UNE SUISSE INDÉPENDANTE ET NEUTRE

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Industrial Process and Energy Systems Engineering, EPFL, Switzerland

youtube : TEDx Martigny Marechal

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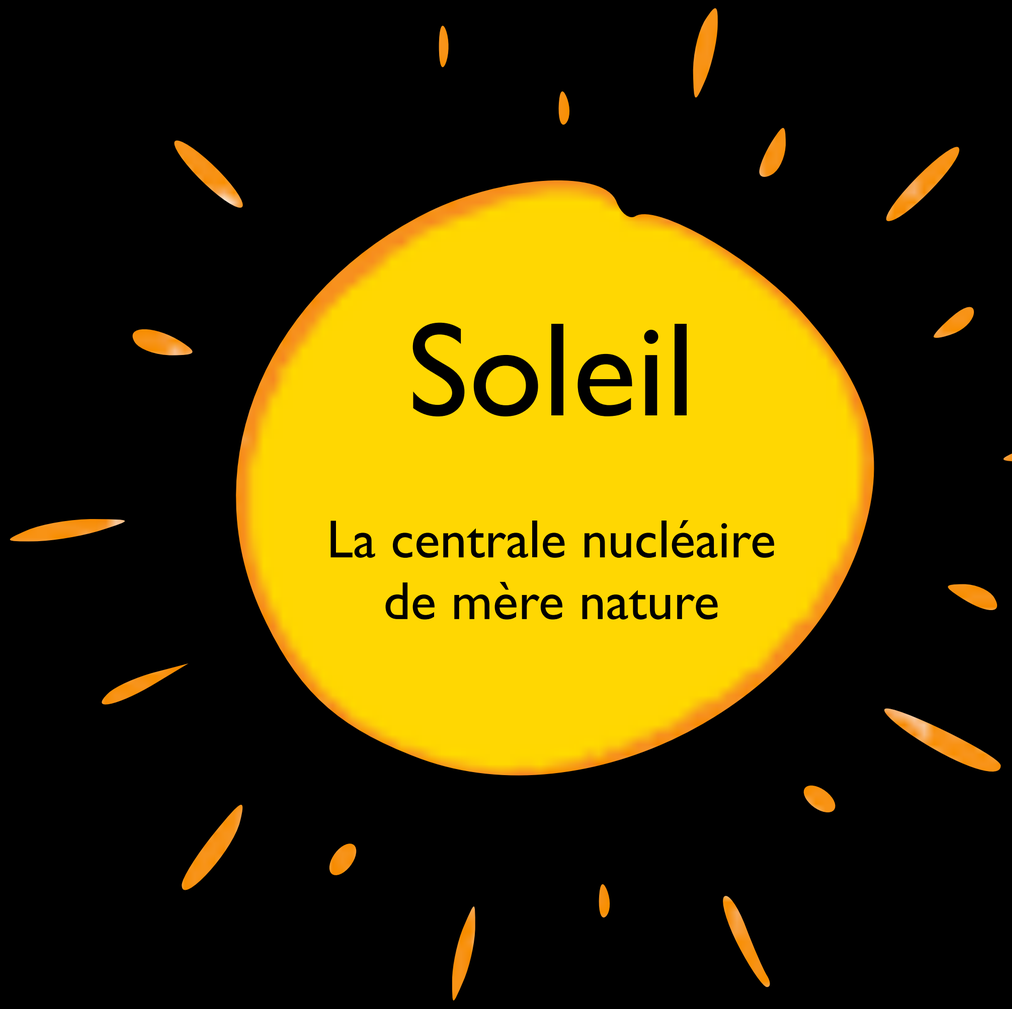
EST CE QUE NOUS AVONS UN PROBLÈME D'ÉNERGIE ?



1.5 heures

temps nécessaire pour fournir nos besoins annuels

6500 ans

Notre survie si nous utilisons 1 an d'énergie solaire

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PEUT-ON APPRENDRE DE MÈRE NATURE ?

100 millions années

1-100 ans

Energie stockée

Atmosphere

Biosphere

Geosphere

20 MJ/kg

Soleil
16'666'666

Photosynthèse

O_2

CO_2

H_2O

engrais

Biomasse
CH_2O

100

Stock !

100 100 l Oil/an/pers

Gestion de l'énergie
- 20% muscles : travail
- 20% cerveau : gestion
- 10% coeur : distribution
- 30% foie : conversion
- 37°C : cogeneration

✓Conversion
✓Stockages
✓Matériaux -> structure + fibres
✓Distribution
✓Gestion multi-échelle
✓Economie circulaire

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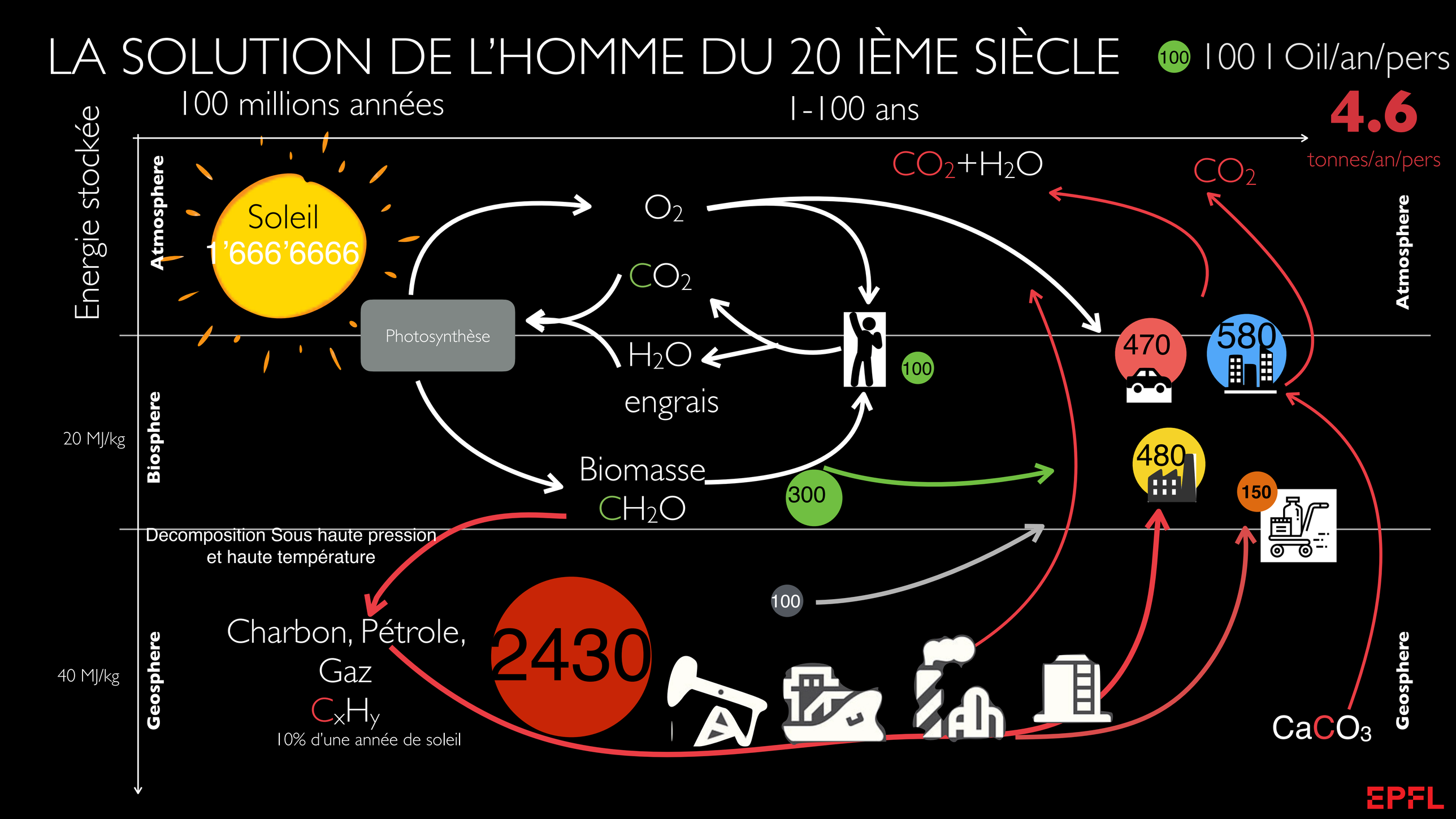
LA SOLUTION DE L'HOMME DU 20 IÈME SIÈCLE

100 1 Oil/an/pers

4.6
tonnes/an/pers



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1896 : les scientifiques savaient

1896 : science is already explaining the impact of CO2 concentration in the atmosphere !

1896

Svante Arrhenius' 1896 Paper

Prof. S. Arrhenius *on the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.*

Series 5, Volume 41, April 1896, pages 237-276.

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

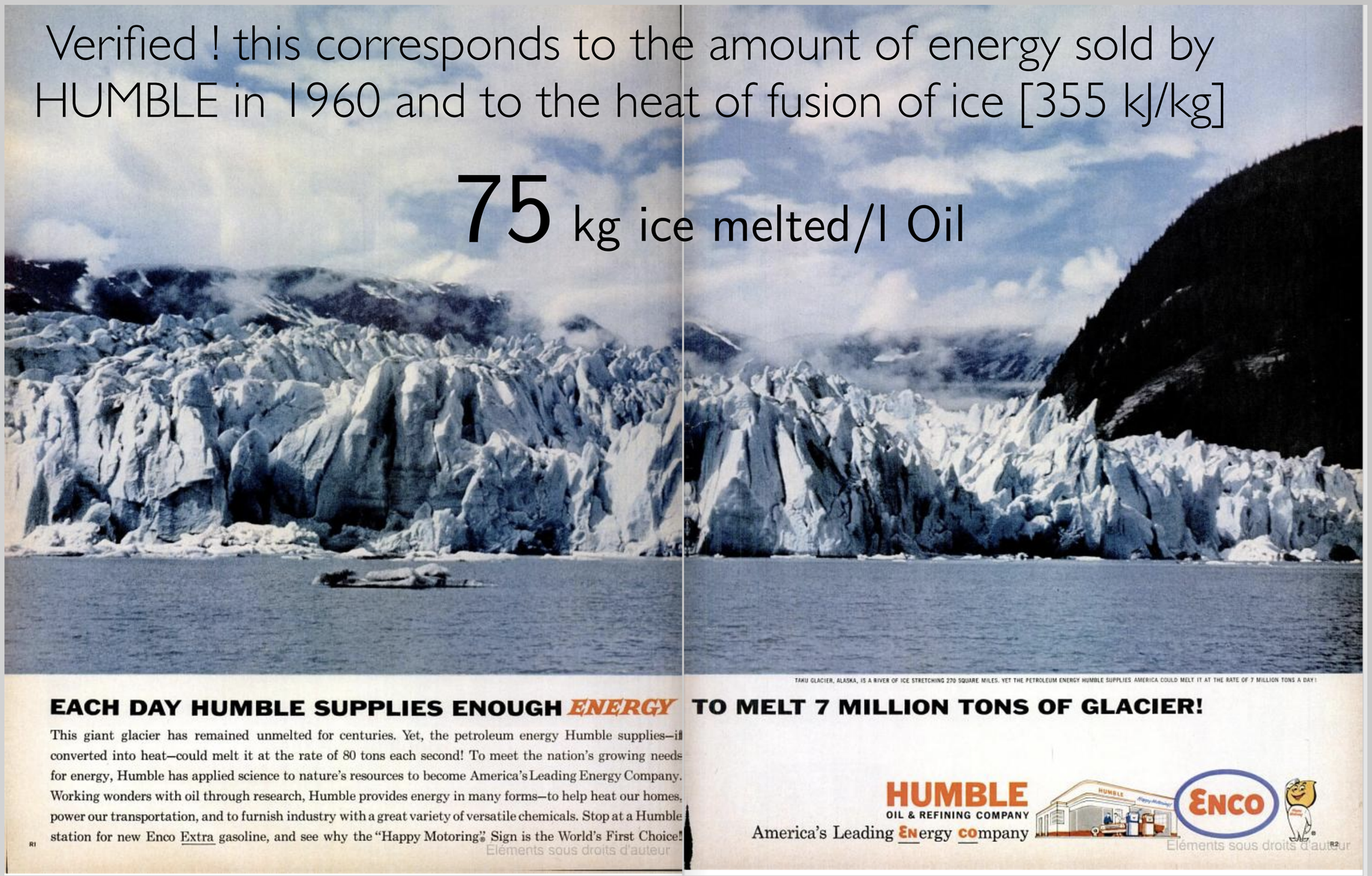
1. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

2x CO_2 in the atmosphere,
T goes up by 5^0 C
Later refined his calculation
to include *feedbacks* to get 2.1^0 C

1960 : L'industrie était fière de "sa" resource



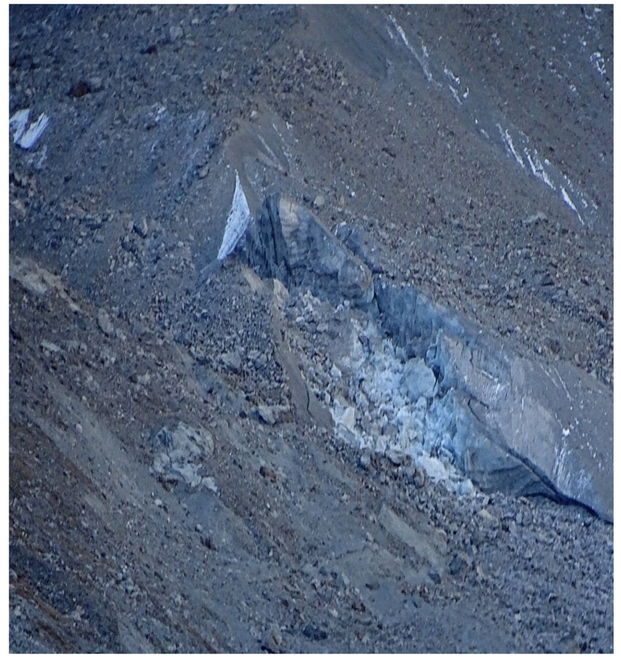
(1)
Inc, T. *LIFE*; Time Inc, 1962.

2023 : LA PERTE DE GLACE EST RÉELLE !

10% en deux ans en Suisse !

- 7-15 kg glace-glacier*/ kg CO2**
- 17- 36 kg glace-glacier/ 1 essence
- 1- 2 kg glace-glacier/km#

#si votre voiture consomme 6l/100 km



La grotte de glace s'est probablement effondrée dans la nuit de lundi à mardi.
Arollablabla

Nature CLiMate ChaNGe | VOL 8 | APRIL 2018 | 305–308 | www.nature.com/natureclimatechange305

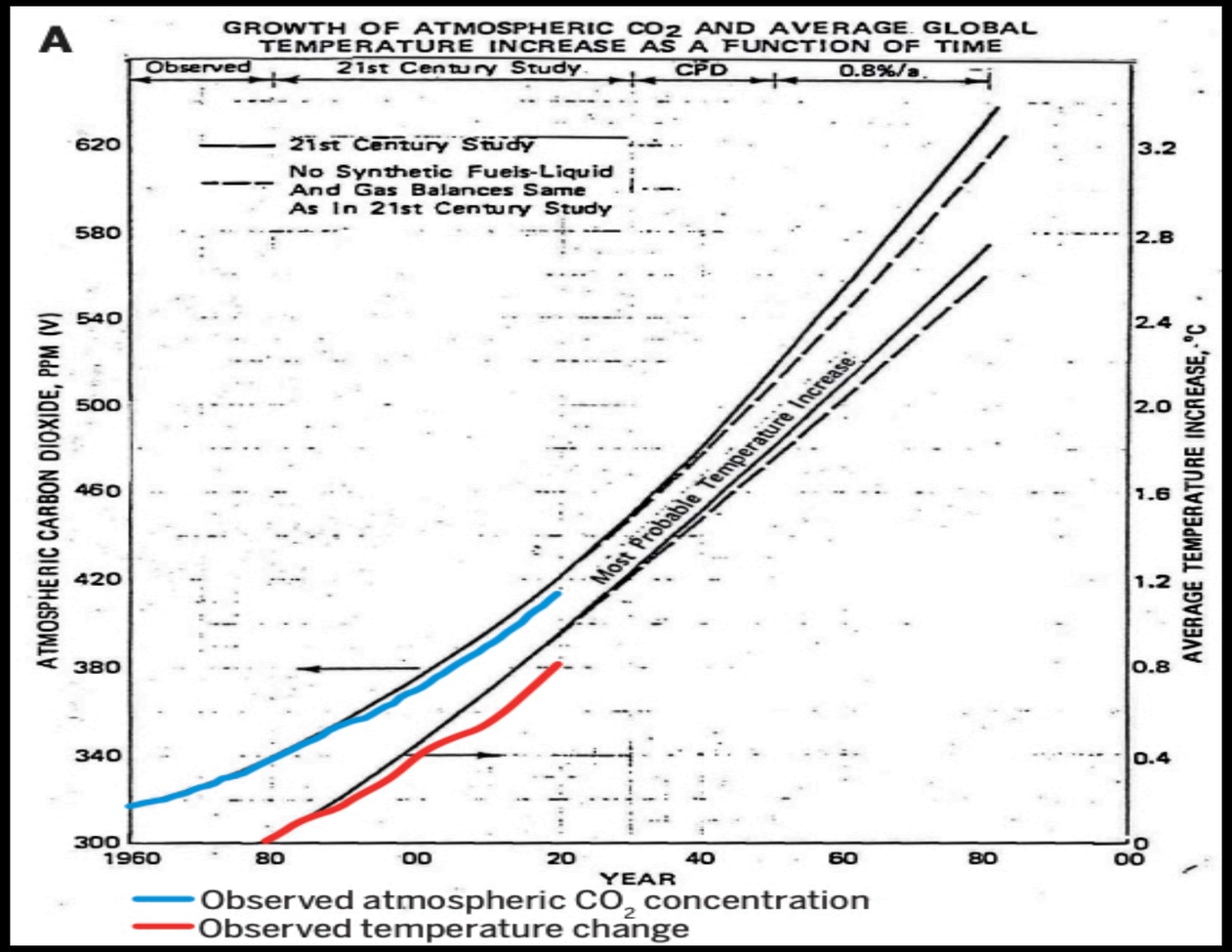
*Zemp, M., Huss, M., Thibert, E. *et al.* Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**, 382–386 (2019).

**IEA, World oil supply and demand, 1971-2020, IEA, Paris

1982 : L'INDUSTRIE SAVAIT

- Exxon study (1982)

Exxon's private prediction of the future growth of carbon dioxide levels (left axis) and global temperature relative to 1982 (right axis). Elsewhere in its report, Exxon noted that the most widely accepted science at the time indicated that doubling carbon dioxide levels would cause a global warming of 3°C. Illustration: 1982 Exxon internal briefing document



Supran et al., Science 379, 153 (2023) 13 January 2023

CO2 EMISSIONS CONSEQUENCES

Floodings

Japan 2018
Germany 2021
India 2021
China 2021
Pakistan 2022
Slovenia 2023
Greece 2023
Spain 2023
China 2023

+ 2°C

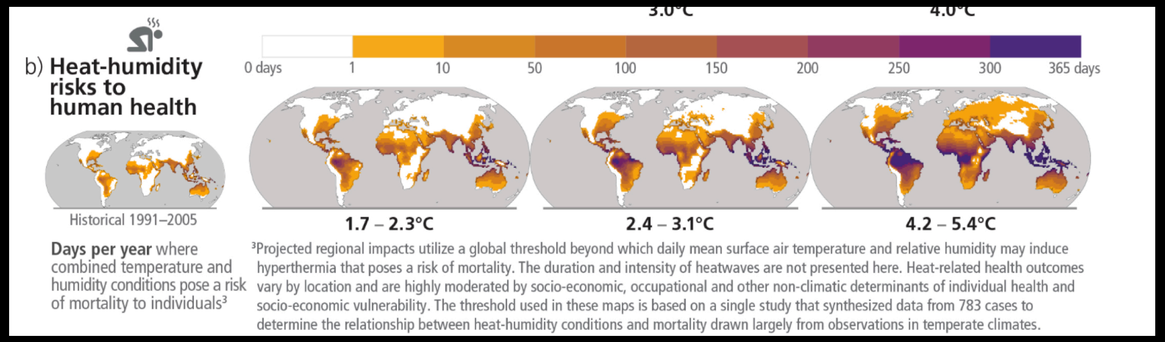
In Switzerland

Heat waves

Europe 2018
China-EU 2022
World 2023

Fires and Droughts

California 2018
Australia 2019
California 2020
California 2021
California 2022
China 2022
Europe 2022
Canada 2023
Greece 2023



Migration

Zones in the world where the bulb temperature is higher than the cooling temperature of the body

AR6 Synthesis Report (SYR)

EPFL

2023 : LE CO2 EST UNE MENACE !

+ 2°C

In Switzerland

Innondations

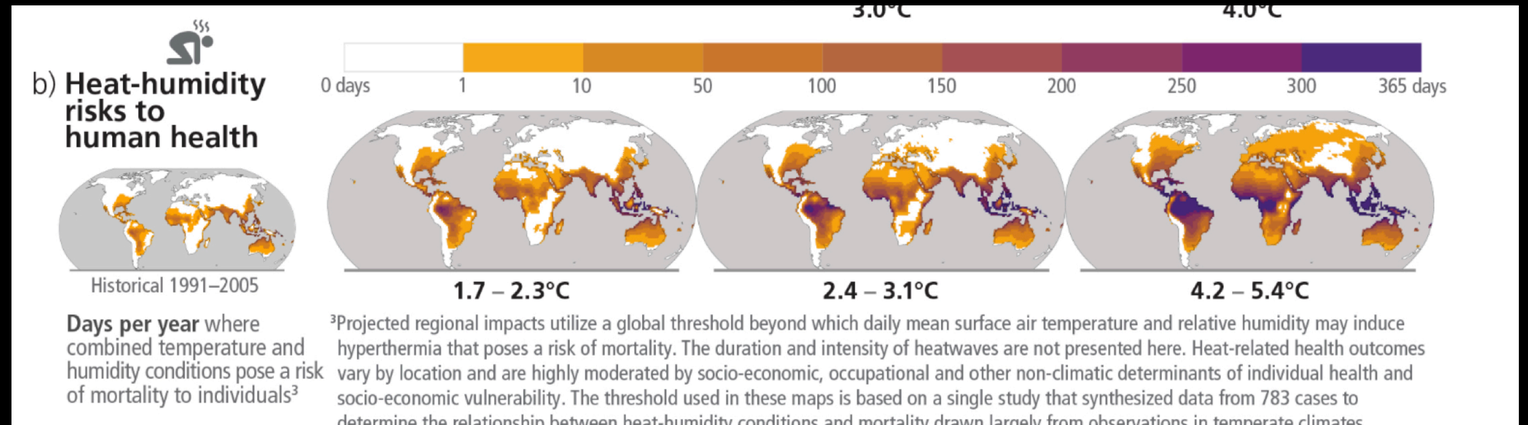
Vague de chaleur

Sécheresse et fuex

La révolution des jeunes

et des scientifiques…

Migration



AR6 Synthesis Report (SYR)

EPFL

URGENCE CLIMATIQUE
COMBIEN DE CO2 PEUT-ON ENCORE ÉMETTRE ?

7 $GtCO_2$/year
have we released to date?

33 $GtCO_2$/year
more can we "safely" release*?

-10 %/an
are left to release?

what's in the ground: 2755

1010 $GtCO_2$
added 1850–1999
55%

500
added 2000–2015
27%

335
our 'carbon budget'
18%

710
in fossil fuel reserves of all energy companies

780
remaining company reserves that could be developed

1,265
other reserves (including state-owned)

CURRENT ANNUAL FOSSIL FUEL EMISSIONS **36** gigatons

TIME BEFORE WE BREAK OUR 'CARBON BUDGET'

8 YEARS
if emissions continue to increase at 2.5% per year

* before 2050 and still have an 80% chance of staying below 2°C warming

informationisbeautiful.org All data & workings: http://bit.ly/CO2Gigatons2016

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We want Switzerland to be Independent and Neutral !

The Youths Revolution

and The Scientists Revolution

ENERGY NEEDS

47%

36%

17%

products **2%**

Import

Export

100 l gasoline/hab/year

Electricity

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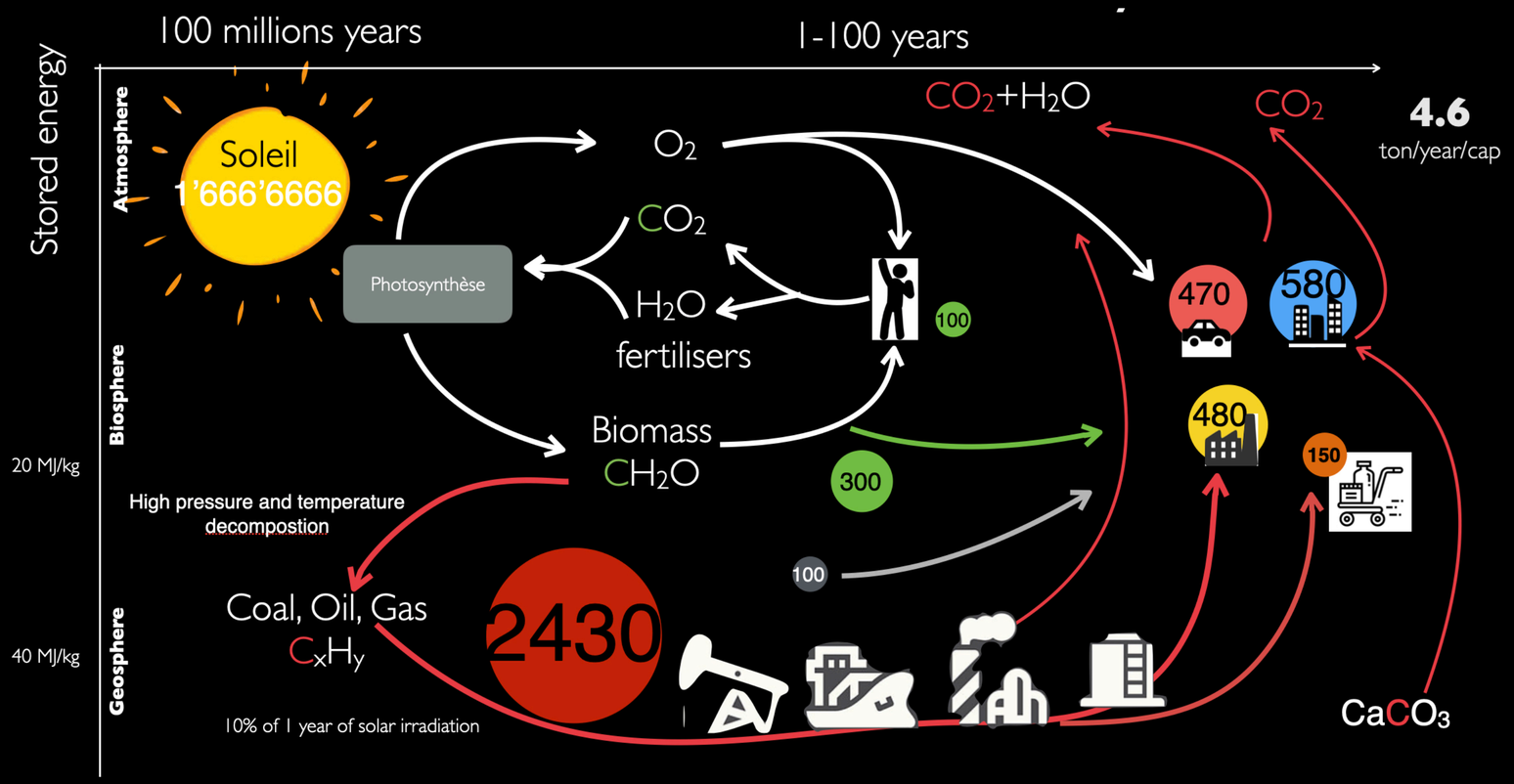
WHAT DID WE MISS ?



- ✓ Conversion
- ✓ Storage
- ✓ Materials
- ✓ Distribution
- ✓ Management

Renewables and circular economy

Our chalenge : Engineering a Net-Zero future

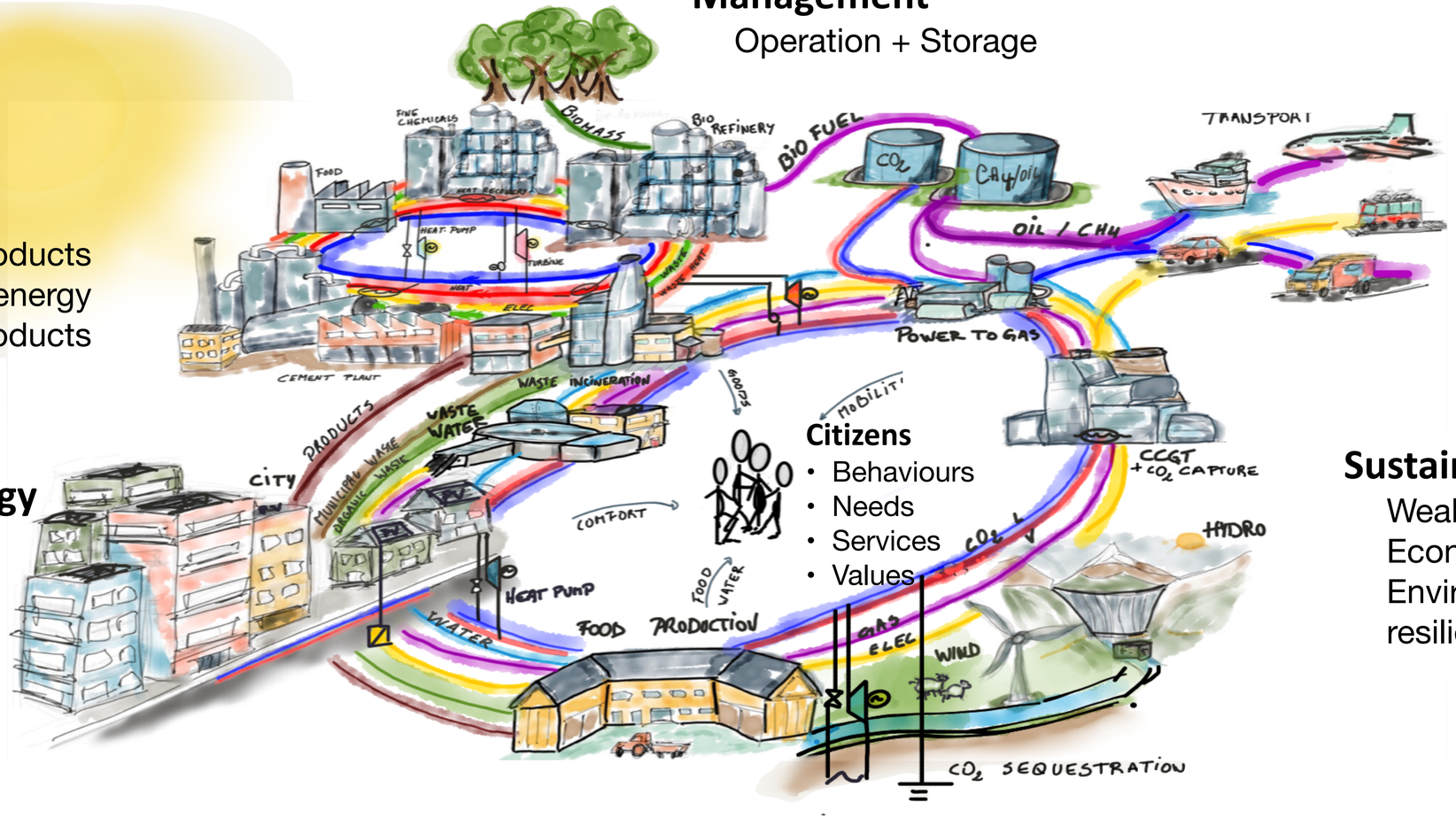
Renewable resources
Where-When-How much ?

Investments
(**New**) Technologies
sizes : conversion and storage
Infrastructure => synergies & mutualisation

Management
Operation + Storage

Demand
Products
Services
Security of supply

Circularity
Waste to products
Waste to energy
CO2 to products

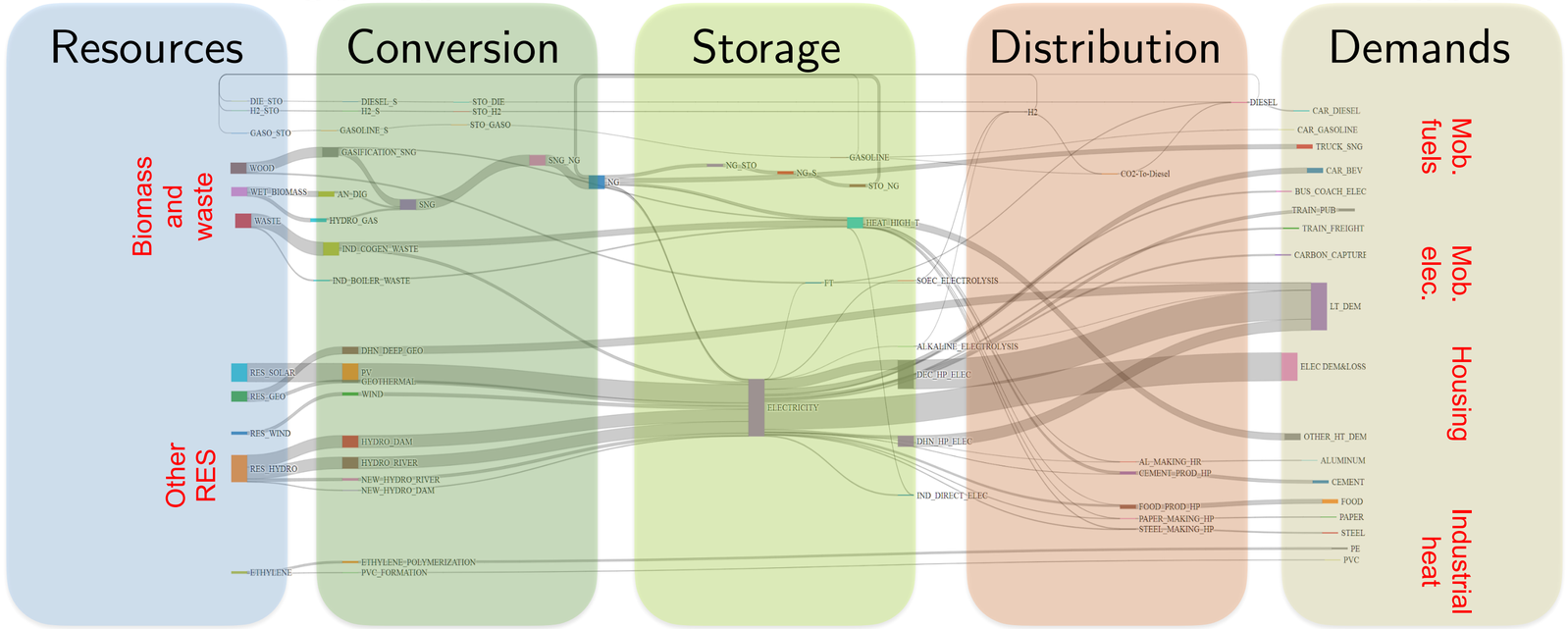


Waste-Water-Energy

Sustainability metrics
Wealth
Economy
Environment
resiliency

CO2 sequestration

Energy system model : when is stored energy needed ?



Technologies : Sizes - Operation

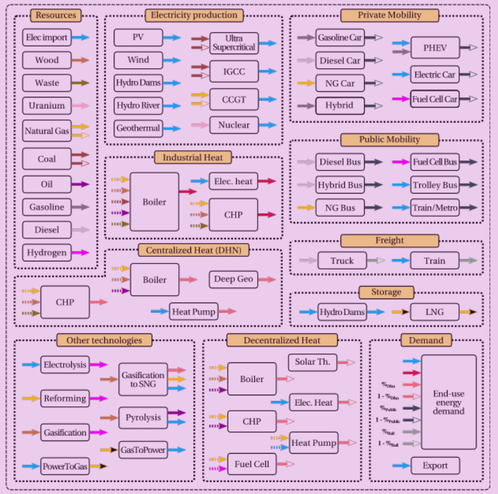
Data base

Conversion

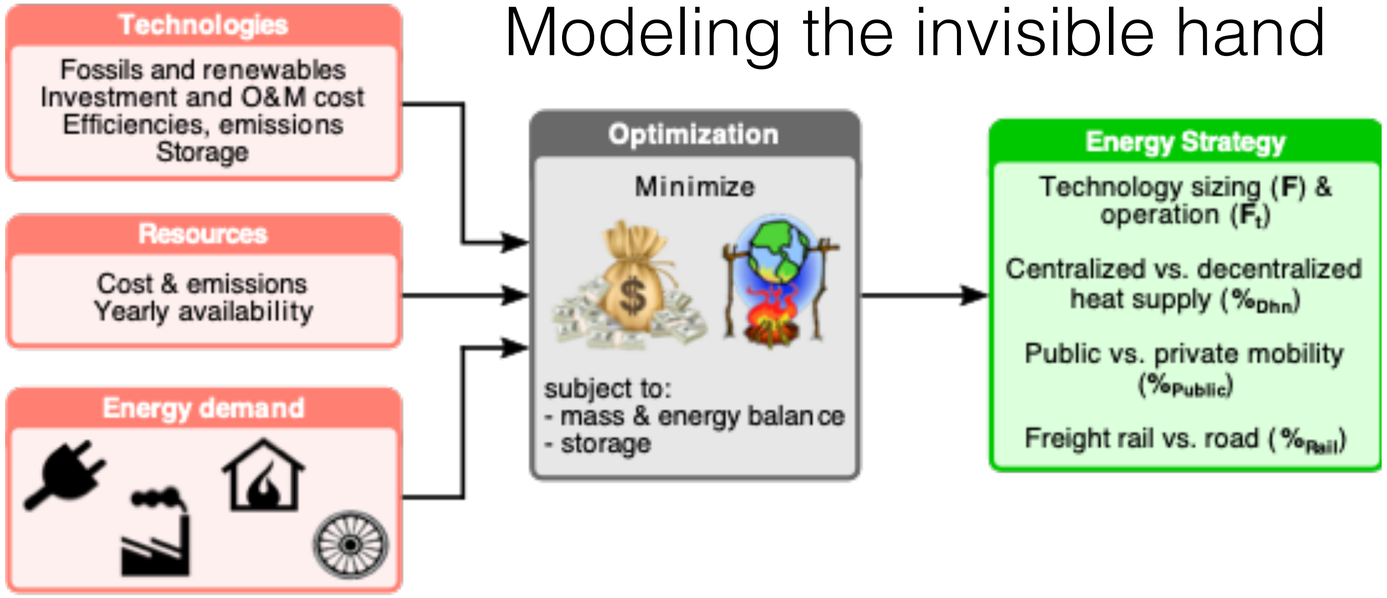
Storage

Distribution

Supply

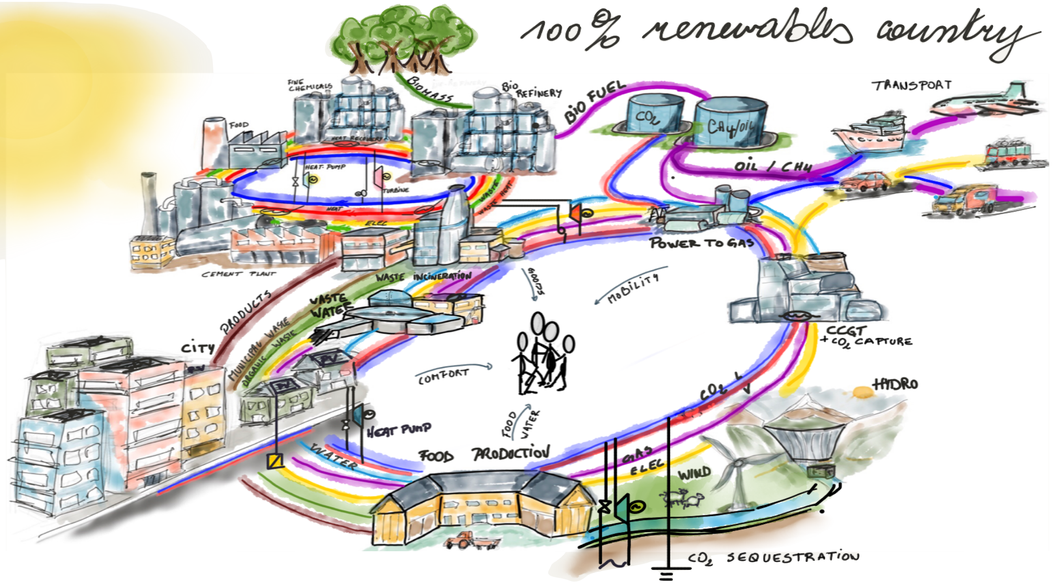


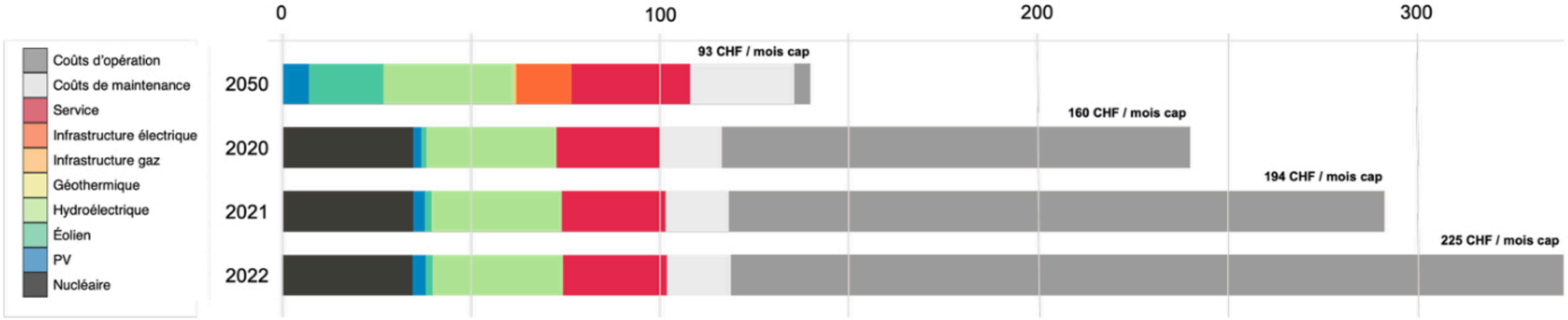
Modeling the invisible hand



The Swiss Energy model

- Le dictateur bienveillant satisfaisant pour une suisse indépendante et neutre





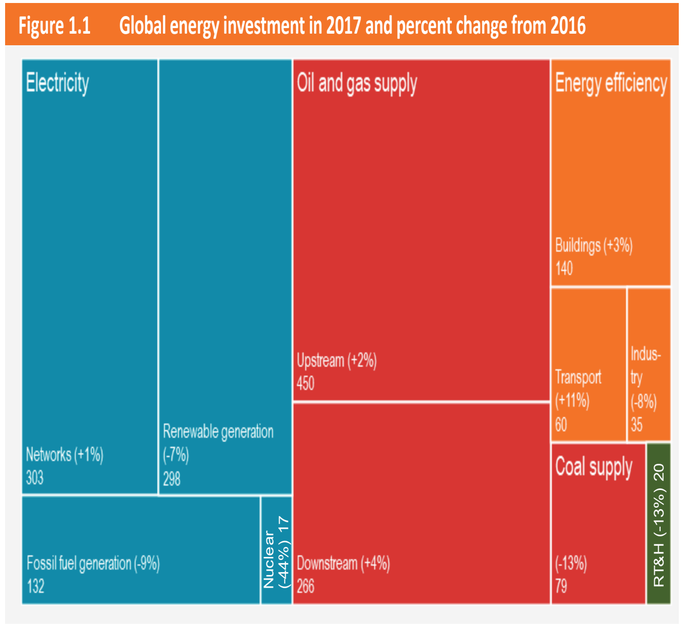
Do we have the money ?
2015 fossil spendings world wide

1.0 US$

Investment by industry

1'800

bUS$/year (2017)



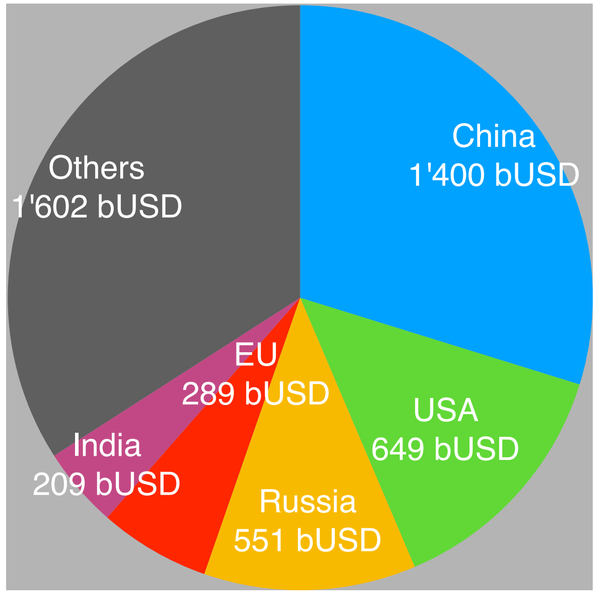
World energy investment 2018 IEA.org

2.5 US$

Subsidies by countries

4'700

bUS$/year (2015)



World energy subsidies 2015 imf.org

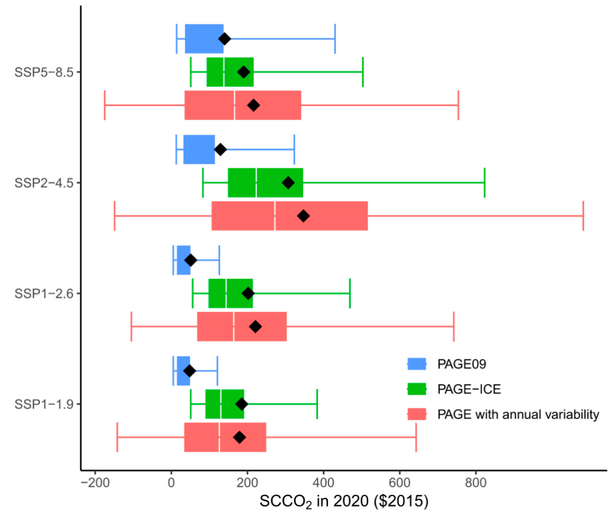
4.0 US$

Social/Repair

7'200

bUS$/year (2015)

repairing the damages



200 USD/t CO2

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

François Maréchal – francois.marechal@epfl.ch

Les clés pour une Suisse indépendante et neutre

(1830) CARNOT : LA FORMULE MAGIQUE

Nicolas Léonard Sadi CARNOT (F)

1796 - 1832

Electricité

sobriété

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

Fraction de la chaleur venant de environnement

HEATING BUILDING IS 50% OF COUNTRY ENERGY CONSUMPTION

120-190

CHF/month/100 m^2

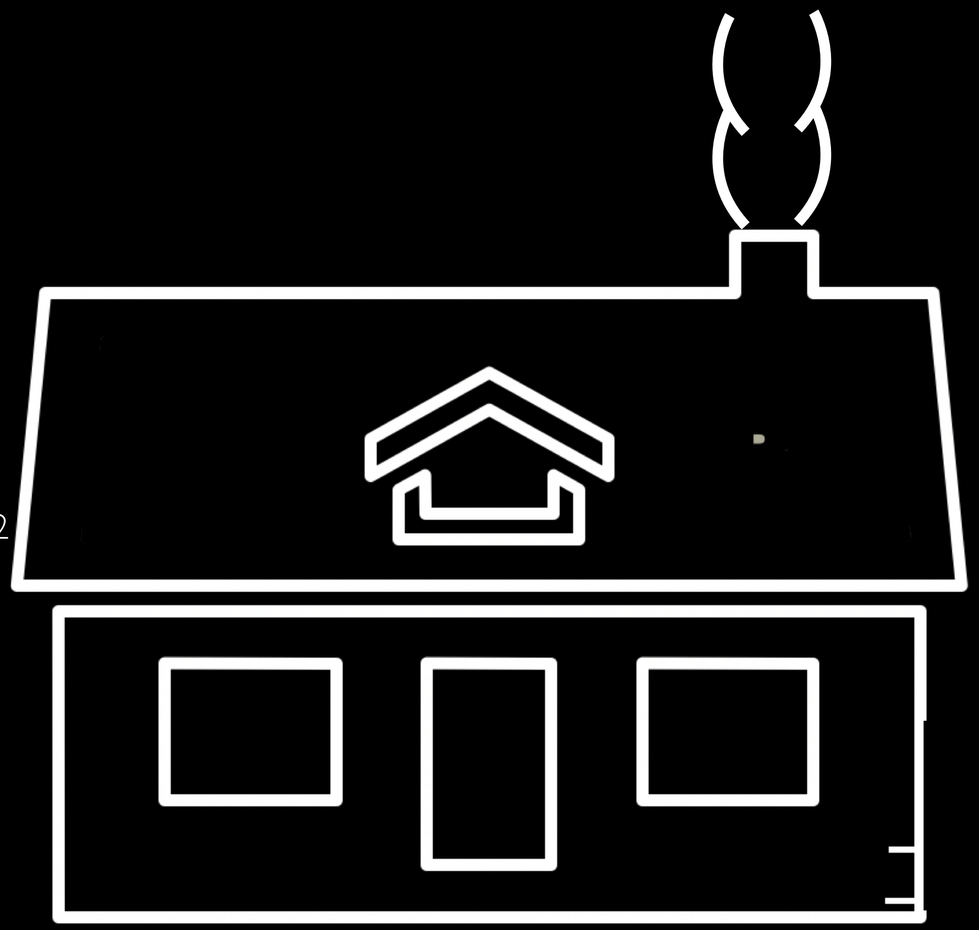
Energy (Oil)

110-180 CHF/month/100 m^2

in which 85-155 CHF/month/100 m^2 import

Boiler

10 CHF/month/100 m^2



3.78

tons CO_2 /year/100 m^2

63

$CHF_{children}$/month/100 m^2

Social cost of CO2: 200 CHF/ton CO2

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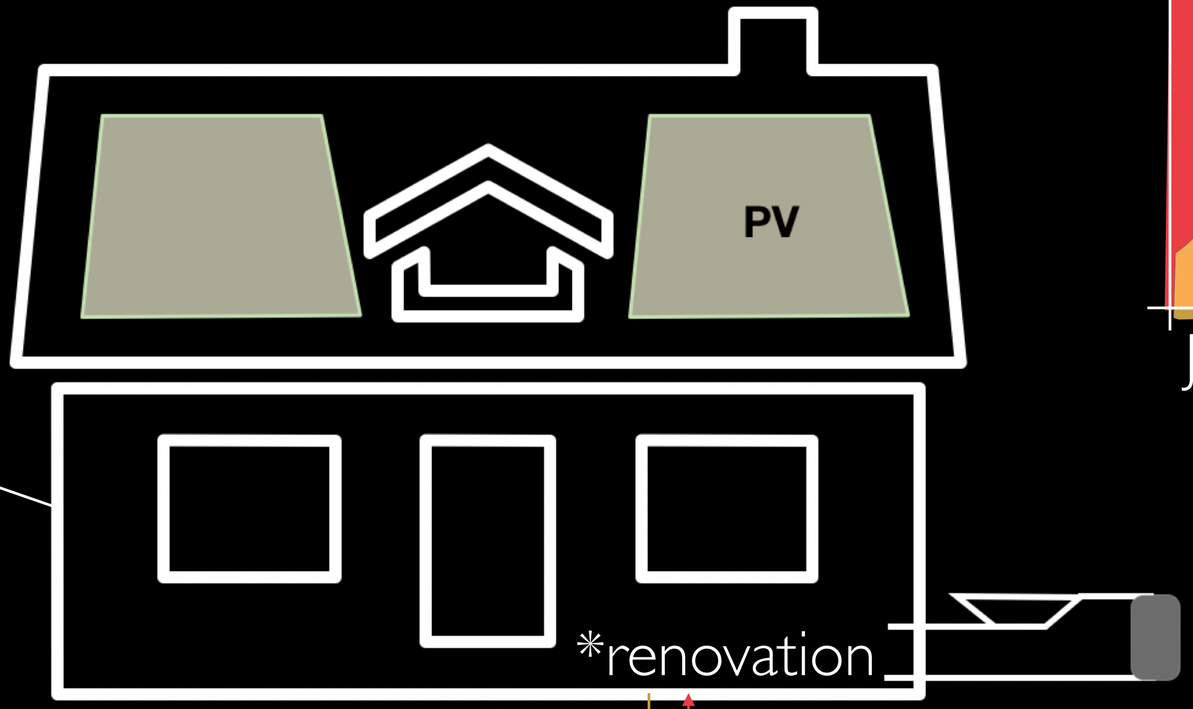
LE BÂTIMENT : UN HUB ENERGIE RENOUVELABLE

Big data - Predictions

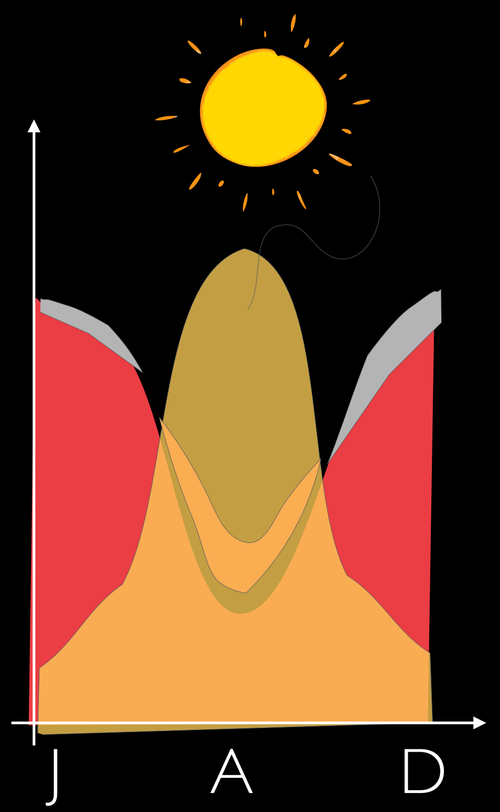
Contrôle prédictif



Batteries
Réservoir d'eau

Pompe à chaleur
Résistance

Réseau électrique



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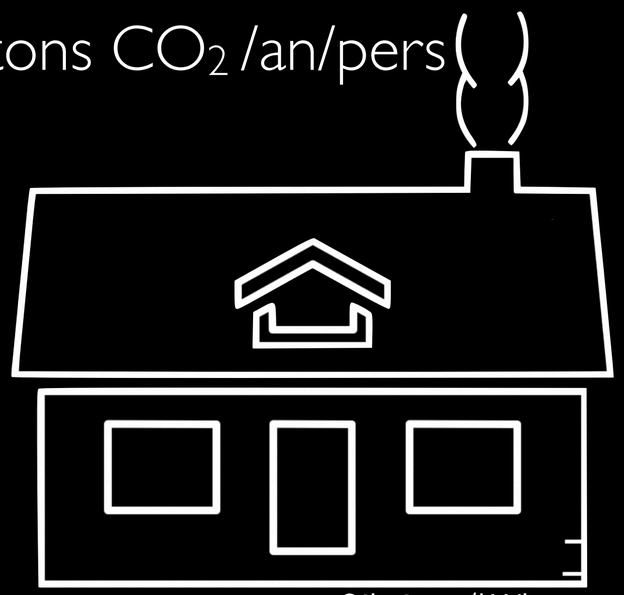
LE BÂTIMENT : HUB ENERGIE RENOUVELABLE
90+ % REDUCTION DES EMISSIONS DE CO2

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

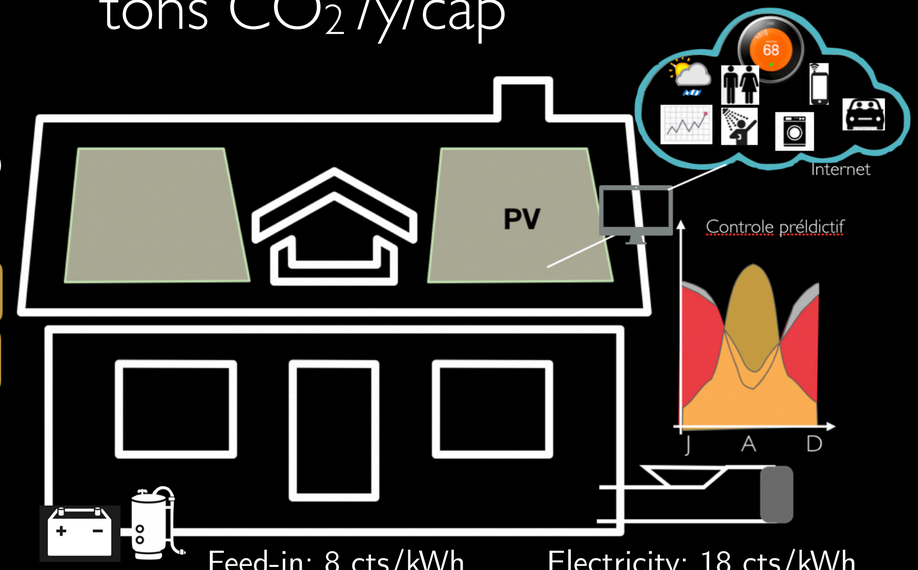
2021

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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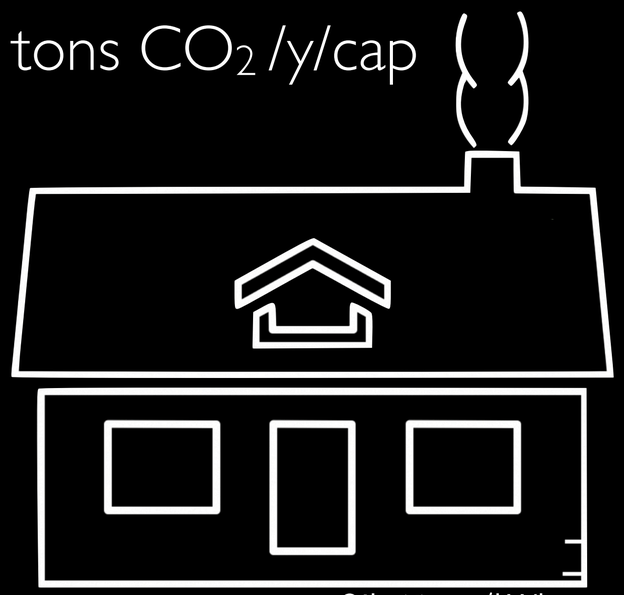
LE BÂTIMENT : HUB ENERGIE RENOUVELABLE
90+ % REDUCTION DES EMISSIONS DE CO2

2.20

tons CO_2 /y/cap



Oil: 11 cts/kWh

Electricity: 28 cts/kWh

1132

CHF/y/cap

Energy : **1102** CHF/y/cap

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

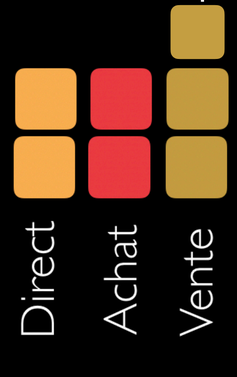
2023

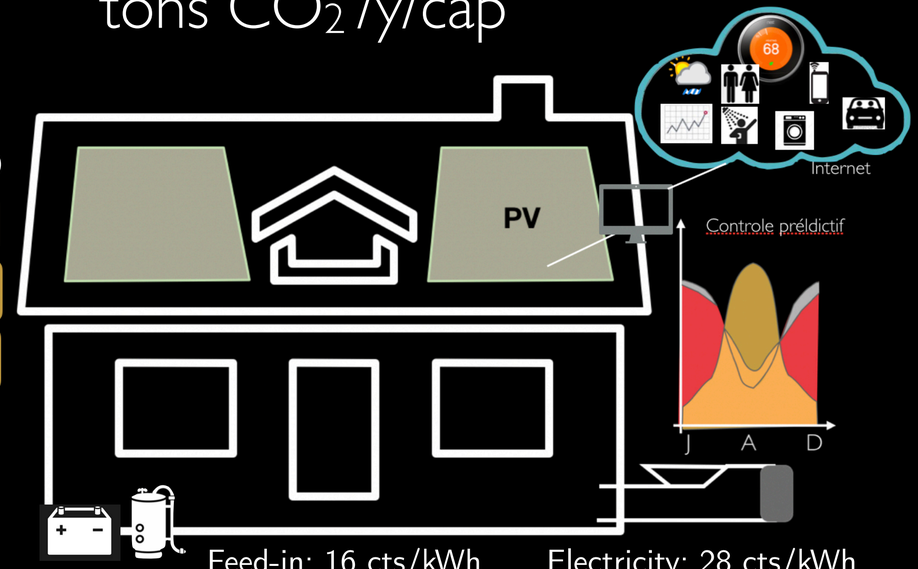
0.25 - 0.04

tons CO_2 /y/cap

15.5

m2PV/cap





Feed-in: 16 cts/kWh

Electricity: 28 cts/kWh

138

CHF/y/cap

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

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

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

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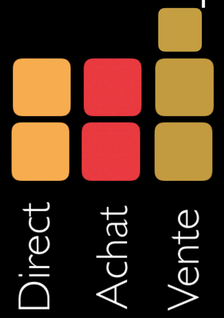
RENEWABLE ENERGY HUB AND E-VEHICULES

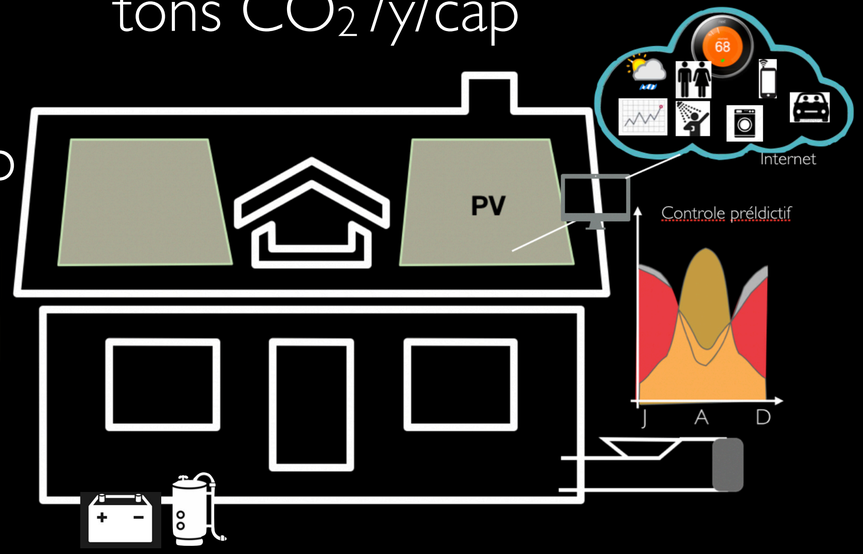
0.25 + 1.74

tons CO_2 /y/cap

15.5

m2PV/cap





138

CHF/y/cap

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

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

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

Building

+ 881

CHF/y/cap

881 CHF/y/cap

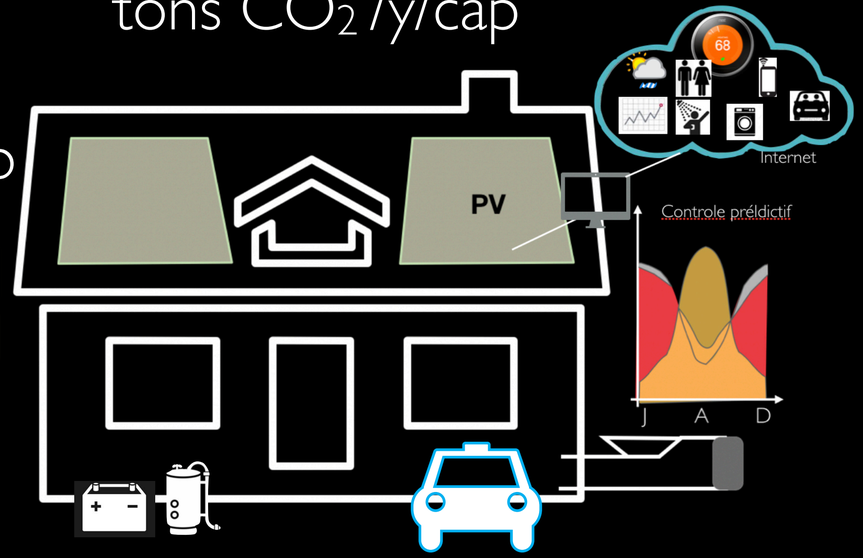
Gasoline car

0.32 (-83%)

tons CO_2 /y/cap

15.5

m2PV/cap



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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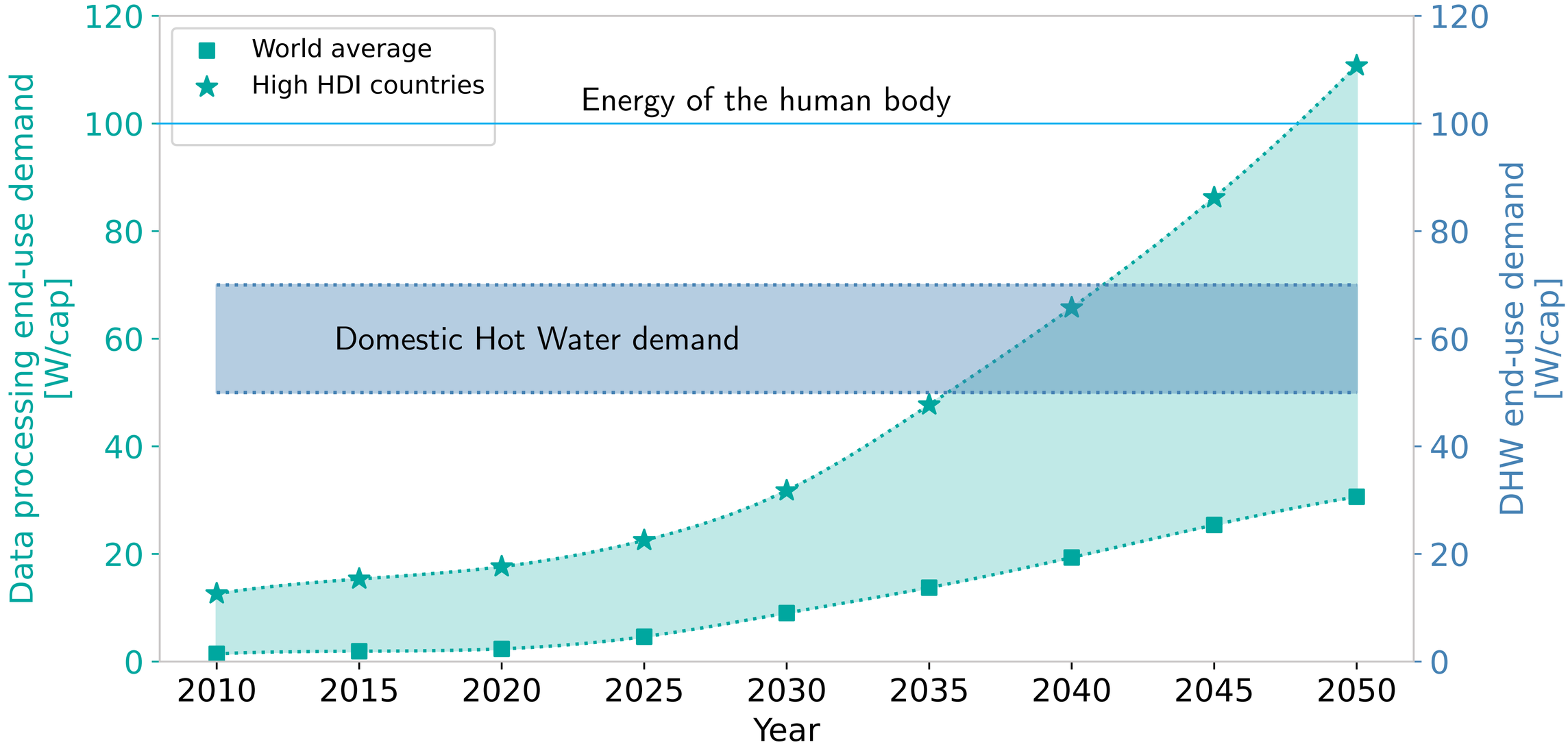
Autres services : la production de données



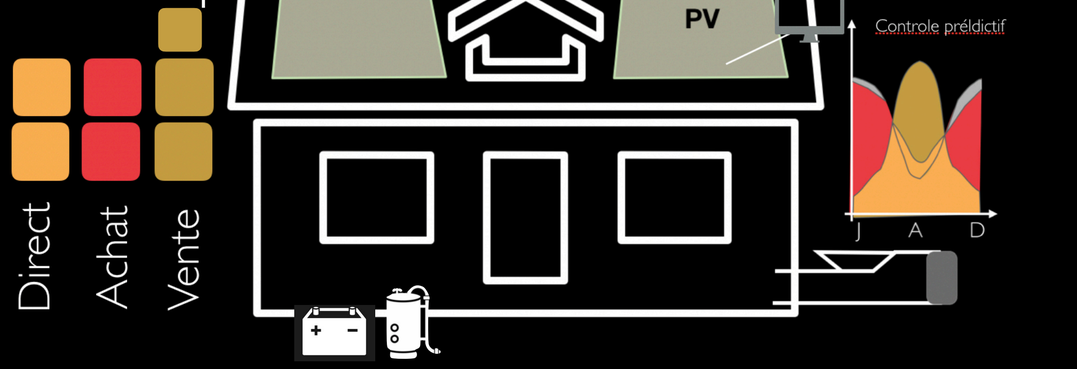
RENEWABLE ENERGY HUB AND DATA PRODUCTION

0.5 (0.25 + 0.24)

tons CO_2 /y/cap

15.5

m2PV/cap



614 (138 + 476)

CHF/y/cap

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

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

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

Building

CHF/y/cap

290 CHF/y/cap

186 CHF/y/cap

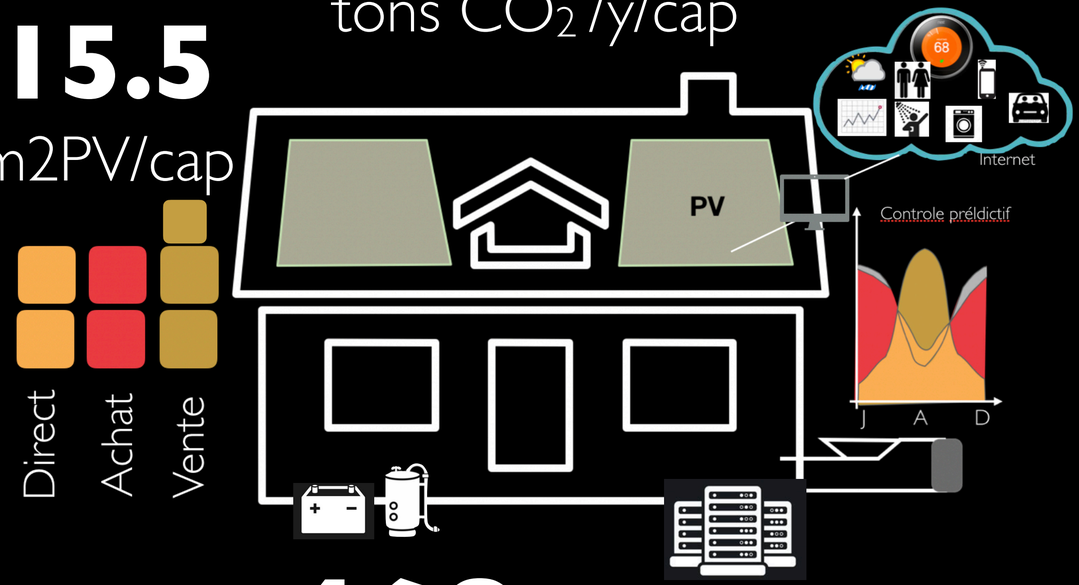
Data center

0.32 (-34%)

tons CO_2 /y/cap

15.5

m2PV/cap



468 (-24%)

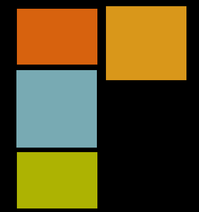
CHF/y/cap

PV feed-in : **-232** CHF/y/cap

Energy : **224** CHF/y/cap

Investment : **250** CHF/y/cap

Bits heater : **226** CHF/y/cap



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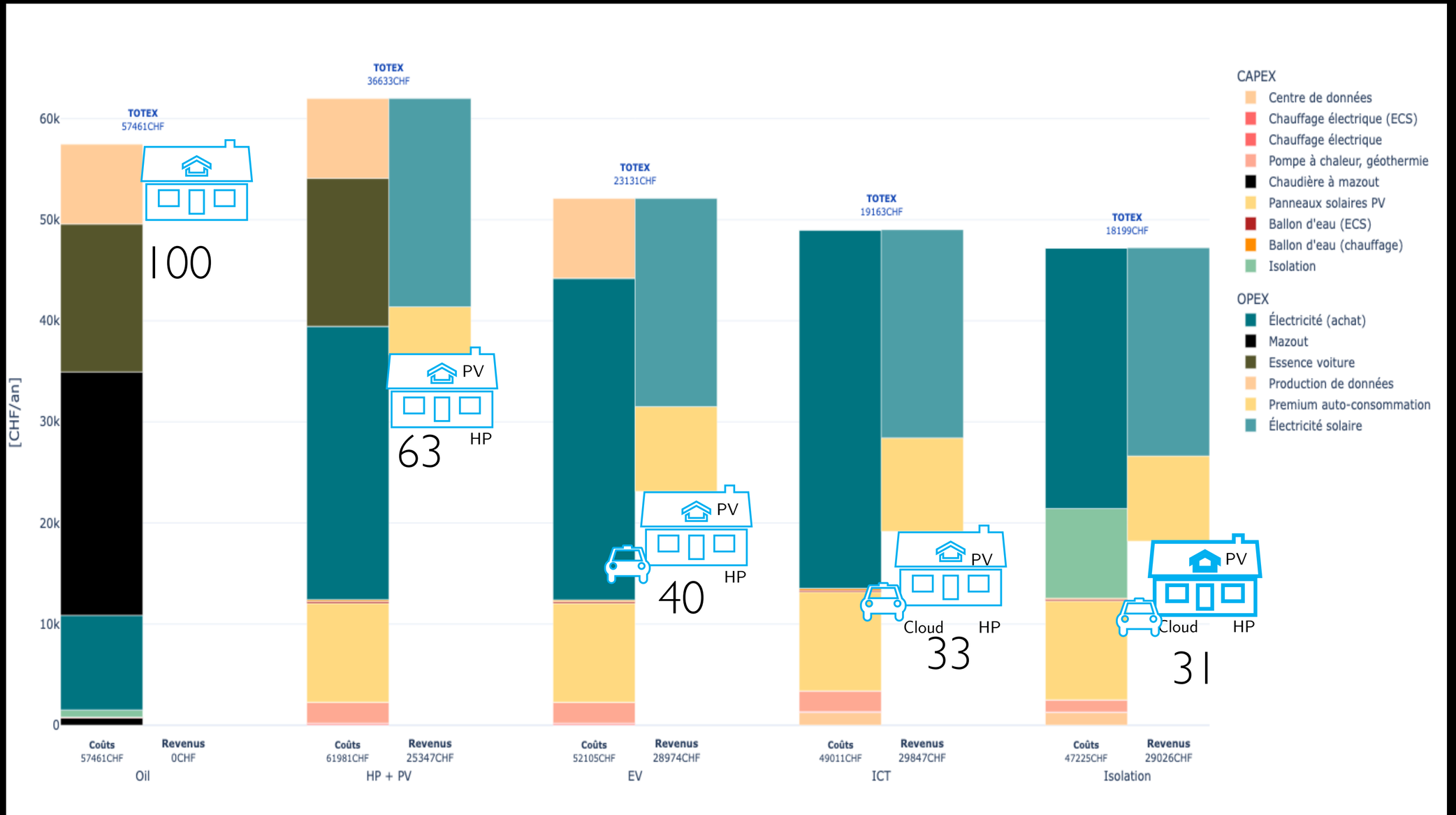
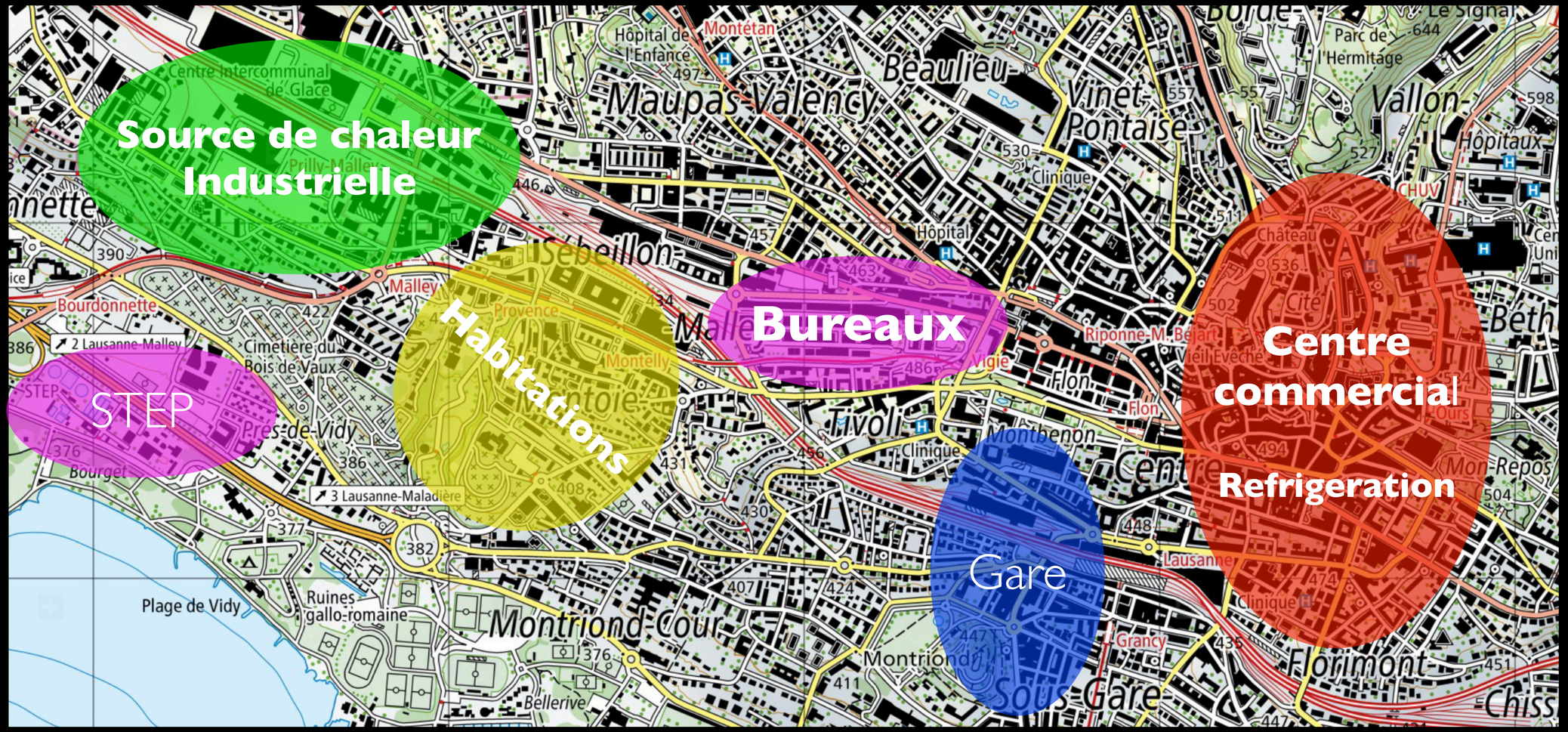
SOLAIRE PV - POMPE A CHALEUR - VEHICULE ELECTRIQUE - DONNÉES



LES HUBS ENERGETIQUES DE LA VILLE



http://urb.io : aide à la décision pour la planification urbaine multi-critère

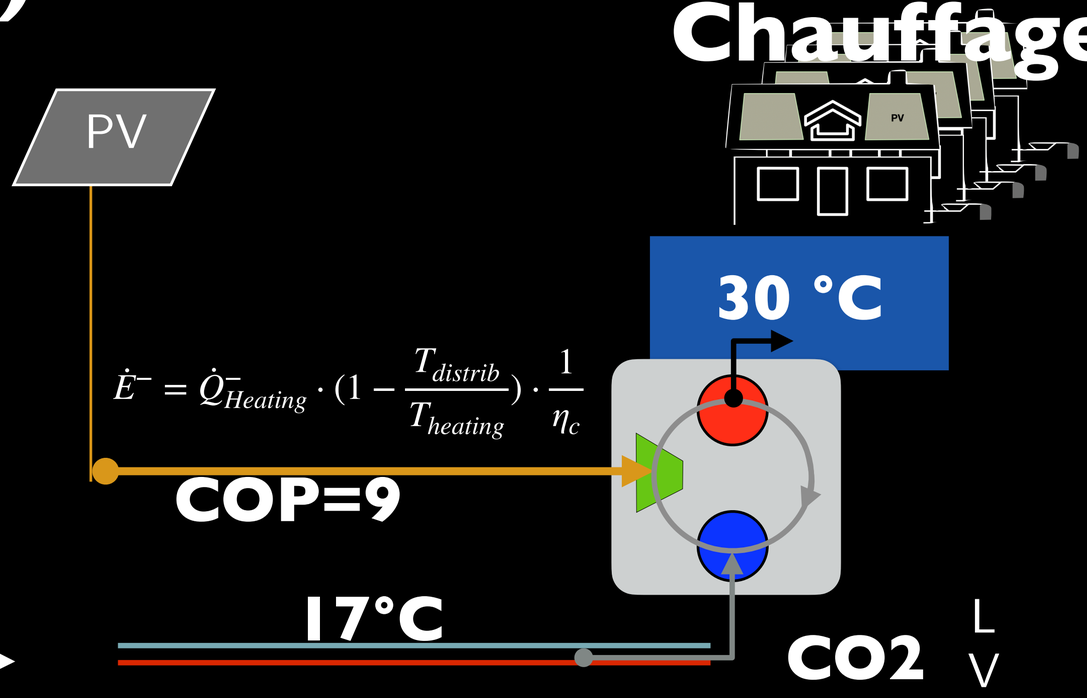
EPFL

PARTAGER LA SOURCE D'ÉNERGIE DANS LA VILLE

Sources de chaleurs (T_{source})

Utilisateurs ($T_{heating}$)

Chauffage



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

Distribution

PARTAGER LA SOURCE D'ÉNERGIE DANS LA VILLE

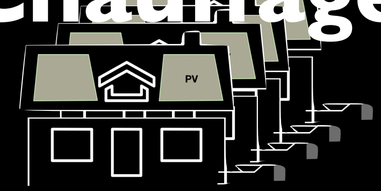
Sources de chaleurs (T_{source})

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

Aquifères : **10** °C
Rivières/Lac : **7**°C
Geothermie : >**10** °C
Refrigeration : **< 0**°C

Utilisateurs ($T_{heating}$)

Chauffage



PV

30 °C

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

COP=9

17°C

CO2 L V

COP=8.5

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

Distribution

EPFL

PARTAGER LA SOURCE D'ÉNERGIE DANS LA VILLE

Sources de chaleurs (T_{source})

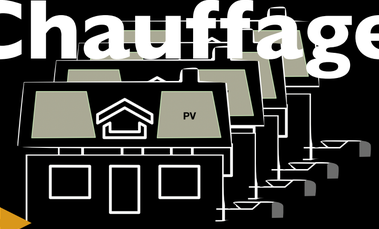
Industrie: **>80**°C

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

Aquifères : **10** °C
Rivières/Lac : **7**°C
Geothermie : >**10** °C
Refrigeration : **< 0**°C

Utilisateurs ($T_{heating}$)

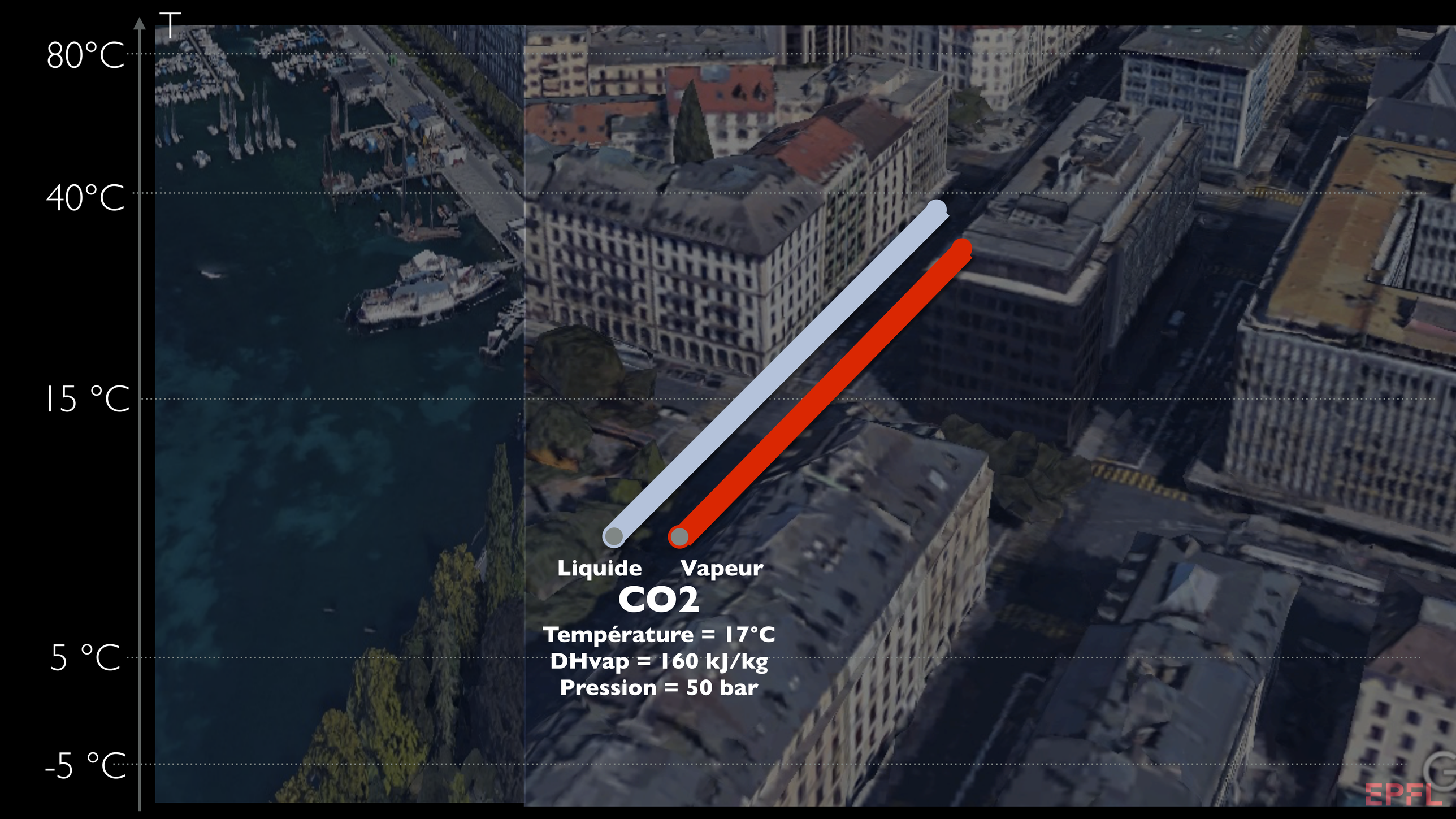
Chauffage

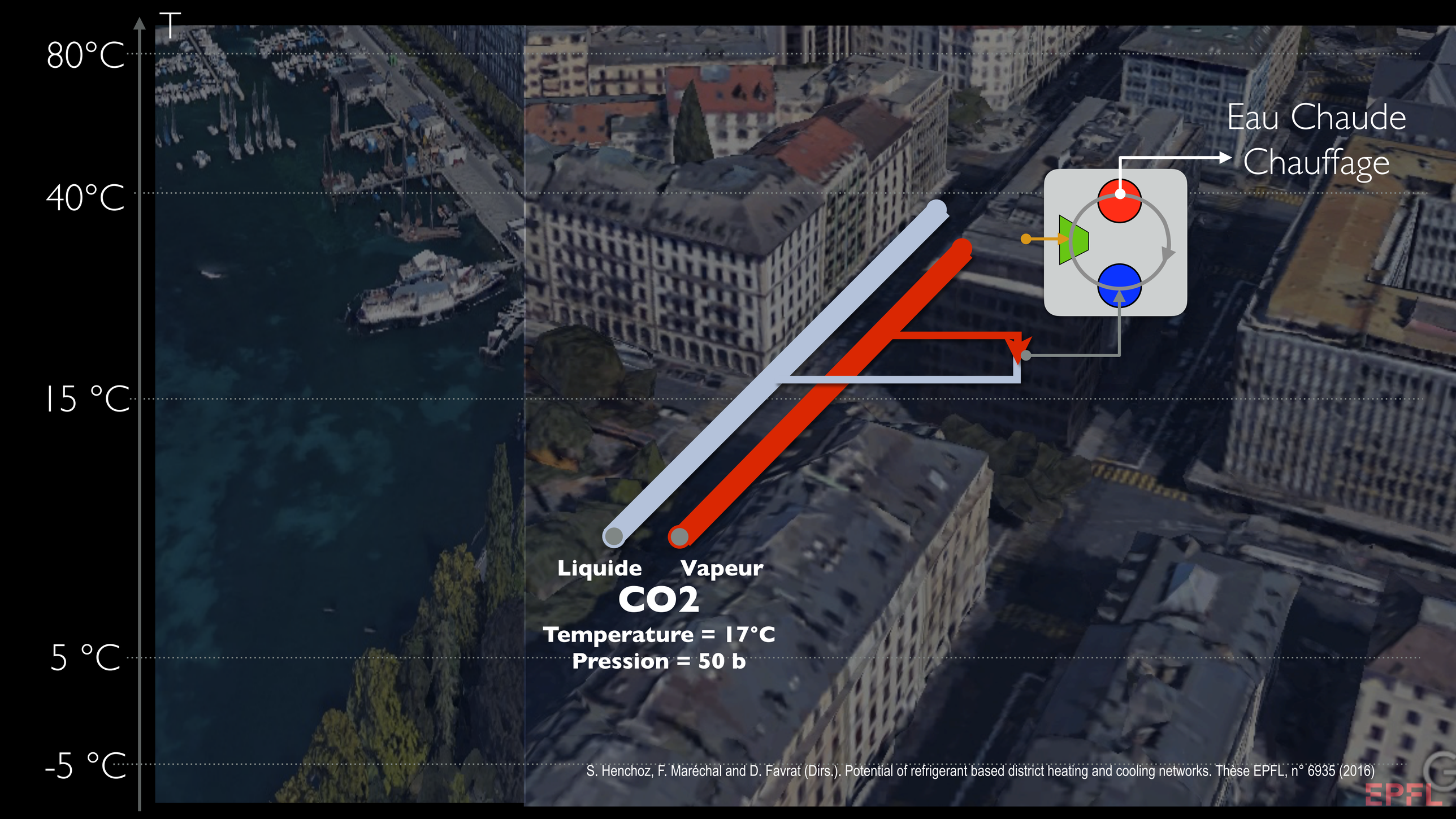


30 °C

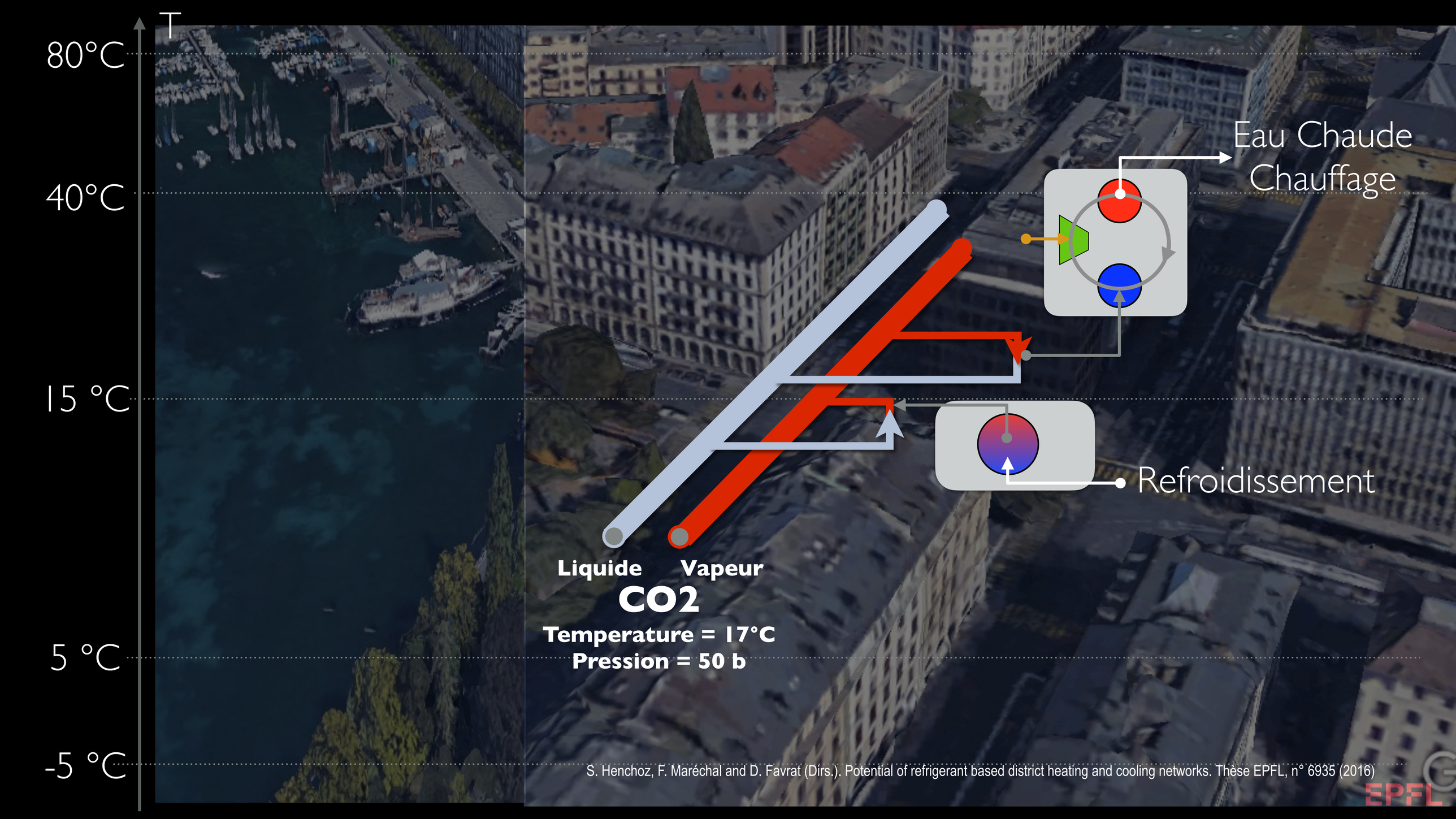
Distribution

EPFL

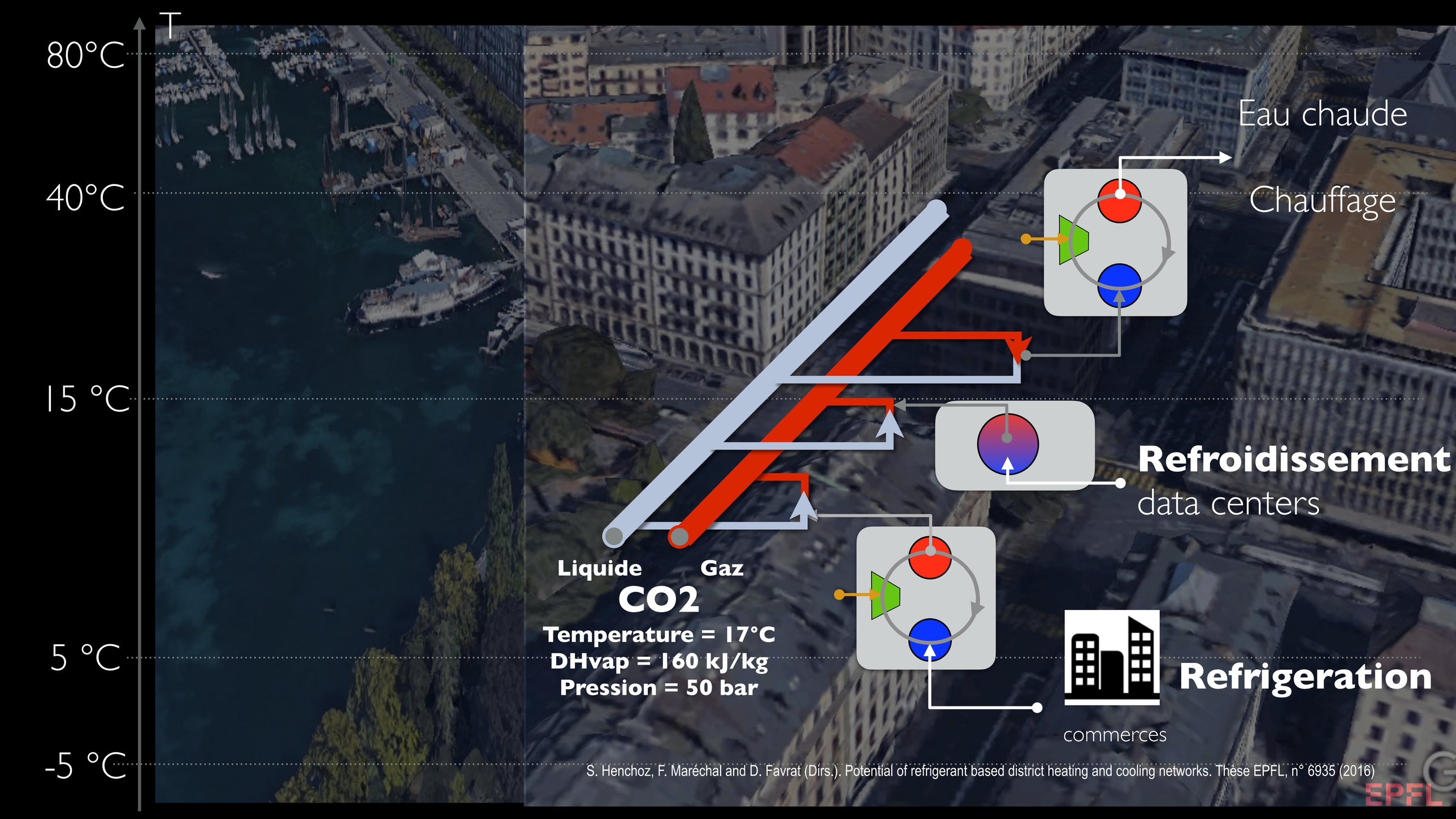

T
80°C
40°C
15 °C
5 °C
-5 °C
Liquide
Vapeur
CO2
Température = 17°C
DHvap = 160 kJ/kg
Pression = 50 bar



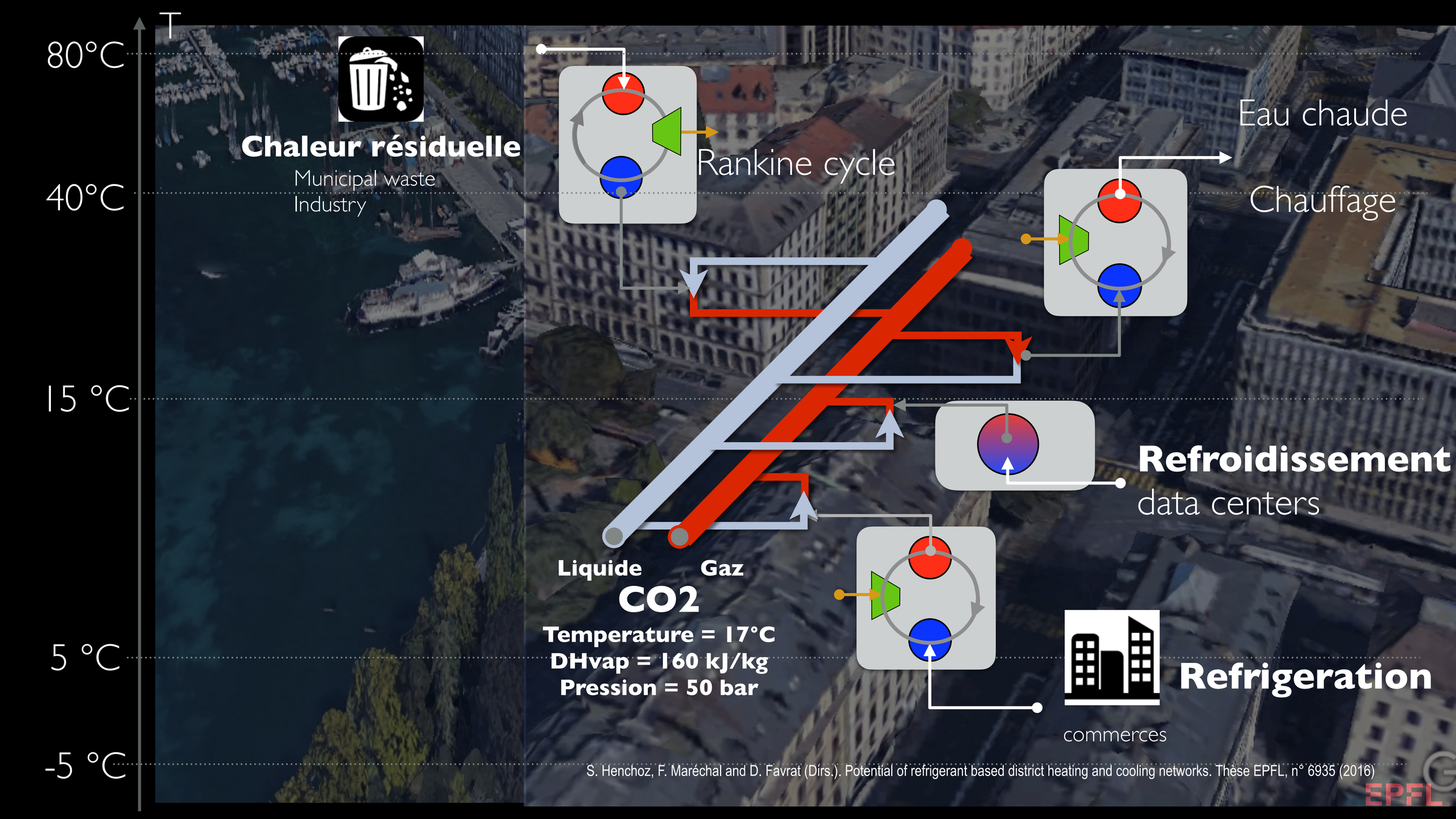
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)



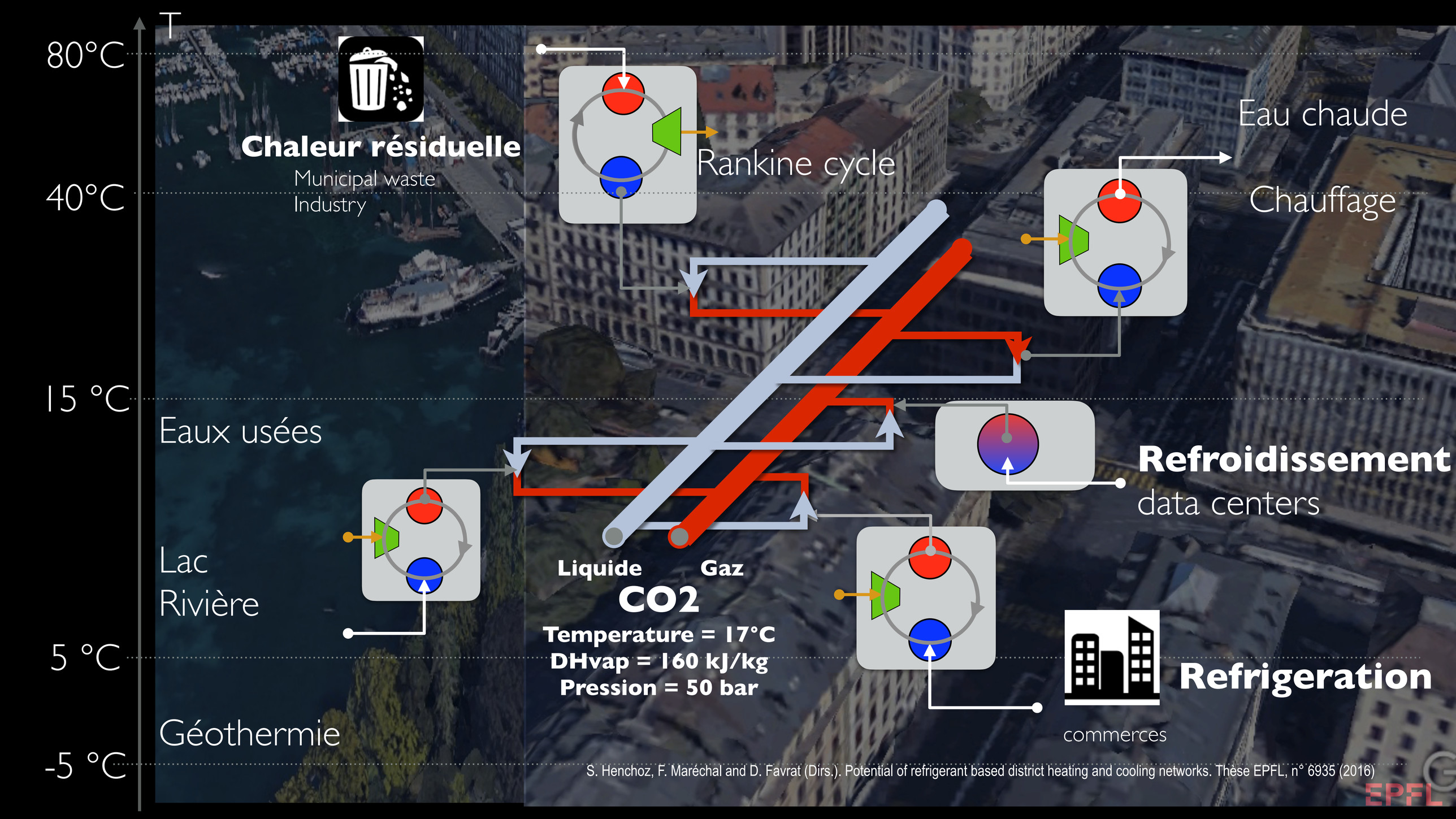
S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)



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



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

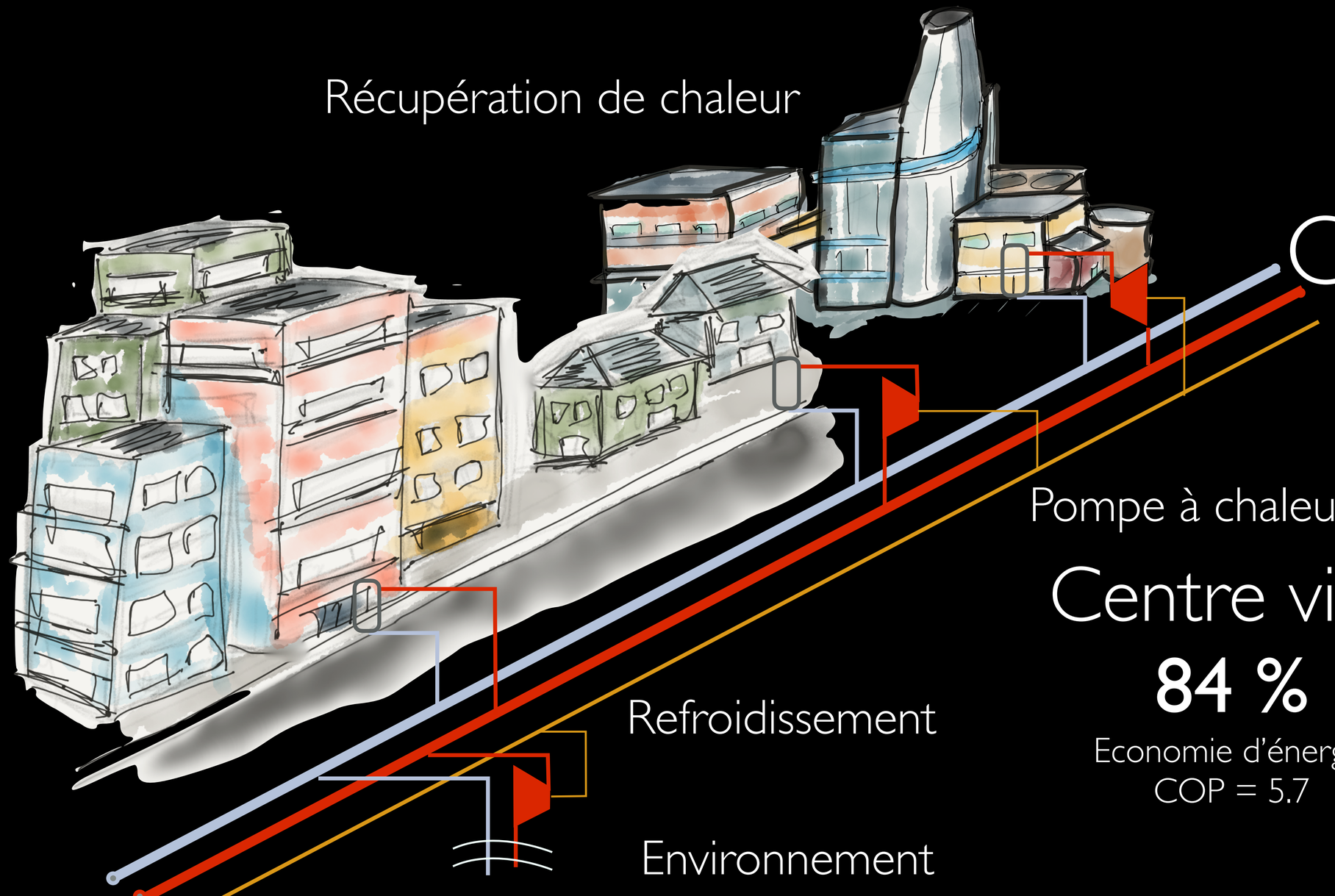


S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)

POMPE À CHALEUR URBAINE

www.exergo.ch

Demonstrateur Valais



Centre ville : bord du lac

84 %

Economie d'énergie
COP = 5.7

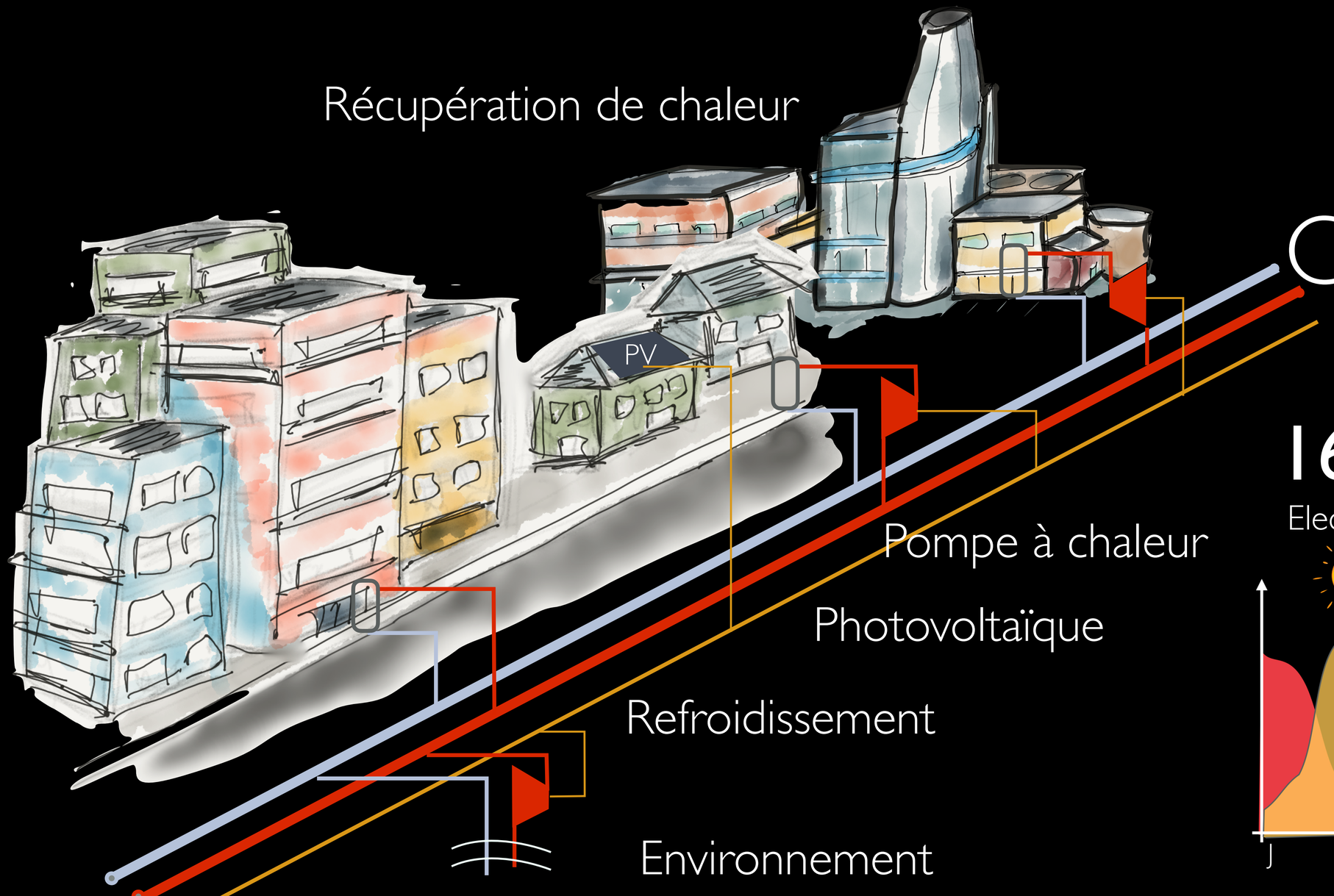
6

ans
temps de retour

EPFL

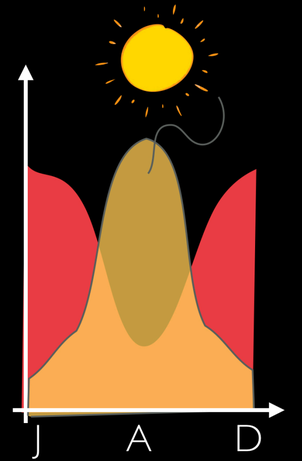
POMPE À CHALEUR URBAINE ET PHOTOVOLTAÏQUE

www.exergo.ch



CO_2 17°C 50 bar

16 %
Electricité



6 %
direct

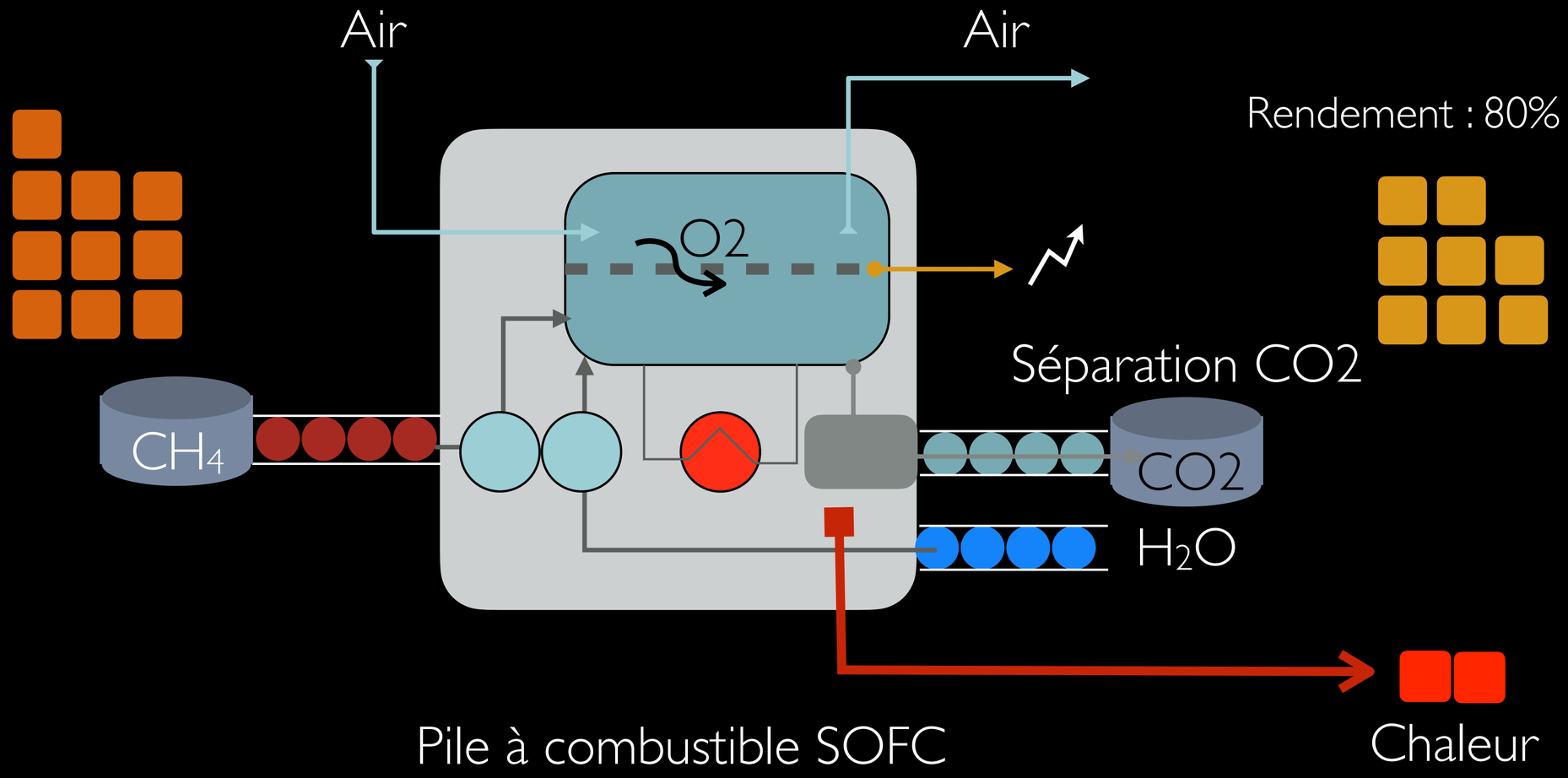
10 %
import

12 %
export

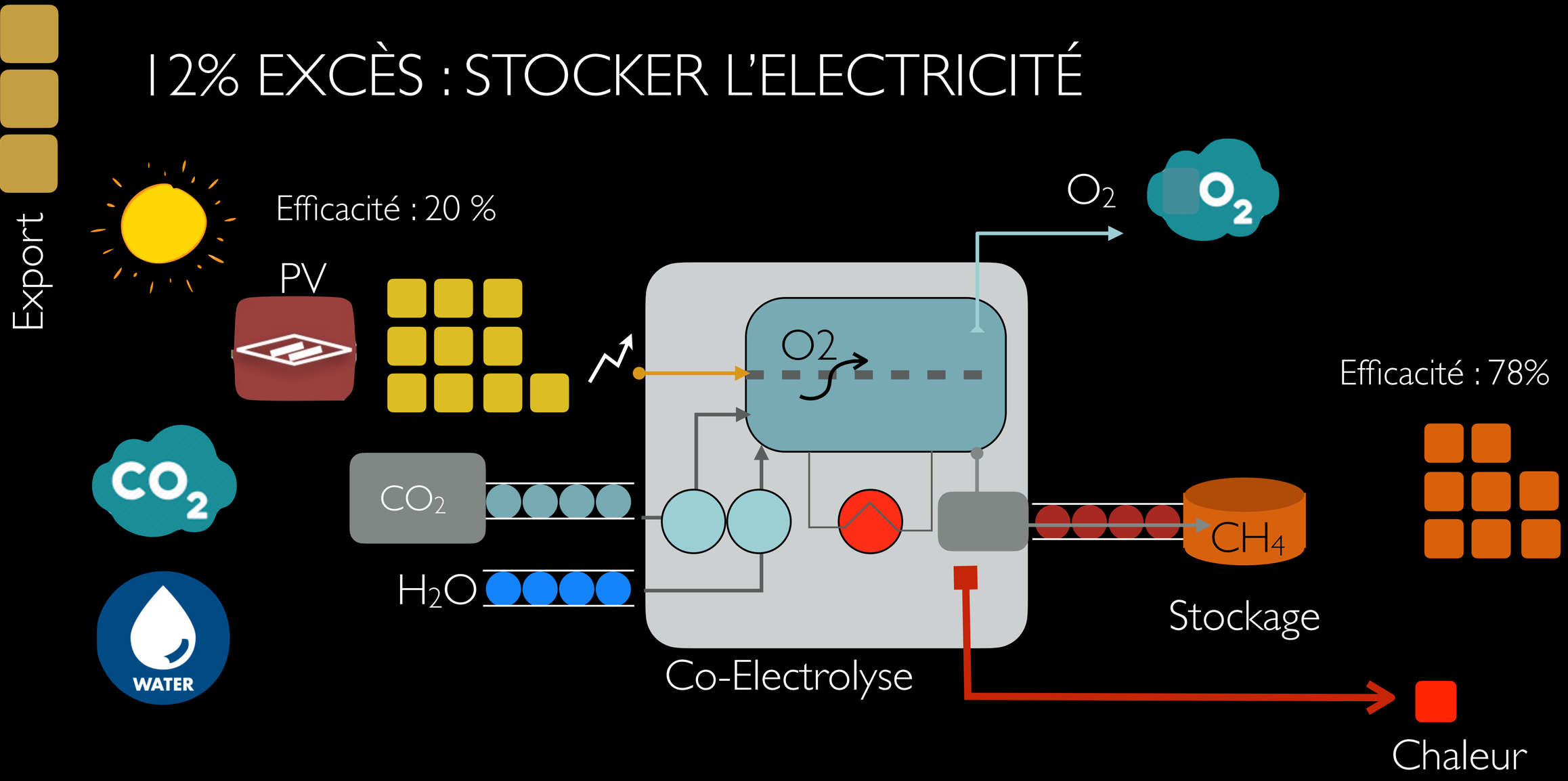
EPFL

Import

10% IMPORT : PILE À COMBUSTIBLE



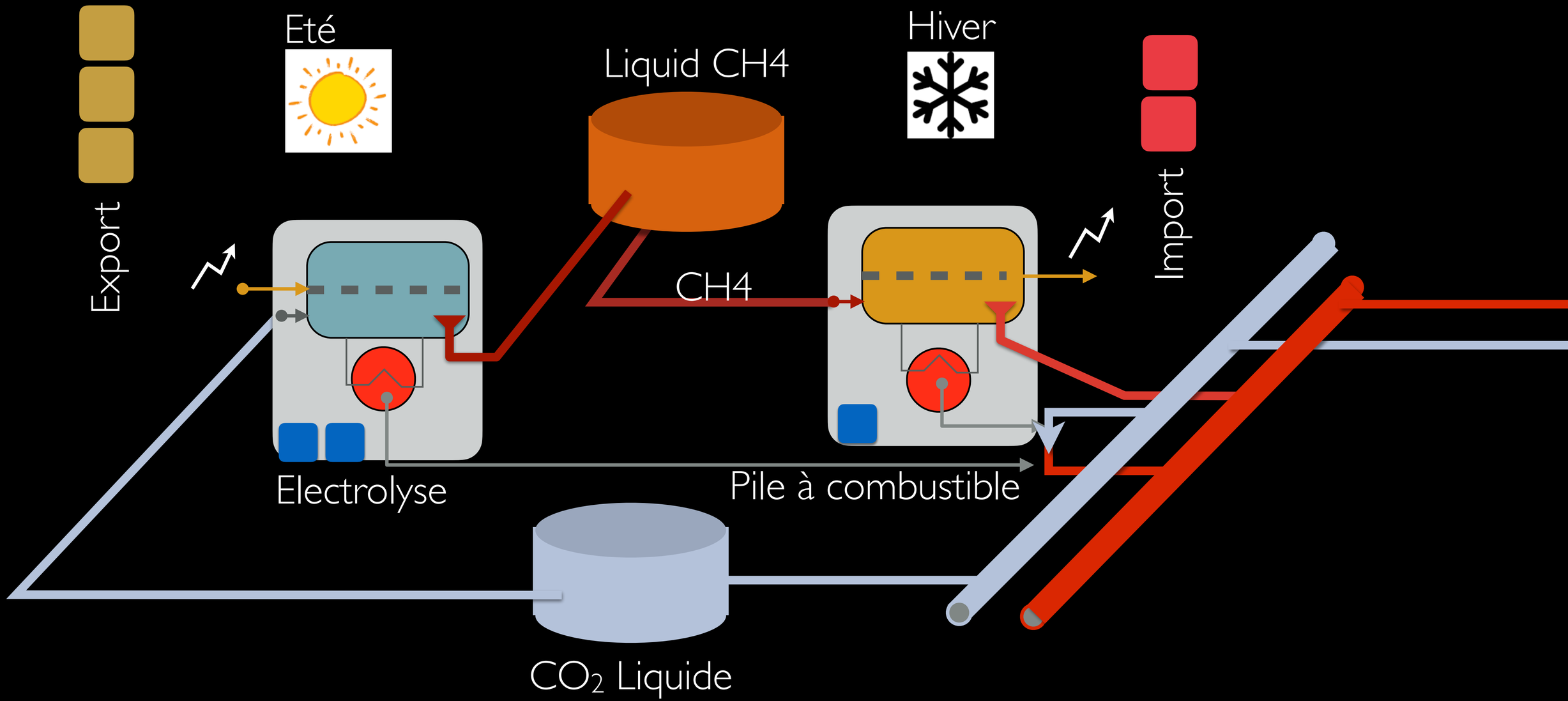
12% EXCÈS : STOCKER L'ELECTRICITÉ



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.

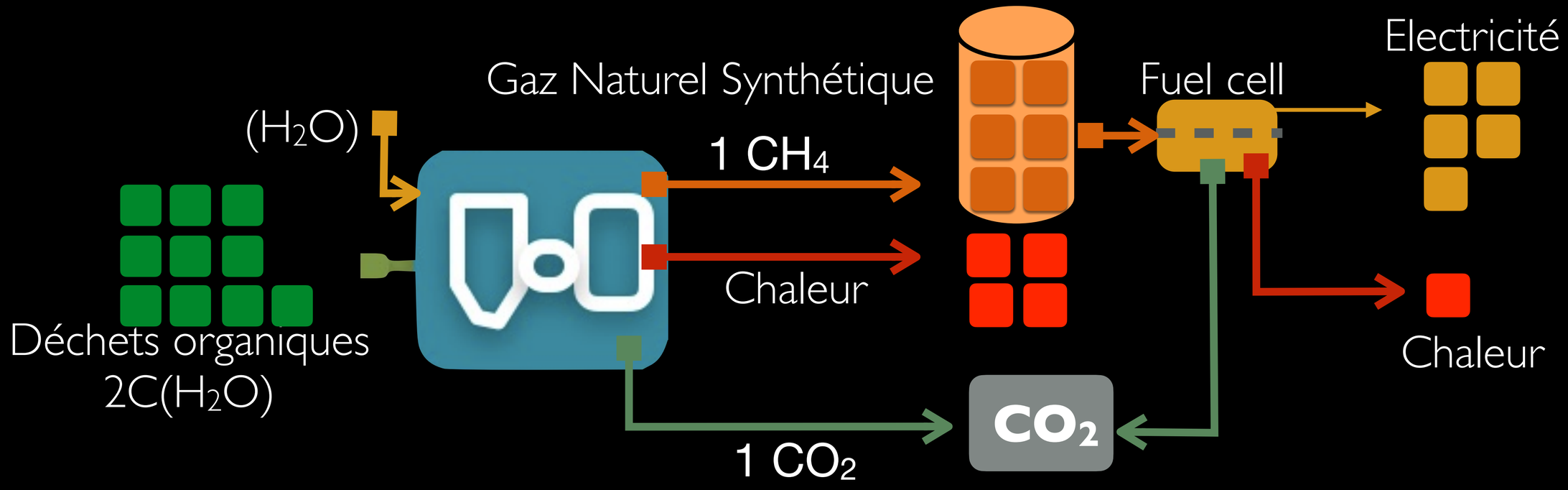
EPFL

COMBINER LES DEUX



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.

CONVERTIR LES DÉCHETS DE LA BIOMASSE



50% : Biomethanisation

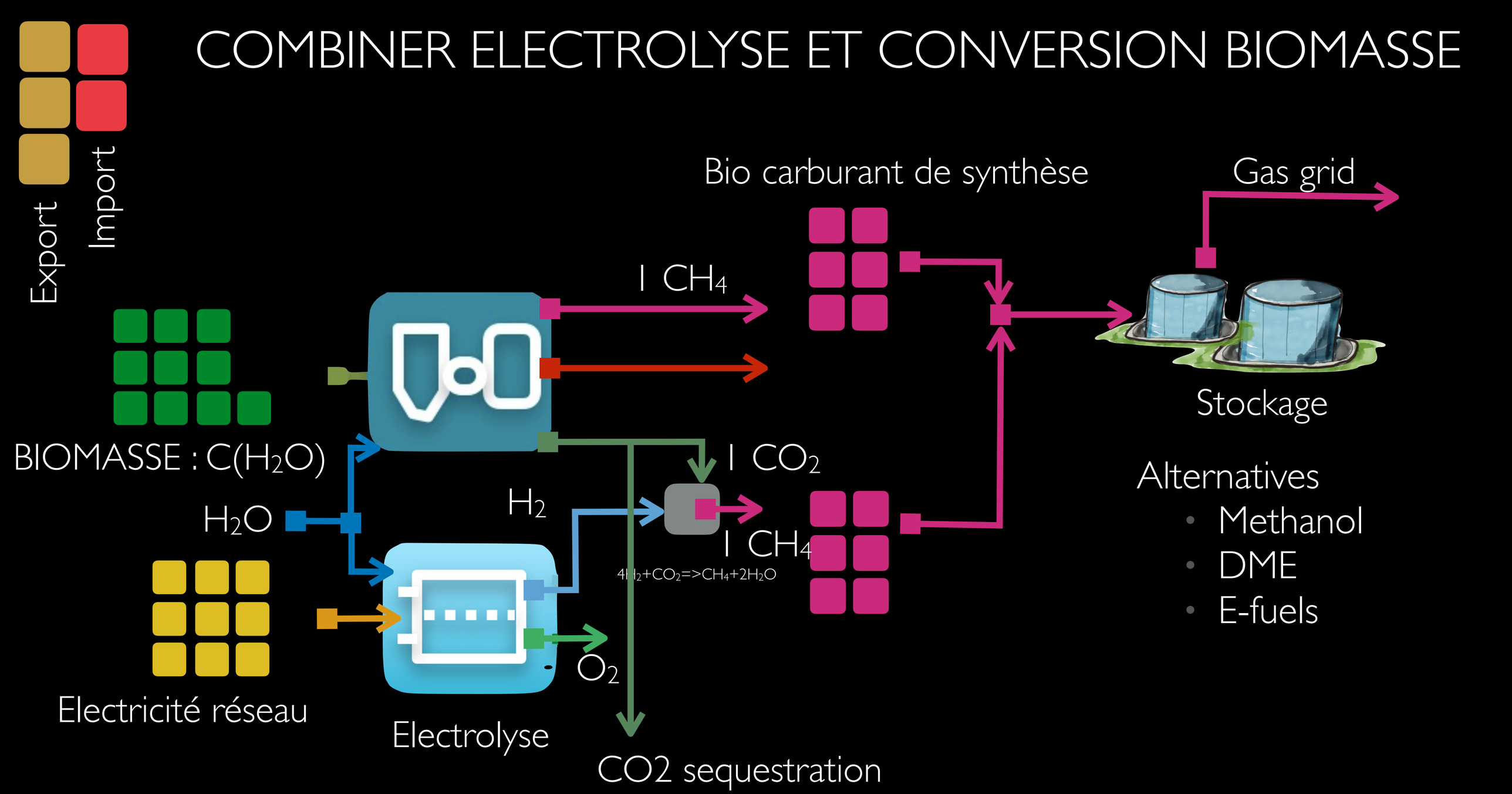
70% : Gasification Hydrothermale (http://trea-tech.com)

70% : Gasification et gaz naturel de synthèse

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

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

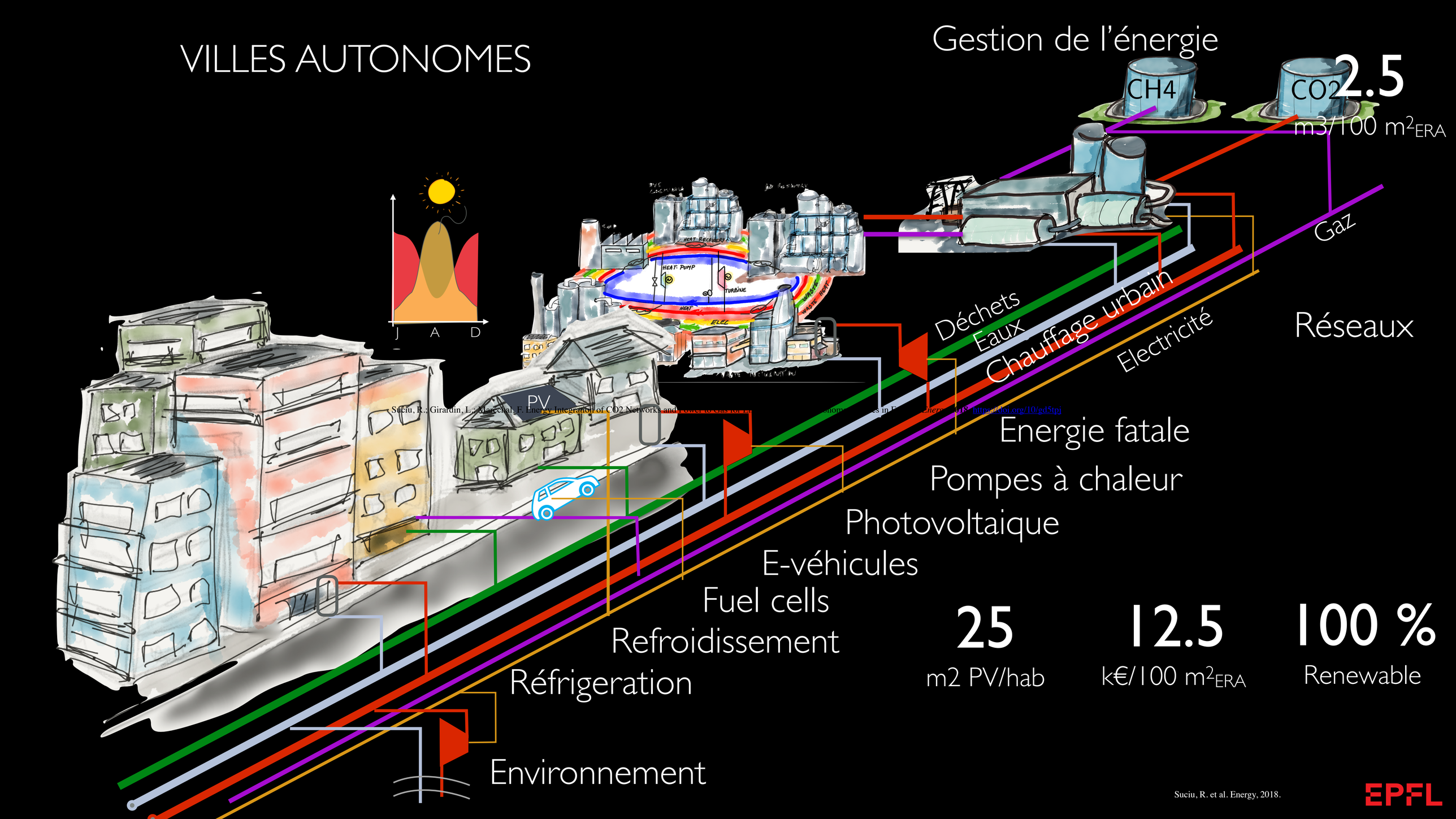
COMBINER ELECTROLYSE ET CONVERSION BIOMASSE



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.

VILLES AUTONOMES

Gestion de l'énergie



Suciu, R. et al. Energy, 2018.

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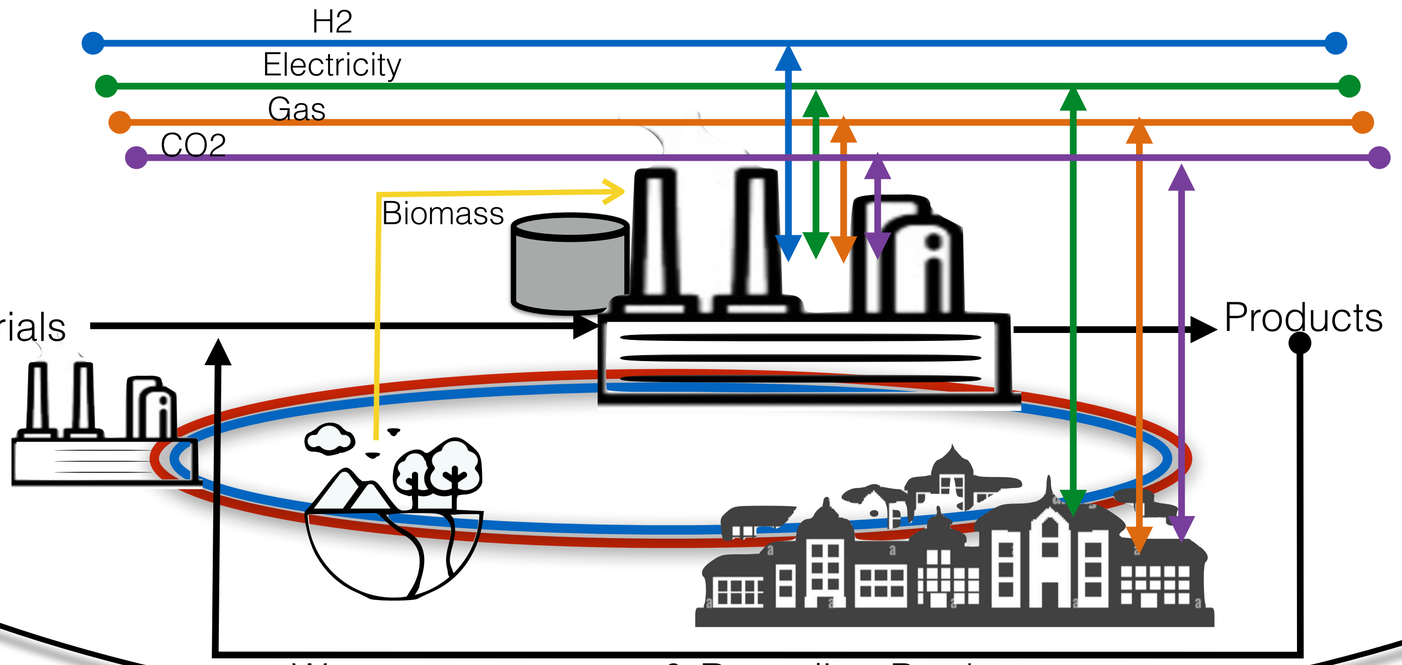
Defossiliser l'industrie

Heat valorisation
Heat pumping
Waste heat to electricity

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

Efficiency
Materials recovery
Heat recovery

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

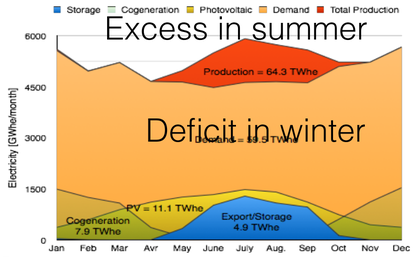
System expansion
District heating/cooling
Industrial symbiosis
Waste-water-energy
Circular economy

Sustainability metrics
CO2 footprint
Resources usage
Environmental impact

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

Thermodynamic metrics
Energy Efficiency
Mass balances
Exergy

Industrial clusters as a circular renewable energy hub



LA MOBILITÉ

36%

Efficacité

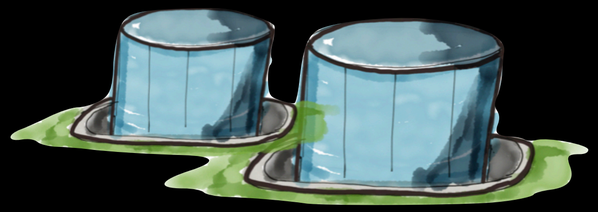
Mobilité douce

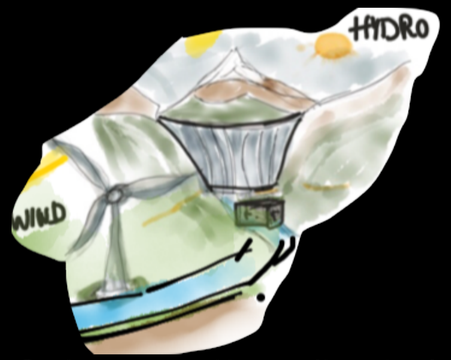
Transport Public : électrique/hybrid (mobilitylab.ch)

Véhicules électriques : 400 km

Camions - Véhicules Hybrides (H2, Biofuels)

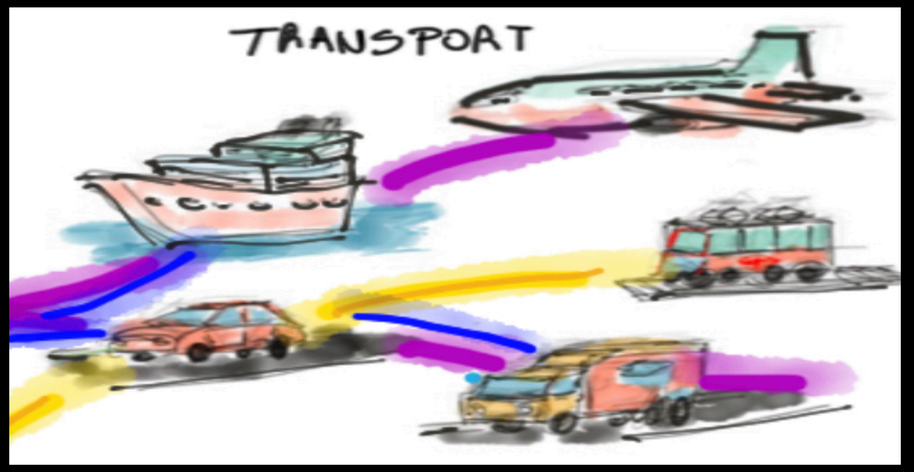
Capture du CO2 sur les véhicules





Bio-Fuel

Hydro et éolien

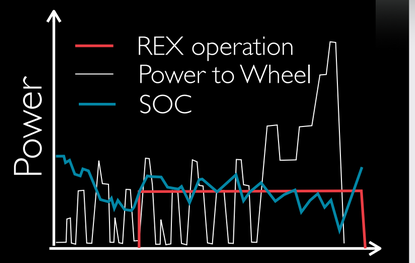


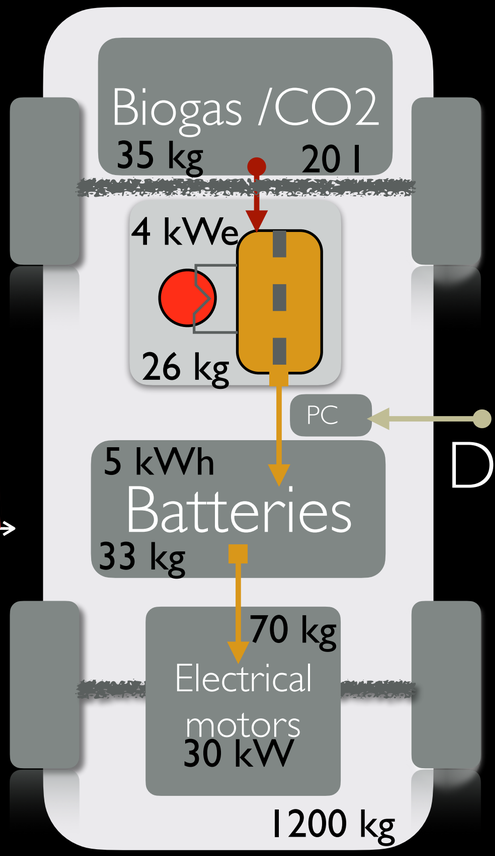
100 l gasoline/hab/year

VEHICULES "RANGE EXTENDERS"

Driving mode

Autonomie : 950 km
Cons : 1.1l/100 km





Data Grid

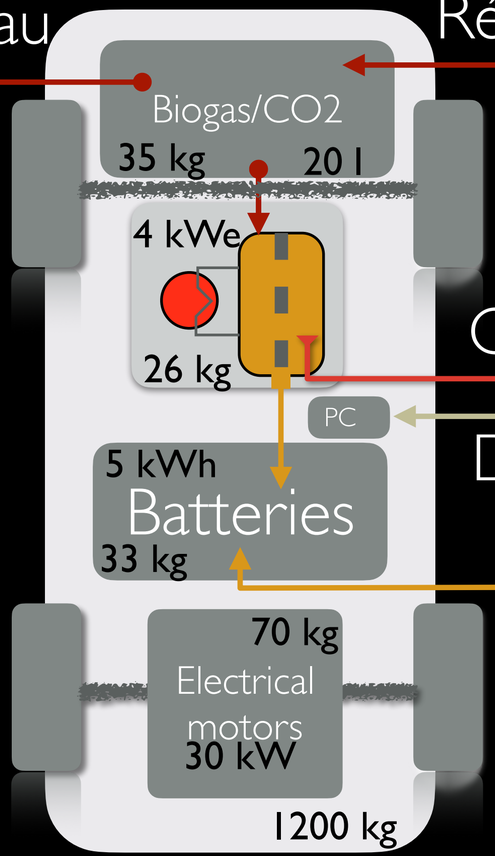
SOFC-GT
Hybrid car

Parking mode

Centrale électrique : 3.5 kWe (eff. >70%)
Batterie : 5 kWh

CO2 réseau

Réseau Gaz



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

PhD PSA

EPFL

CAPTURER LE CO2 SUR LES CAMIONS

www.qaptis.com

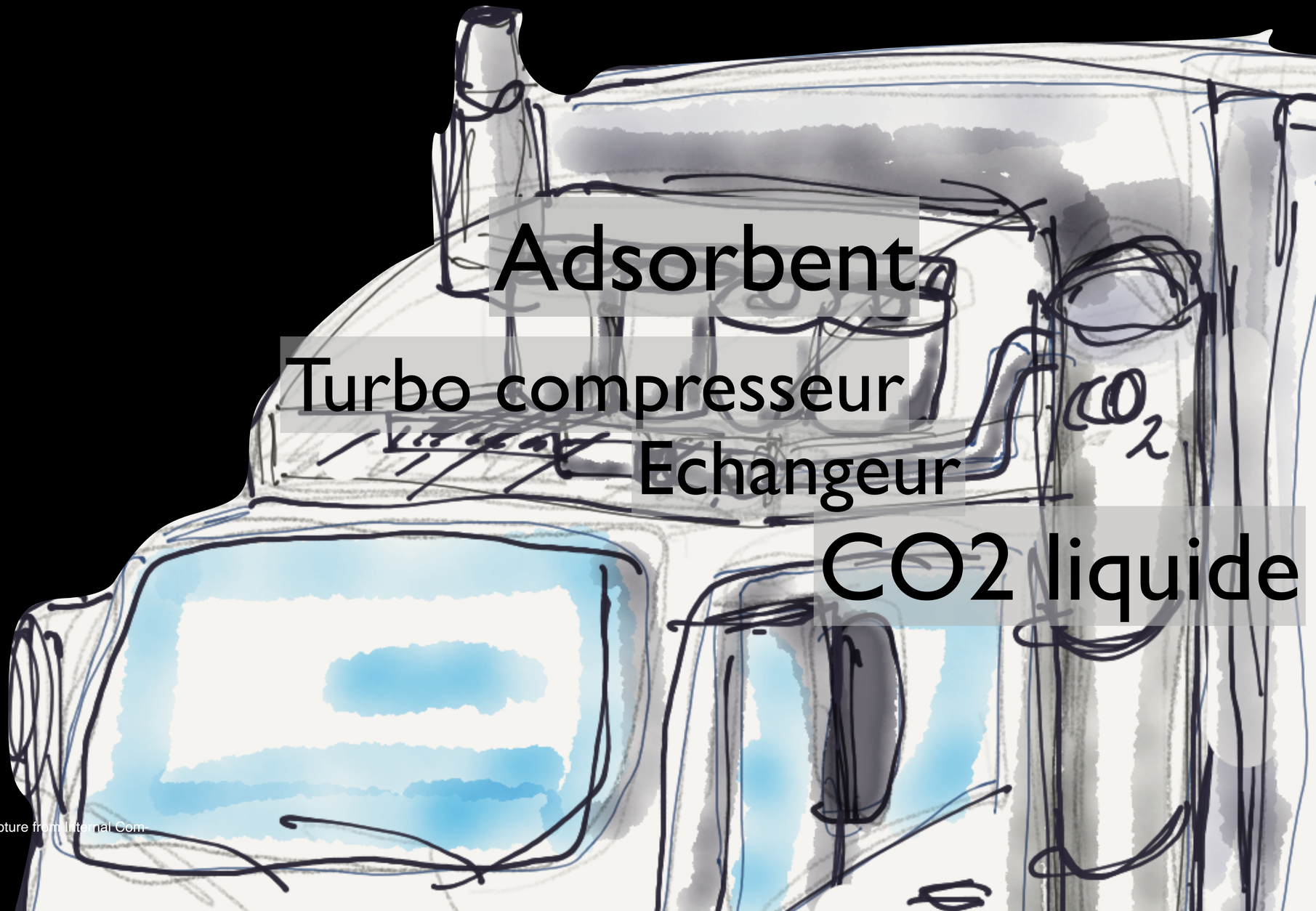
90% CO2 capture

3

l CO_2/l fuel

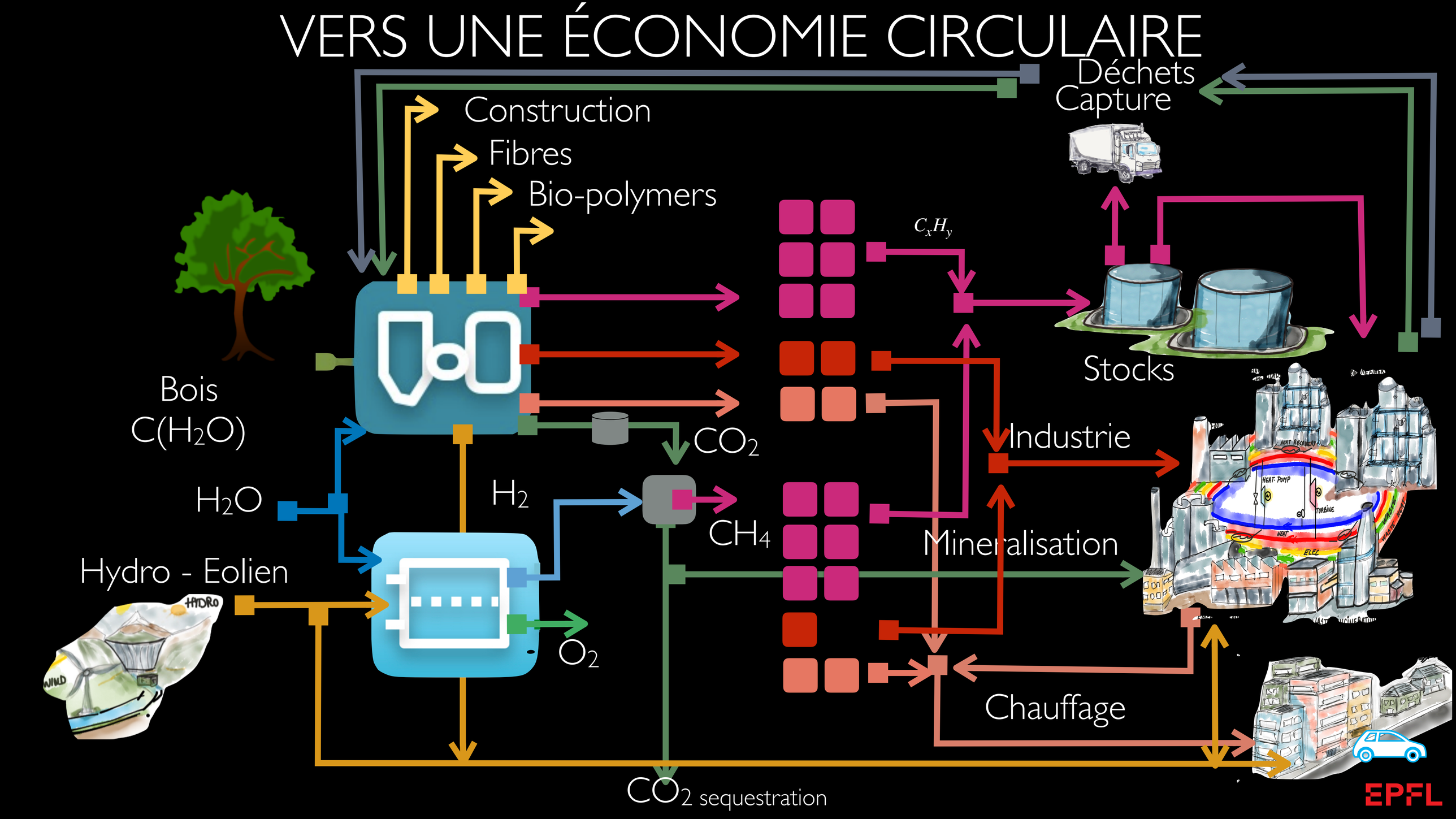
5%

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.

VERS UNE ÉCONOMIE CIRCULAIRE

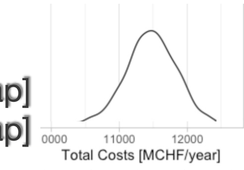


energyscope.ch : pour une suisse indépendante et neutre

Biomass : 290 - 340 [W/cap]
Waste : 180 - 230 [W/cap]

Chemical storage
Liquid fuel : 20 - 90 [W/cap]
CH_4 : 60 - 170 [W/cap]
H_2: 20 - 110 [W/cap]

Investment
Technologies : 1000 - 2000 [CHF/y/cap]
Infrastructure : 1450 [CHF/y/cap]

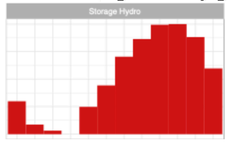


Transport Air : 240 - 290 [W/cap]
Freight : 70 - 90 [W/cap]
Public: 60 - 90 [W/cap]
Private: 100 - 140 [W/cap]

Industry Elec: 110 - 140 [W/cap]
Industry heat: 210 - 250 [W/cap]

Building Elec: 270 - 320 [W/cap]
Building heat : 630 - 740 [W/cap]

PV : 230 - 570 [W/cap]
Wind : 20 - 80 [W/cap]
Hydro : 380 - 500 [W/cap]



HP : 460 - 680 [W/cap] (21 - 34 %)
DHN : 340 - 460 [W/cap] (48 - 72 %)
Other : 110 - 170 [W/cap] (19 - 33 %)

CO_2 seq : 1 - 1.5 [t/y/cap]
Net CO_2 emission: -0.6 - 0 [t/y/cap]

IPESE
Industrial Process and Energy Systems Engineering

REMERCIEMENTS

- **Soleil** : pour nous fournir l'énergie
- **Mère Nature** : pour nous montrer la voie de la gestion de l'énergie
- **Carnot** : pour nous apprendre l'importance de l'efficacité et de l'environnement
- **Recherche** : pour fournir les méthodes et les fondements technologiques
- **Ingénieurs** : pour choisir, développer, assembler et opérer les technologies
- **Industrie** : pour fournir les technologies
- **Formation** : pour former les réalisateurs de l'ingénierie à la mise en oeuvre
- **Autorités** : pour développer le système éducatif et les infrastructures
- **Finance** : pour utiliser l'(notre) argent de manière responsable envers les générations futures
- **Citoyens** : pour adopter des comportements responsables (sobre)

EPFL