIBLE TO MAKE A COUNTRY AUTONOMOUS ?

- without CO2 emissions
- without importing energy
- without reconstructing the whole infrastructure
- without loosing money

# ENERGY NEEDS




100 l gasoline/hab/year

Electricity

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# THE CONVERSION CHAIN

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

Primary resource

→ Conversion resource->distributed

→ Efficiency distributed->service

→ Sobrety service->needs

→ Needs needs->hab

→ Population hab

# THE NEEDS

Sobriety
service->m2 heated

*

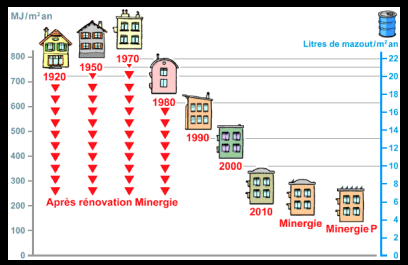
Comfort
m2->hab

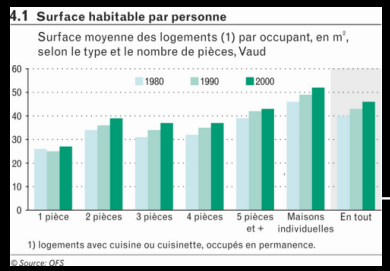
*

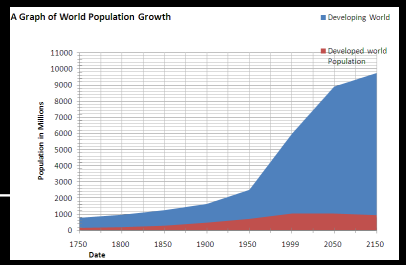
Population
hab

=

Service
service/hab



# HOW TO SUPPLY HEAT IN BUILDINGS ?

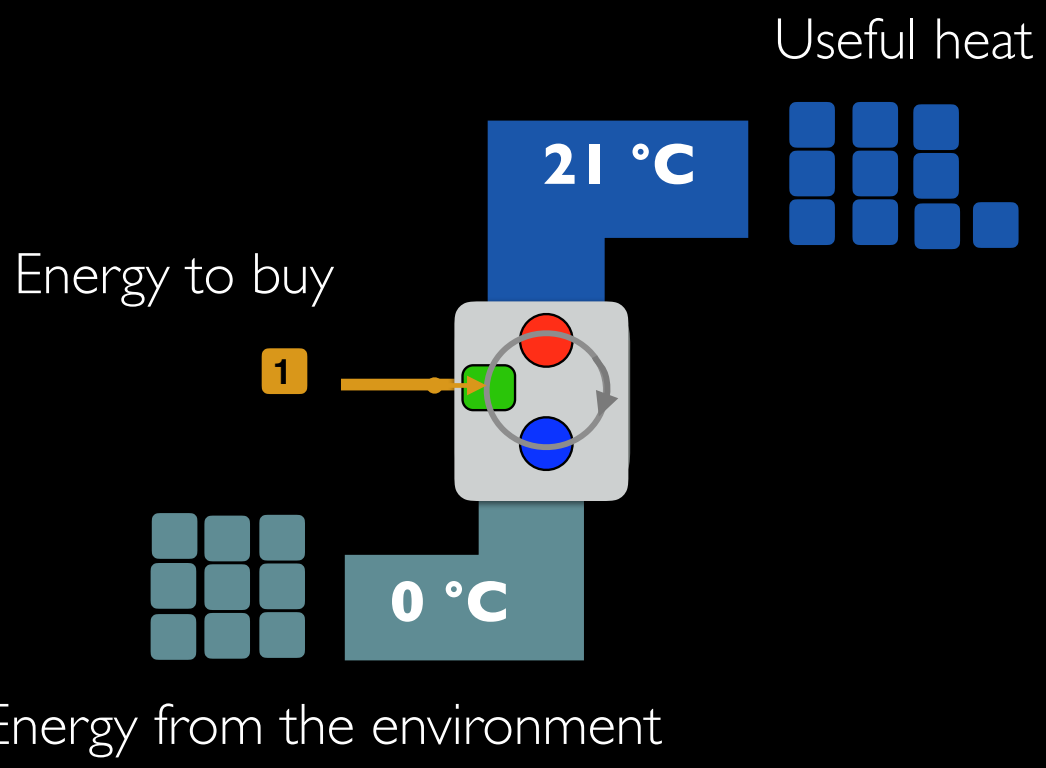
## WHAT THERMODYNAMICS TELLS US ?

For 10 units of heat take 9 in the environment and buy one in form of electricity

Nicolas Léonard Sadi CARNOT (F)
1796 - 1832

$$\dot{E} = \dot{Q}(1 - \frac{T_{cold}}{T_{hot}})$$

*fraction to be taken in the environment*

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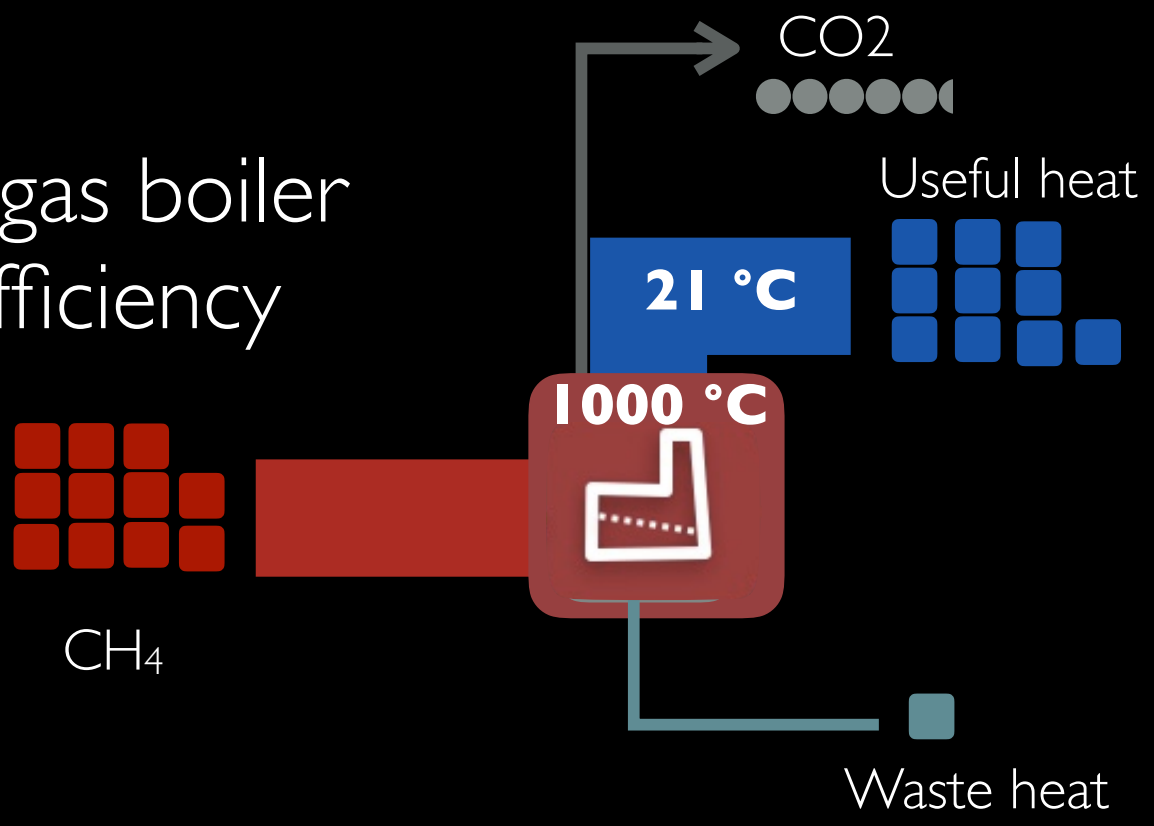
# HEATING A BUILDING

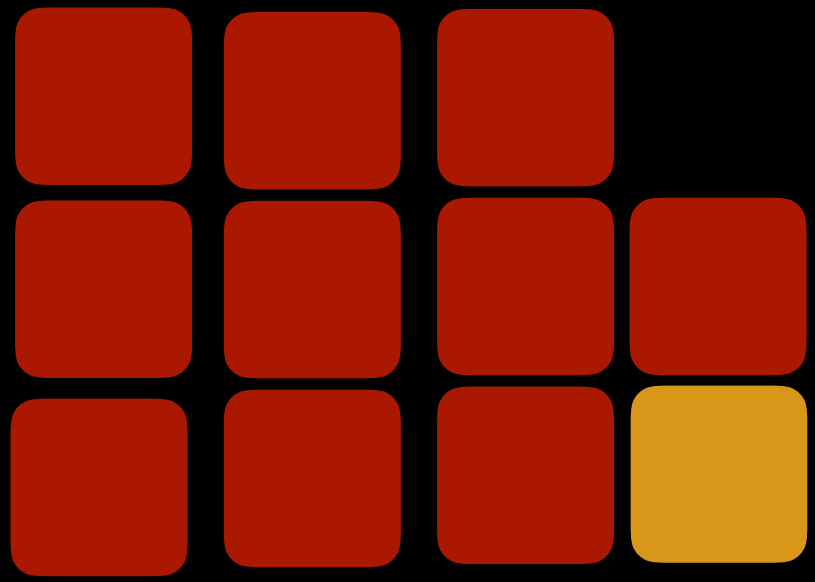
**47%**

Natural gas boiler
90% efficiency



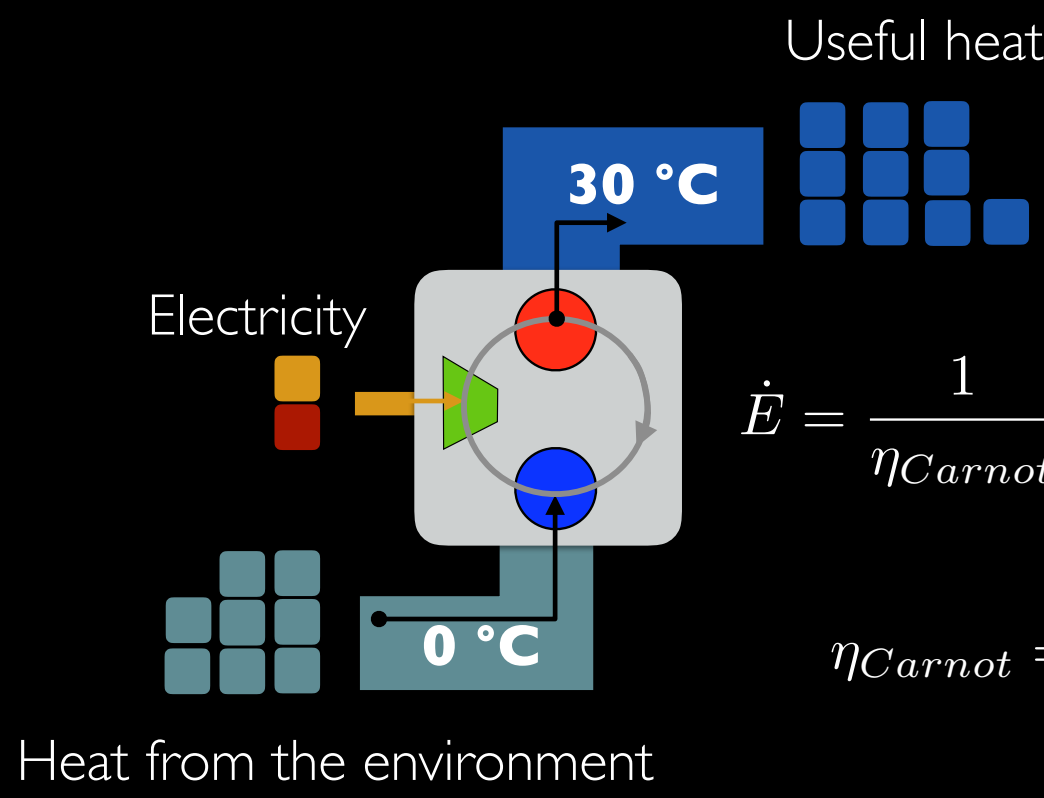
# WHAT IS WRONG ?
# WHY DO WE BUY 10X MORE ?

FUEL



CO2

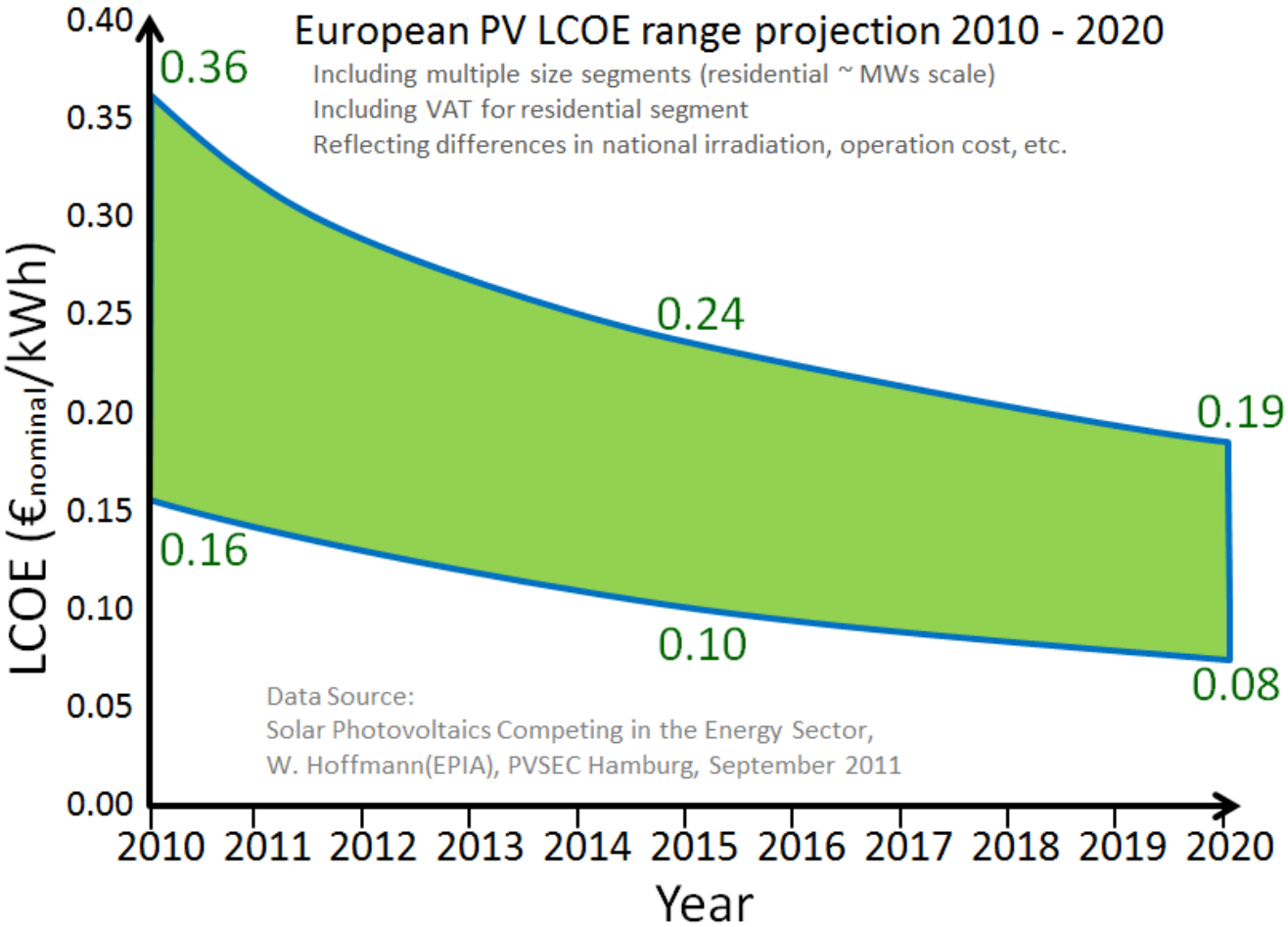
# HEAT PUMP IS THE SOLUTION




$$\dot{E} = \frac{1}{\eta_{Carnot}} \cdot \dot{Q} \cdot (1 - \frac{T_{cold}}{T_{hot}})$$

$$\eta_{Carnot} = 0.55 = \frac{\dot{E}_{min}}{\dot{E}}$$

# The energy source for heat pumps : photovoltaics

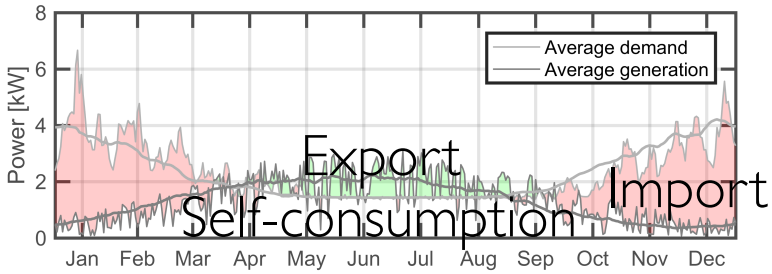


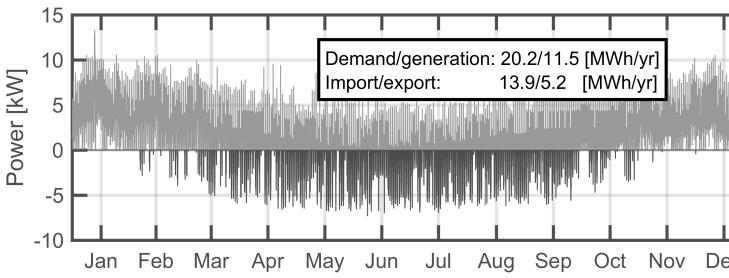

**4.0cts USA**

**2.4cts Abu Dhabi**

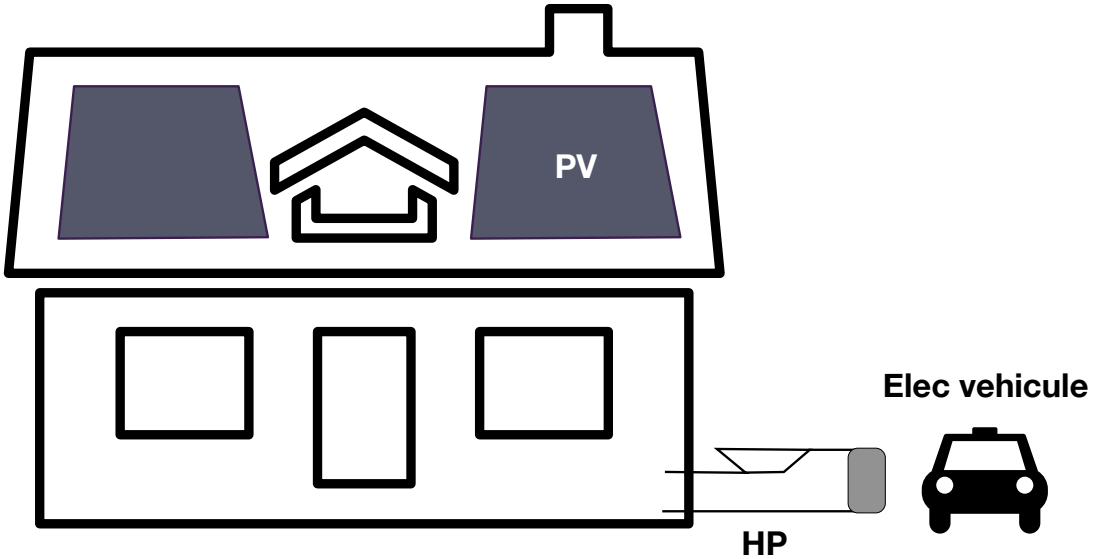
**1.8cts Saudi Arabia**

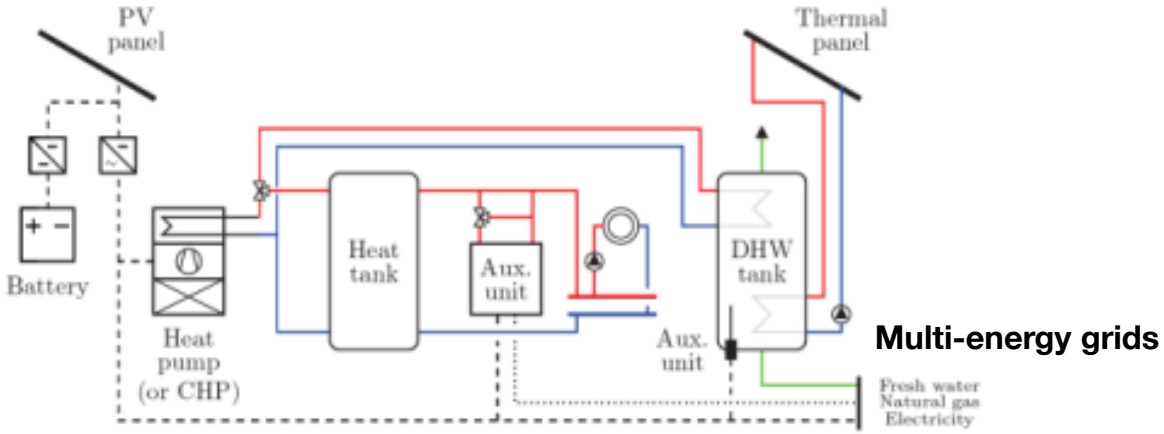
# Smart energy system
# Integration of renewable energy sources in the built environment







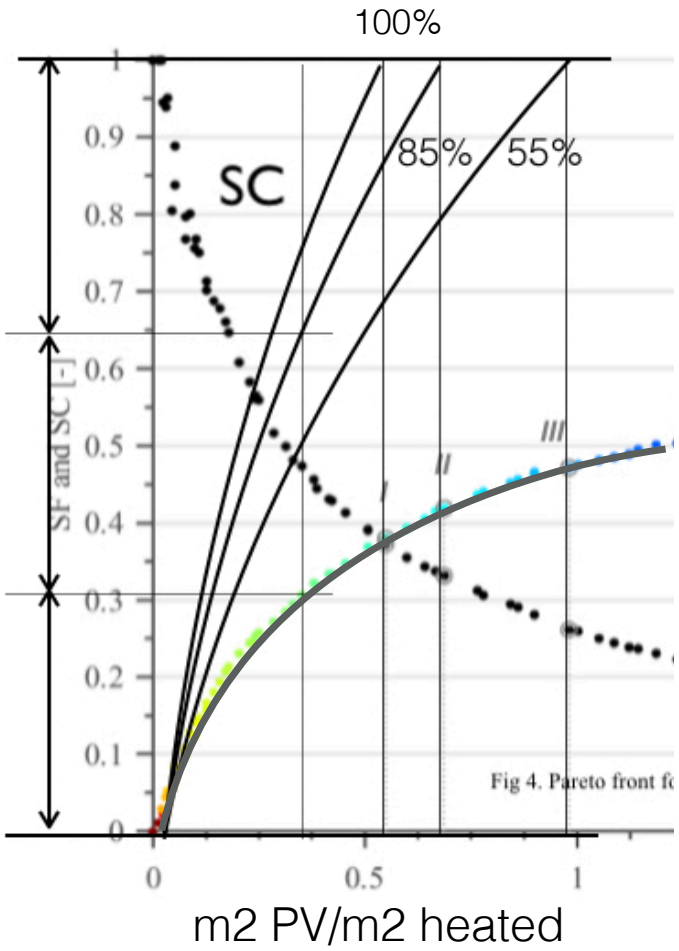



# Defosilizing the housing sector
# Integration of renewable energy sources in the built environment

Import

Seasonal storage

Self-consumption




## The grid is a seasonal battery

**Case I**

| Energy system | | Off-site storage | |
|---|---|---|---|
| PV array | 88 $m^2$ | Redox Battery | |
| Battery | 4.95 *kWh* | 8.14 *MWh* | |
| HW tank | 2.43 $m^3$ | 406.9 $m^3$ | (20 Wh/l) |
| Heat Pump | 3.59 *kW* | 4'070'000 € | (500 €/kWh) |

Annual energy balance

**Case II**

| Energy system | | Off-site storage |
|---|---|---|
| PV array | 109.7 $m^2$ | Redox Battery |
| Battery | 7 *kWh* | 10.8 *MWh* |
| HW tank | 2.46 $m^3$ | 540.2 $m^3$ |
| Heat Pump | 3.5 *kW* | 5'400'000 € |

Long term storage : 85%

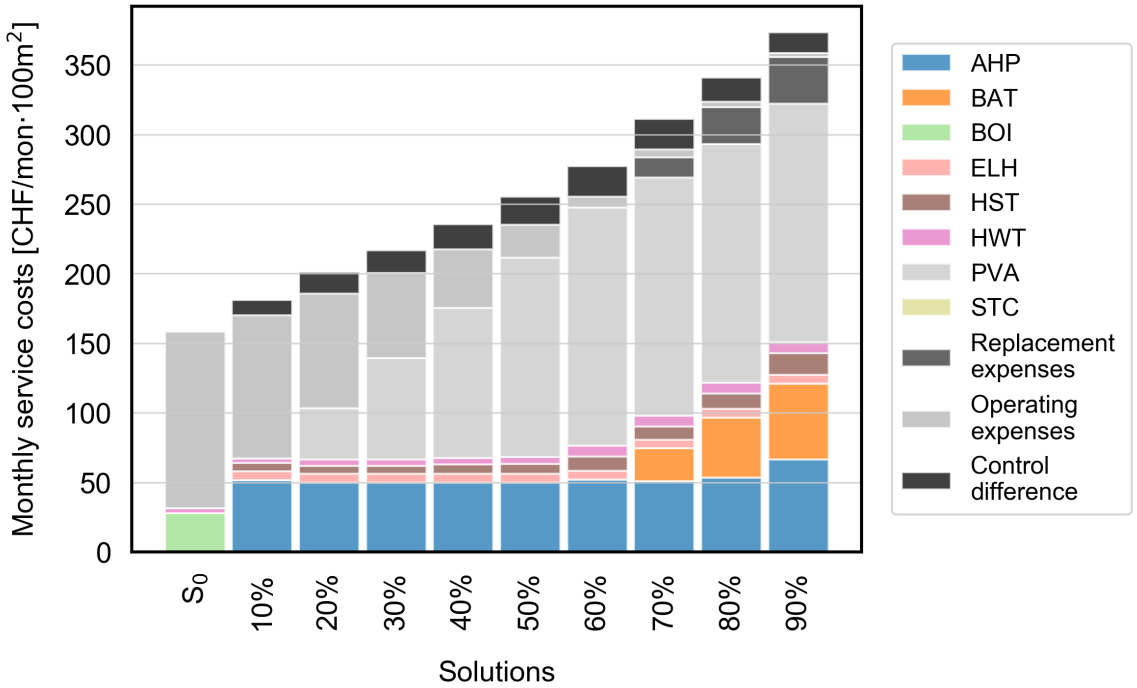
**Case III**

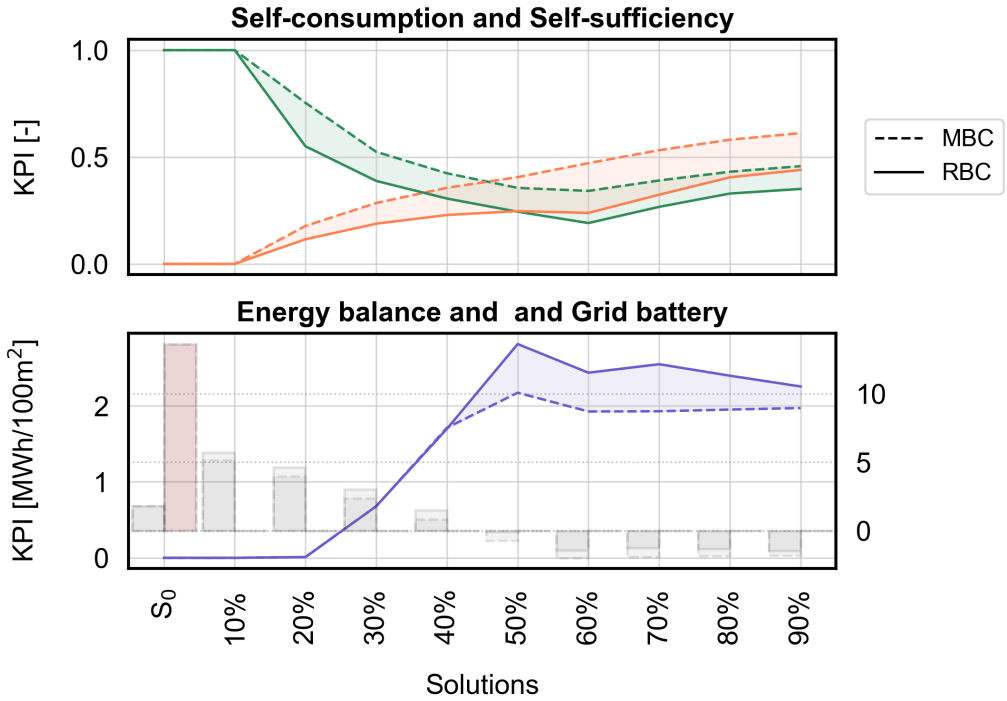
| Energy system | | Off-site storage |
|---|---|---|
| PV array | 156.9 $m^2$ | Redox Battery |
| Battery | 8.63 *kWh* | 17.1 *MWh* |
| HW tank | 2.39 $m^3$ | 854.6 $m^3$ |
| Heat Pump | 3.7 *kW* | 8'550'000 € |

Long term storage : 55%

Single family house - 160 m2 - Heat pump

# Solutions with heat pump & PV as a function of investment




Single family house 1980 Heat pump/ no renovation

Investment : +180 CHF/month/100 m2 i.e. + 4% real estate value (geneva, CH)
Operation : -100 CHF/month of Oil avoided (50 $/bbl)

# Defosillising Cities : Energy Policy

## Considering the complete building stock

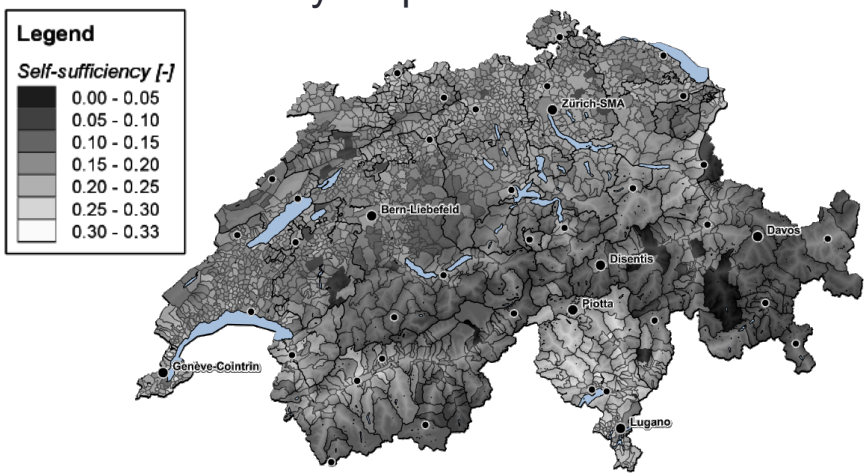
**(a)** 19 billion CHF/yr for factor 5 CO2 emissions reduction

**(b)** Boiler replace by heat pumps before renovation

**(c)** PV and renovation

Further reduction needs seasonal storage

Self-sufficiency maps




CH-Map of solution nº 50 (upper investment bound)

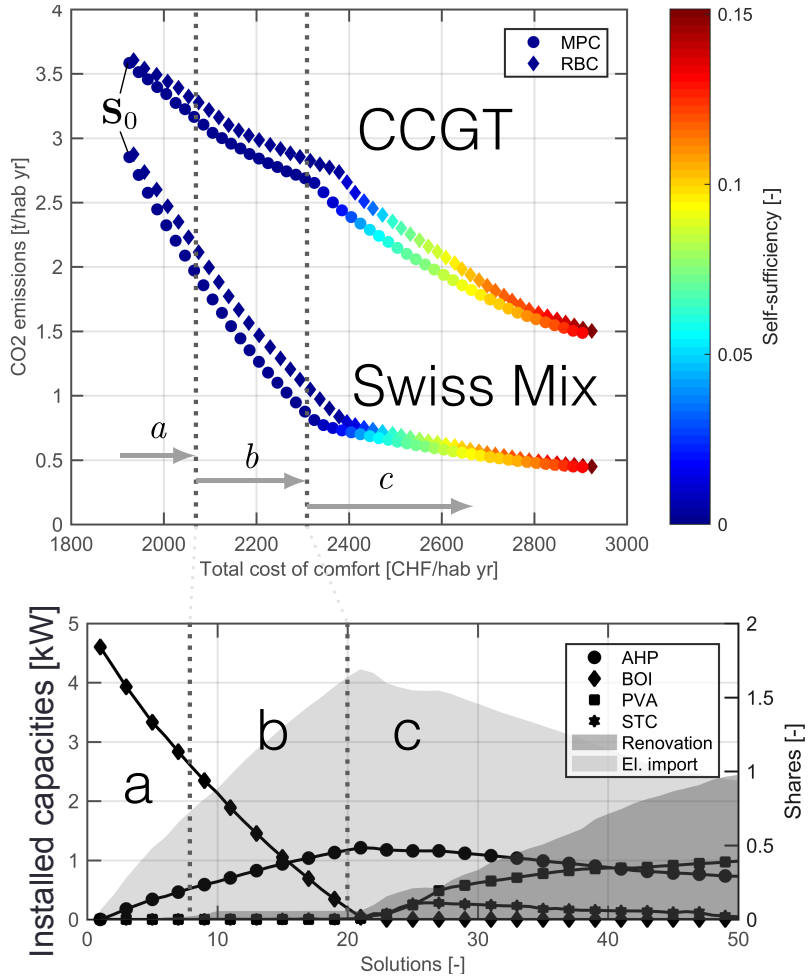
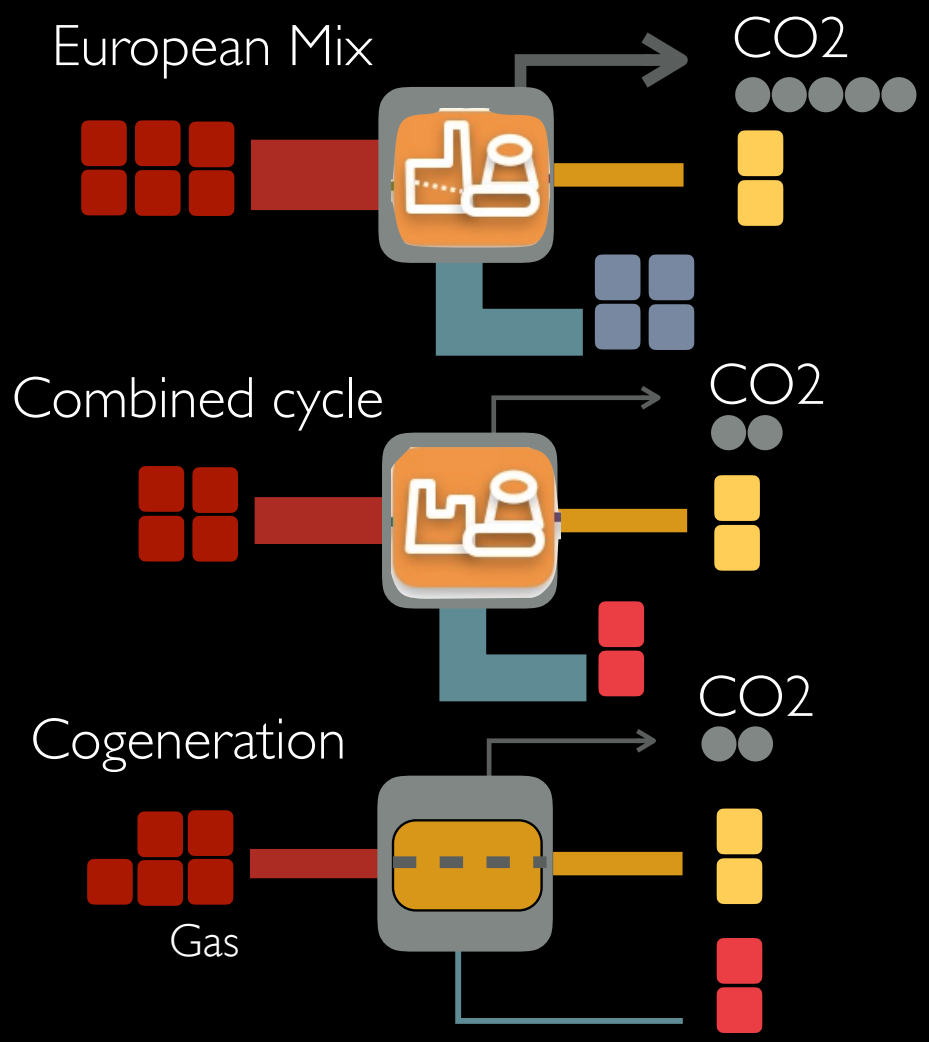
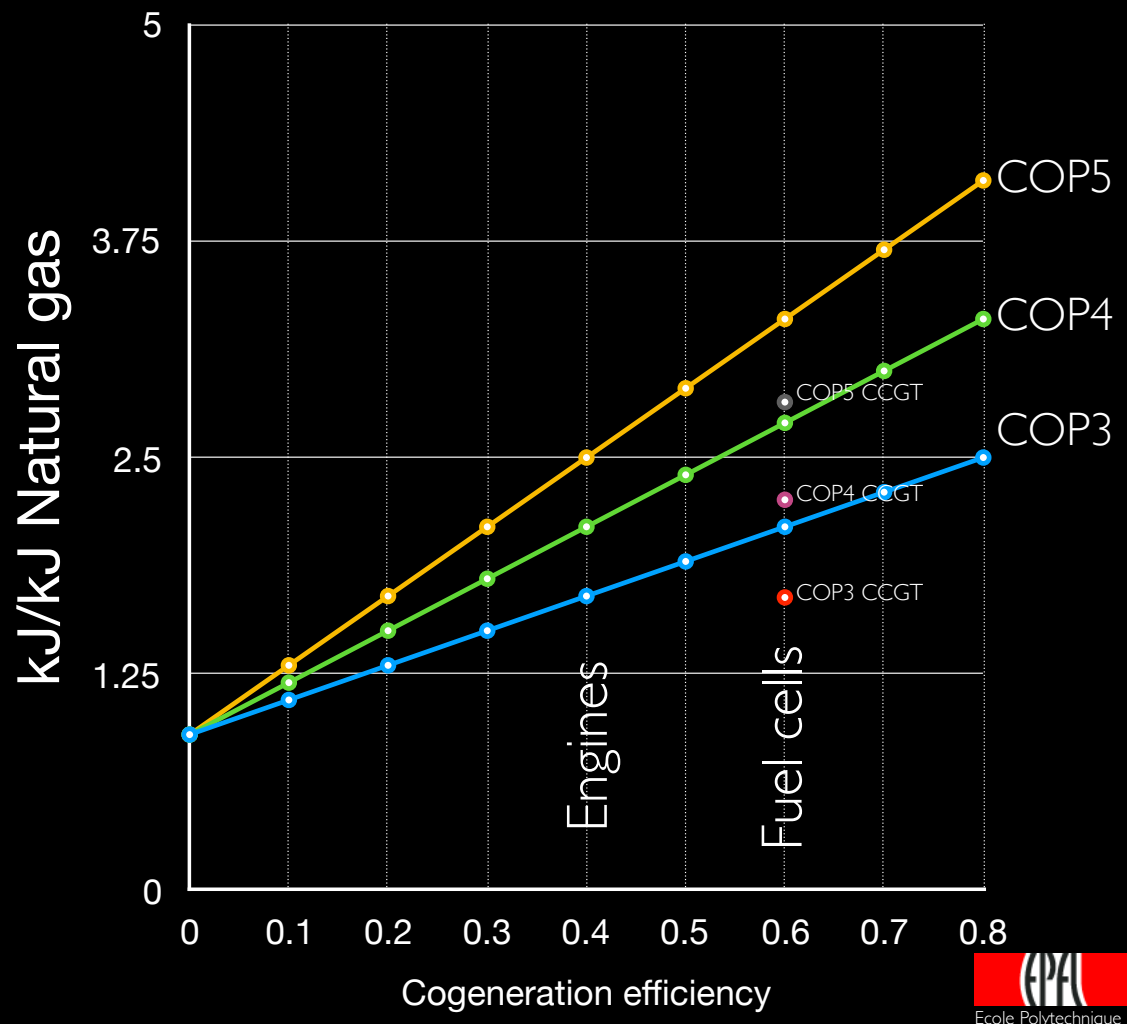



**FIGURE 12** | Pareto fronts for Switzerland when applying MPC (circles) and RBC (diamonds). The marker size reflects the renovation share of the current built environment.

# PRODUCING THE ELECTRICITY DEFICIT

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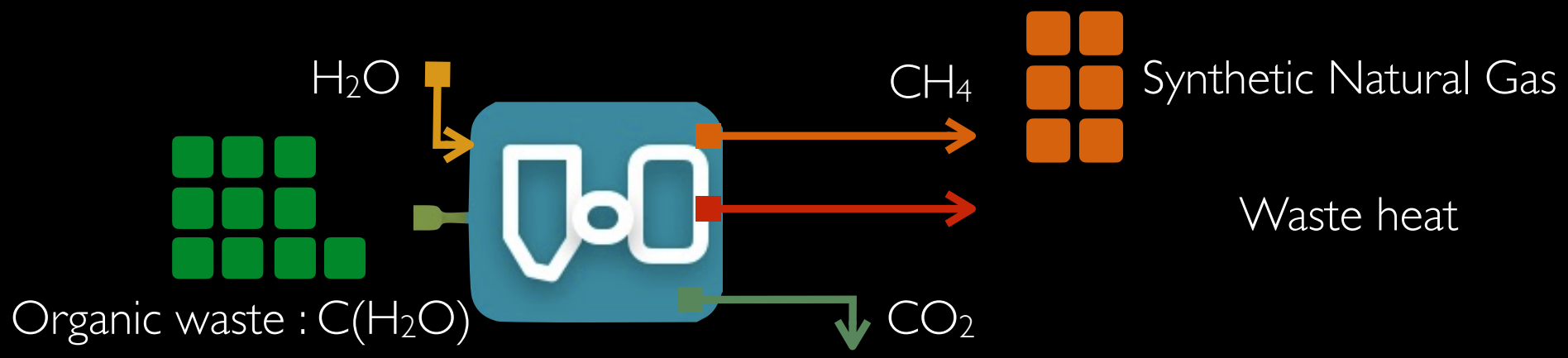
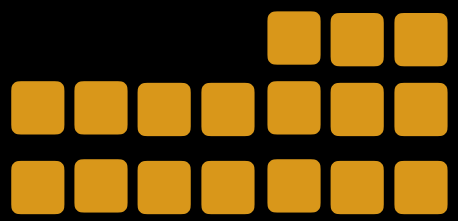
# BIOMASS FUEL PRODUCTION



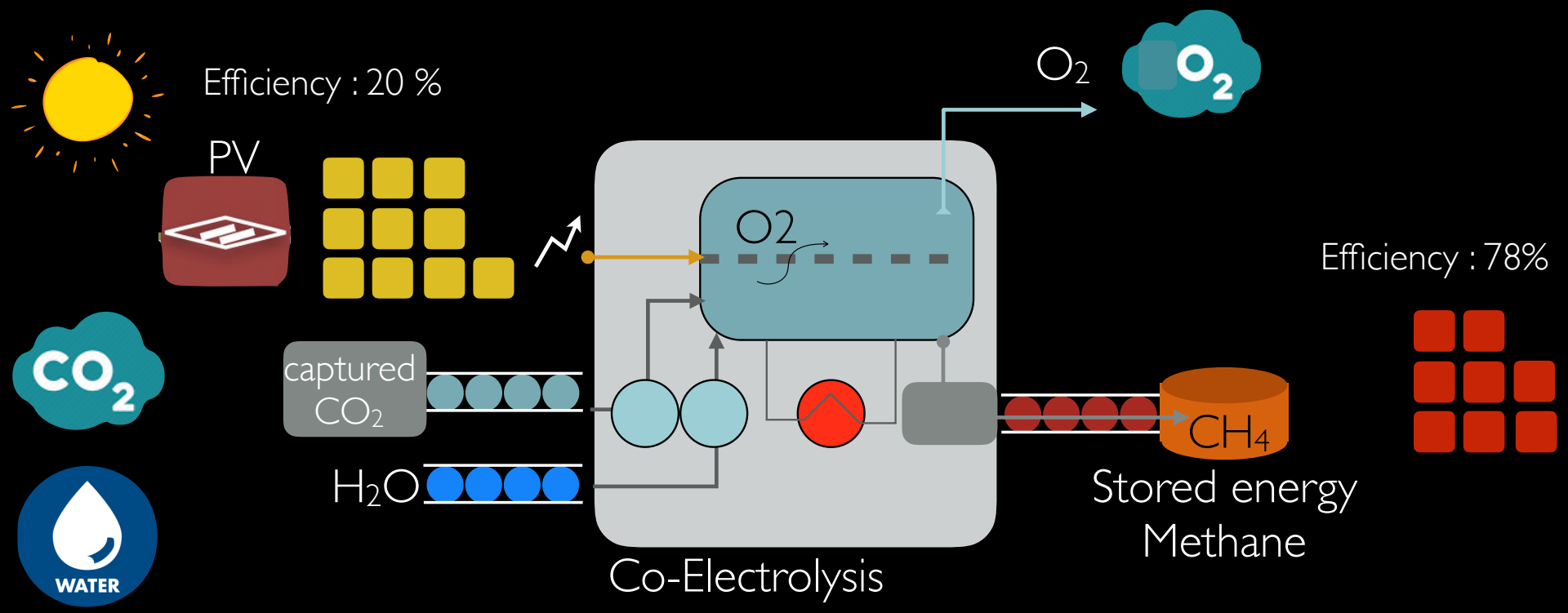
Biomethanisation
Hydrothermal gasification
Synthetic Natural Gas

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

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

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

# 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.*

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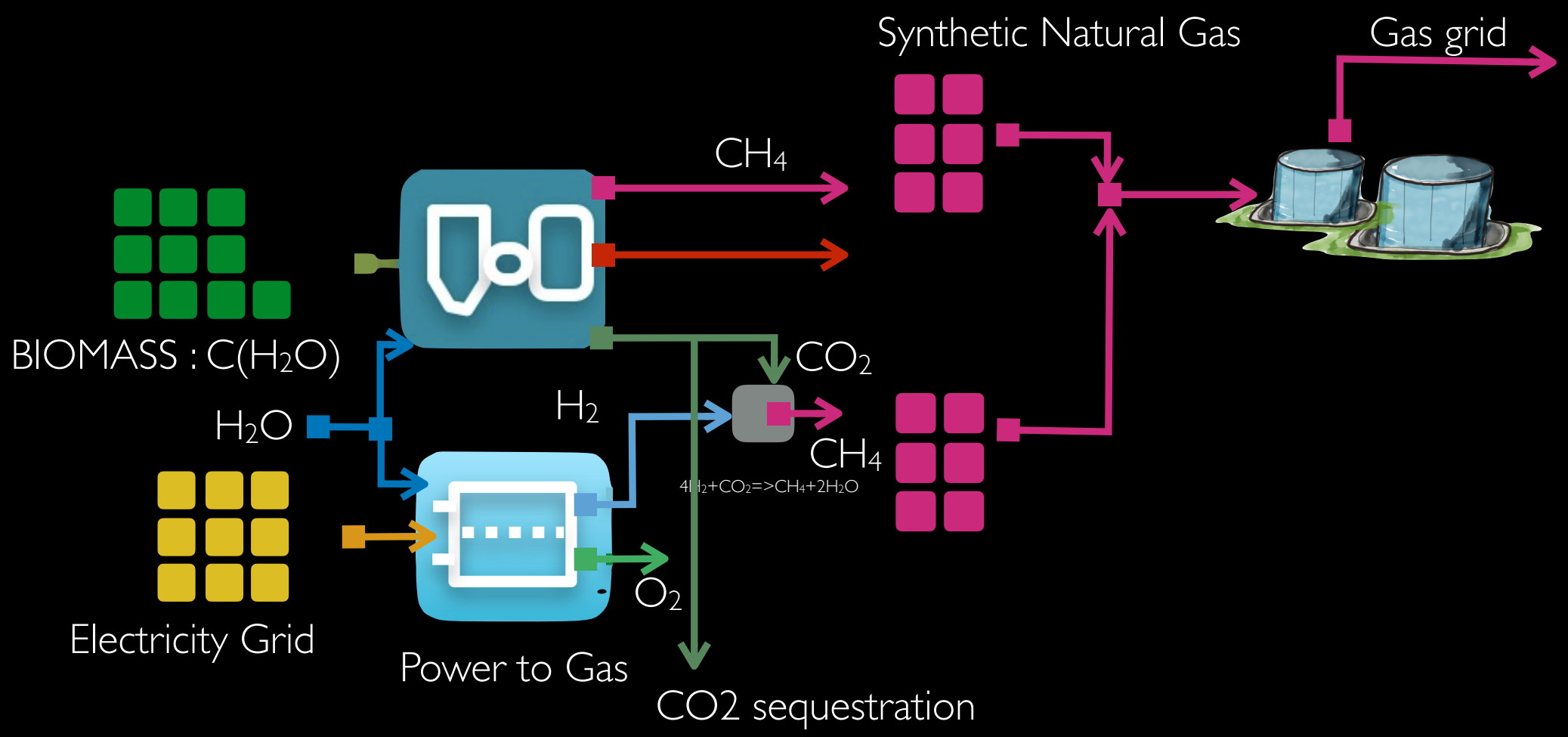
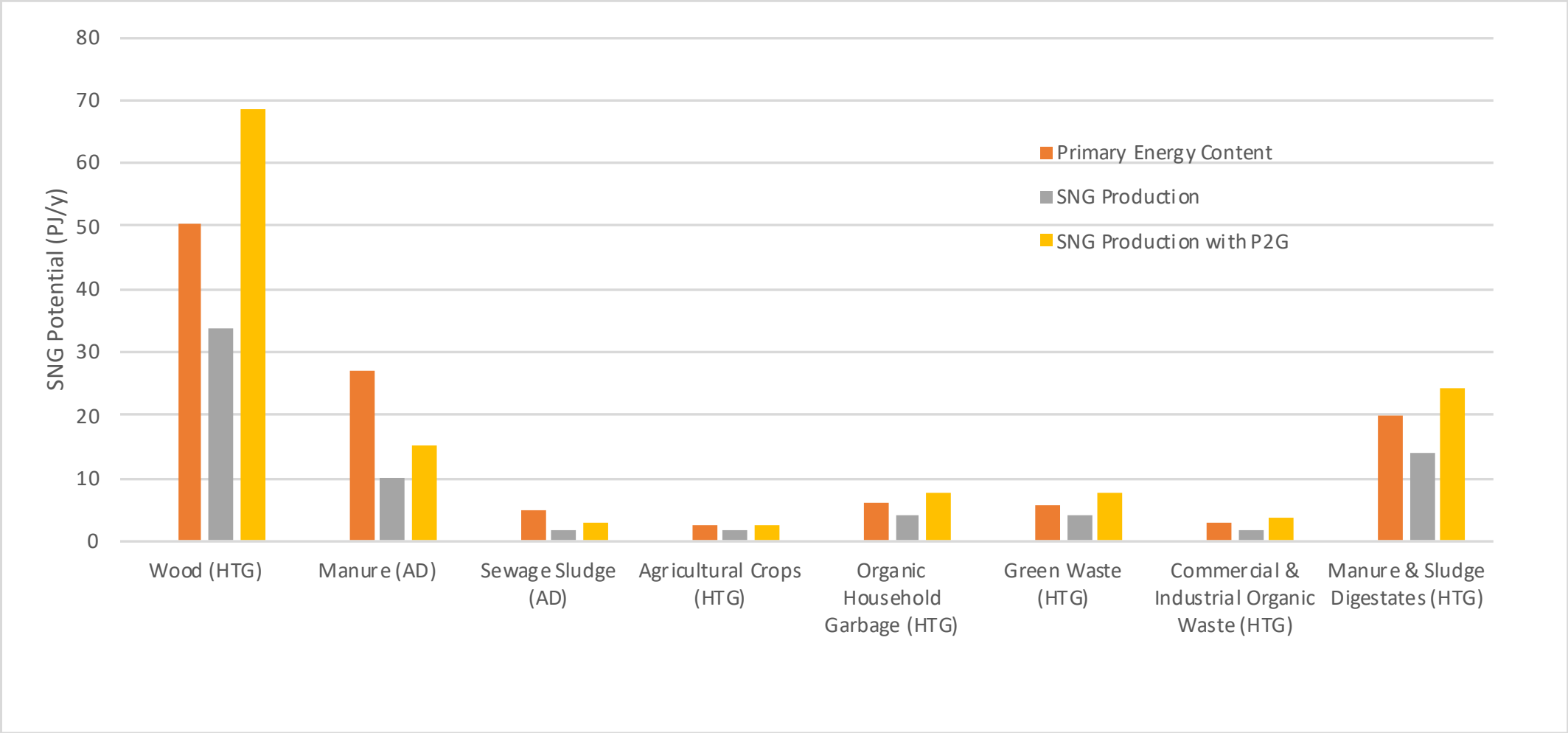
# ON THE USE OF THE BIOMASS AS AN ENERGY SOURCE

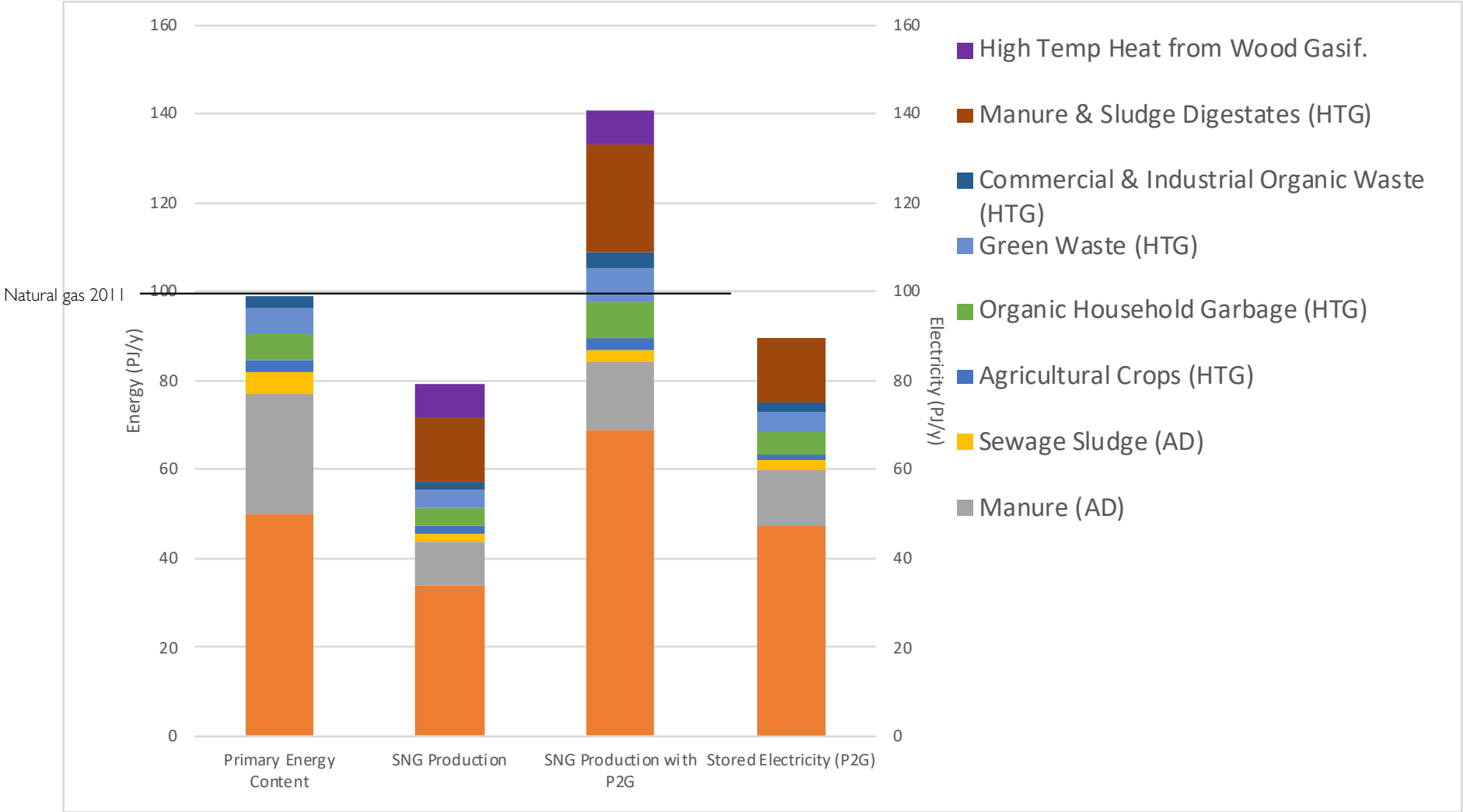



Gassner, Martin, and François Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." Energy 33.2 (2008): 189-198.

# SNG from biomass potential in Switzerland

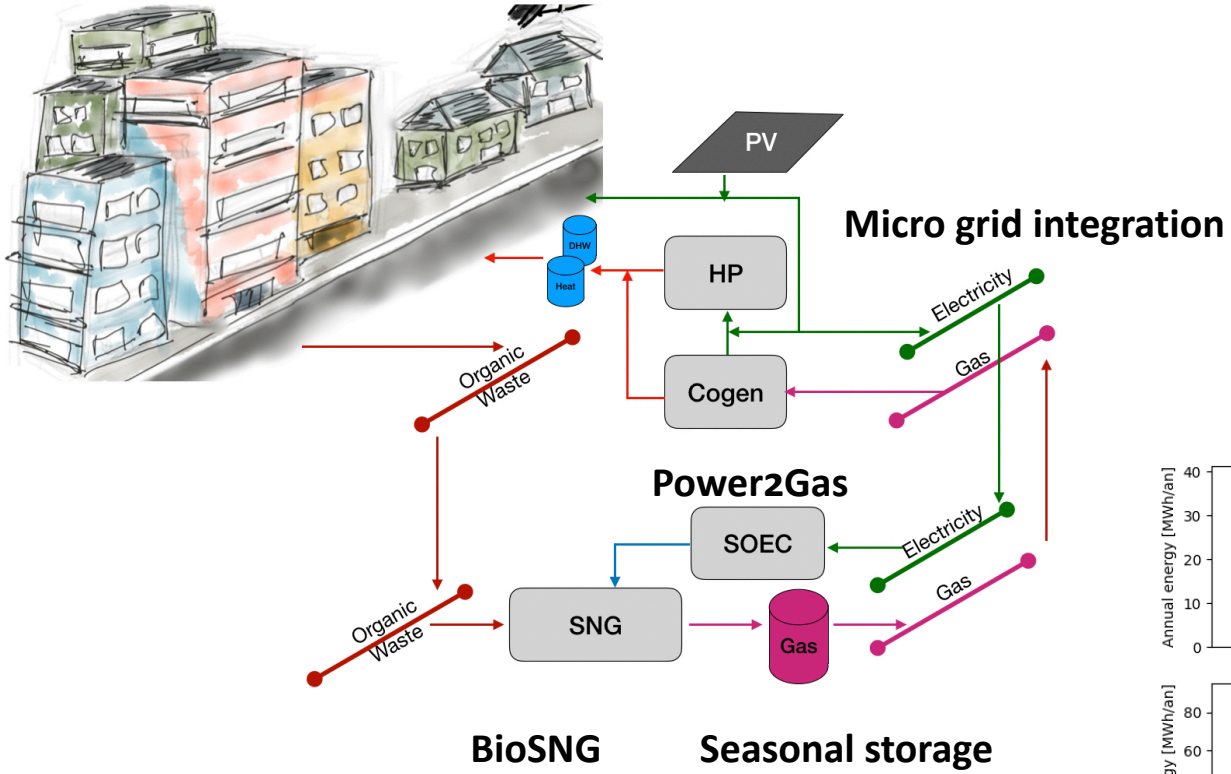


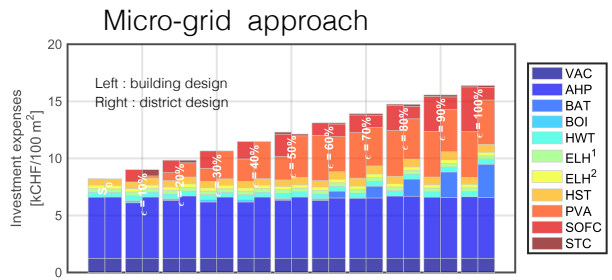
# SNG from biomass potential in Switzerland

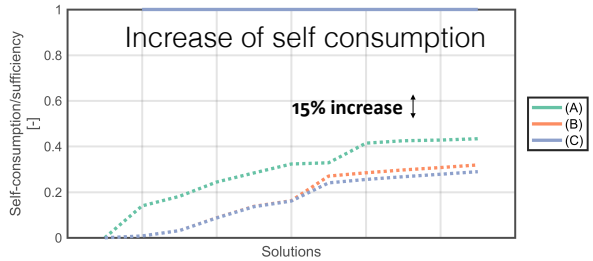


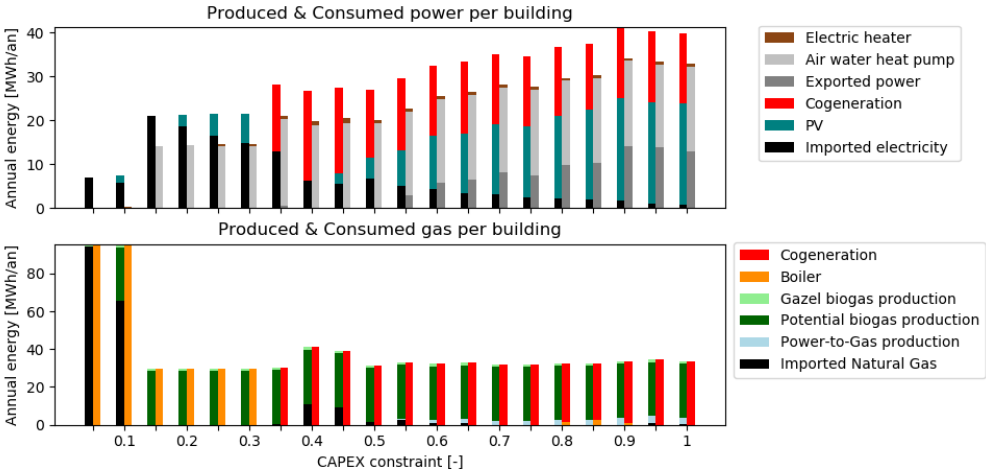
# Integrating Renewable Energy Sources : Biogas + PV+ Power2gas

- Replacing oil boilers



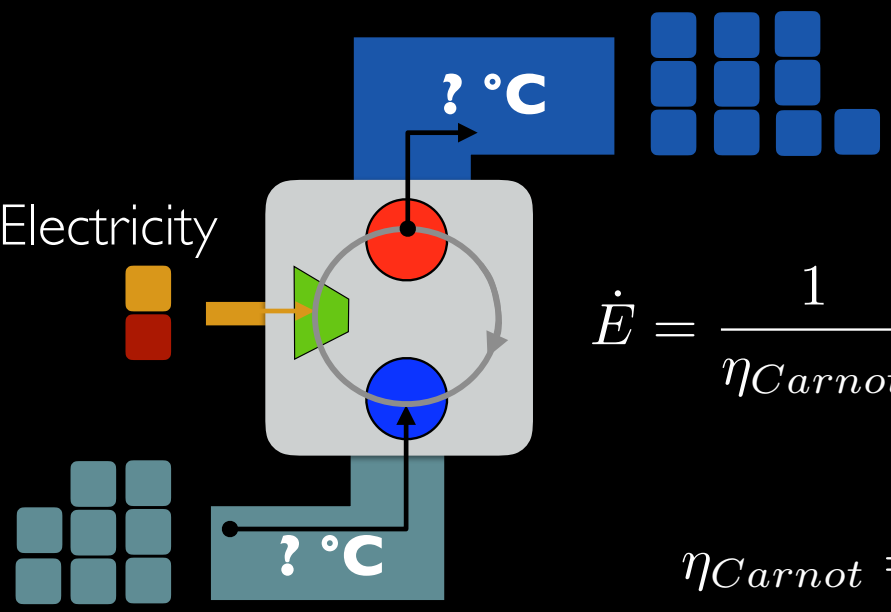




SCCER-BIOSWEET, SCCER-FURIES & SCCER-JA S&M
Support from Gaznat

# HEAT PUMP IS THE SOLUTION

Useful heat

Old building 65°C
New buildings 30 °C




$$\dot{E} = \frac{1}{\eta_{Carnot}} \cdot \dot{Q} \cdot (1 - \frac{T_{cold}}{T_{hot}})$$

$$\eta_{Carnot} = 0.55 = \frac{\dot{E}_{min}}{\dot{E}}$$

Waste heat : 30°C
Waste water : 13-20 °C
Ground water : 10 °C
Lake water : 7°C

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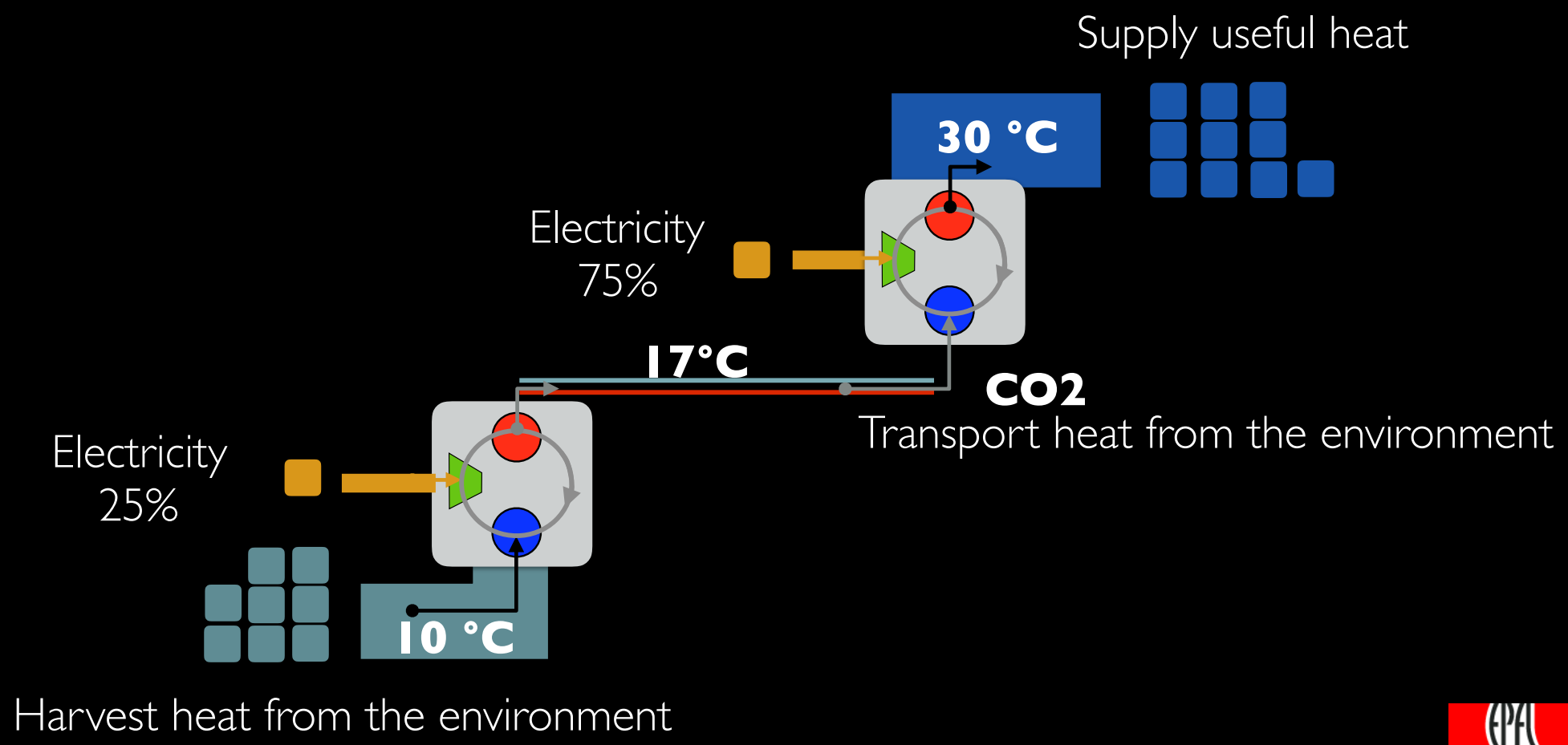
# REACH THE GOOD RESOURCES
# SUPPLY WHAT IS NEEDED




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

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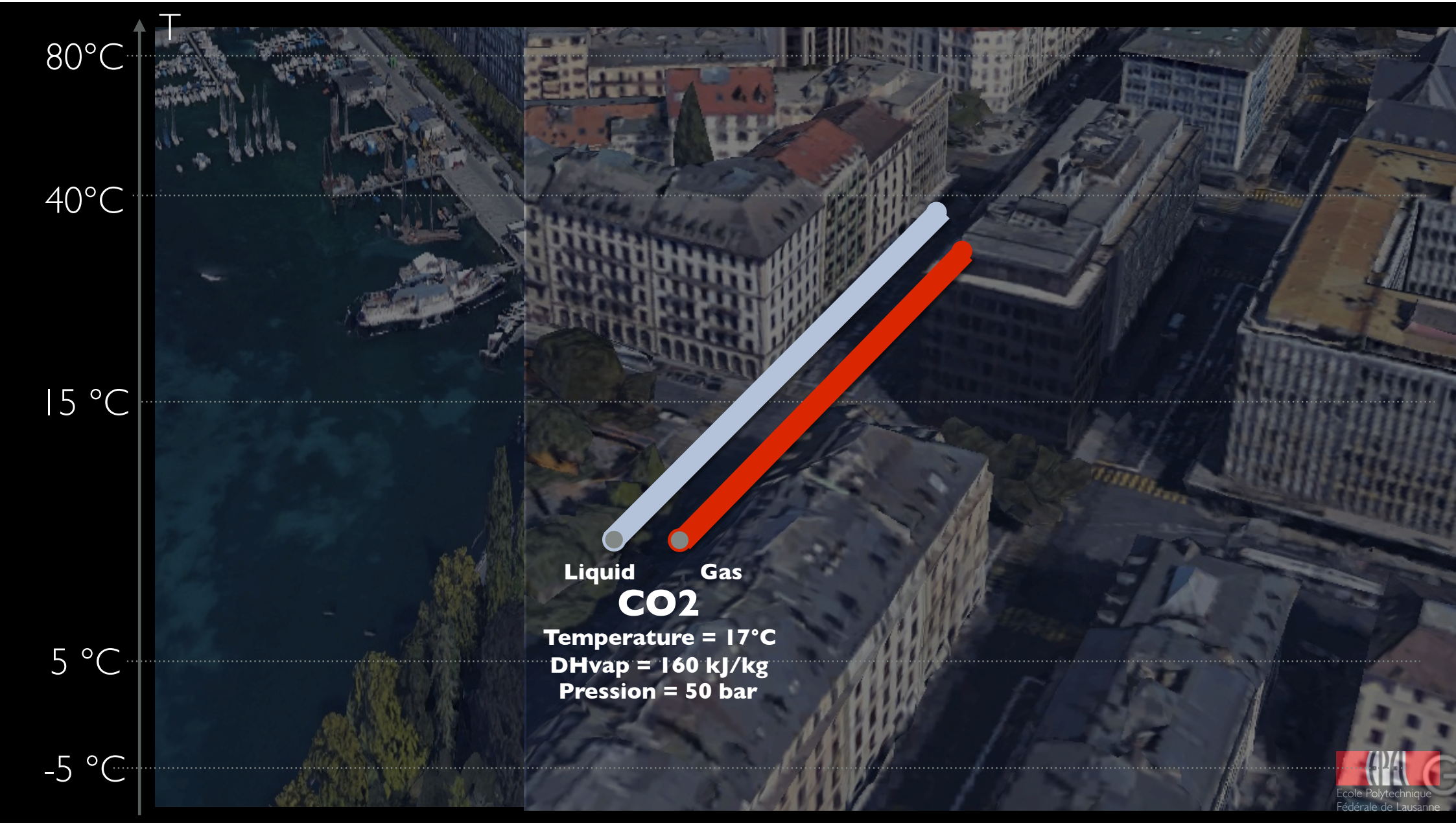
T
80°C
40°C
15 °C
5 °C
-5 °C
Liquid
Gas
CO2
Temperature = 17°C
DHvap = 160 kJ/kg
Pression = 50 bar
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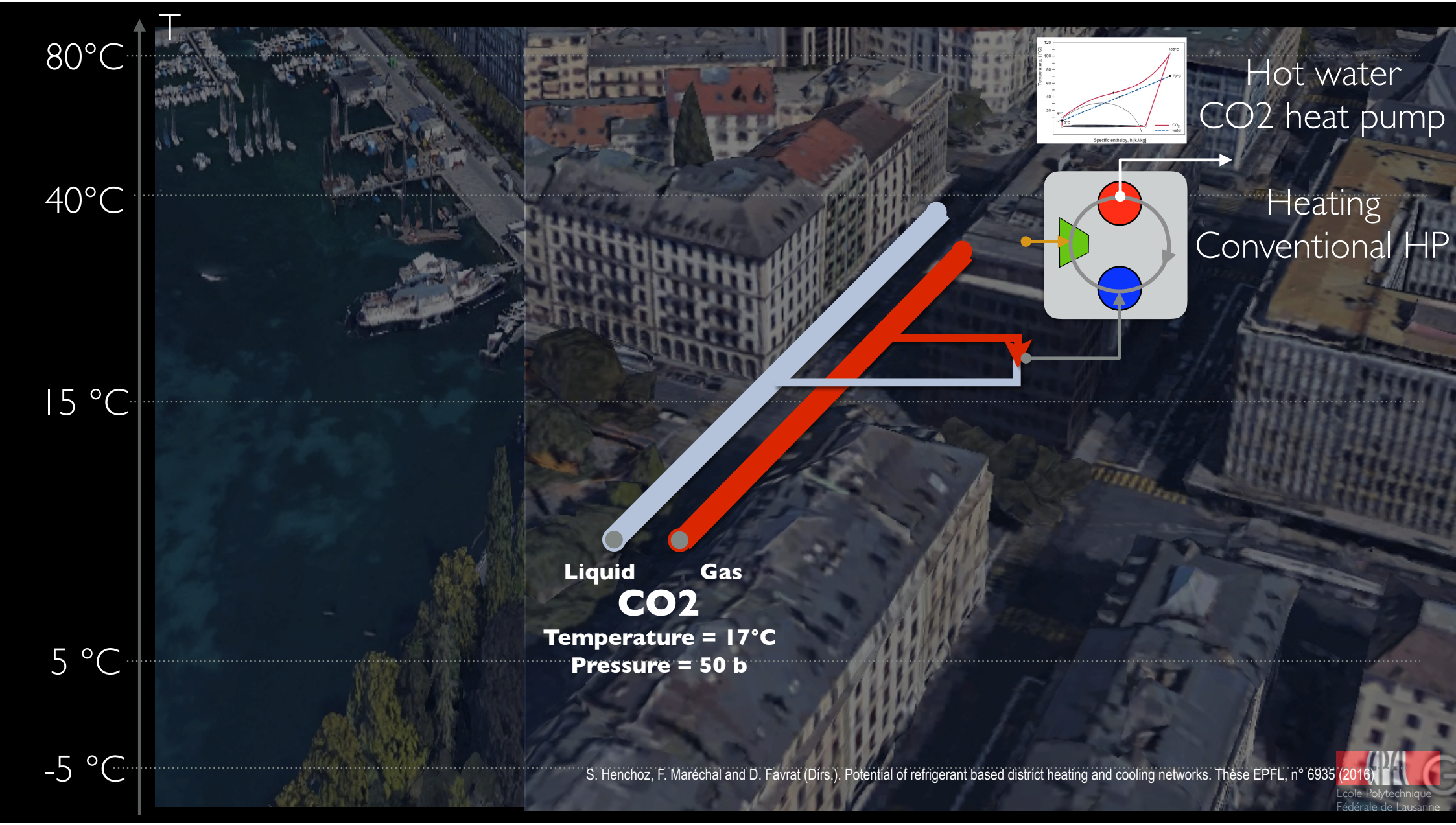


S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)

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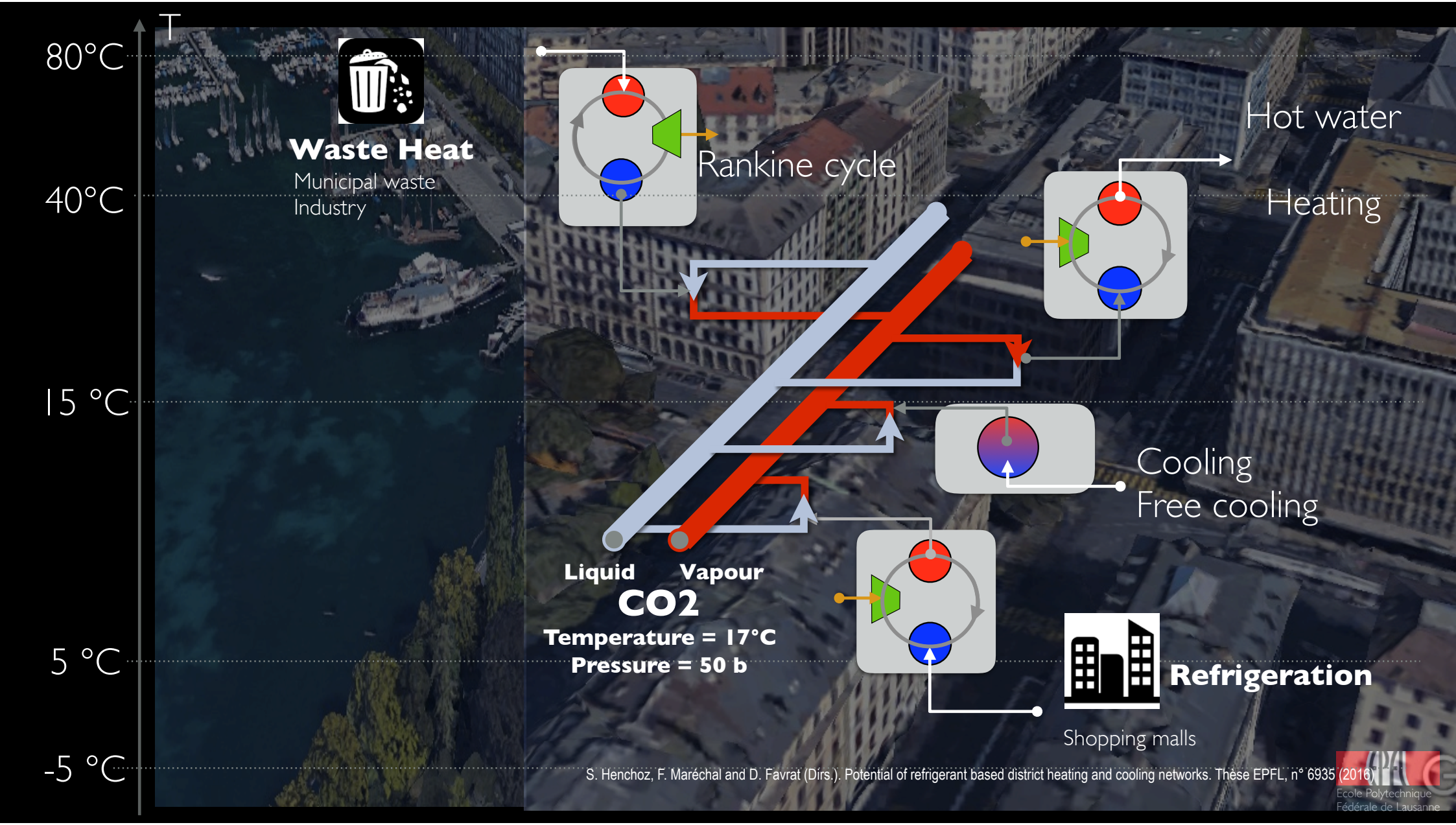
T
80°C
40°C
15 °C
5 °C
-5 °C
Waste Heat
Municipal waste
Industry
Rankine cycle
Hot water
Heating
Cooling
Free cooling
Liquid
Vapour
CO2
Temperature = 17°C
Pressure = 50 b
Refrigeration
Shopping malls
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling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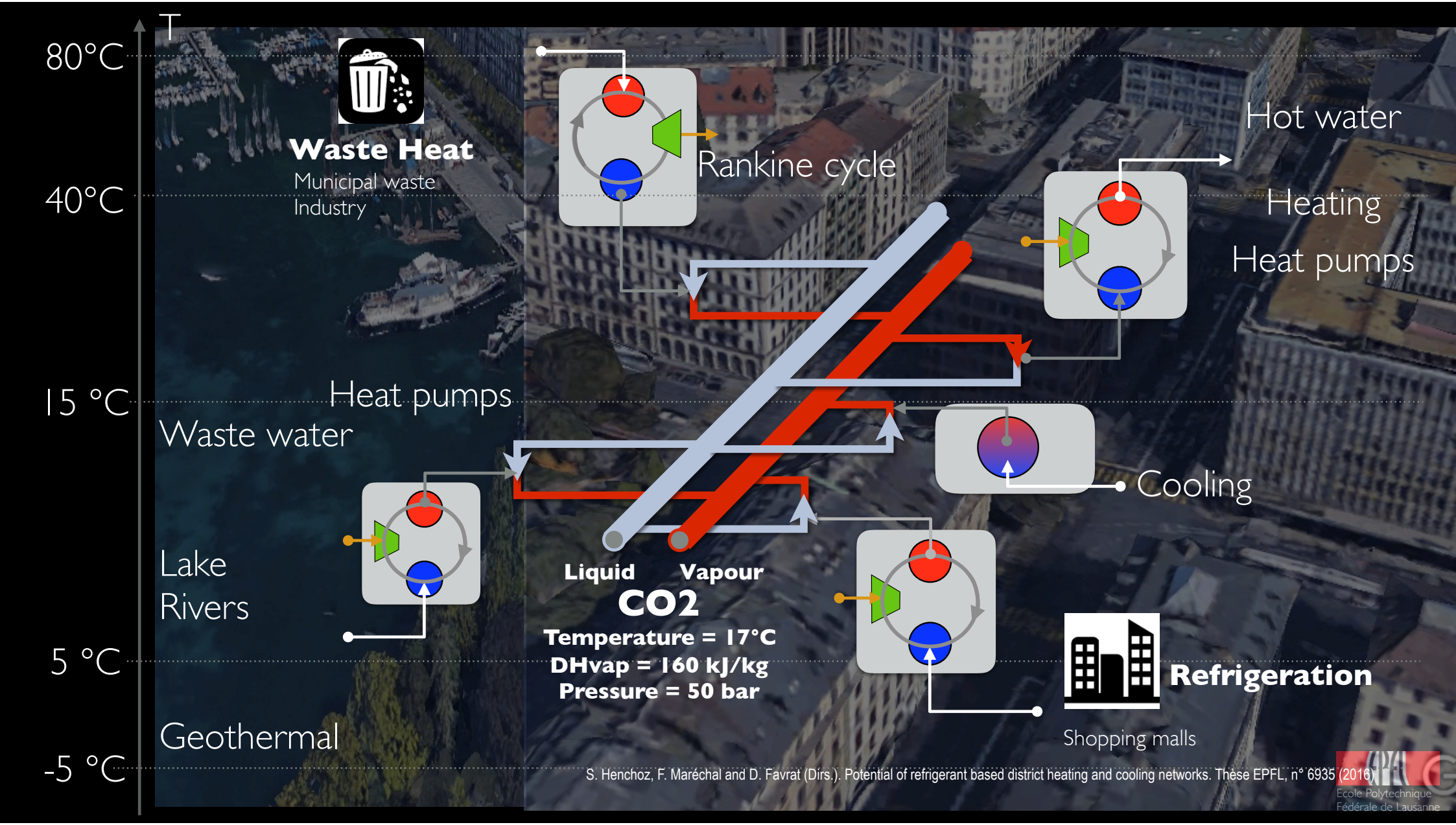
T
80°C
40°C
15 °C
5 °C
-5 °C
Waste Heat
Municipal waste
Industry
Rankine cycle
Hot water
Heating
Heat pumps
Heat pumps
Waste water
Cooling
Lake
Rivers
Liquid
Vapour
CO2
Temperature = 17°C
DHvap = 160 kJ/kg
Pressure = 50 bar
Refrigeration
Shopping malls
Geothermal
S. Henchoz, F. Maréchal and D. Favrat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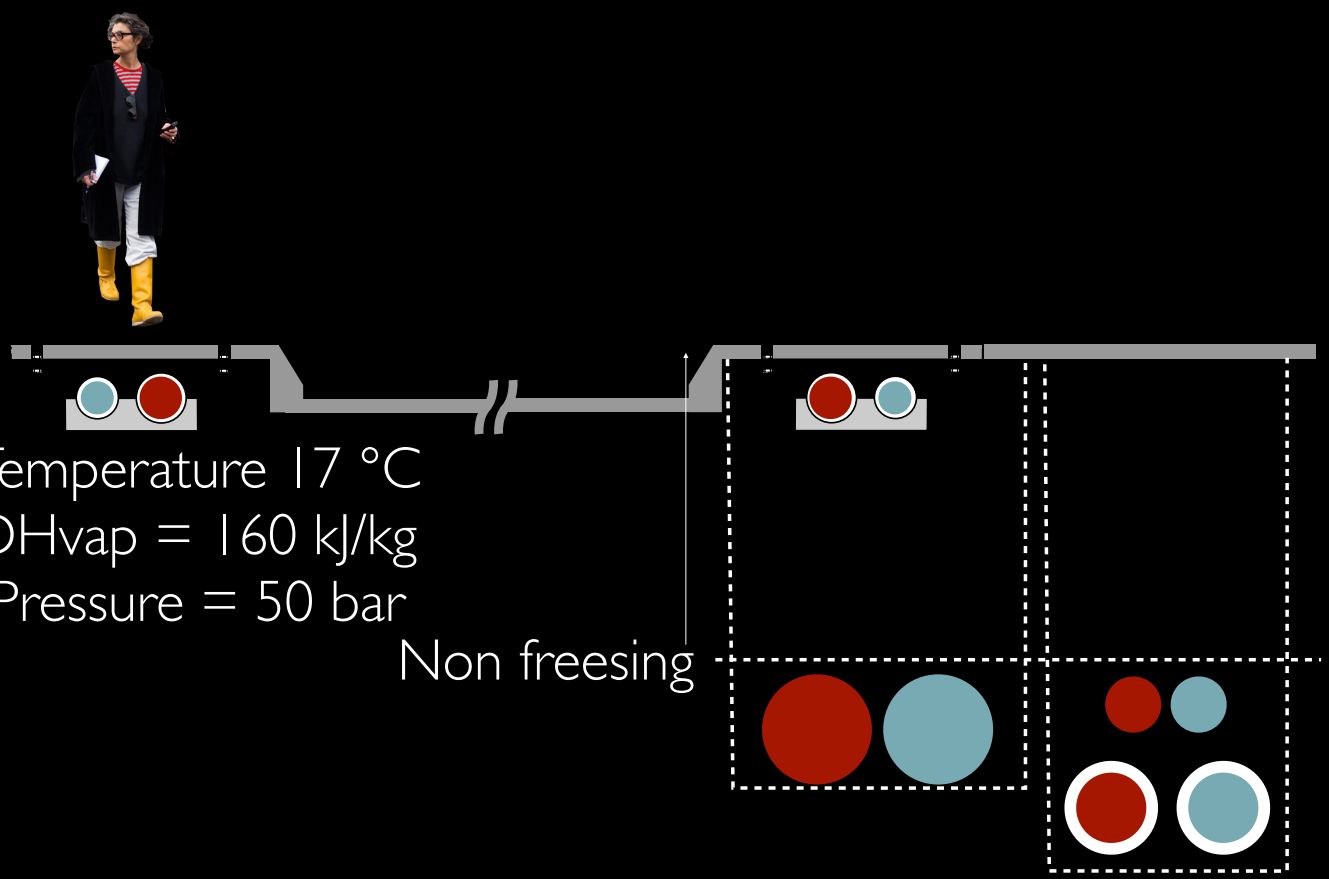
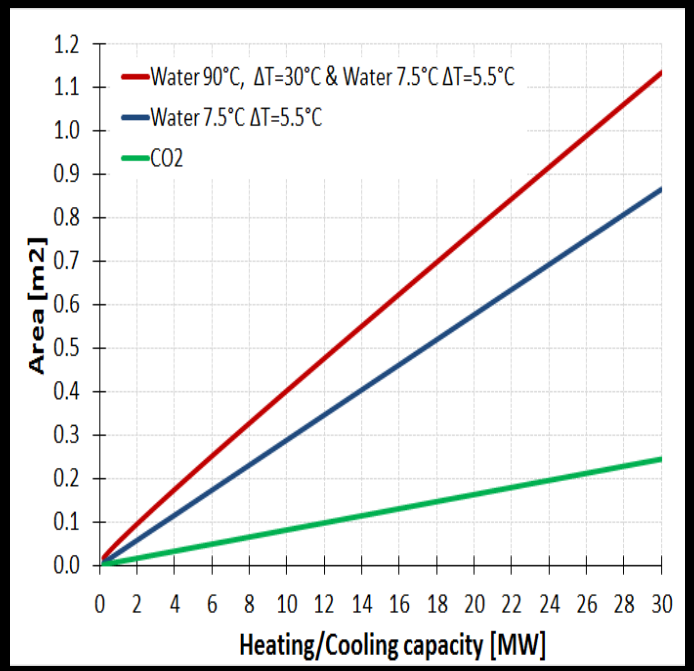
# ADD THE PIPES IN THE PEDESTRIAN WAYS




Instead of putting them underground

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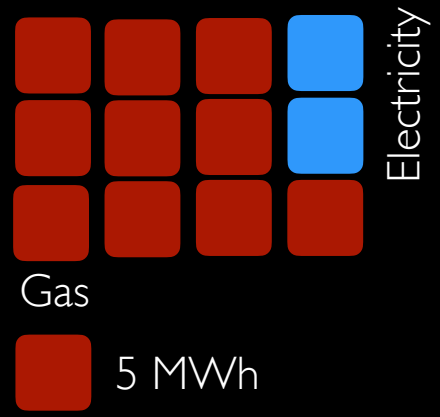
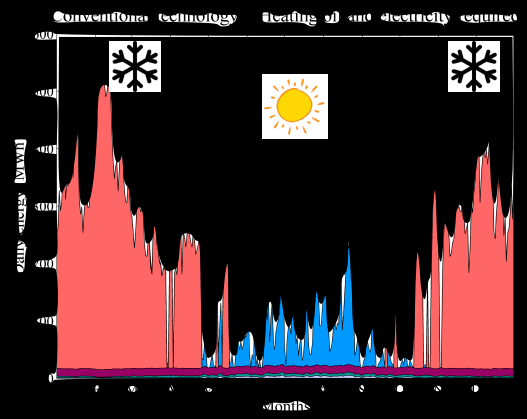
# APPLICATION TO A DISTRICT

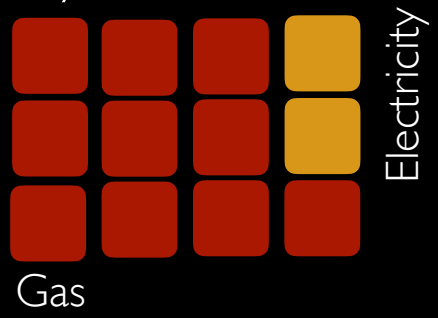



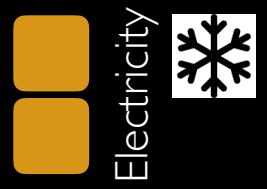
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL n° 6935 (2016)

# APPLICATION TO A CITY DISTRICT

Today




Tomorrow




**COP =5.7**

**-84 %**

**No CO2 emissions**

**Pay back 6 years**

**Investment : 10 k€/cap**

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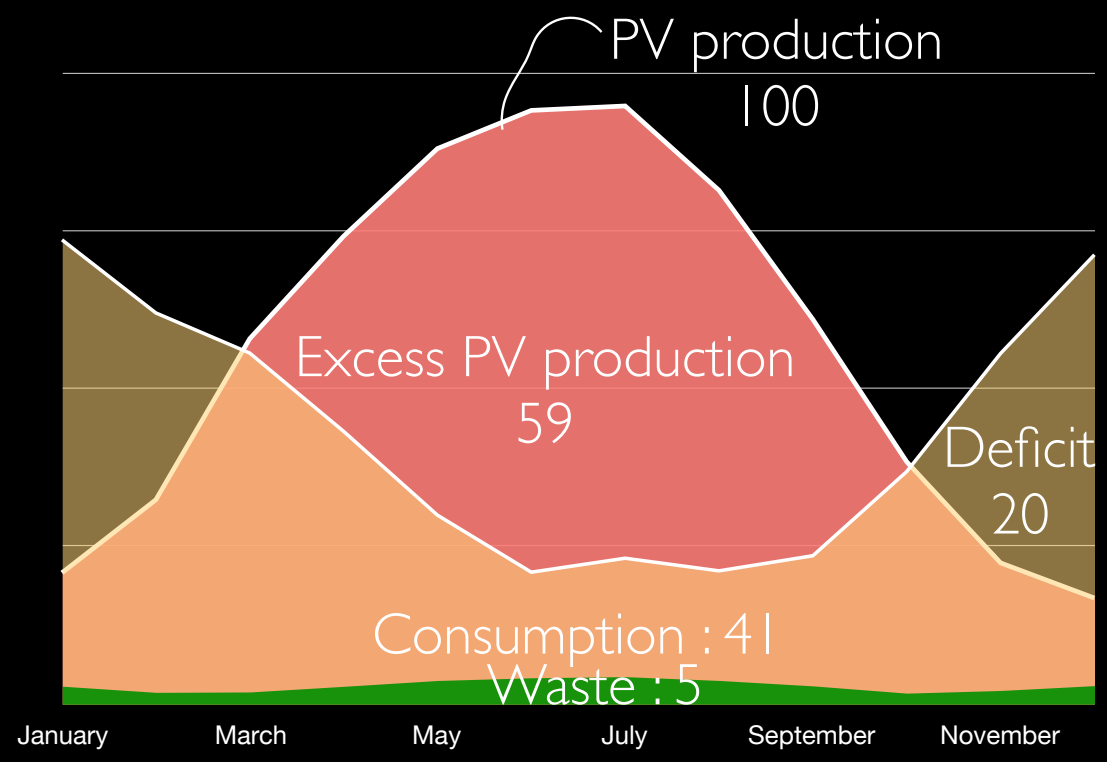
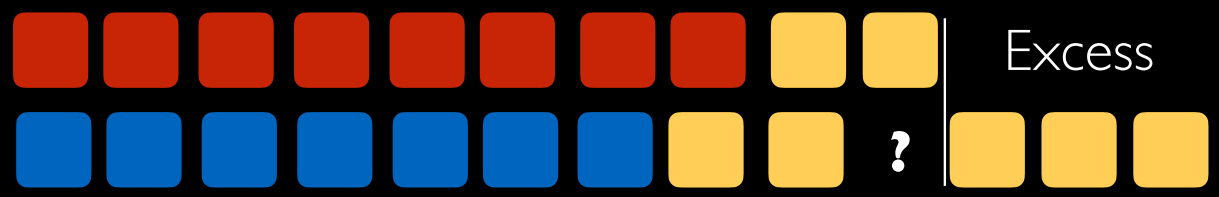
# HOW TO SUPPLY ELECTRICITY ?




PV PANELS ON THE ROOF

PV efficiency = 20 %
Full roofs area covered (30 m2/cap)
Remaining energy to import
- 10% of the total needs

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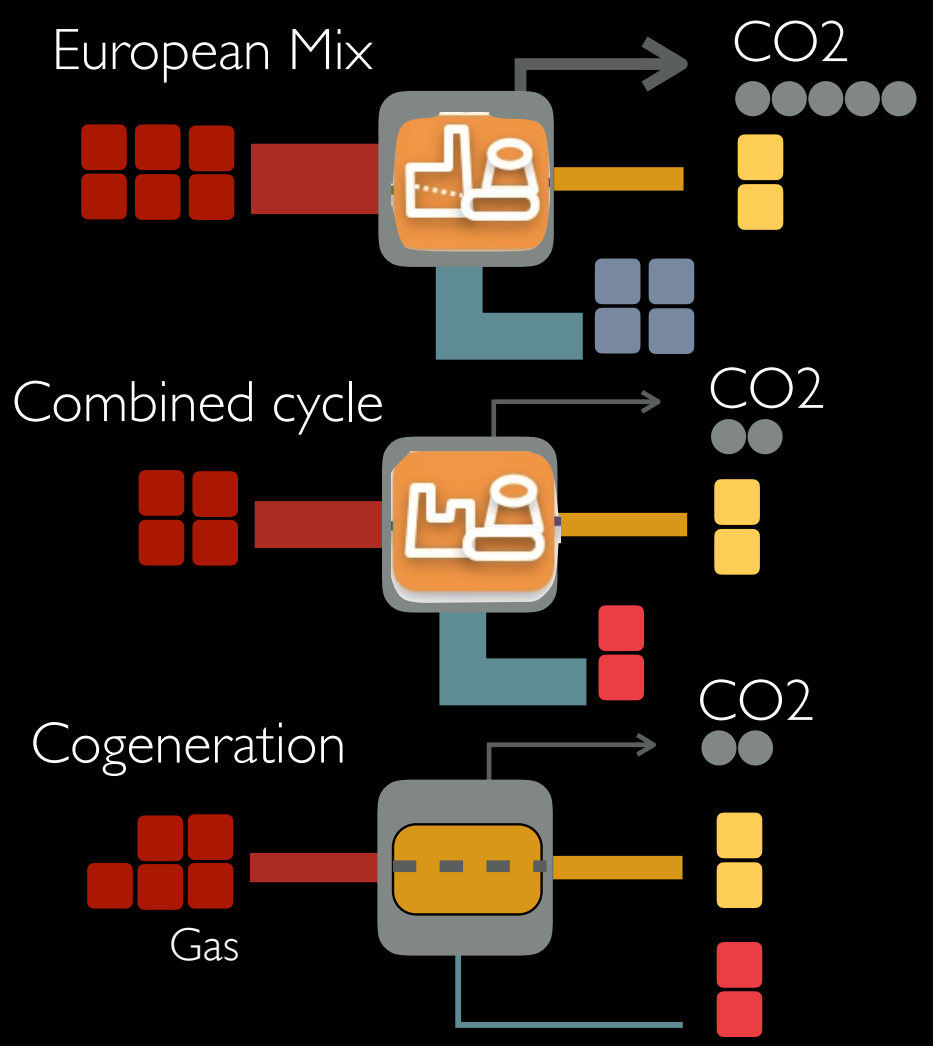
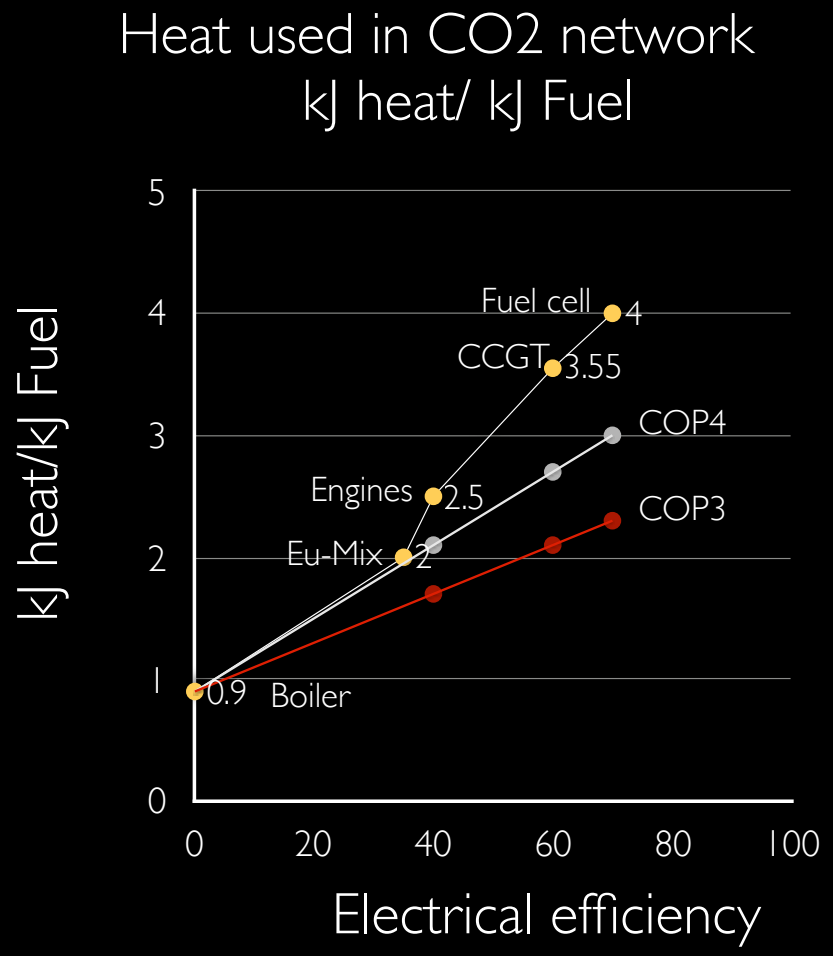
# PRODUCING THE ELECTRICITY DEFICIT

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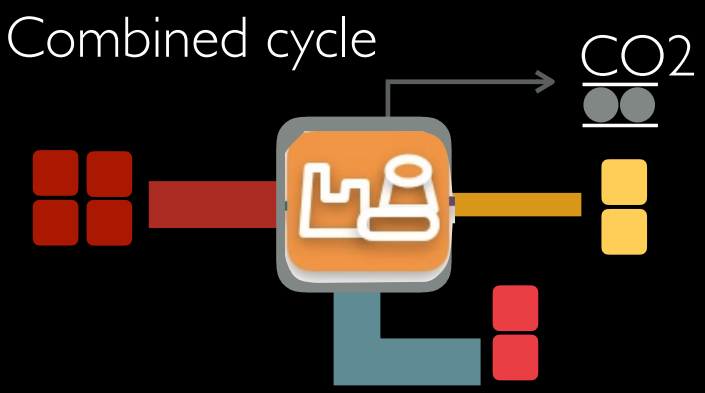
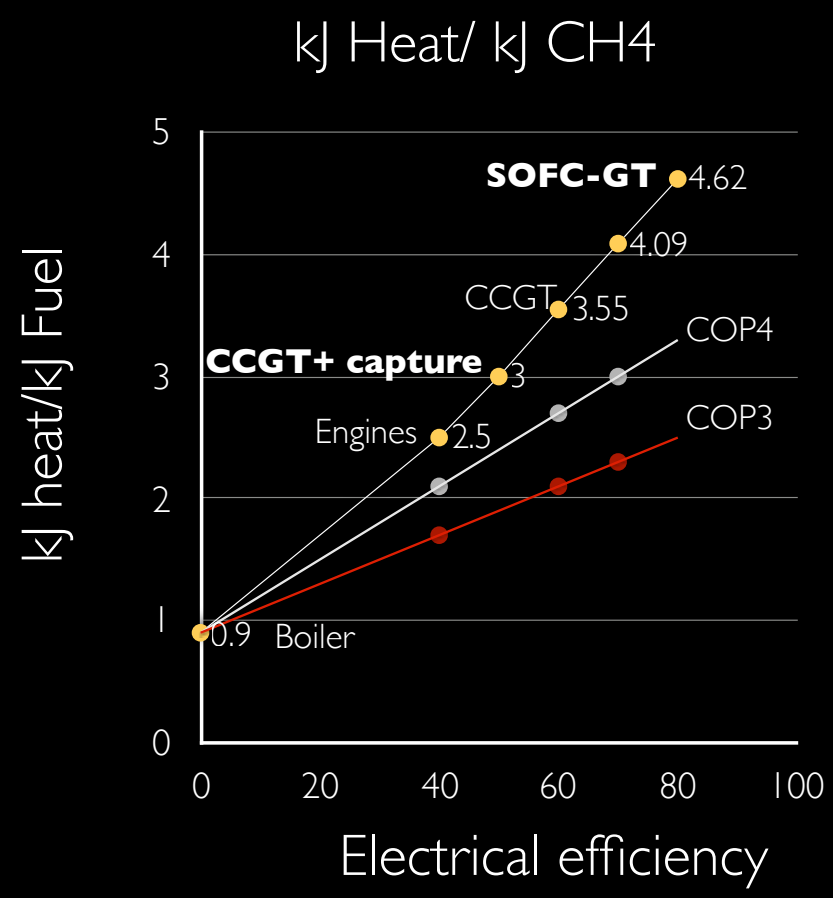
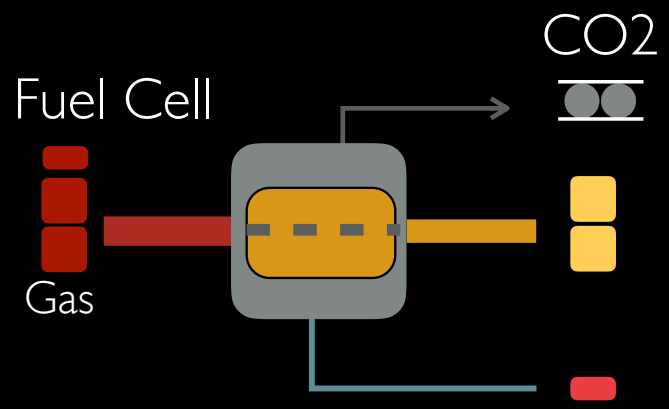
# CO2 CAPTURE




**Products** :

Electricity :80 %

Heat : 20%

CO2 captured

H2O

[1]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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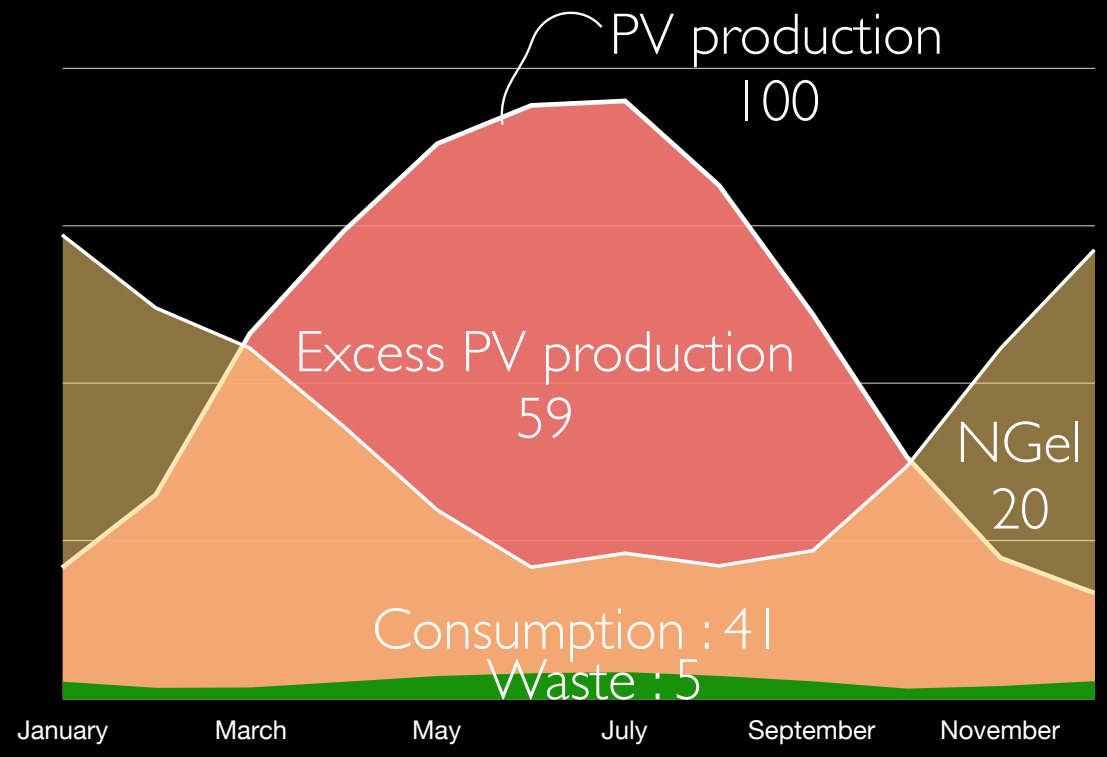
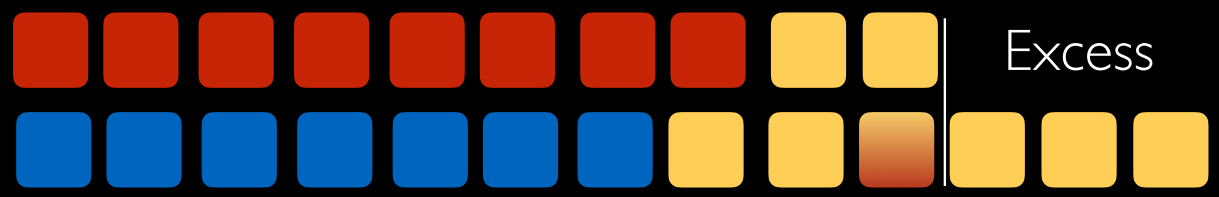
# EXCESS OF ELECTRICITY ON THE ROOFS




PV efficiency = 20 %
Total capacity
=> 70% Needs
=> 40% Self consumption
30% by CH4 and CO2 capture

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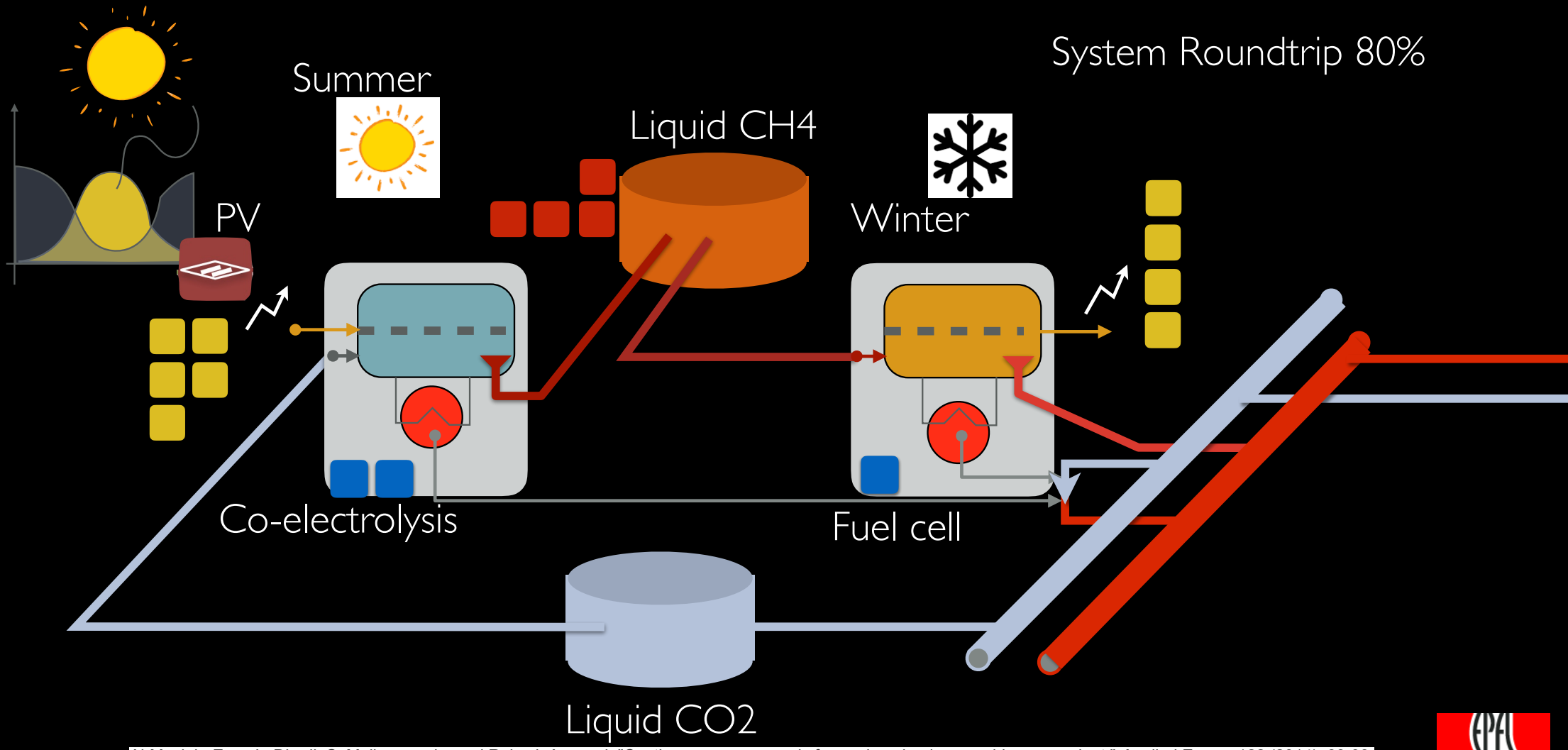
# INTEGRATED ENERGY MANAGEMENT




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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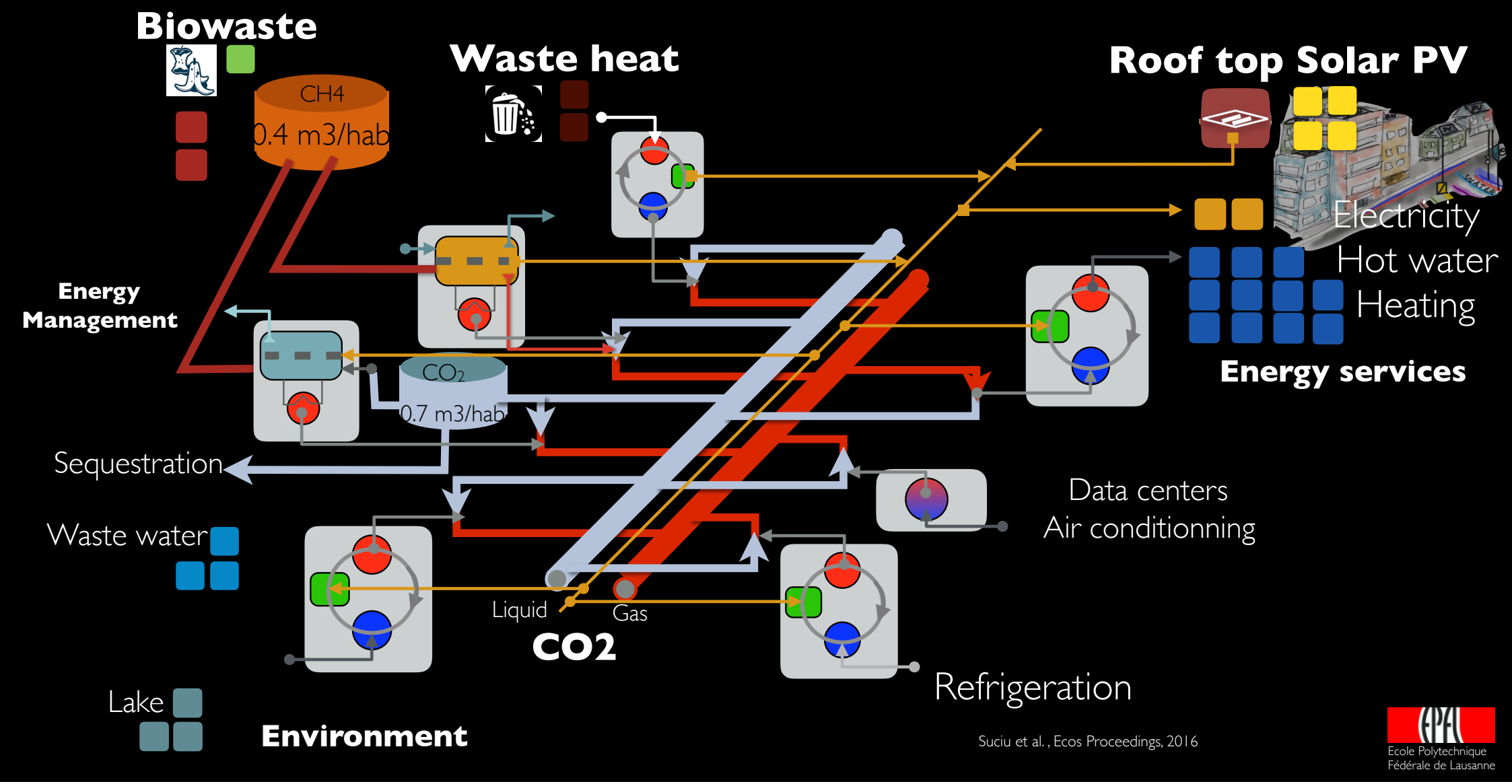
# CO2 network : 5th generation district heating/cooling system

exergo.ch




Suciu et al., Ecos Proceedings, 2016

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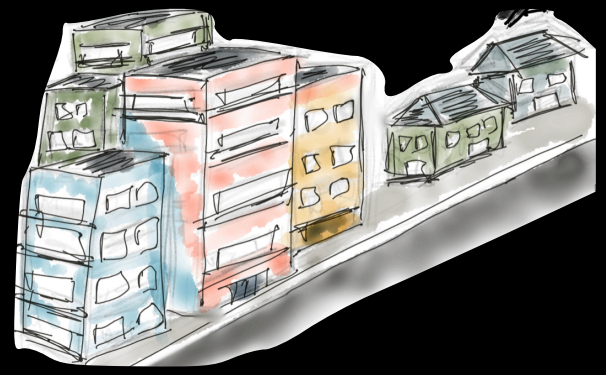
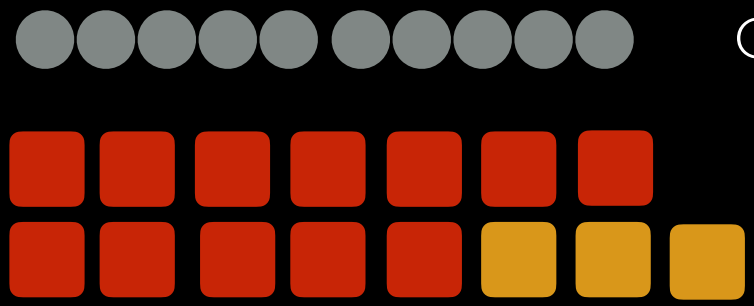
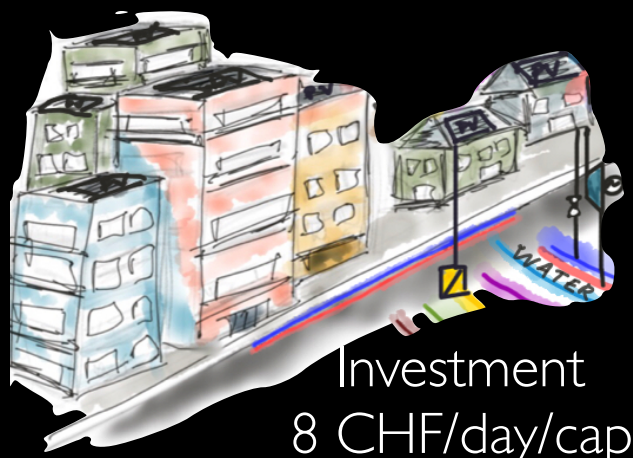
# A CITY 100% RENEWABLES AND CO2 NEUTRAL BY 5 G DHC

Before






After





Investment $

8 CHF/day/cap

25 m2 PV/cap

1 m pipe/cap

12 kg CO2/cap

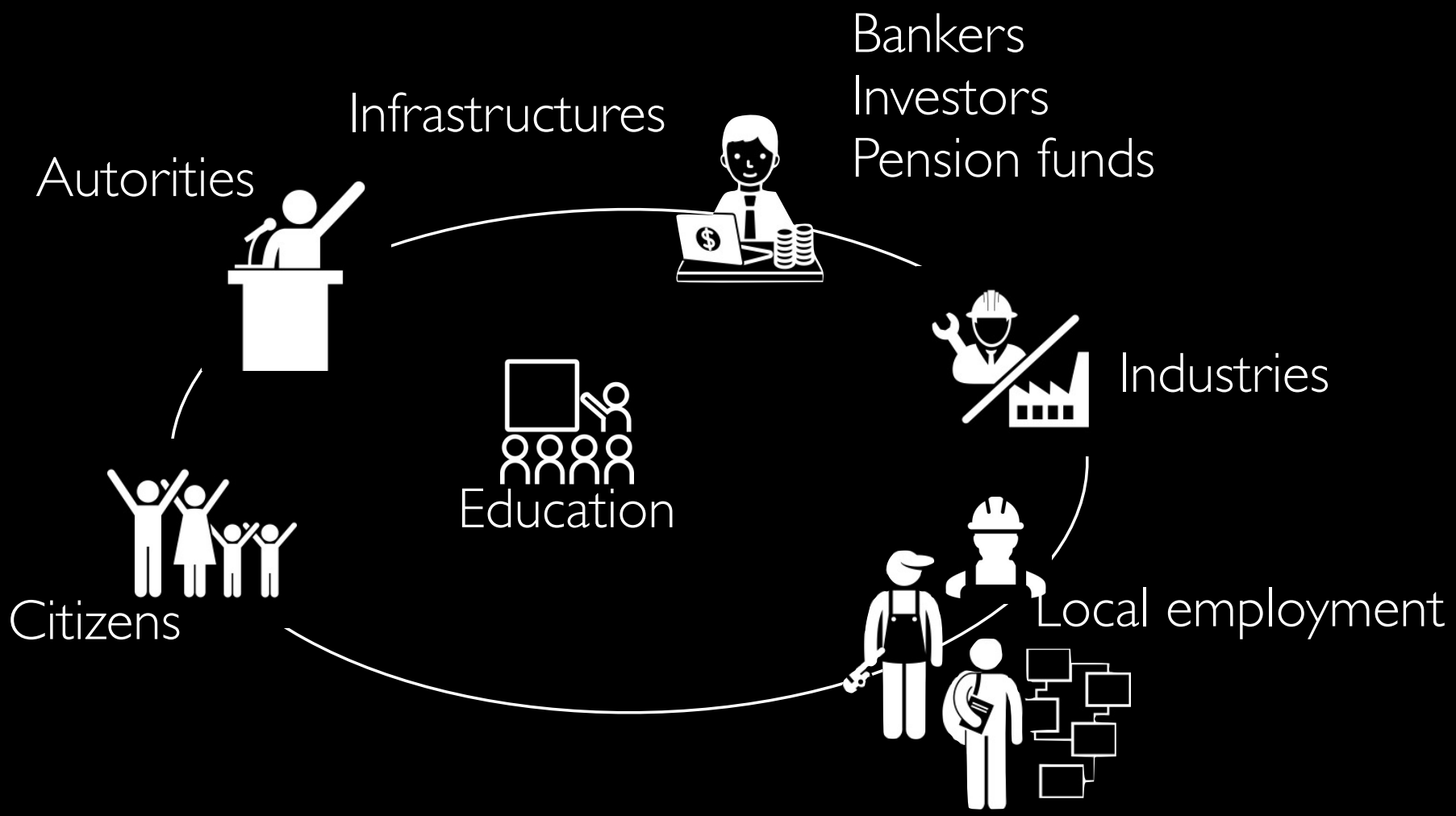
Storage : 1 m3/cap

100 l gasoline/hab/year

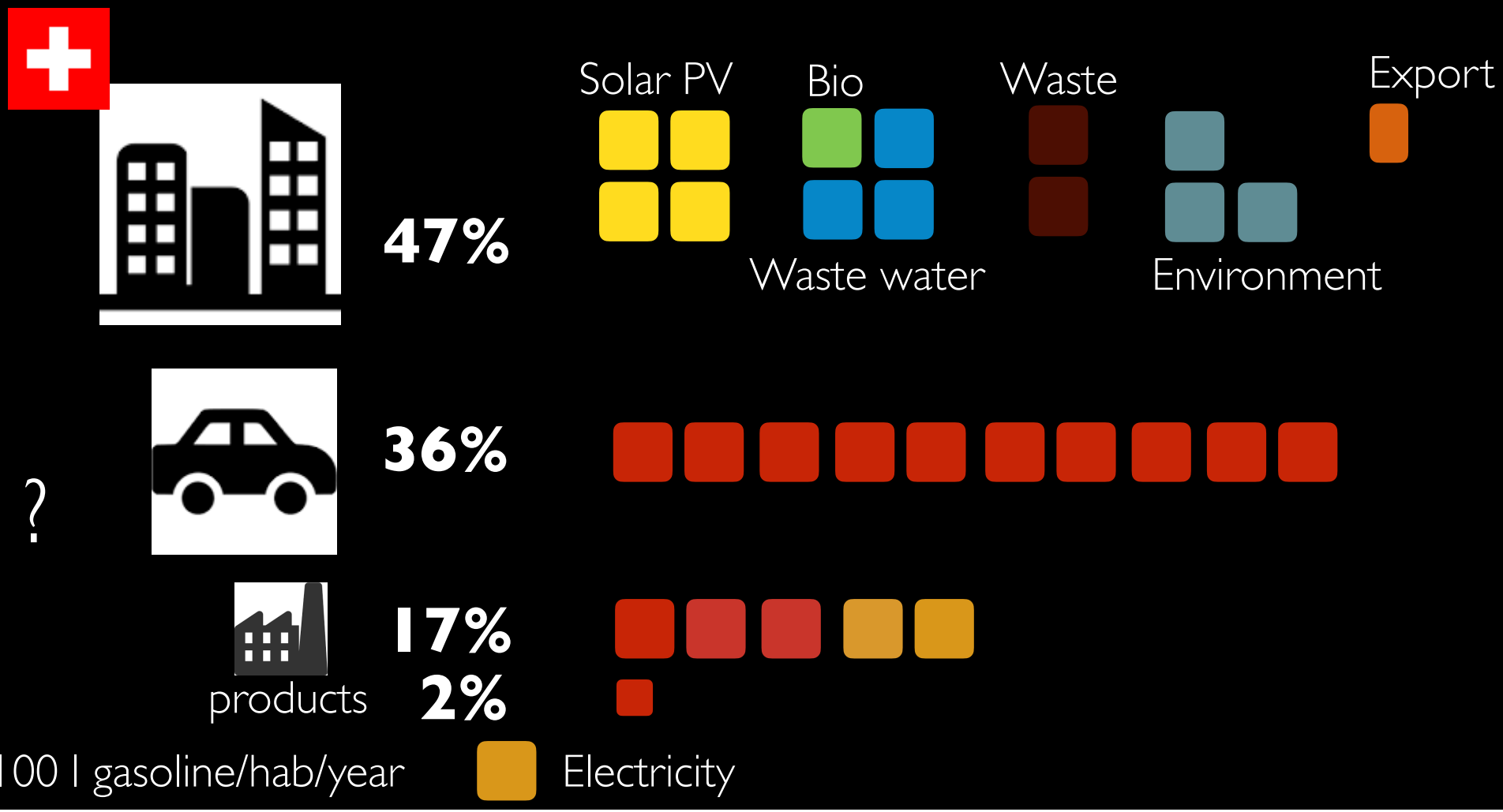
Electricity

R. Suciu et al., Energy integration of $CO_2$ networks and Power to Gas for emerging energy autonomous cities in Europe, ECOS 2017 Proceedings

# A SOLUTION BASED ONLY ON LOCAL RESOURCES



# THE ENERGY SYSTEM

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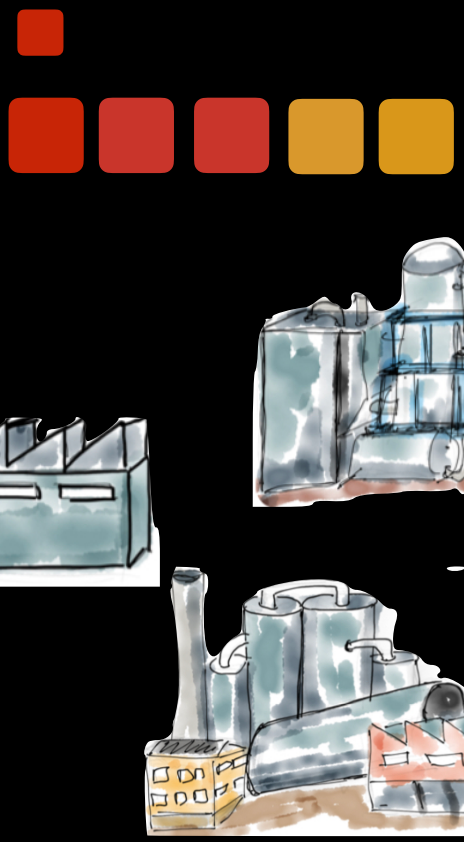
# THE INDUSTRY

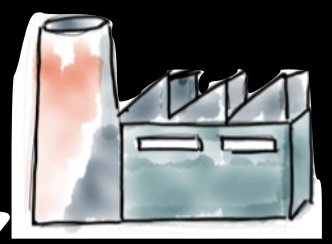
products **2%**

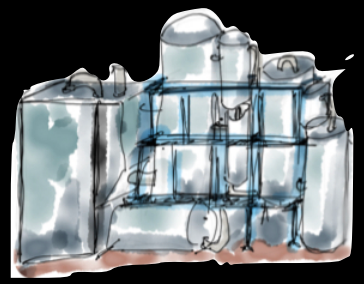
**17%**

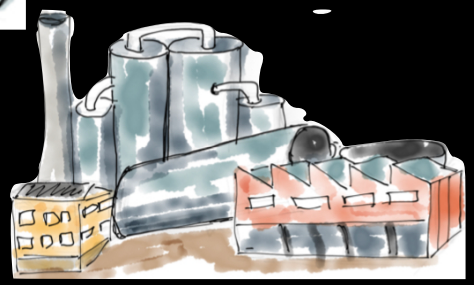
Industry



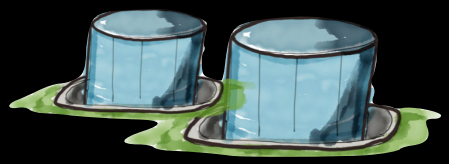
Oil



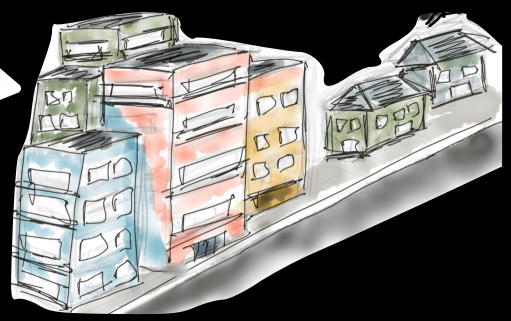




fuels



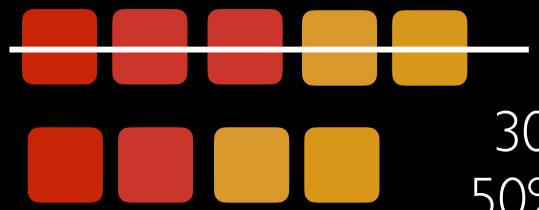
products



# ENERGY EFFICIENCY

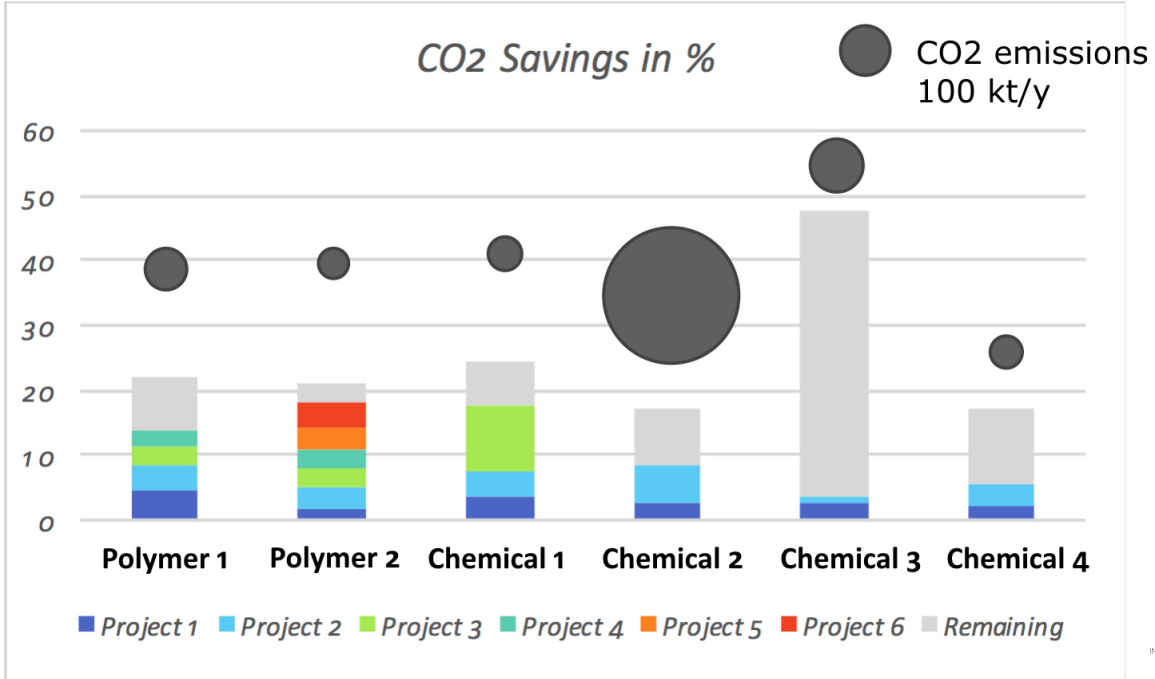
**17%**

Efficiency



30 % heat by Heat recovery
50% by heat pump integration

15 Projects realised in collaboration with industry




Energy audits
Process efficiency
Energy targets
Heat recovery
Heat pump integration

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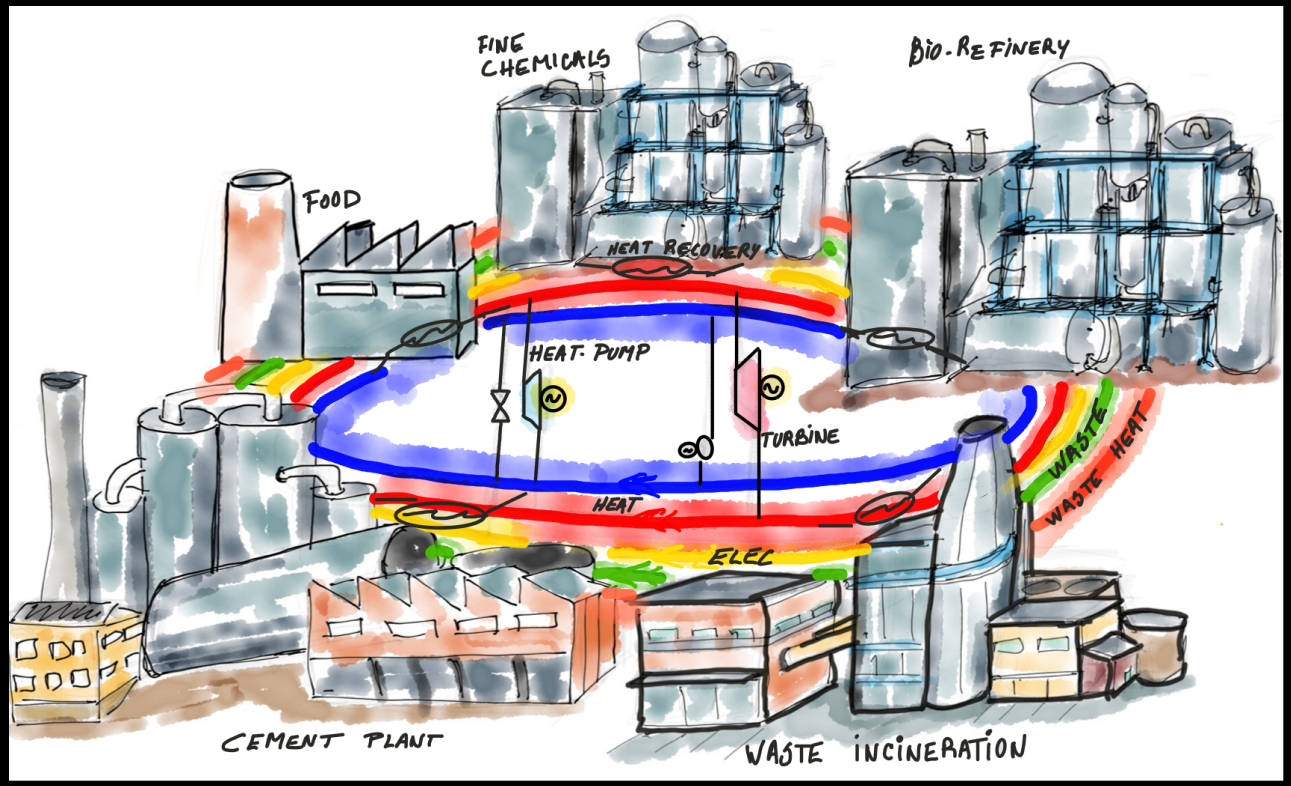
# INDUSTRIAL SYMBIOSIS

products **2%**

**17%**

Heat and mass (waste) exchanges




Heat recovery
Heat pumping
ORC and steam Rankine cycle
Energy and water integration
Waste management
Resource efficiency
Industrial Symbiosis
Combined fuel and heat

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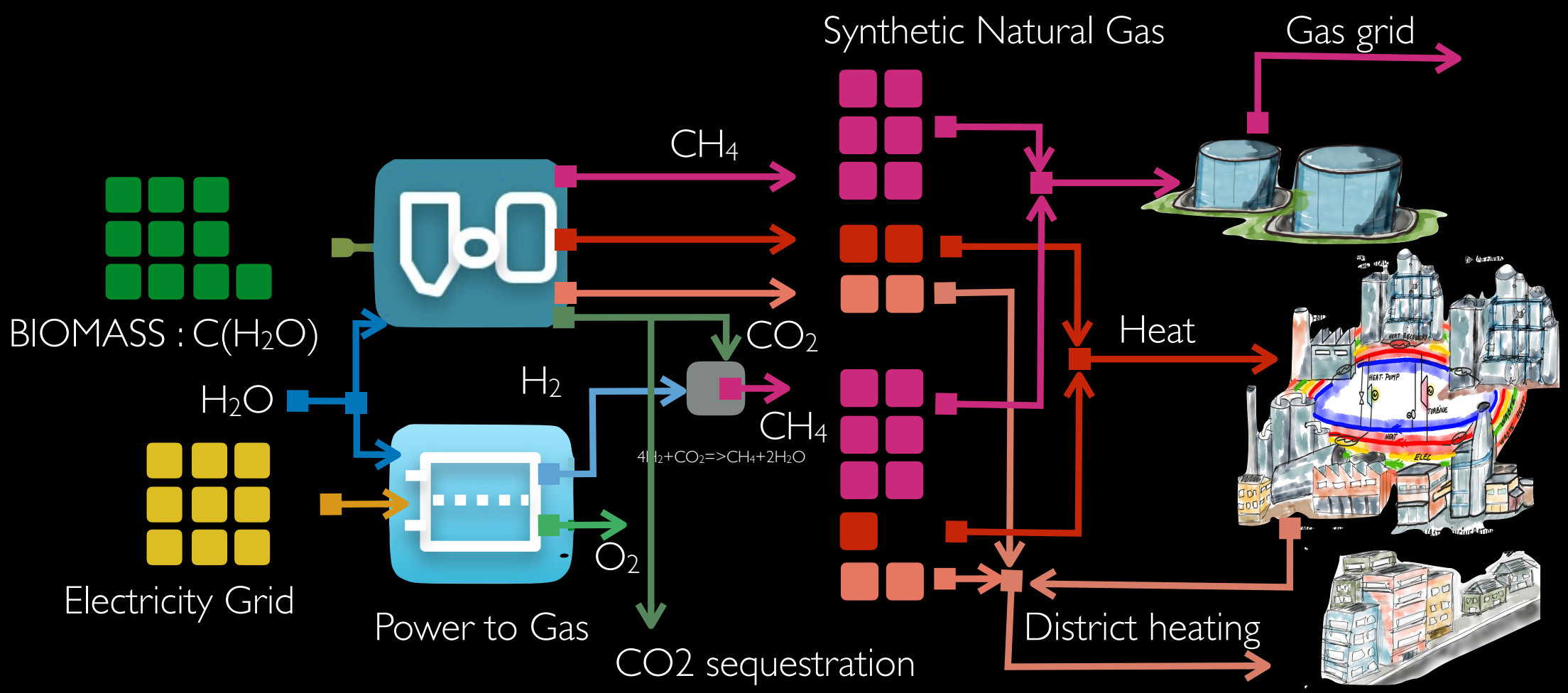
# ON THE USE OF THE BIOMASS AS AN ENERGY SOURCE




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.

# CIRCULAR ECONOMY : WASTE MANAGEMENT

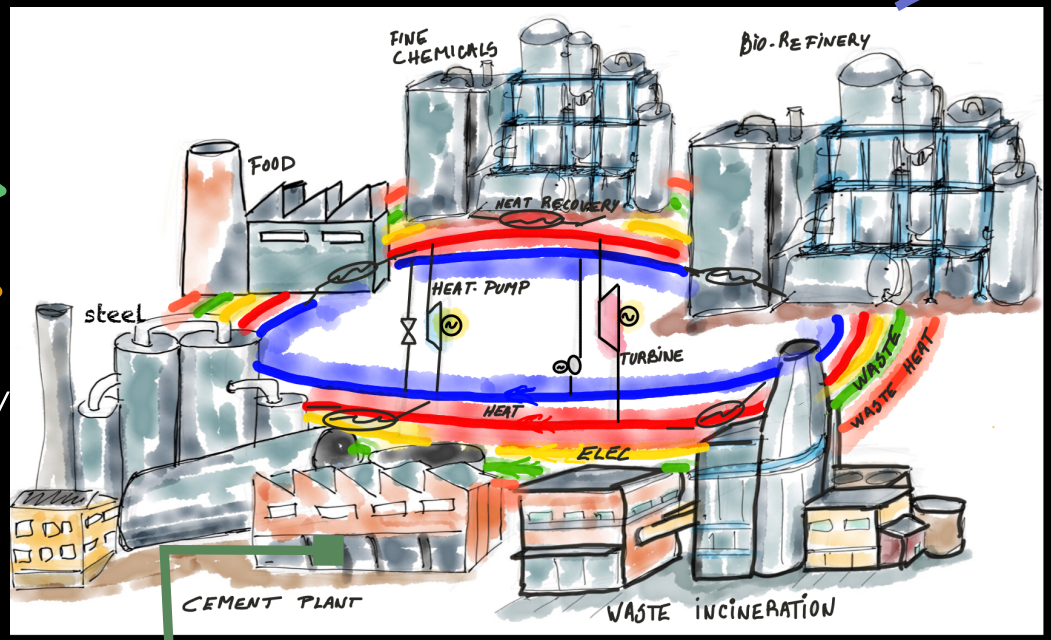
products **2%**

**17%**

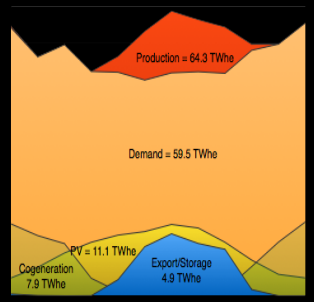
Biomass

Combined heat and fuel

Natural Gas




excess electricity



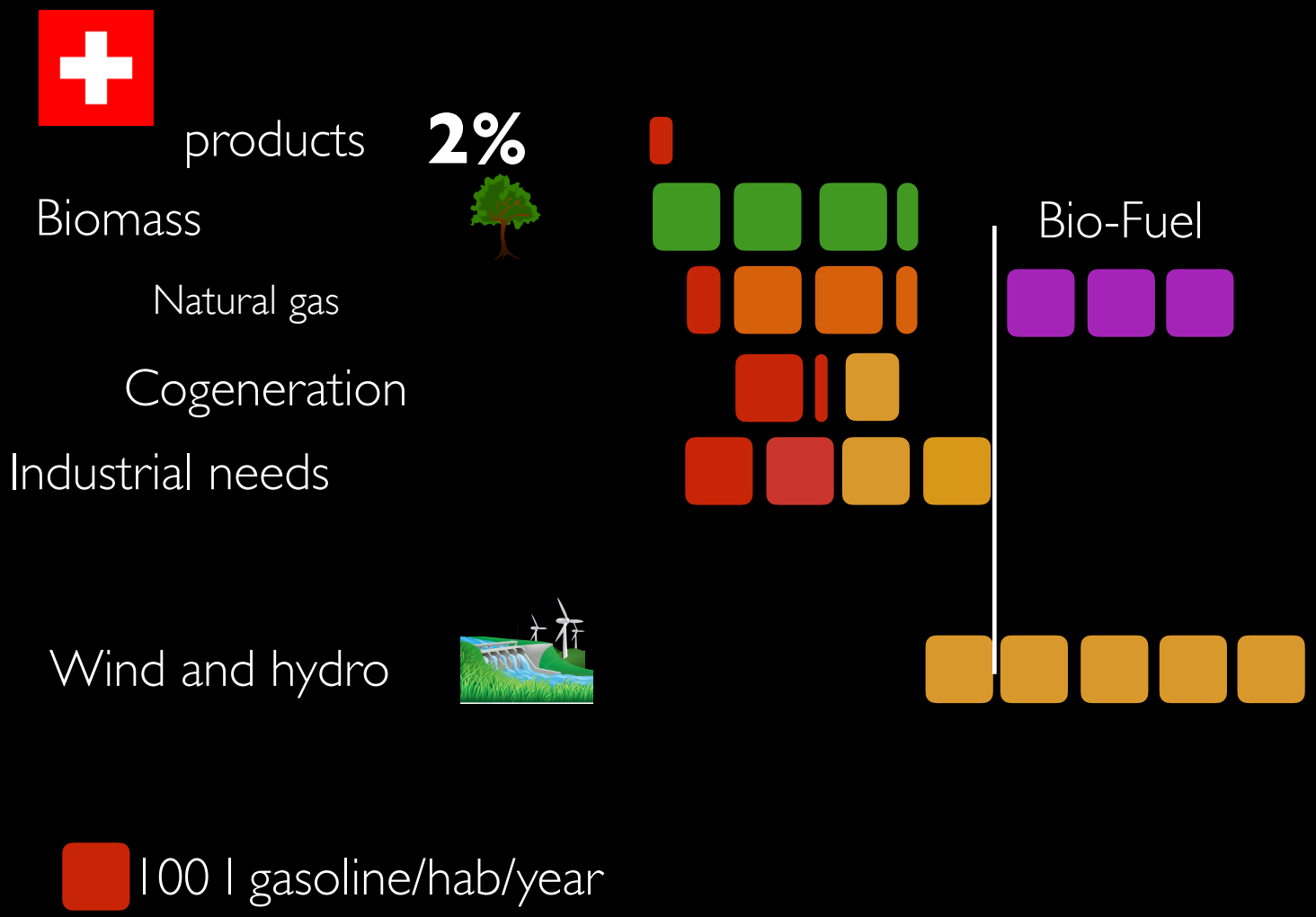

Products

Heat

Waste

$CO_2$

# SATISFYING THE SWISS ENERGY NEEDS




data : www.energyscope.ch

# ELECTRIFYING MOBILITY

**36%**

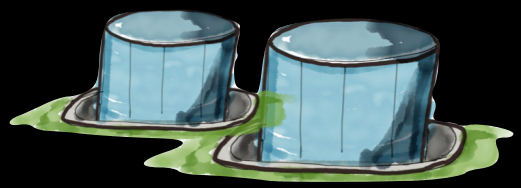
Efficiency

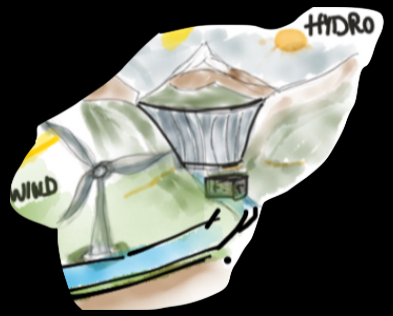
Electric vehicles

Hybrid and range extenders vehicles

CO2 capturing in fuel powered vehicles

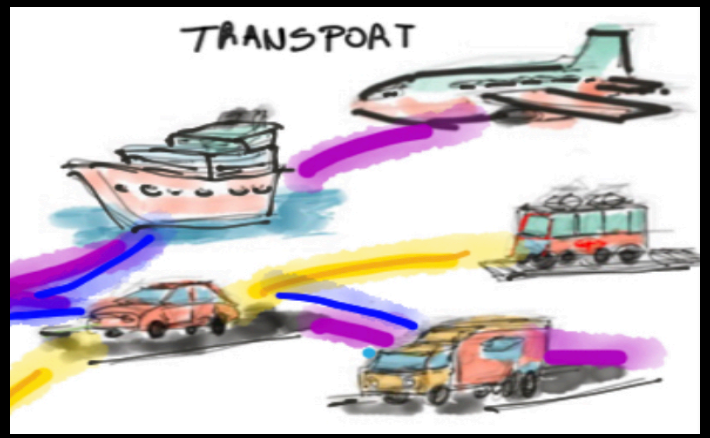
Public transport : electric/hybrid






Bio-Fuel

Available electricity




1000 l gasoline/hab/year

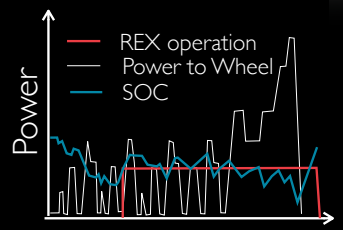
# RANGE EXTANDERS VEHICULES

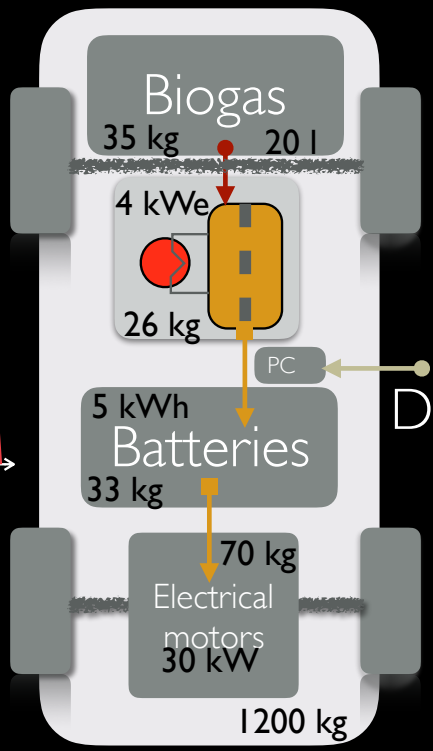
## Driving mode

Autonomy : 950 km
Cons : 1.1l/100 km


## Parking mode

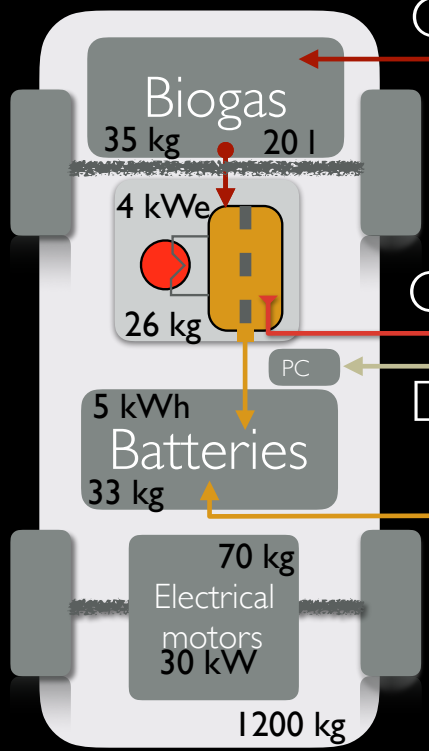
Power plant : 3.5 kWe (eff. >70%)
Battery : 5 kWh




Data Grid

SOFC-GT
Hybrid car




Gas Grid

CO2 Grid

Data Grid

Micro
El. Grid

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

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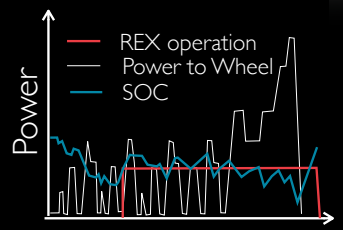
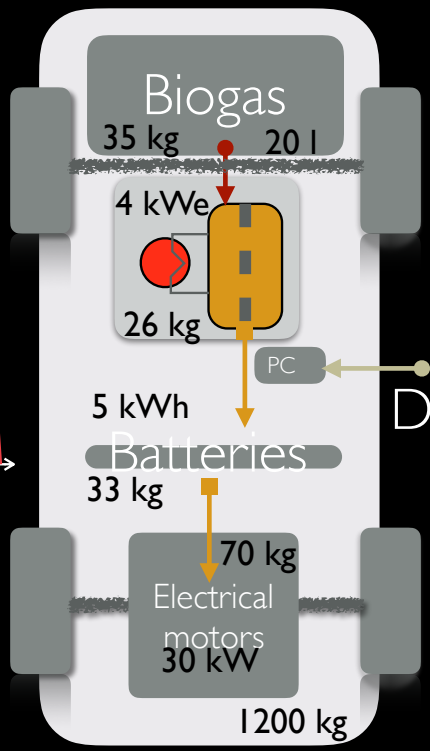
# SMART CARS

## 12 m2 PV/car

Autonomy : 950 km
Cons : 1.1l/100 km



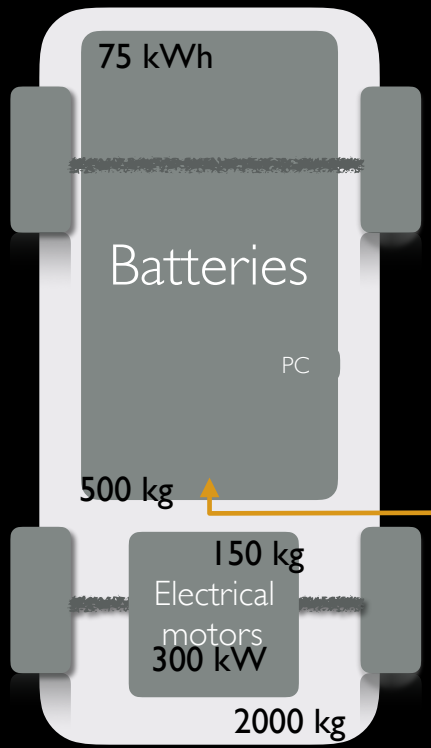




Data Grid

SOFC-GT
Hybrid car

## 24m2 PV/car

Power plant : 3.5 kWe (eff. >70%)
Battery :75 kWh




Micro
El. Grid

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

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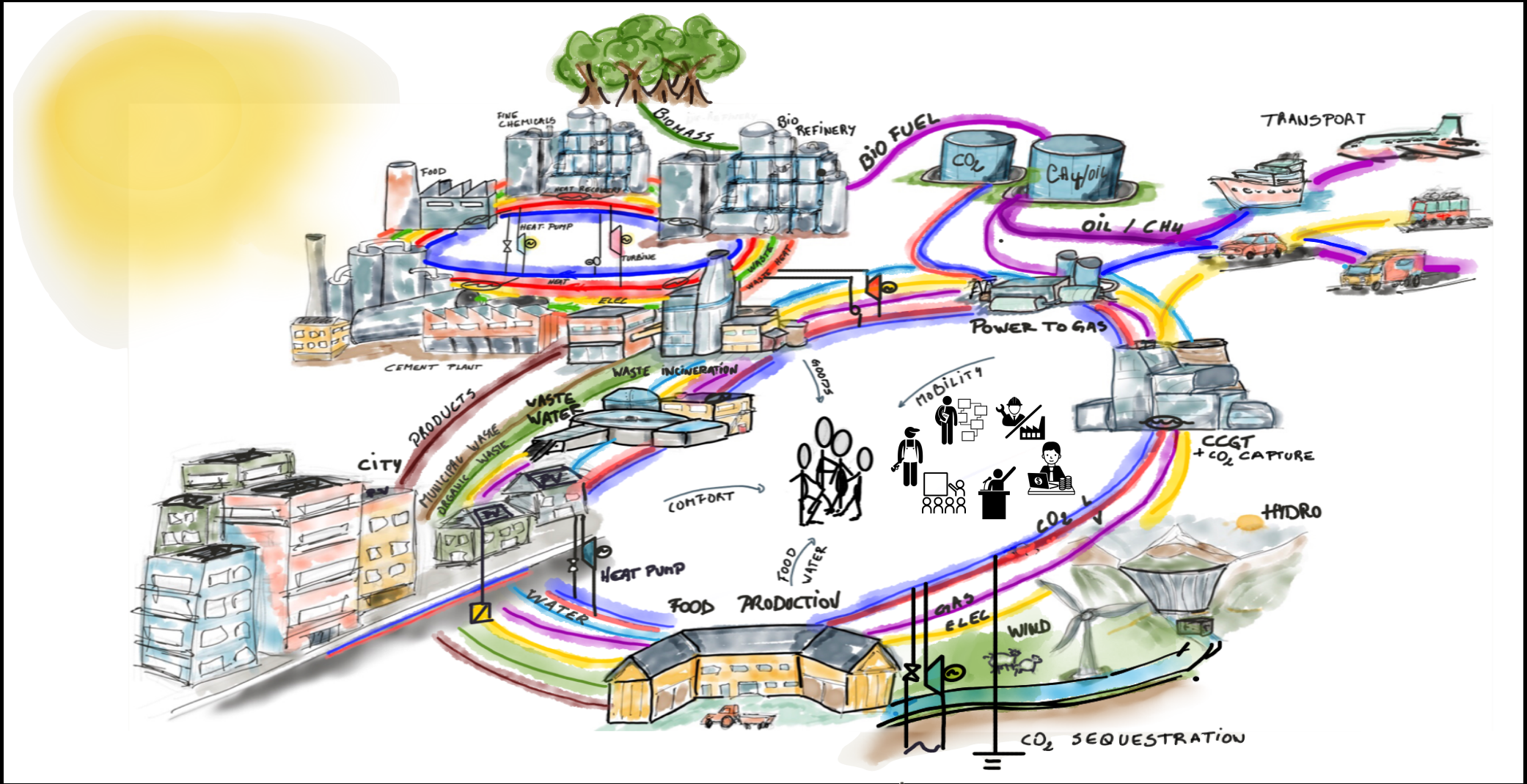
# ENERGY SYSTEM INTEGRATION



# 100 % RENEWABLE COUNTRY

**47%**

**36%**

products **17%**
**2%**

PV

Bio

Waste

Waste water

Environment

Biomass

Wind and Hydro

Export

Storage capacity

100 l gasoline/hab/year

Electricity

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# 100 % RENEWABLE AND INDEPENDENT

**47%**

**36%**

products **17%**
**2%**

PV

Bio

Waste

Waste water

Environment

Biomass

Wind and Hydro

100 l gasoline/hab/year

Electricity

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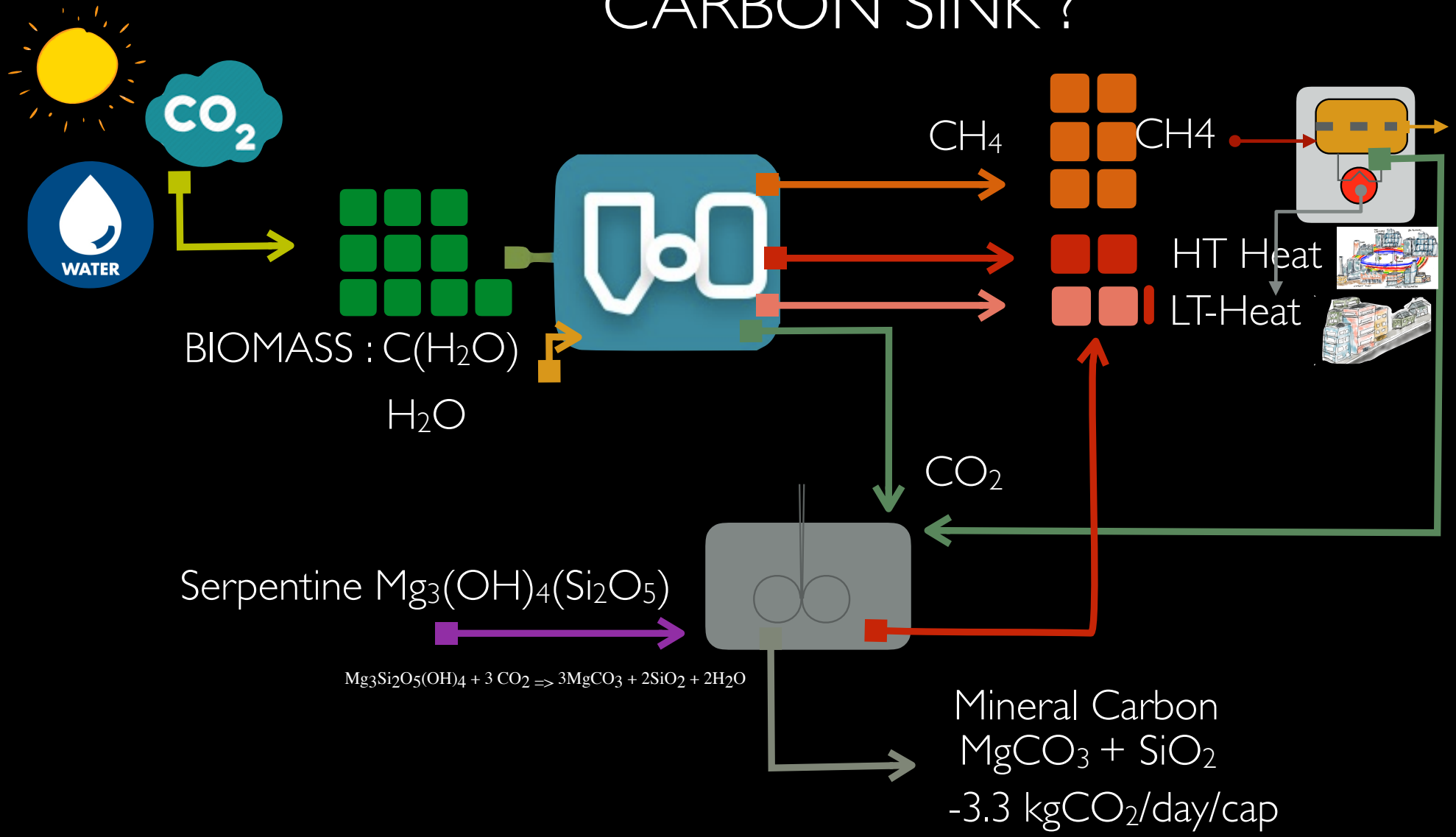
# CARBON SINK ?




78.4 MJ/kgC

54.4 MJ/kgC

4.4 MJ/kgC

0 MJ/kgC

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# ACKNOWLEDGMENTS


- **Sun** : for the energy supply
- **Mother Nature** : to show us the way to store energy
- **Carnot** : to show us the importance of ambiance
- **Industry** : to give us the technologies
- **Engineers** : to assemble and use the technologies in the right way at the right time
- **Research** : to educate the population that solutions exists
- **(Authorities)** : to develop education system and the infrastructure
- **(Finance)** : to ethically use (our) money for the right goals


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | VALAIS WALLIS

Thank **You** !

© Arne Naevra

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