Les villes dans la perspective net-zero

Prof François Marechal

Industrial Process and Energy Systems Engineering

Institute of Mechanical Engineering

Faculty of Engineering

EPFL Valais Wallis

CH-1950 Sion

IPESE
Industrial Process and Energy Systems Engineering

AND THEY KNEW : CO2 AND GREENHOUSE EFFECT

1896

Svante Arrhenius' 1896 Paper

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

Philosophical Magazine and Journal of Science
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. 435 (Lond., 1863).
‡ *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

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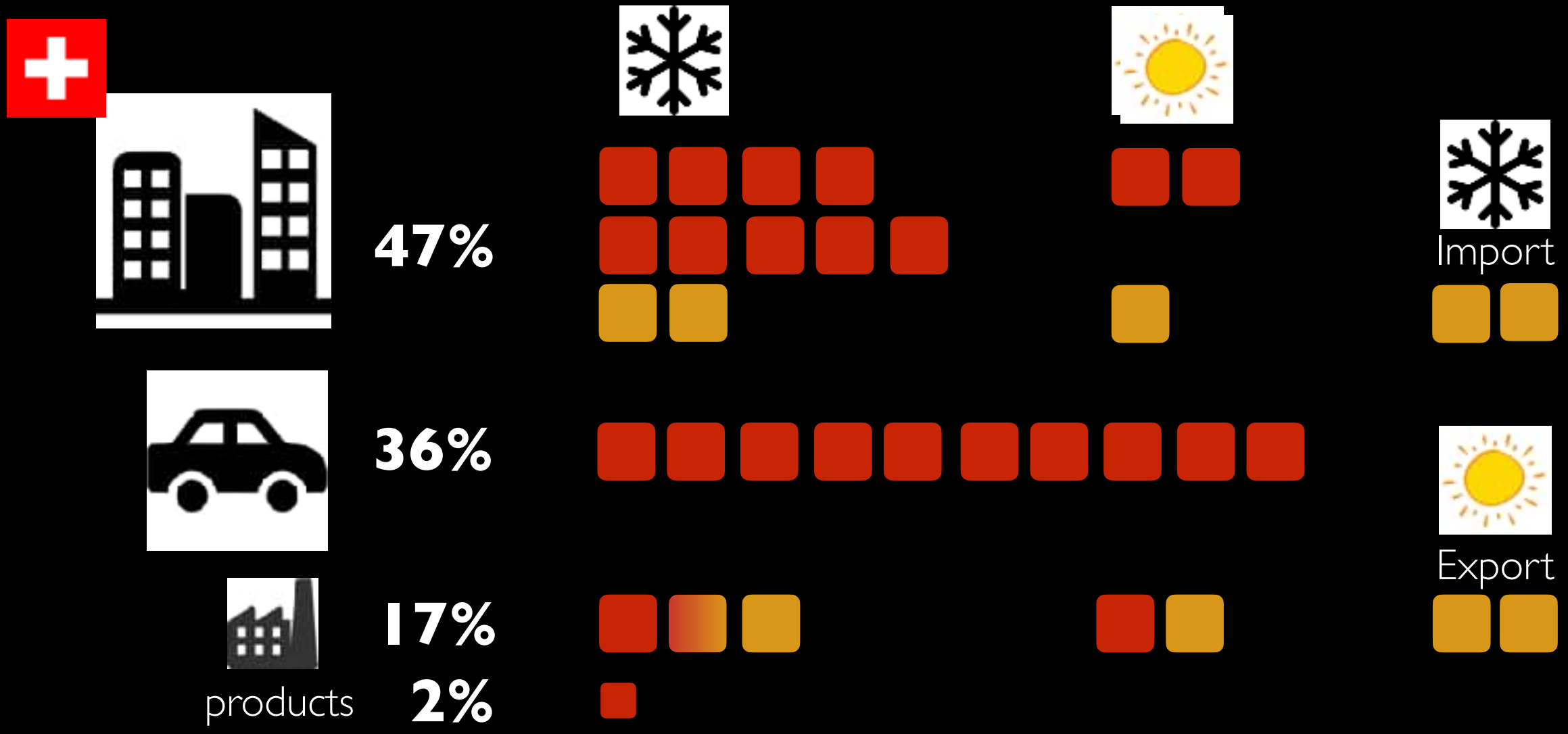
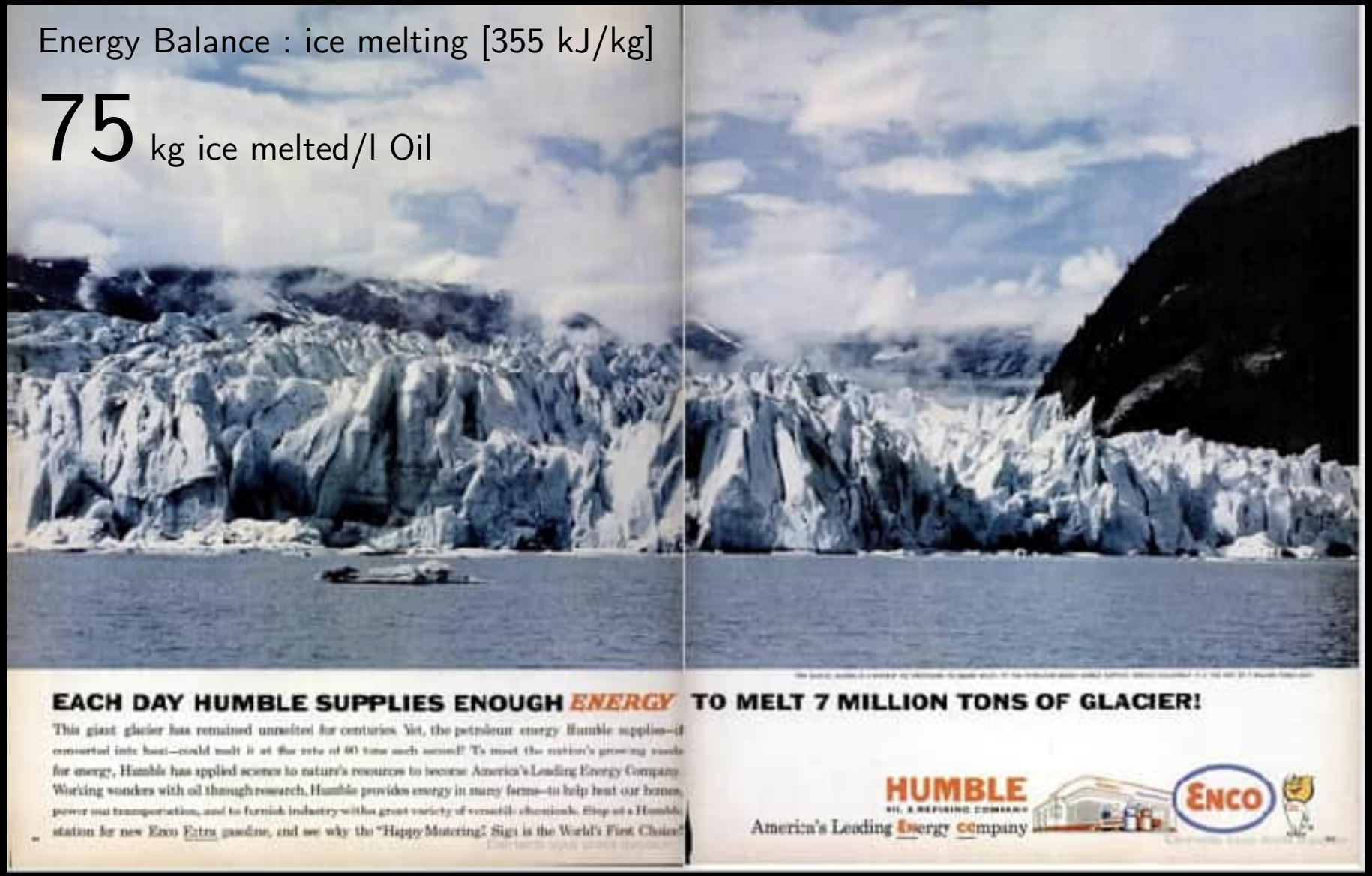
NOS BESOINS ÉNERGÉTIQUES



1960 : PUBLICITÉ HUMBLE (PREV EXXON)



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LES BESOINS ÉNERGÉTIQUES D'UN BÂTIMENT

170

CHF/mois/100 m^2

Energie

140 CHF/mois/100 m^2

! 75% import

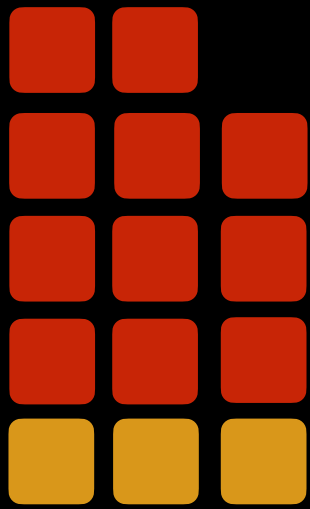
Chaudière

30 CHF/mois/100 m^2

3.8

tonnes **CO_2** /an/100 m^2

70 CHF/mois/100 m^2



Maison unifamiliale typique

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EN RÉALITÉ

7

kg glacier/kg CO_2

18.8 kg / litre d'essence

1 kg glacier / km (6l/100 km car)

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

From 1970-2021 : Glacier inventory vs CO_2 emissions

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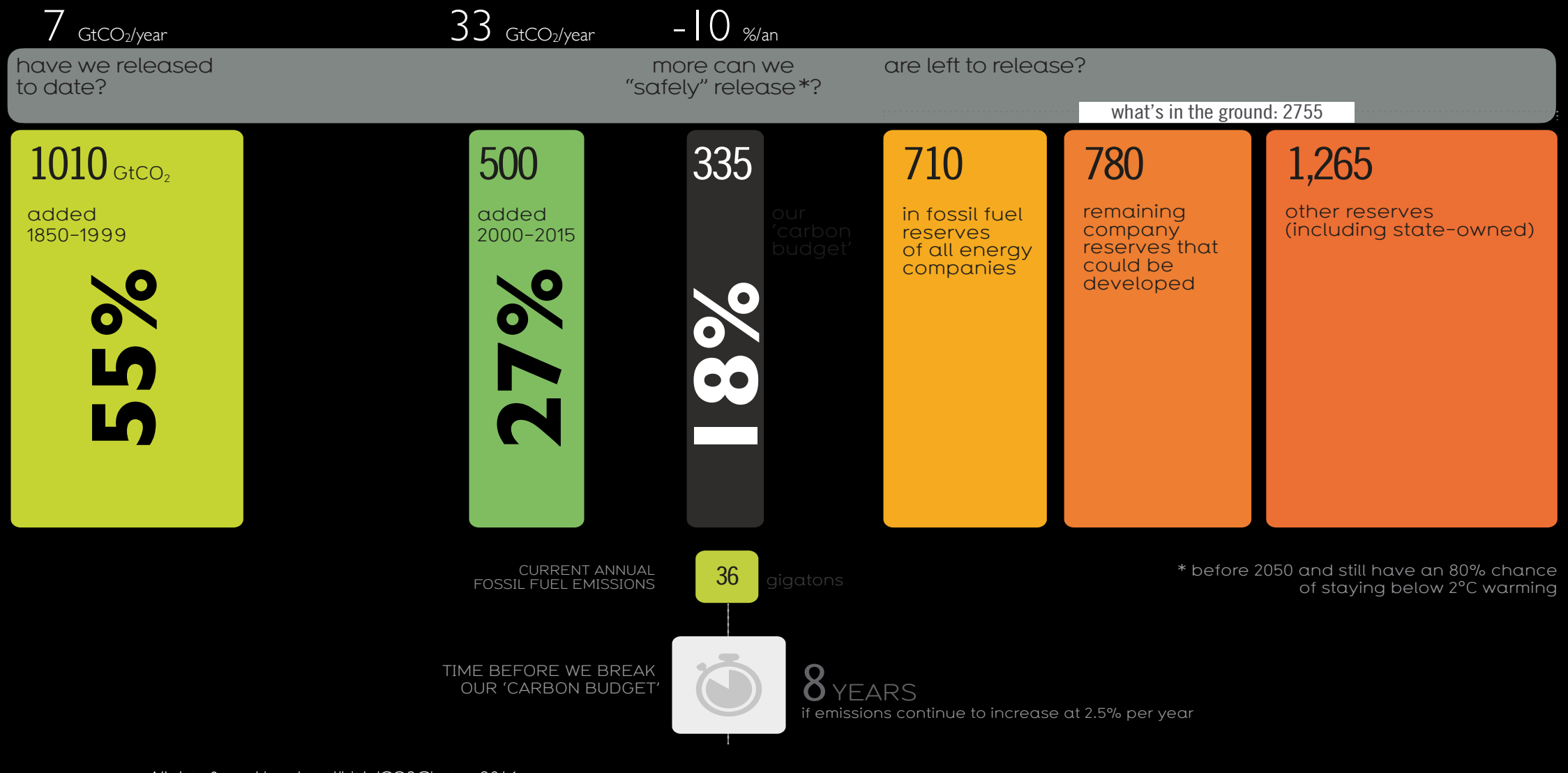
URGENCE CLIMATIQUE !



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

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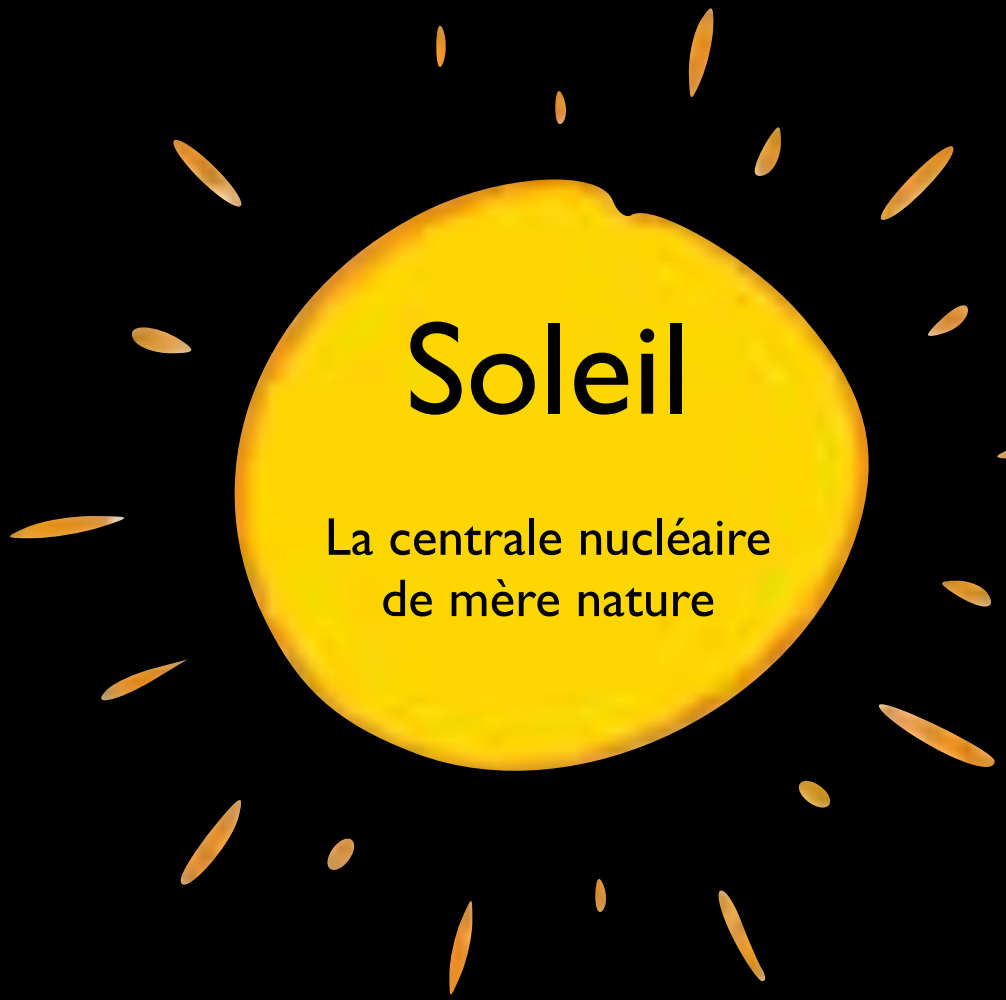
EST CE QUE NOUS AVONS UN PROBLÈME D'ÉNERGIE ?



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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Our chalenge : Engineering the Efficiency for a Net-Zero future

Renewable resources
Where-When-How much ?

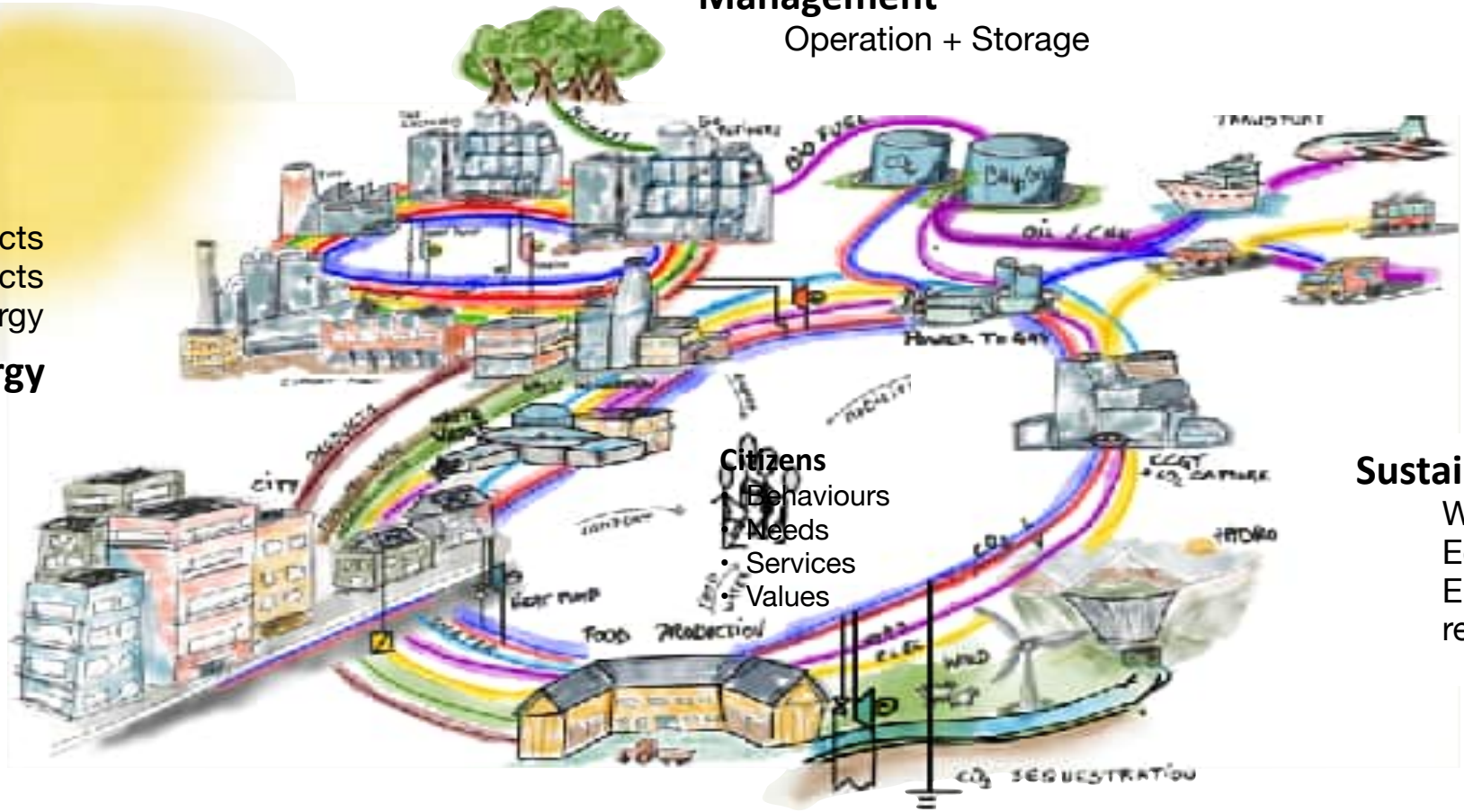
Investments
(**New**) Technologies
sizes : conversion and storage
Infrastructure => synergies & mutualisation

Demand
Products
Services
Security of supply

Management
Operation + Storage

Circularity
Waste to products
CO2 to products
Waste to energy

Waste-Water-Energy

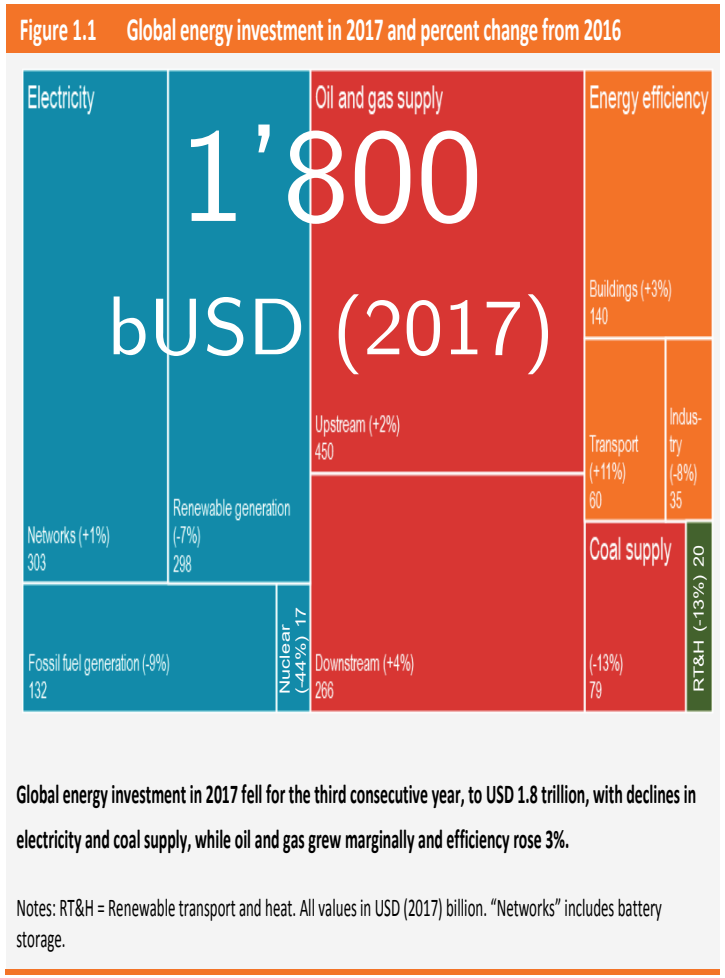


Sustainability metrics
Wealth
Economy
Environment
resiliency

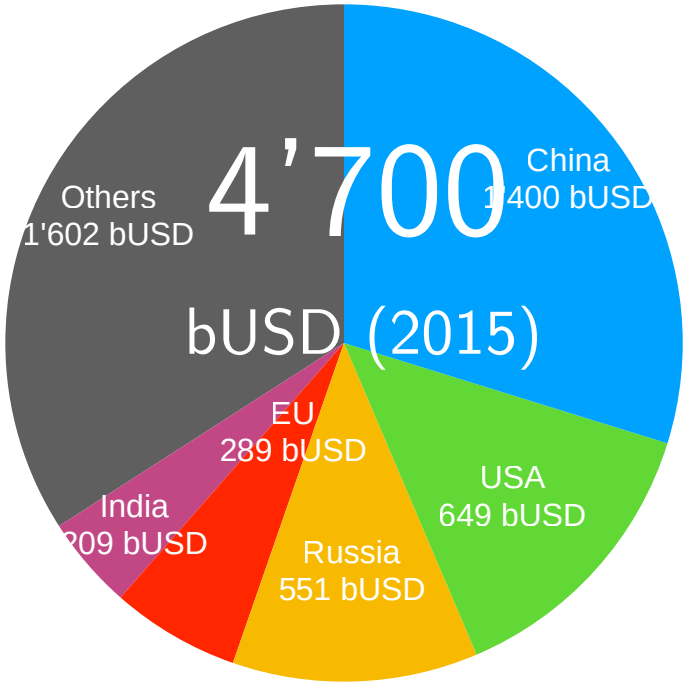
CO2 sequestration

Est-ce que ca coûtera trop cher ?

1 :Investment by industry



2.5 :Subsidies by countries

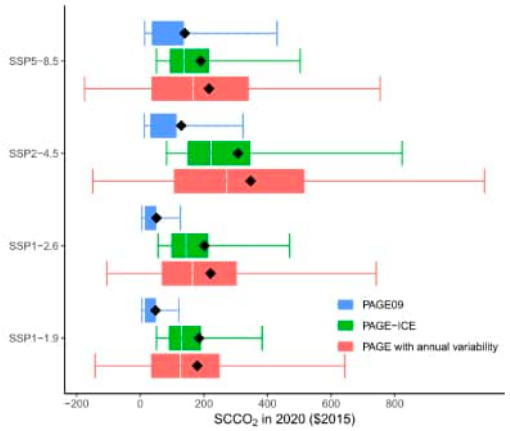


4.0 :Social cost to be paid by next gen

7'200

bUSD (2015)

repairing the damages



200 USD/t CO2

World energy investment 2018 IEA.org

World energy subsidies 2015 imf.org

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

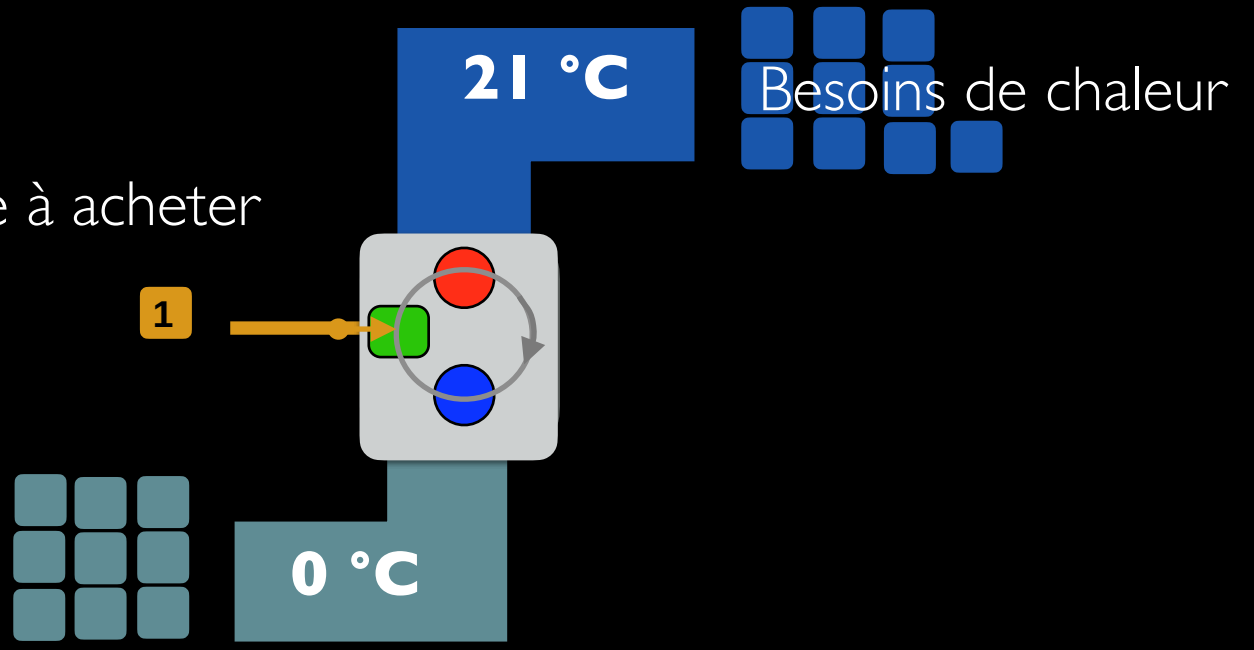
François Maréchal – francois.marechal@epfl.ch

1830 : LA FORMULE MAGIQUE

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

Pour 10 unités de chaleur, 9 viennent de l'environnement et 1 sous forme de travail

Nicolas Léonard Sadi CARNOT (F)
1796 - 1832

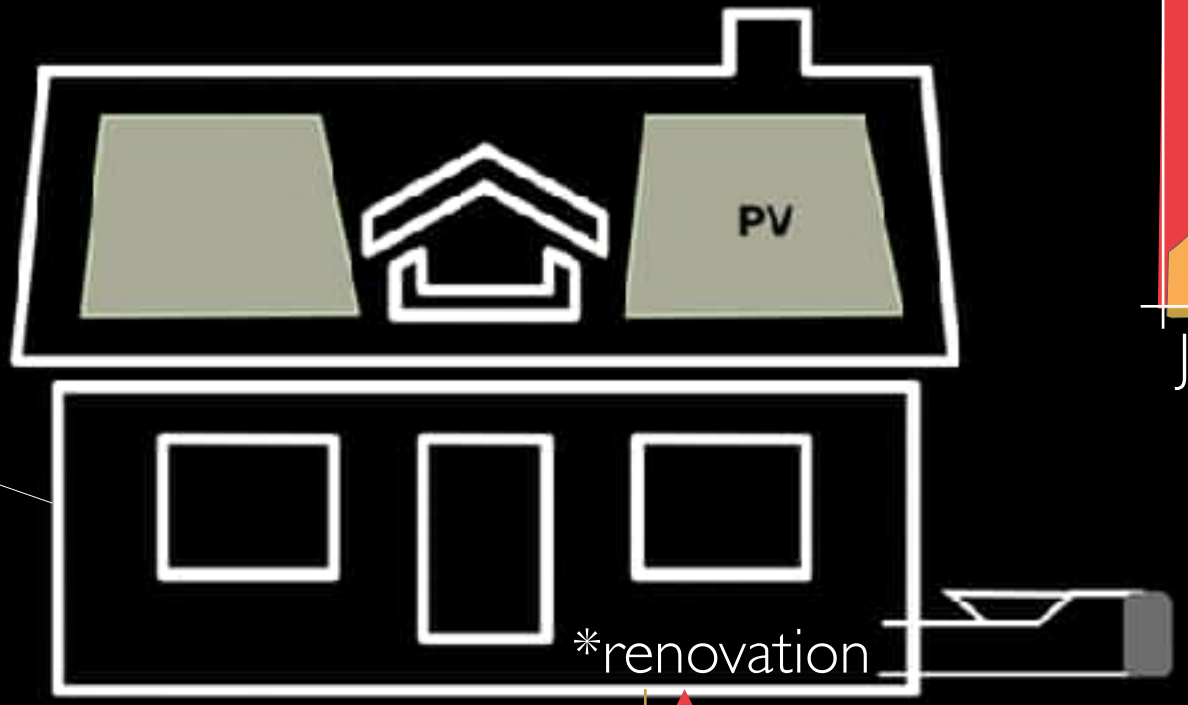


Source : chaleur de l'environnement

RENEWABLE ENERGY HUB

Big data - Forecasting

Predictive control

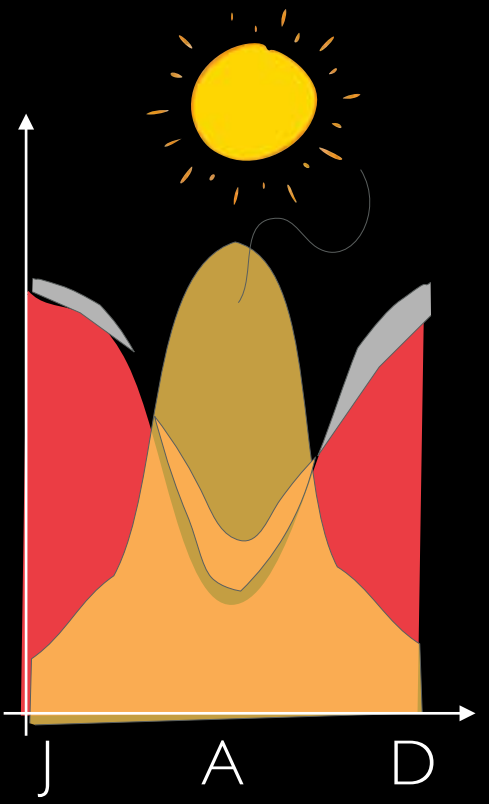


*renovation

Batteries
Hot water tanks

Heat pumps
Peak power

Electrical grid



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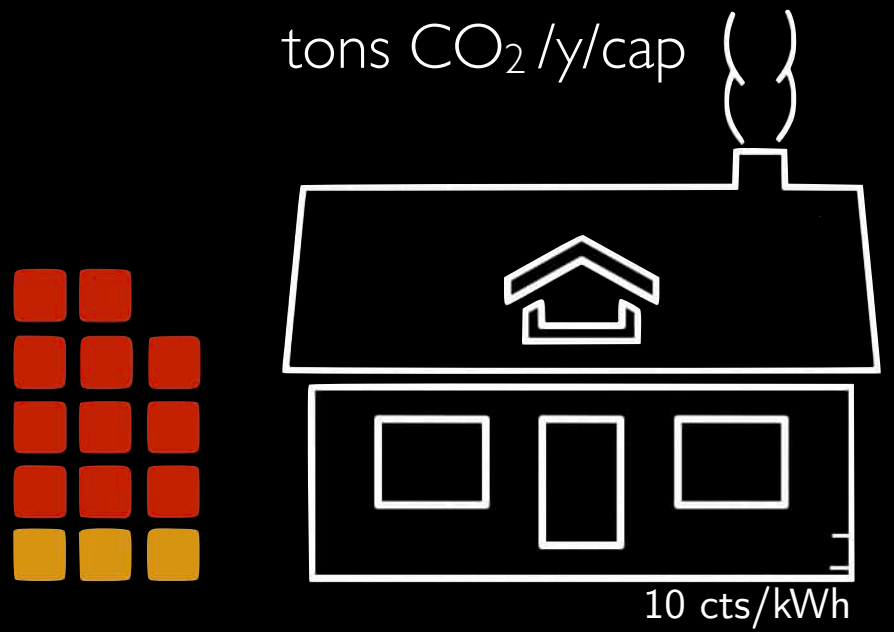
RENEWABLE ENERGY HUBS
75+ % CO_2 EMISSIONS REDUCTION

1.10

tons CO_2 /y/cap



592

CHF/y/cap

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

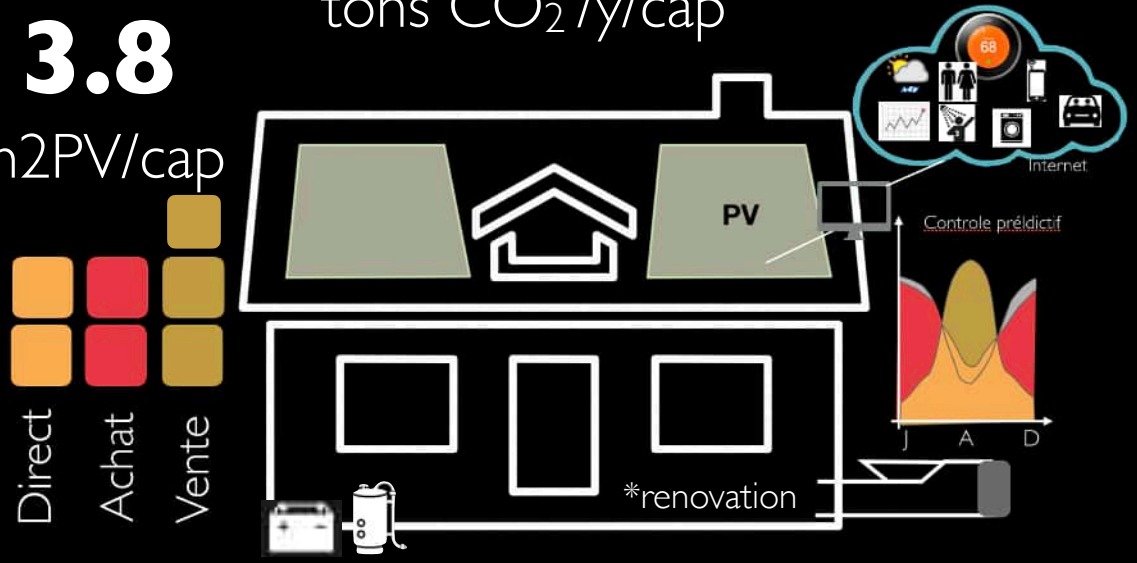
Investment : **50** CHF/y/cap

0.25 - 0.04

tons CO_2 /y/cap

3.8

m2PV/cap



493

CHF/y/cap

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

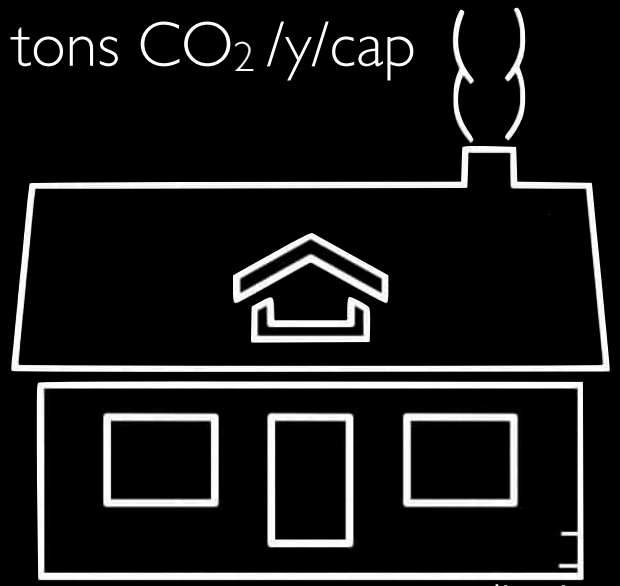
Investment : **450** CHF/y/cap

EPFL

RENEWABLE ENERGY HUBS
75+ % CO_2 EMISSIONS REDUCTION

1.10

tons CO_2 /y/cap



10 cts/kWh

2022

1018

CHF/y/cap

Energy : **968** CHF/y/cap

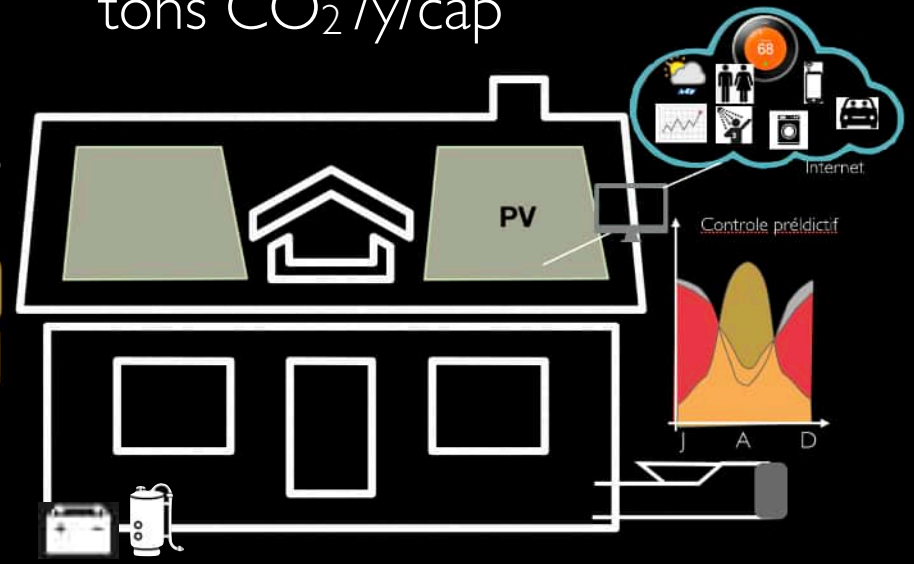
Investment : **50** CHF/y/cap

0.25 - 0.04

tons CO_2 /y/cap

3.8

m2PV/cap

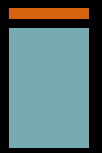


493

CHF/y/cap

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

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



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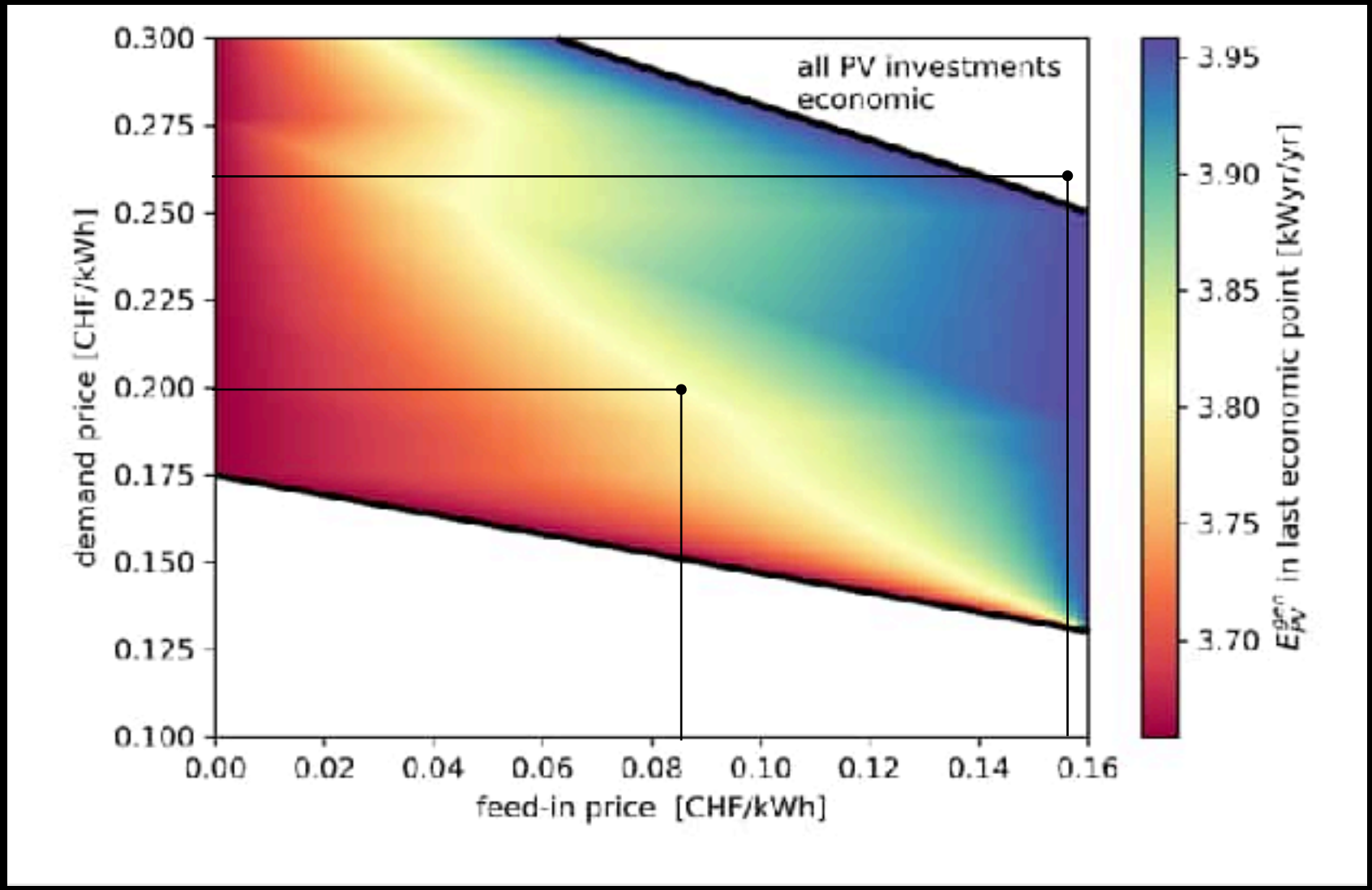
RENEWABLE ENERGY HUB
LE DISTRIBUTEUR DÉCIDE DES INVESTISSEMENTS



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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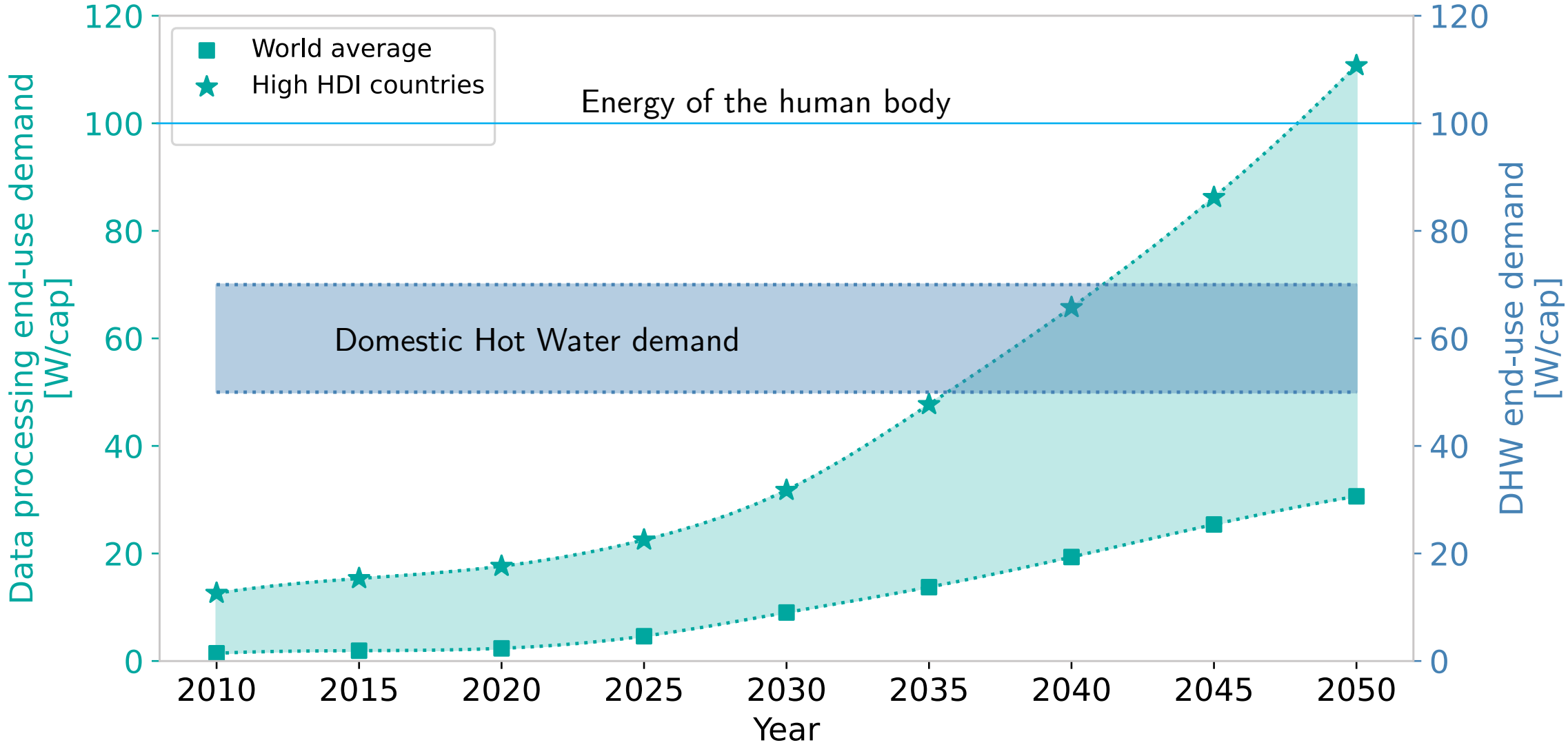
Data production and energy system



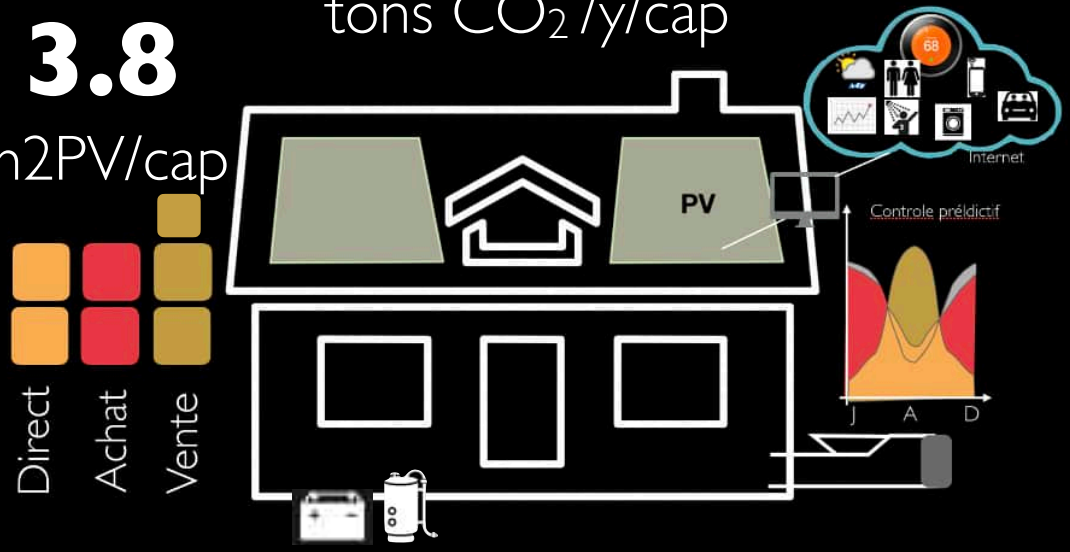
RENEWABLE ENERGY HUB AND DATA PRODUCTION

0.25 + 0.24

tons CO_2 /y/cap

3.8

m2PV/cap

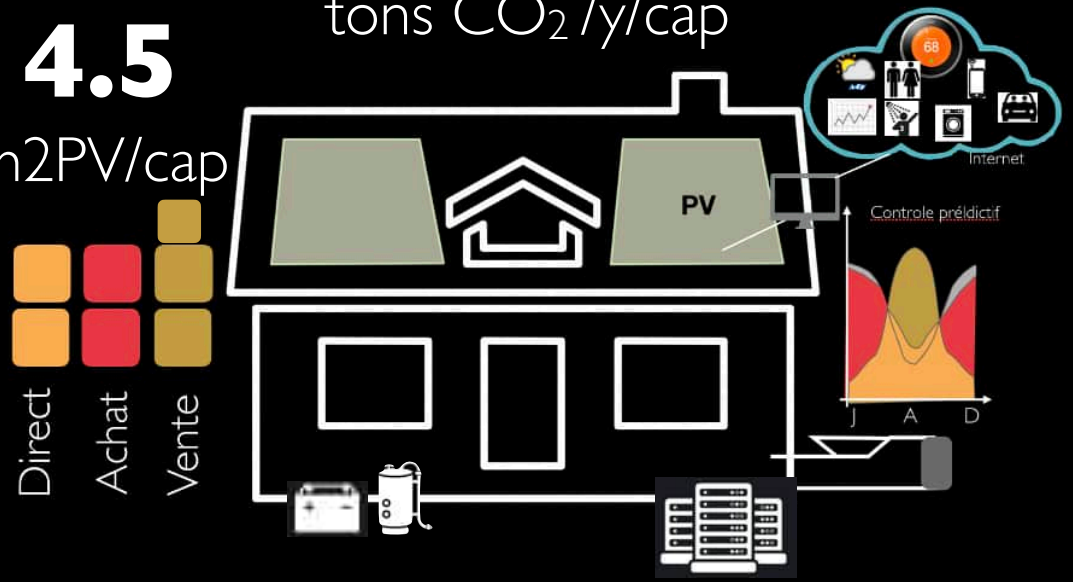


0.32

tons CO_2 /y/cap

4.5

m2PV/cap



969= 493 + 476

CHF/y/cap

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

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

Building

CHF/y/cap

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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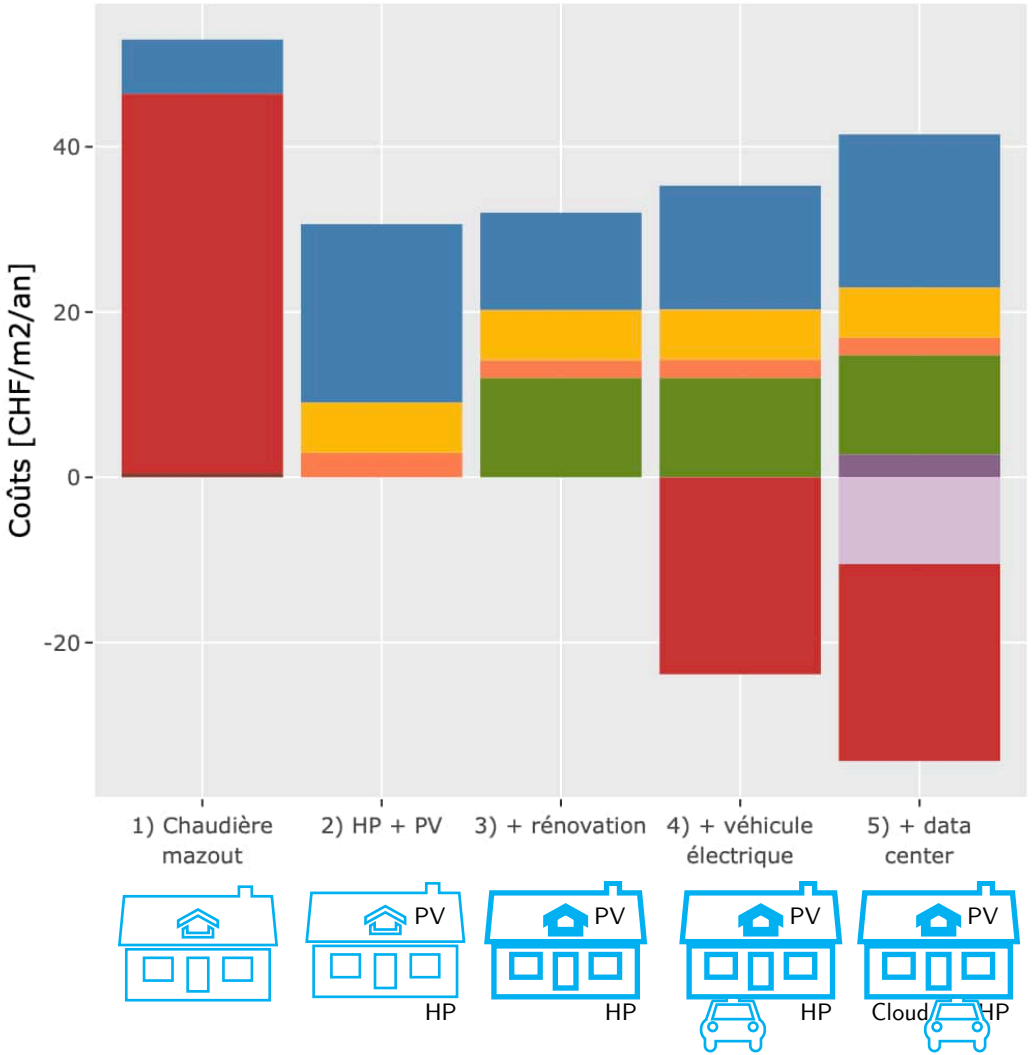
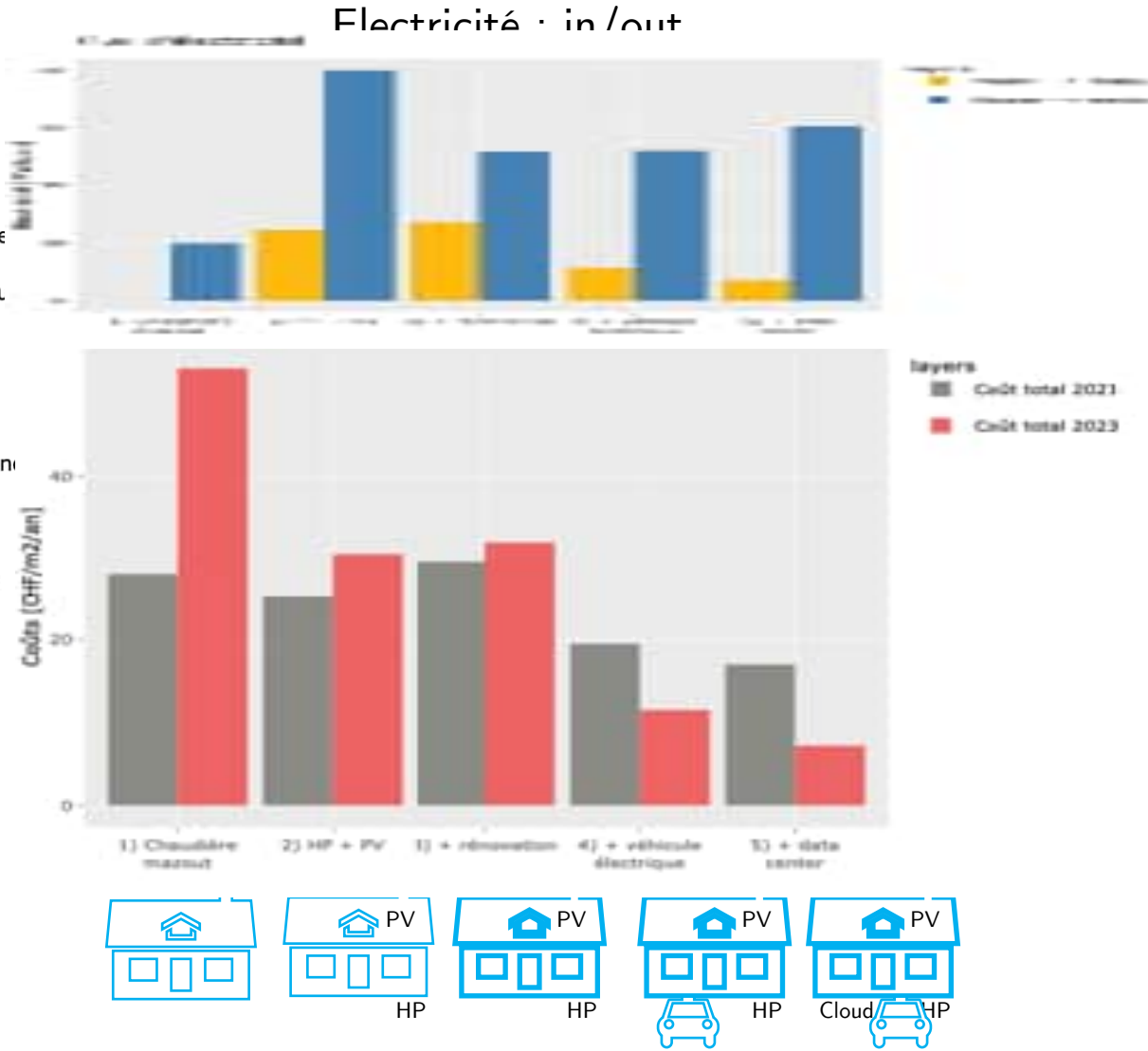
L'approche système

Coût système énergétique en 2023





RÉSEAU ANERGIE : MISE EN OEUVRE DANS LA VILLE

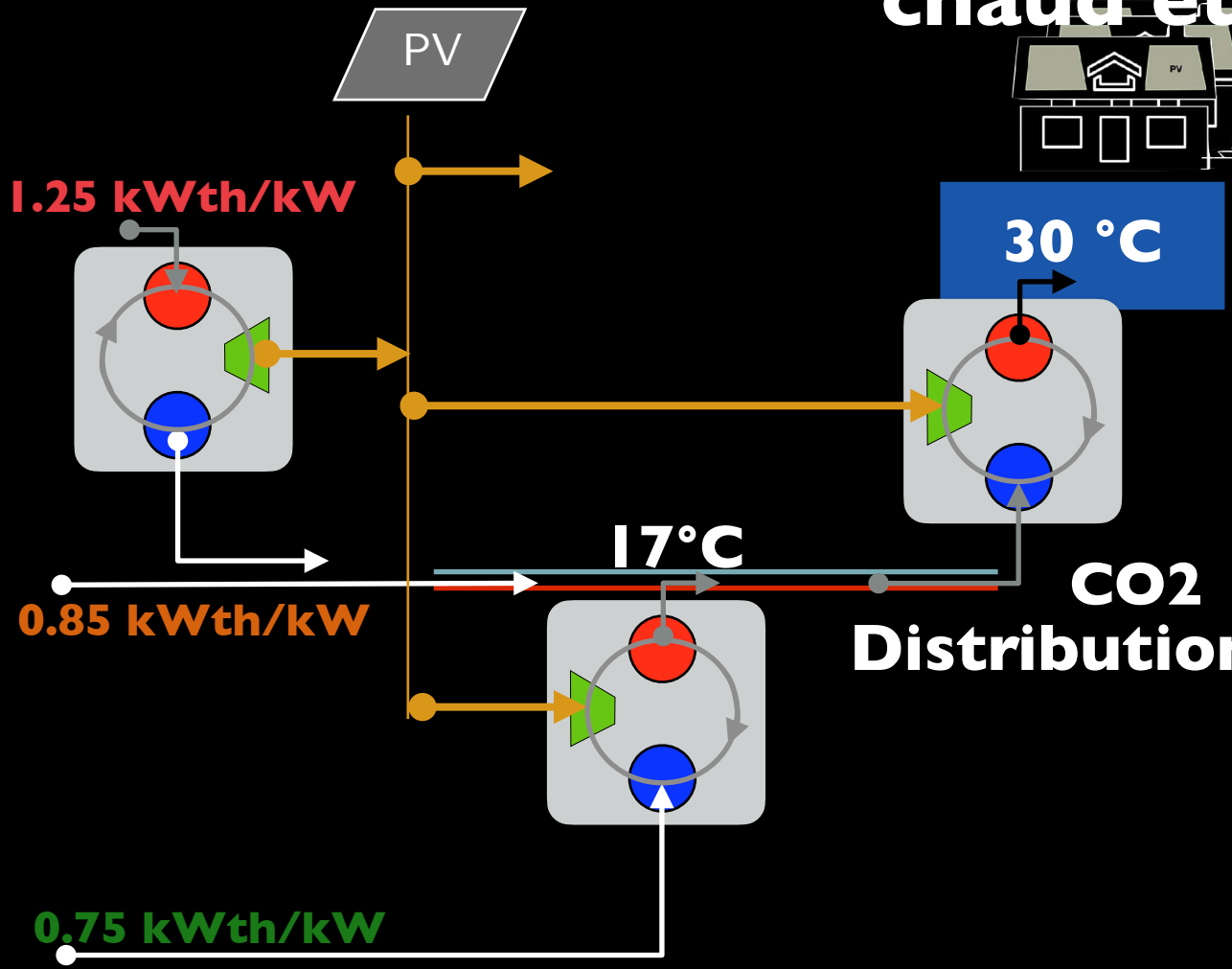
Sources de chaleurs

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

Industrie: **>80**°C

Data center : **30**°C
Eaux usées : **13-20** °C

Eau Nappe : **10** °C
Rivières/lac : **7**°C
Géothermie : >**10** °C
Refrigeration : **< 0**°C



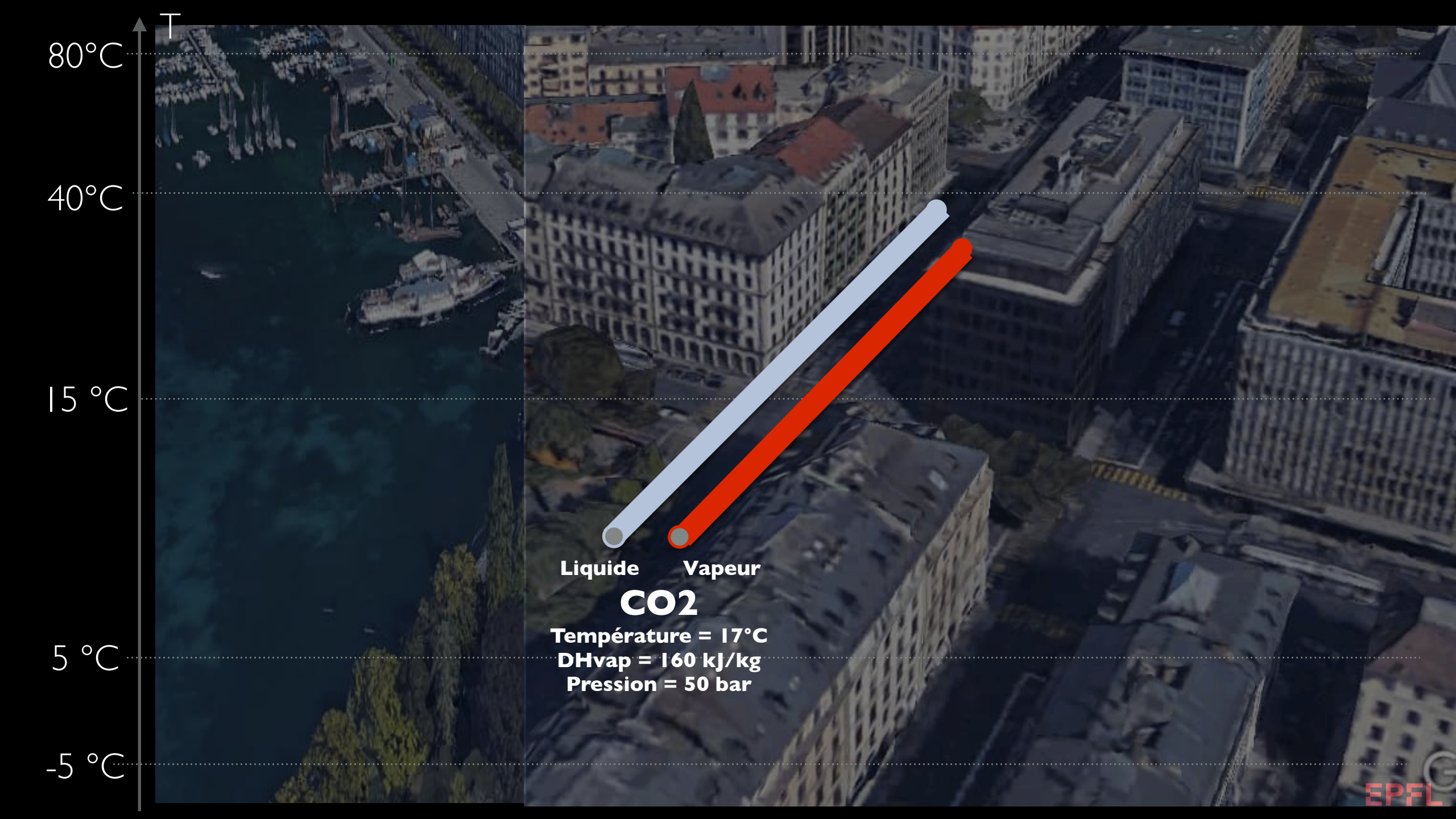
Utilisateurs chaud et froid

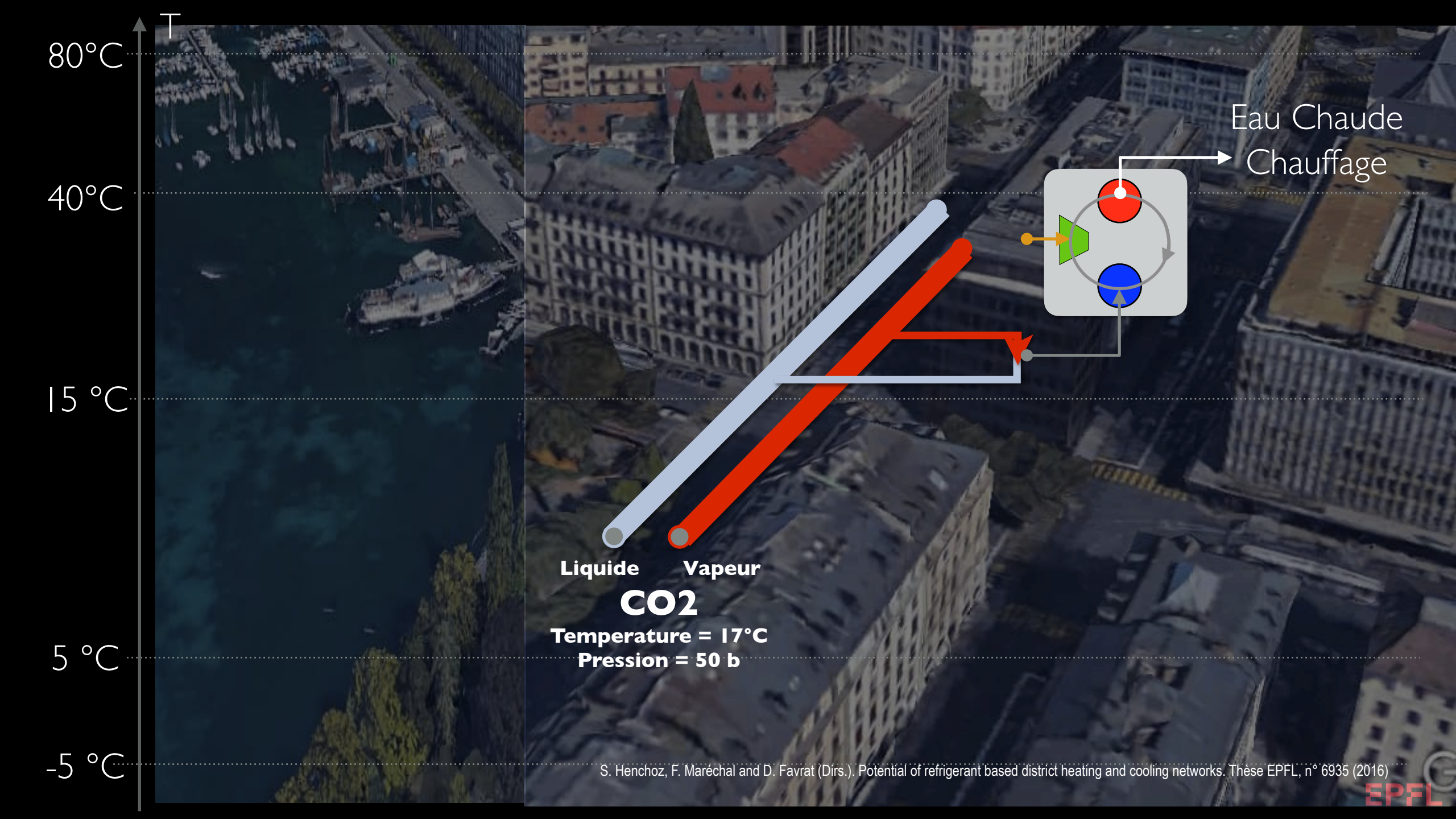
CO2 L V

Distribution : anergie

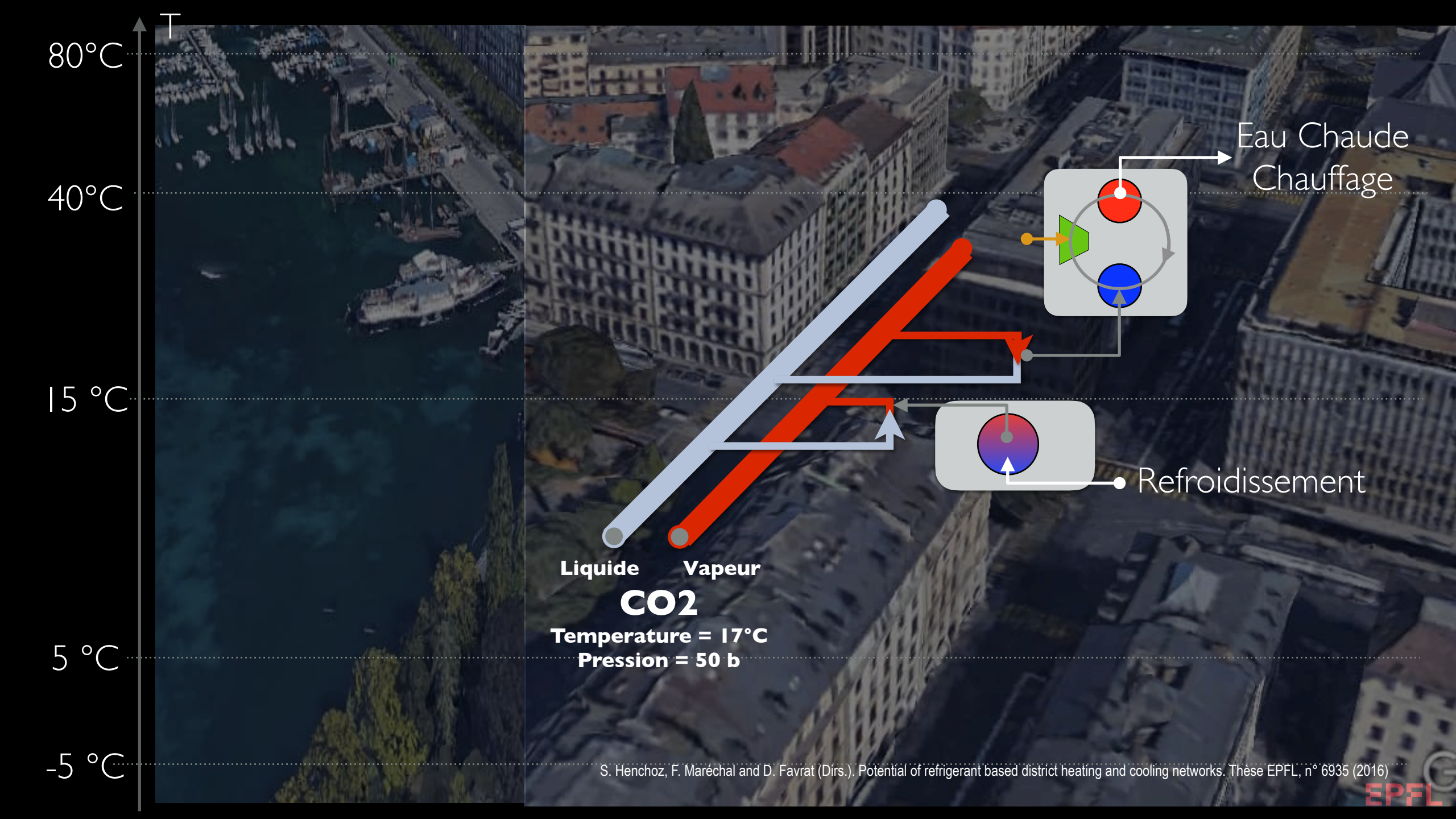
D. Favrat, C. Weber, CO2 based district energy system, U.S. Patent 2010018668

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)



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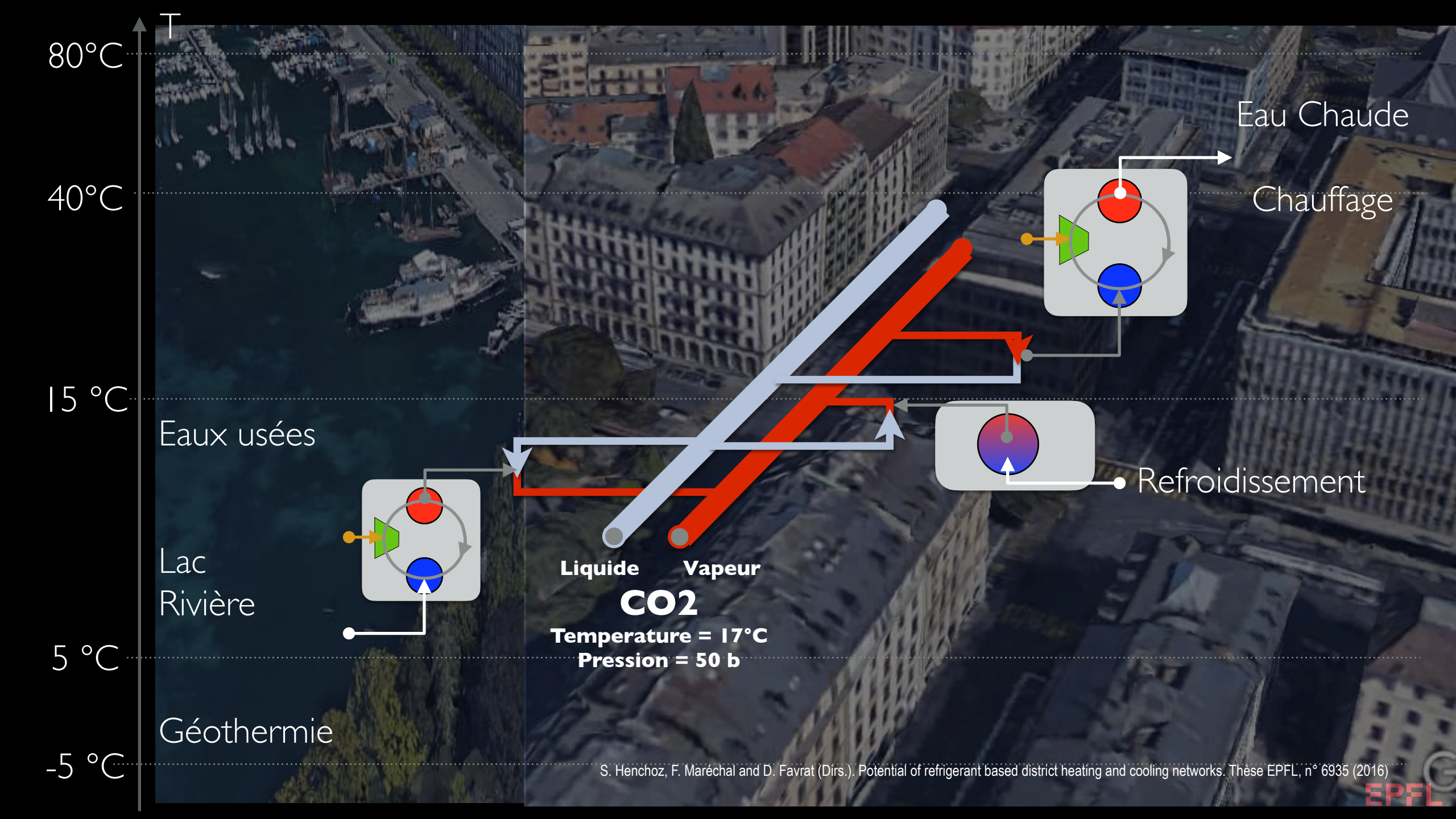
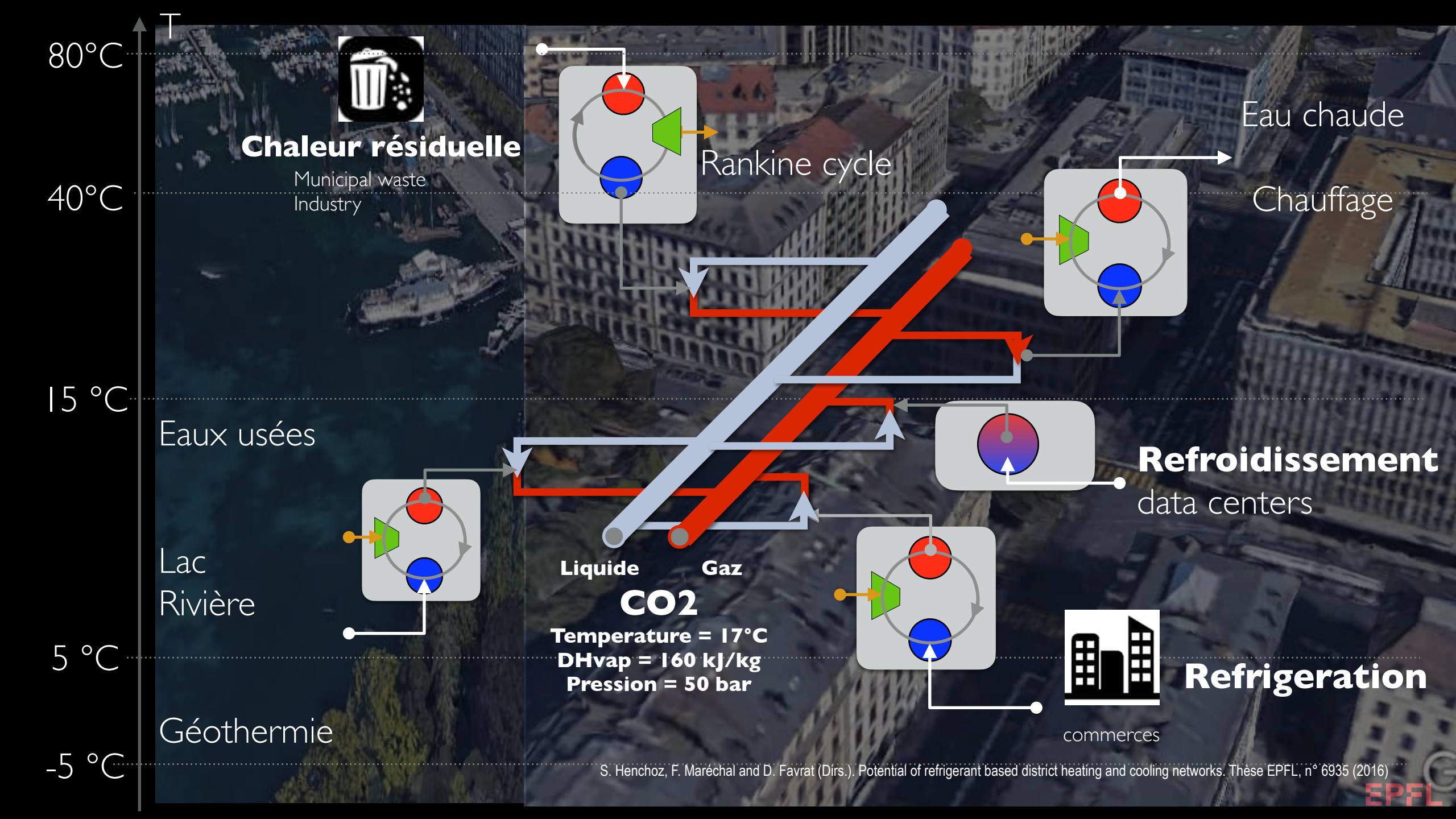


S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)

EPFL

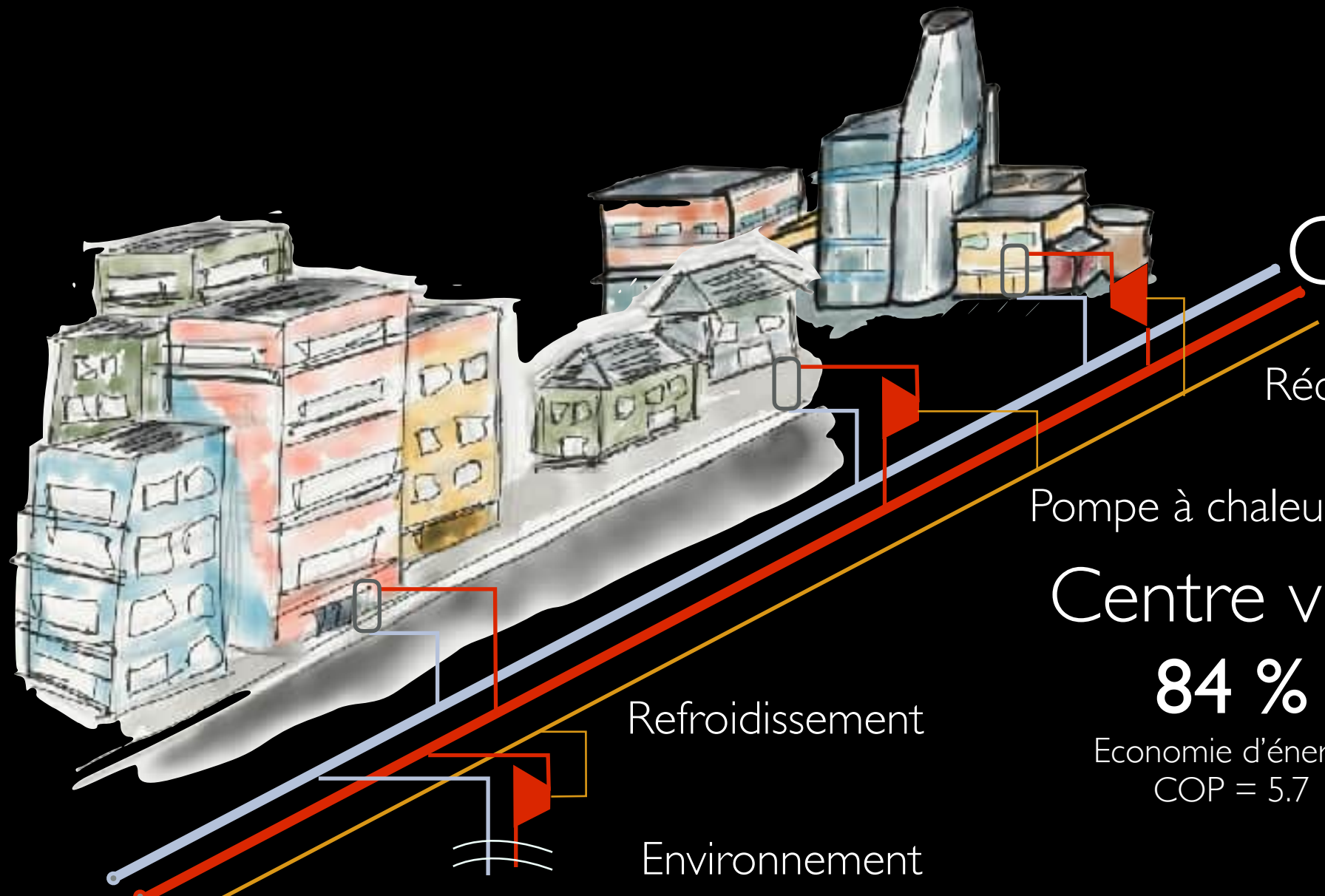


S. Henchoz, F. Maréchal and D. Favrat (Dirs.). Potential of refrigerant based district heating and cooling networks. Thèse EPFL, n° 6935 (2016)

POMPE À CHALEUR URBAINE

www.exergo.ch

Demonstrateur Valais



CO_2 17°C
50 bar

Récupération de chaleur

Pompe à chaleur

Refroidissement

Environnement

Centre ville : bord du lac

84 %
Economie d'énergie
COP = 5.7

6
ans
temps de retour

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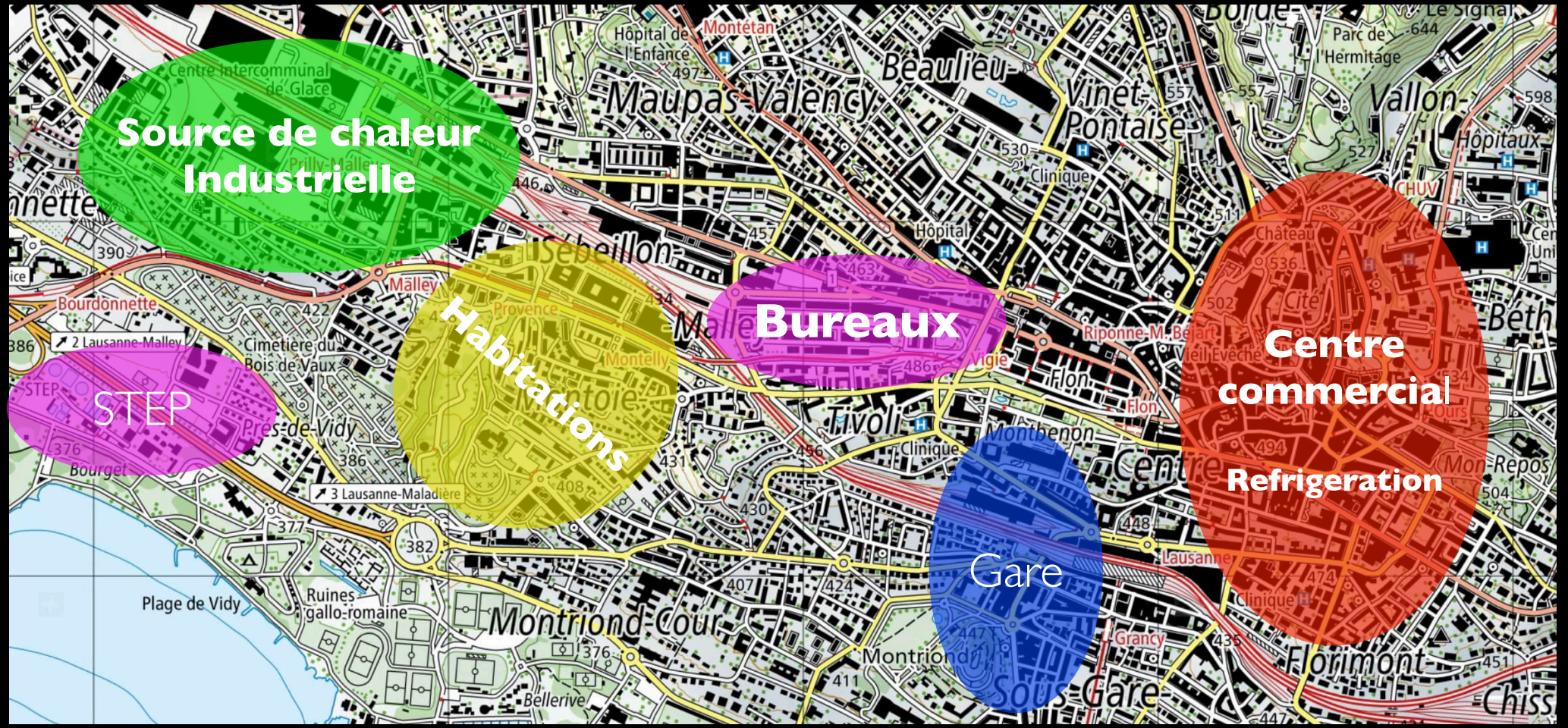
LES HUBS ENERGETIQUES DE LA VILLE

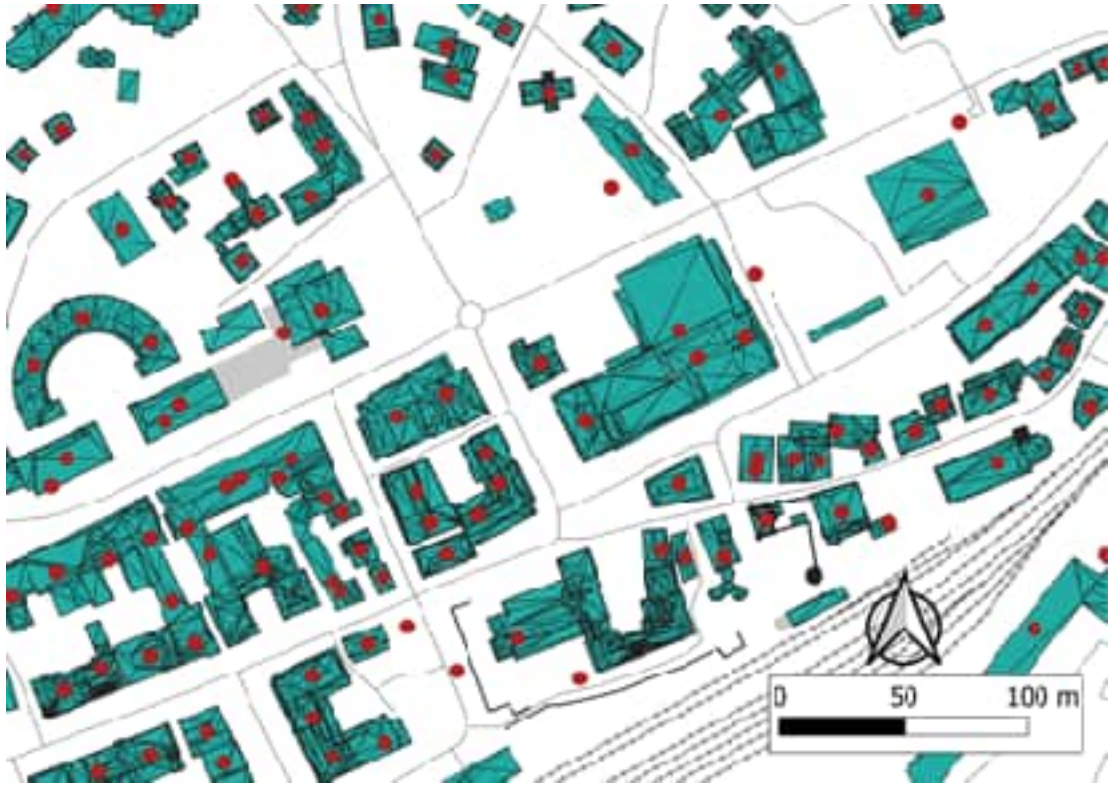


: aide à la décision pour la planification urbaine multi-critère

EPFL

Evaluation de la demande : GIS System

Raphaël Briguet



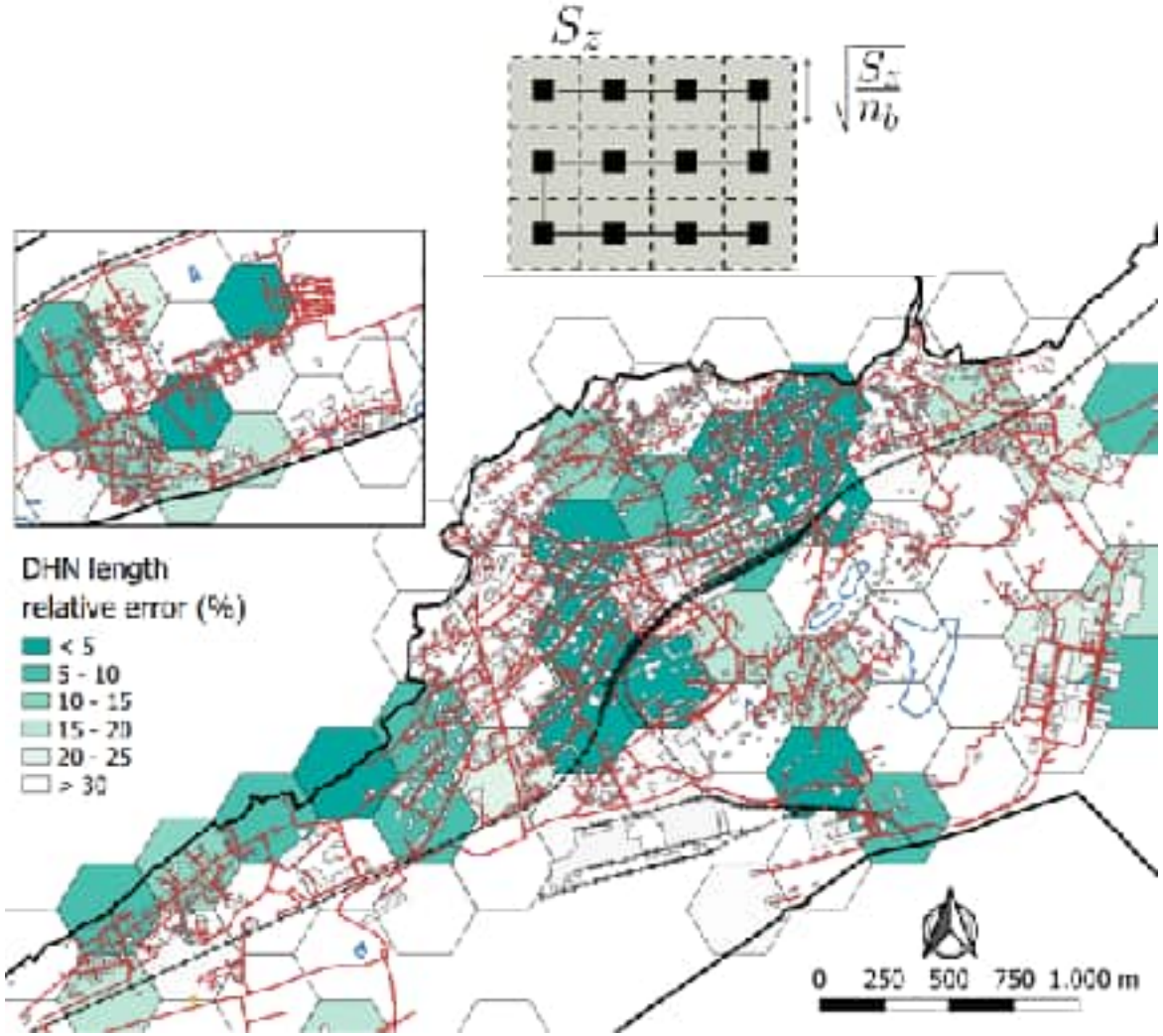
Les points rouges représentent le RegBL et les zones bleues les modèles 3D des bâtiments

- Méthode statistique basée sur le travail de Girardin [1]
- 3 bases de données nécessaires:
  - **RegBL**
  - **SwissTLM3D**
  - **SwissBuilding3D**
- Attribuer un des 80 bâtiments types définis par [1]
- **Signature thermique:**

$$\dot{q}^{SH} = k_1 + T_o \cdot k_2 \qquad [kW/m^2]$$

Qui connecter et comment ?

Design connexion intra-quartier



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

- Estimation de la longueur

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

- Utilisation du réseau de gaz pour calibrer le K
- Jusqu'à moins de 5% dans les quartiers clés

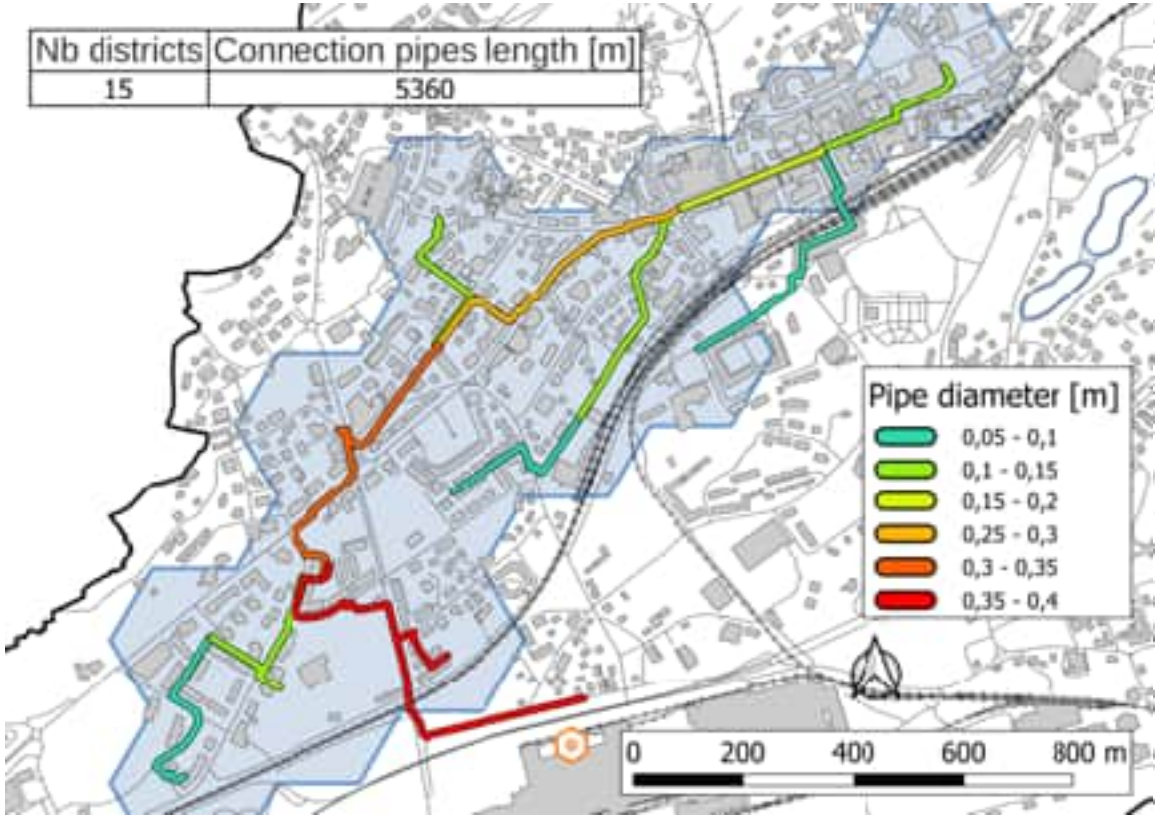
\+ Peu de données requises
\+ Réseau CAD proche du réseau gaz

\- Données pas disponibles partout
\- Considère un modèle en série

Travail diplôme Briguet 2022, Sierre

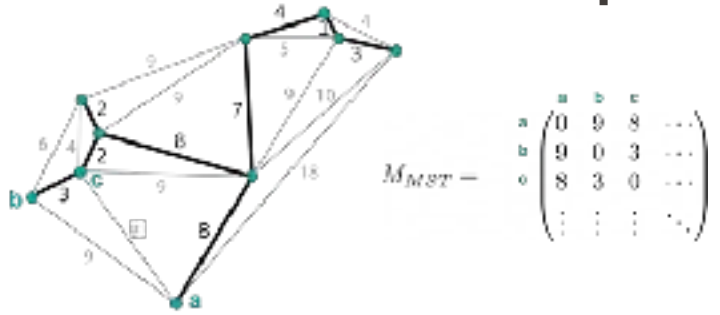
Qui connecter et comment ?

Design connexion entre-quartier



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

- Utilisation du **Minimum Spanning Tree**



- ***OpenStreet Map*** **:** optimise l'itinéraire

⊕ Tracé réalistique
⊕ Ajout de contraintes possibles

⊖ Temps de calcul plus élevé
⊖ Ne prend pas en compte les puissances

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

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

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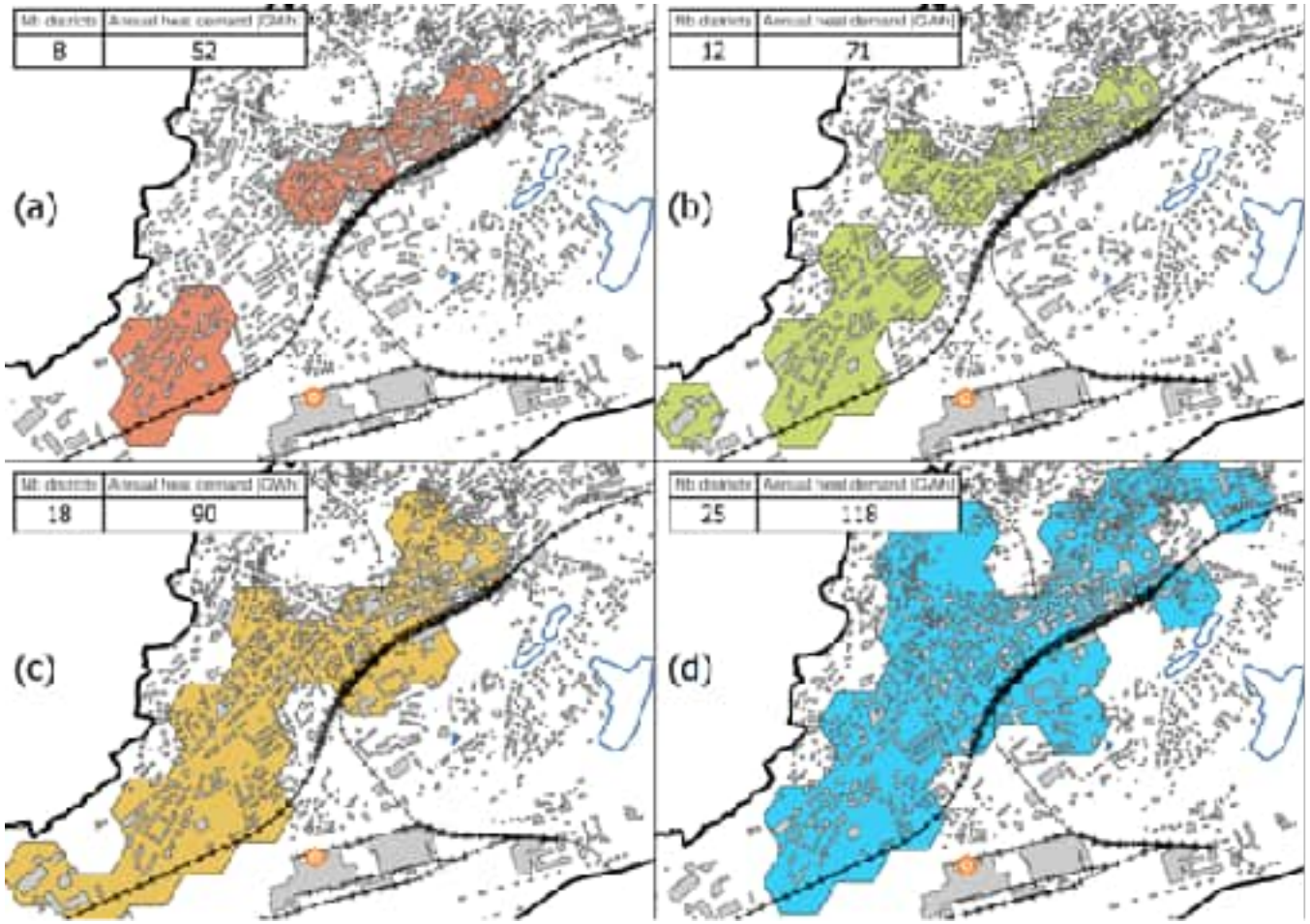
IPESE
Industrial Process and Energy Systems Engineering

Extension Géographique paramétrique

Raphaël Briguet



Représentation de l'expansion du réseau.

- (a) s'étend depuis le **centre ville** et depuis la zone **Rossfeld**
- (b) s'étend à l'hôpital
- (c) connecte le sud de la gare
- (d) zone résidentielle faible densité

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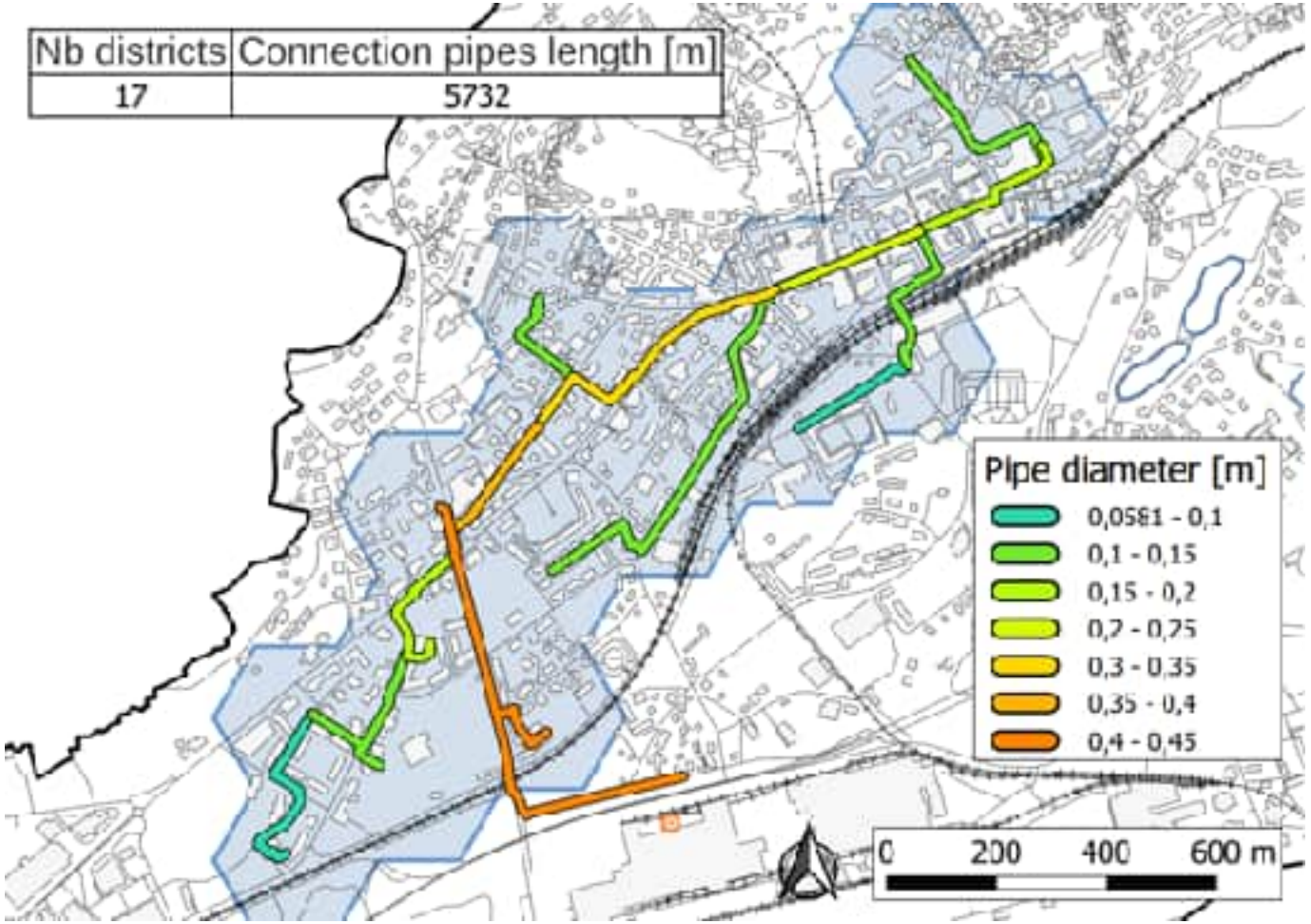
Infrastructure énergétique

Raphaël Briguet



Tracé optimisé du CAD pour un système à 55/45 °C

- Accès à la ville depuis l'ouest
- Rejoint le sud de la gare depuis le centre ville

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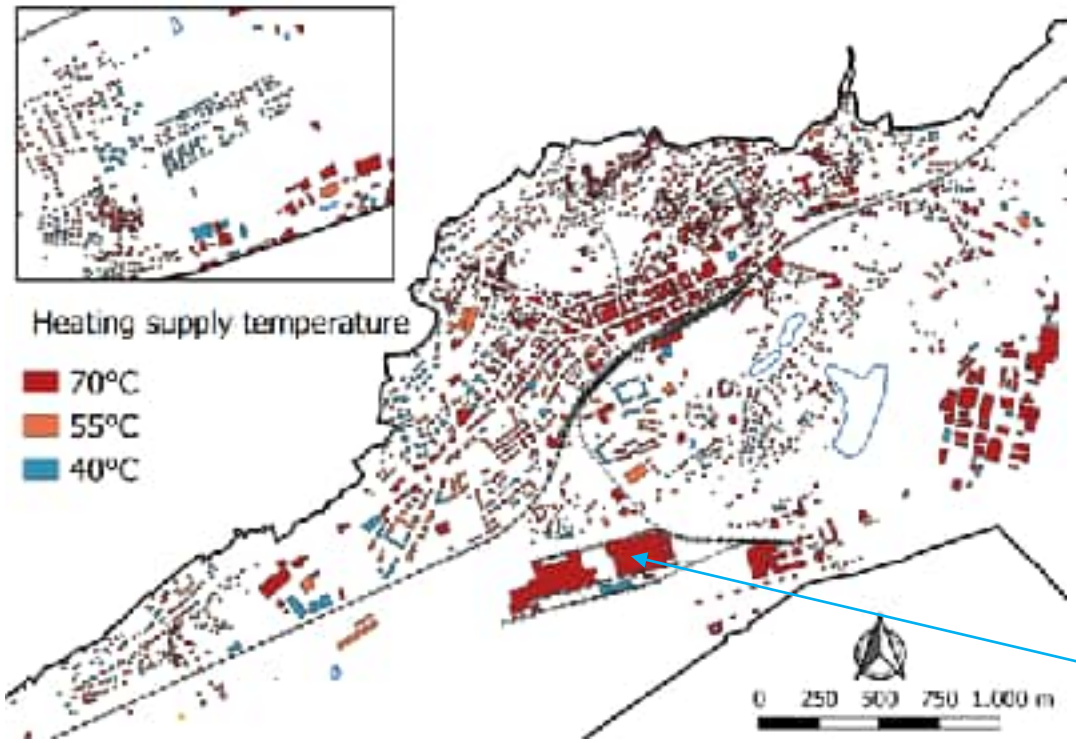
Choisir le système de distribution de chaleur

Raphaël Briguet



Niveau de température requis par les bâtiments pour le système de chauffage. 12% de la surface de référence énergétique (SRE) requiert une température de 40°C.

4 systèmes comparés

- **95/75 :** pas d'unité décentralisée
- **55/45 :** pas unité décentralisée pour les bâtiments modernes (12% de la SRE)
- **25/20** : unité décentralisée pour tous
- **15/15 (CO2)** : unité décentralisée pour tous

Source de chaleur industrielle

- 18 MW
- 30 °C

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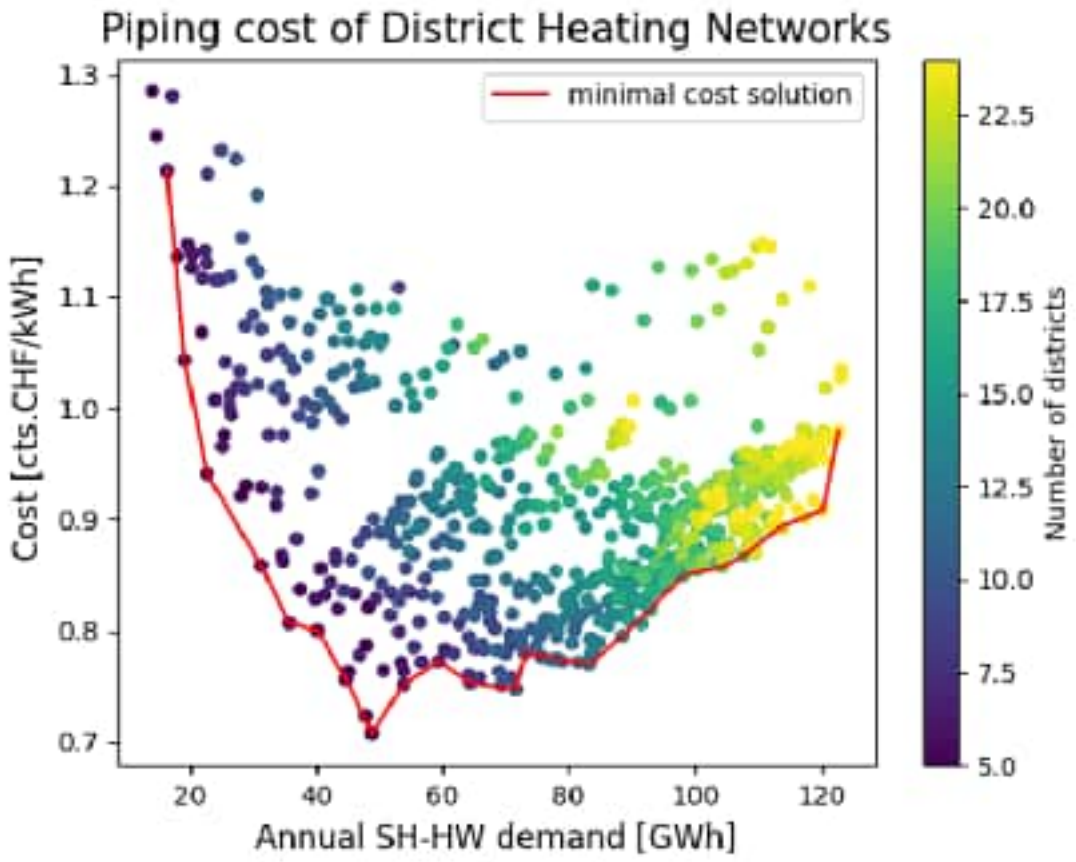
Optimisation des configurations

Raphaël Briguet



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

Pour chaque niveau de température:

- Génération paramétrique de solutions

  [cts/kWh]/[GWh/an]

Anergie : **coût total** comprend:

- Investissement PACs décentraliséss
- Opération PACs
- Investissement réseau
- Sources de chaleur

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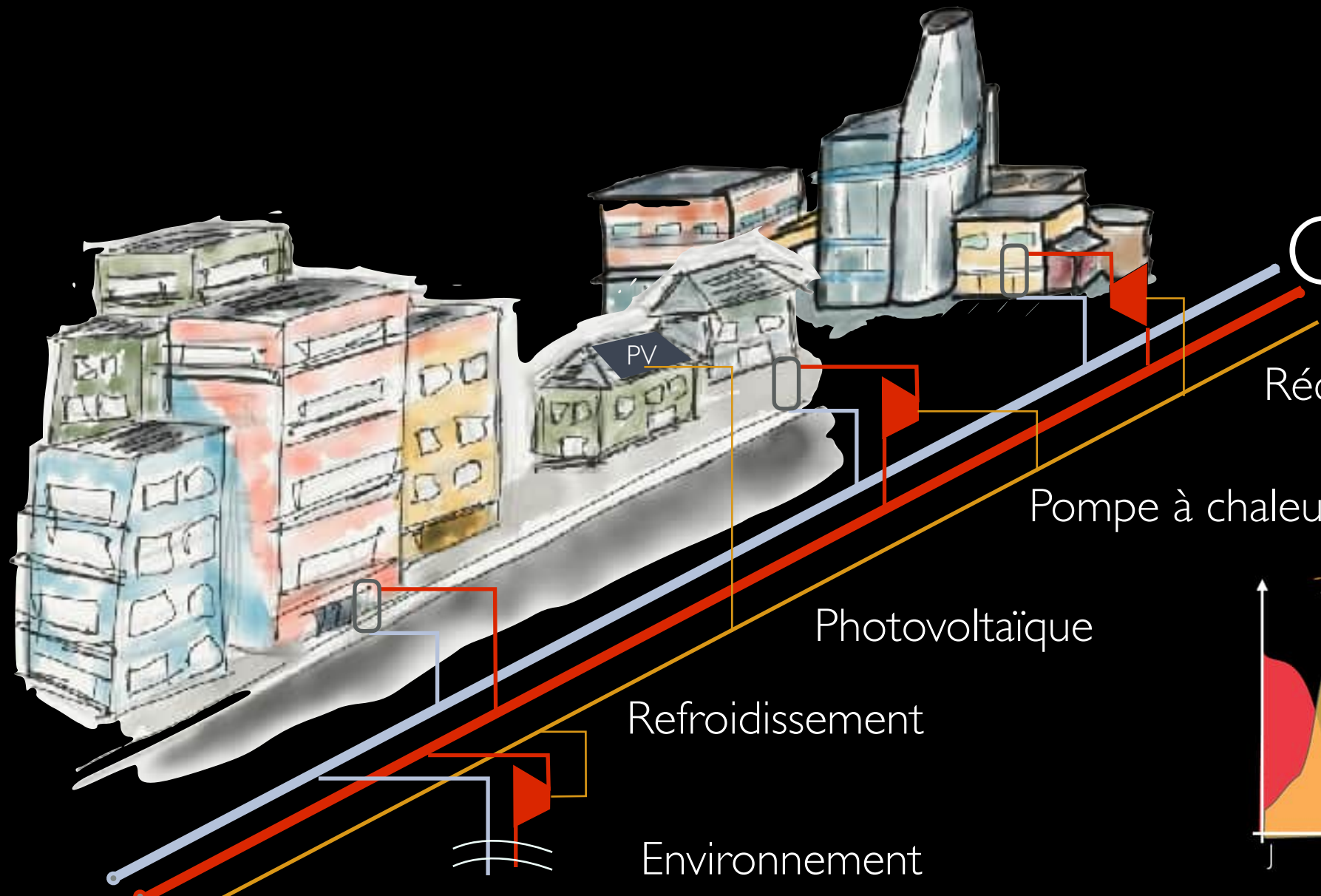
POMPE À CHALEUR URBAINE ET PHOTOVOLTAÏQUE

www.exergo.ch



CO_2 17°C 50 bar

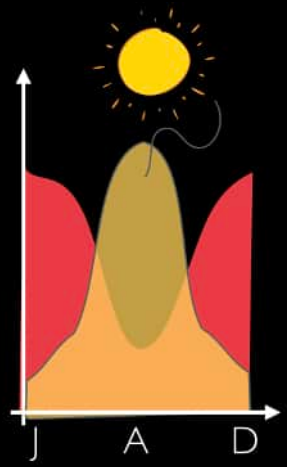
Récupération de chaleur

Pompe à chaleur

Photovoltaïque

Refroidissement

Environnement



EPFL

Integrating Renewable Energy Sources : Biogas + PV+ Power2gas

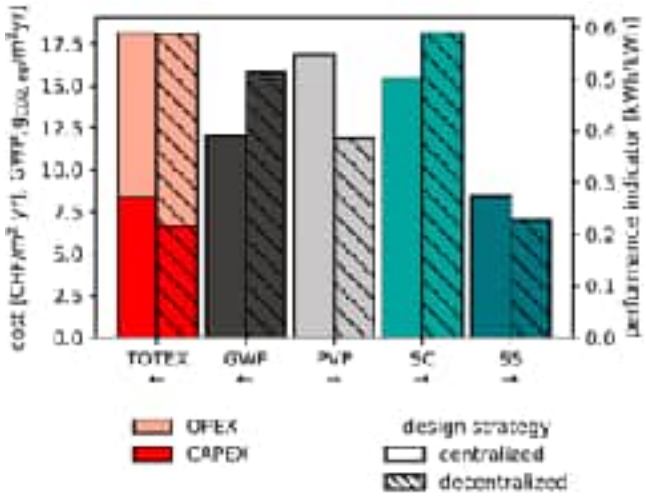
- District scale => interactions between buildings

Micro grid integration

BioSNG **Seasonal storage**

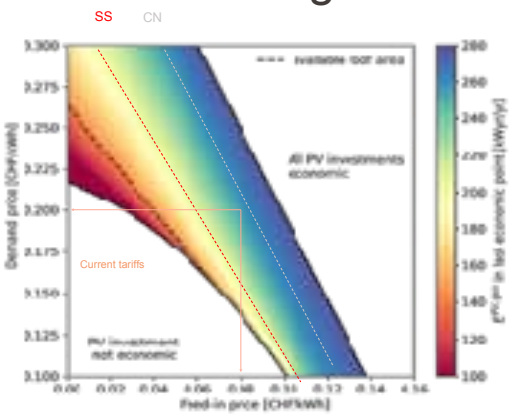
m2 = heated surface

building vs community

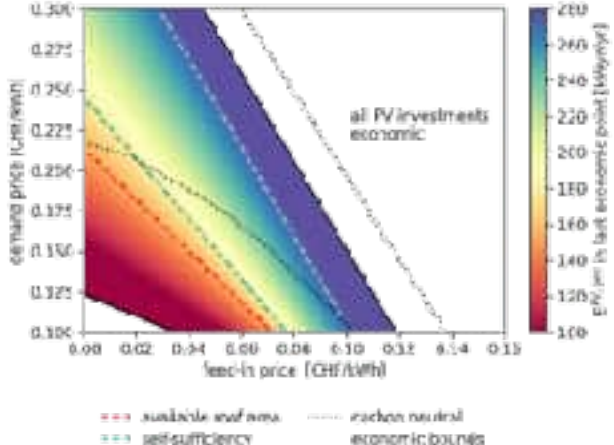


→40% increase PV
→20% GWP reduction
→16-40% facades

→building

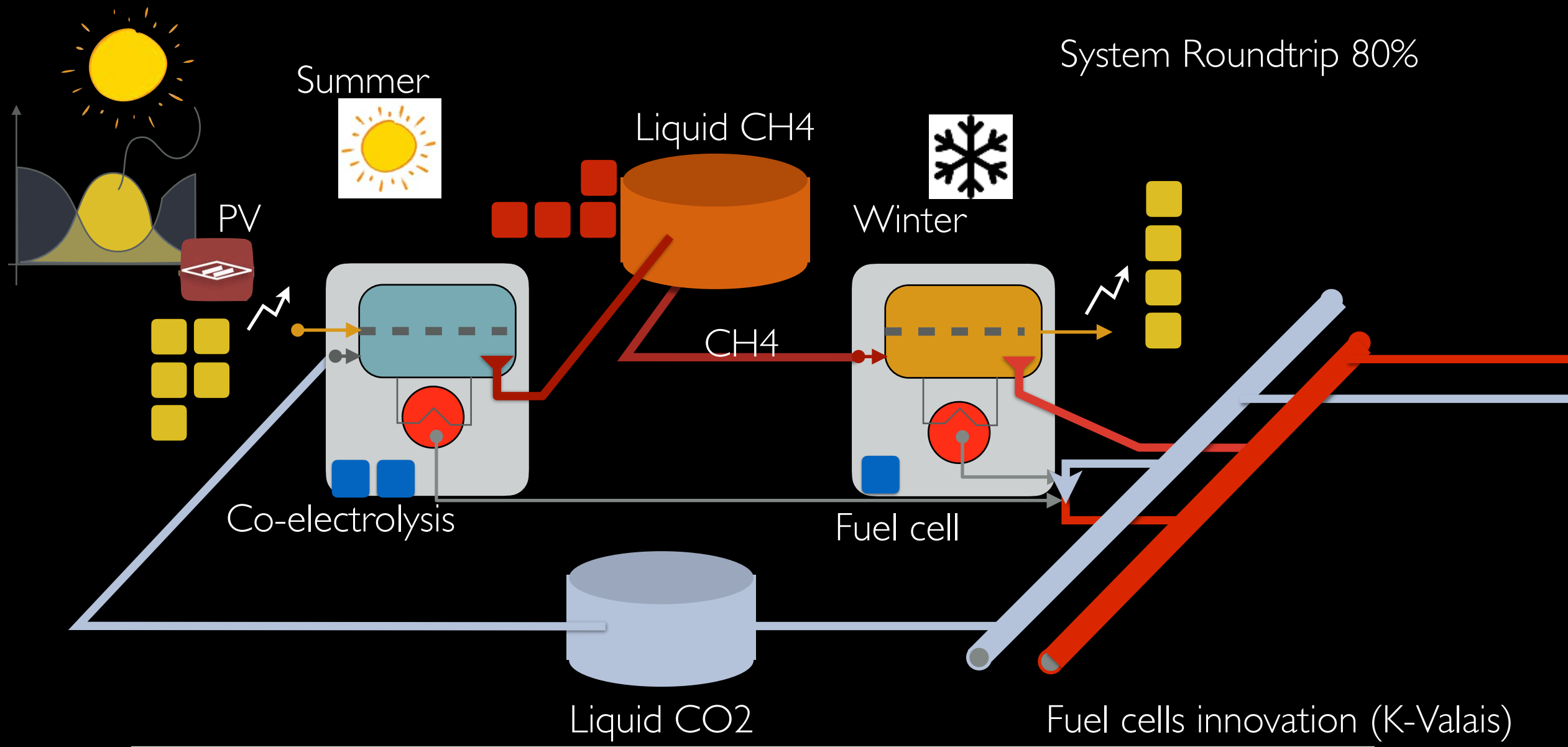


→district



IPESE
Industrial Process and Energy Systems Engineering

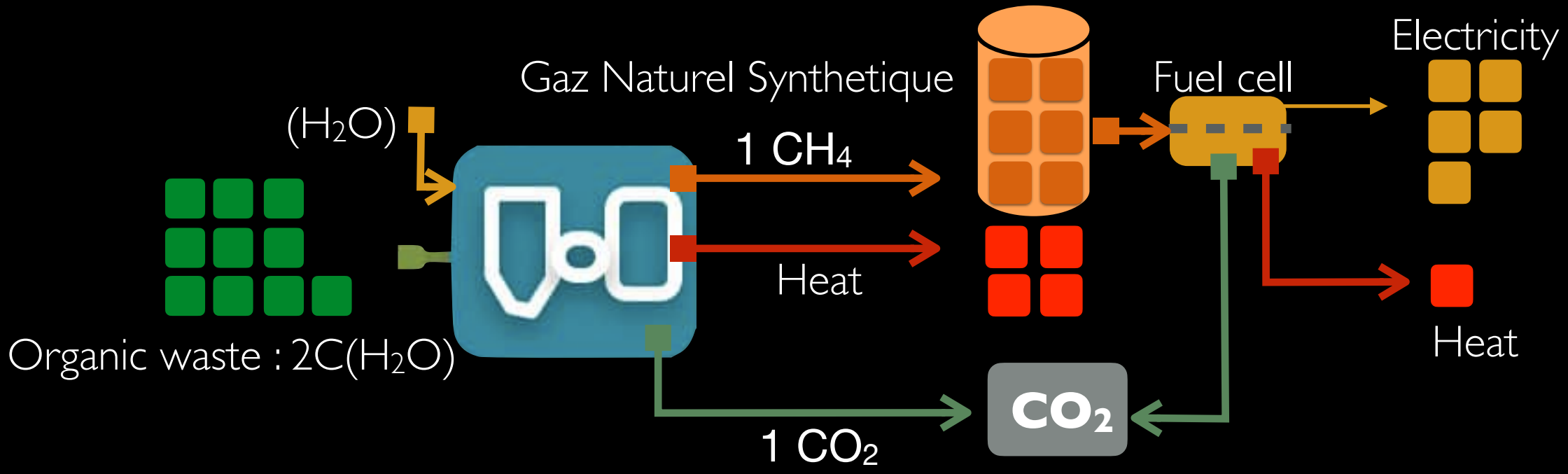
INTEGRATED ENERGY MANAGEMENT



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.

EPFL

FOURNIR L'IMPORT PAR NOS DÉCHETS ?



30% : Biomethanisation

70% : Hydrothermal gasification ( )

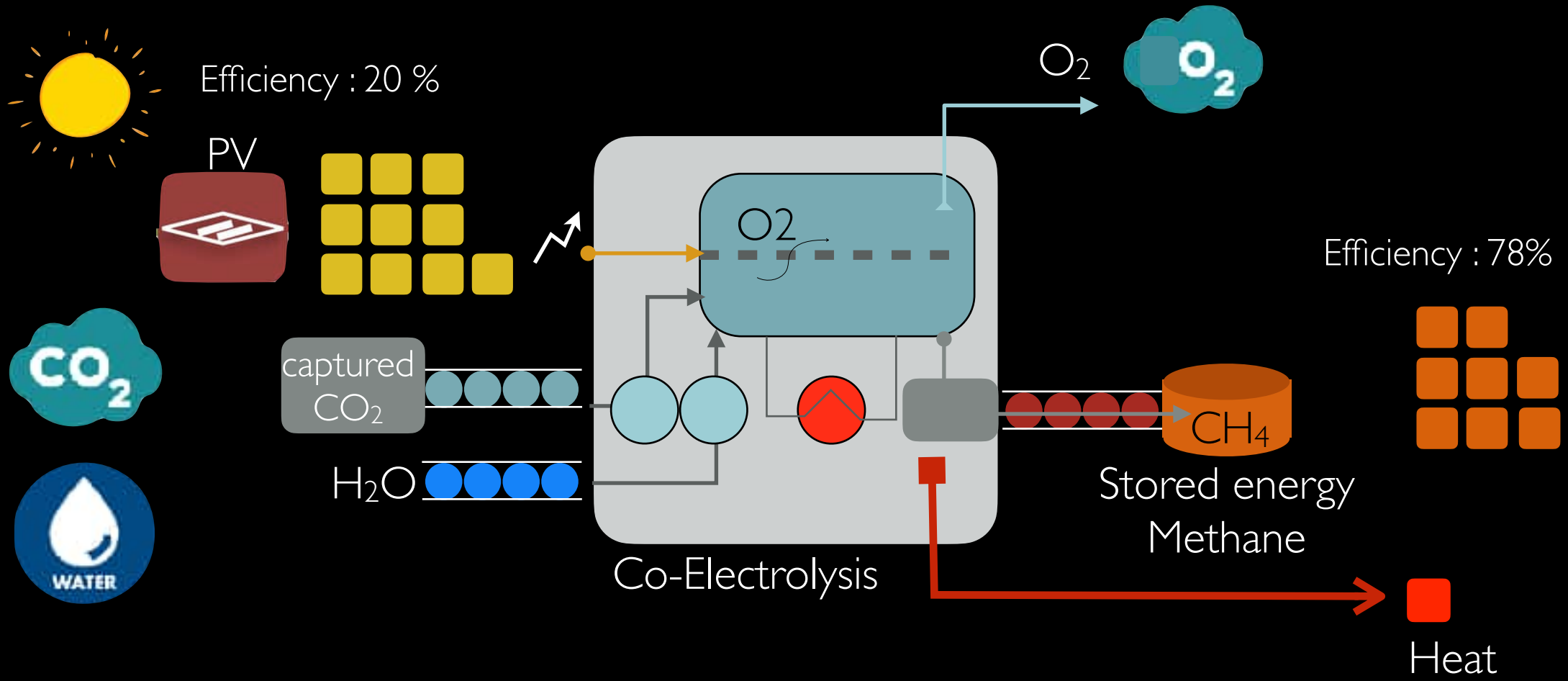
70% : Synthetic Natural Gas

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

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

PV
PV

STOCKER L'EXCÈS D'ELECTRICITÉ

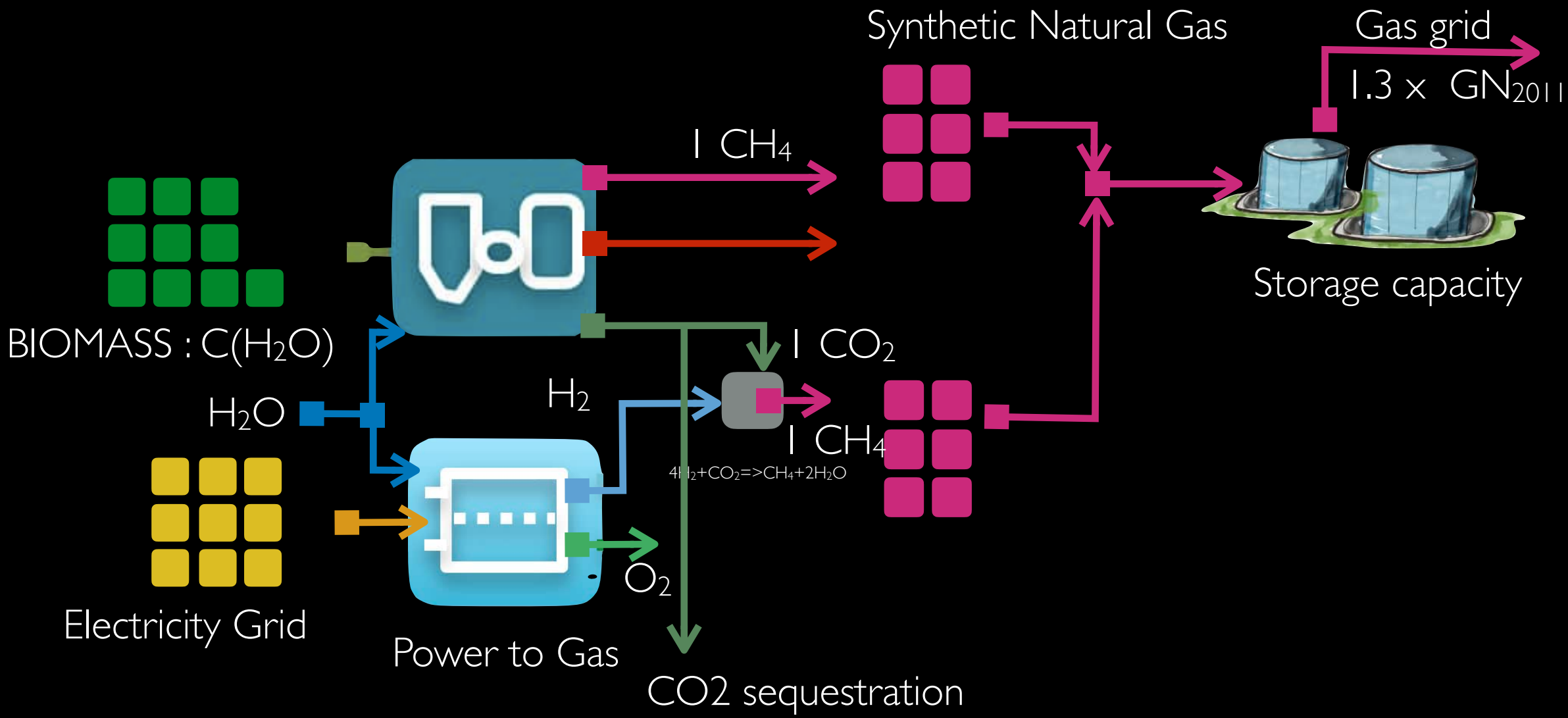


Artificial photosynthesis : 13-16 % Solar efficiency

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.

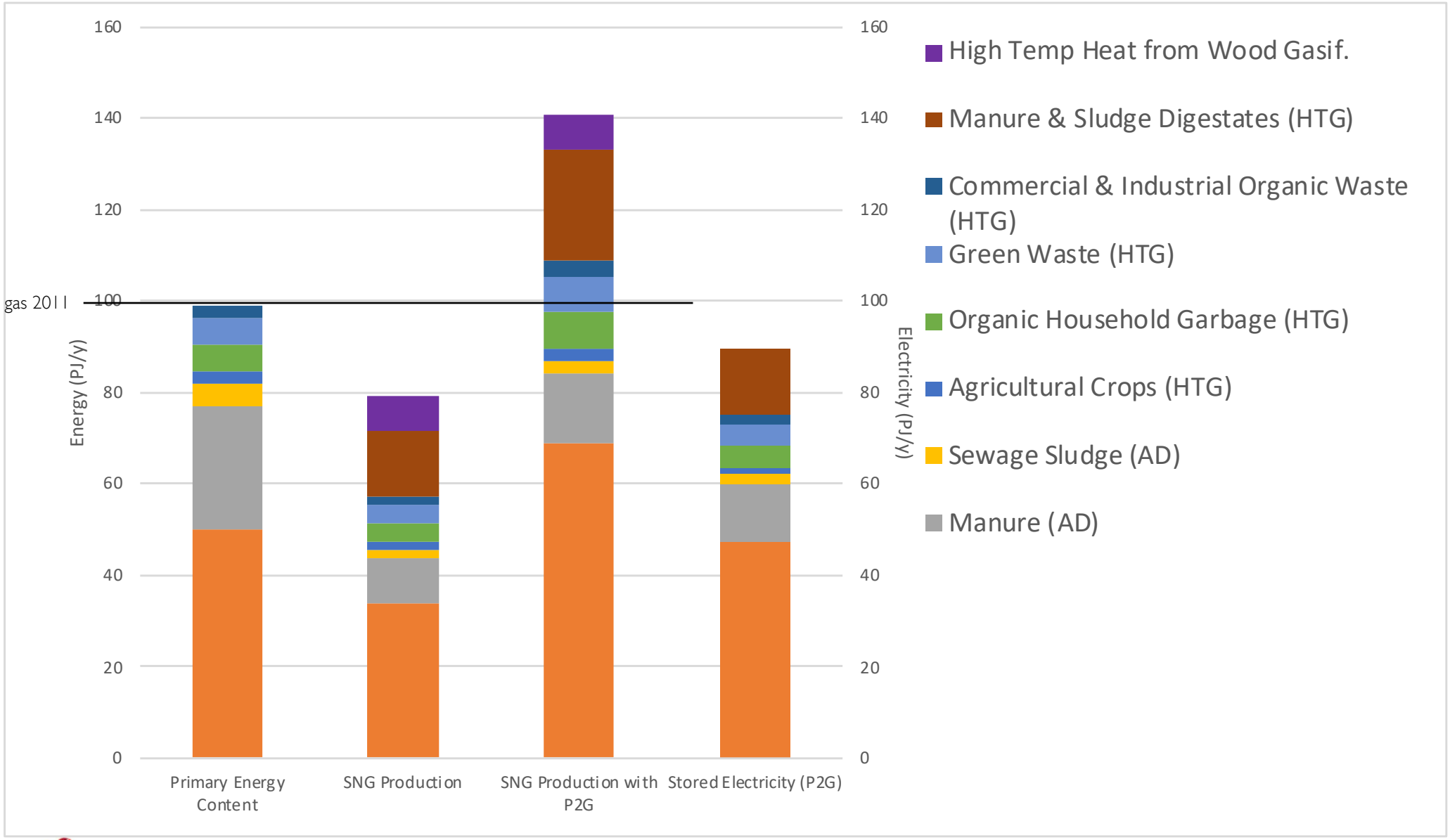
EPFL

COMBINER LES DEUX …

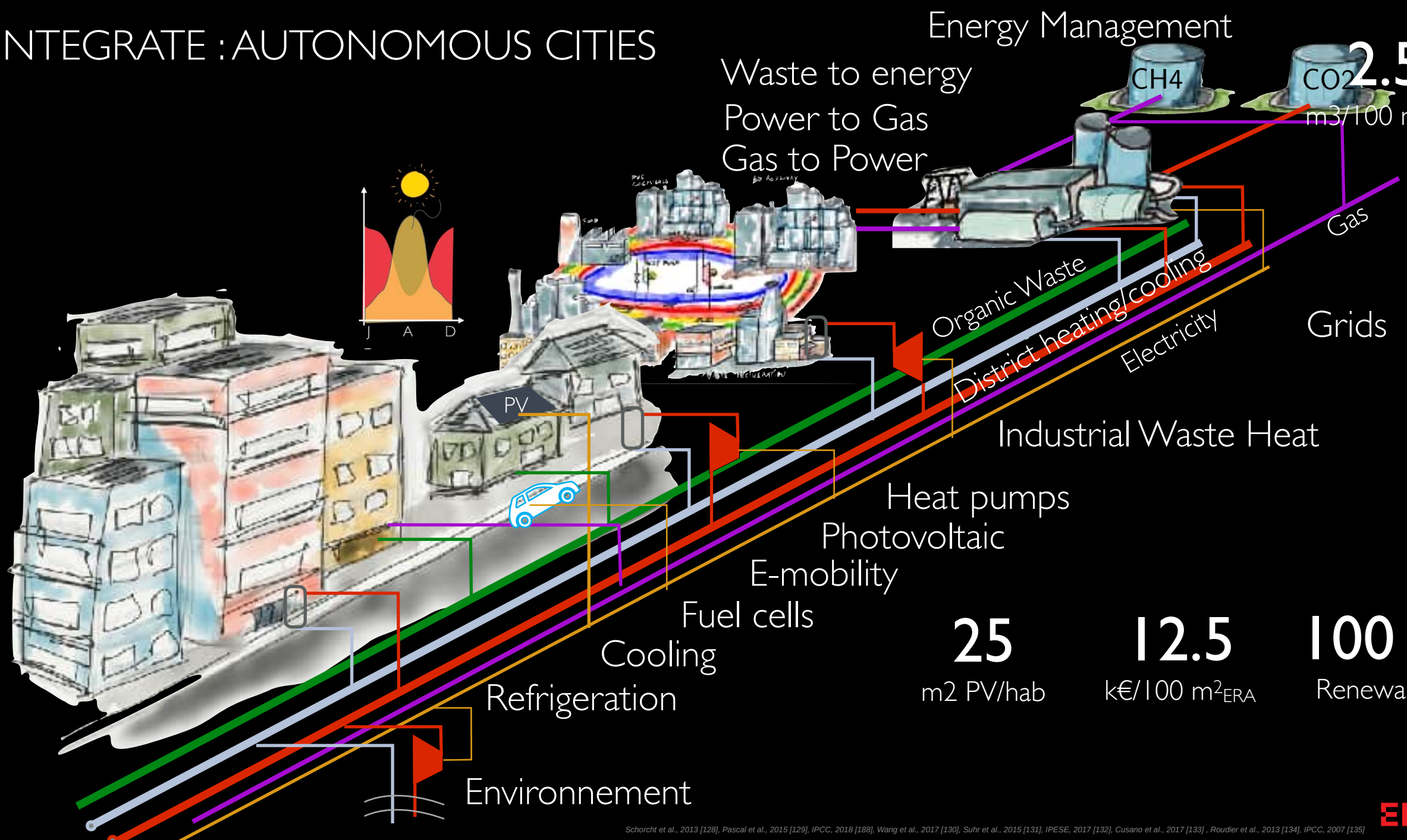


Gassner, Martin, and François Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." Energy 33.2 (2008): 189-198.

Potentiel biomasse et stockage de l'électricité



INTEGRATE : AUTONOMOUS CITIES



25
m2 PV/hab

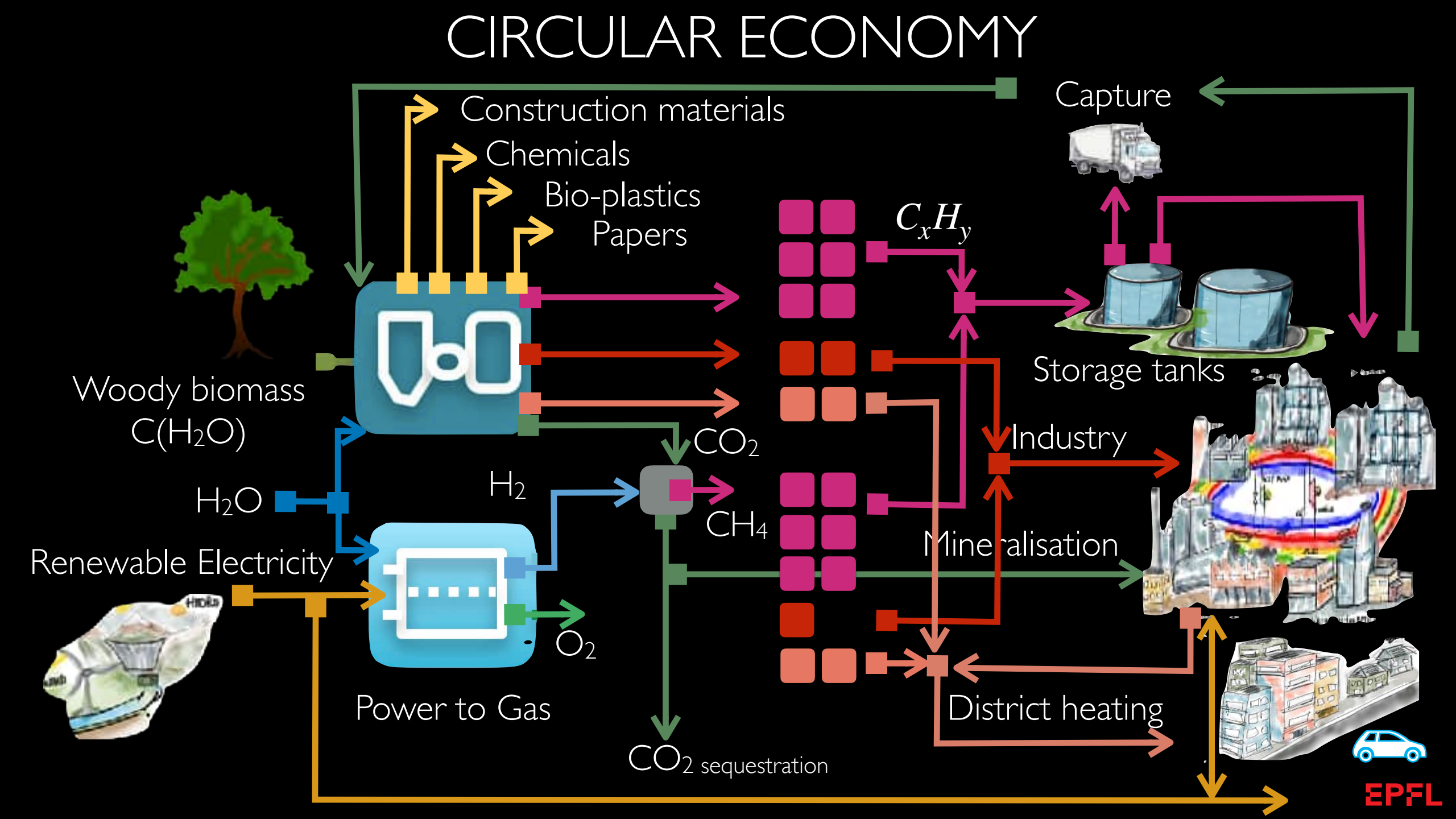
12.5
k€/100 m^2_{ERA}

100 %
Renewable

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]

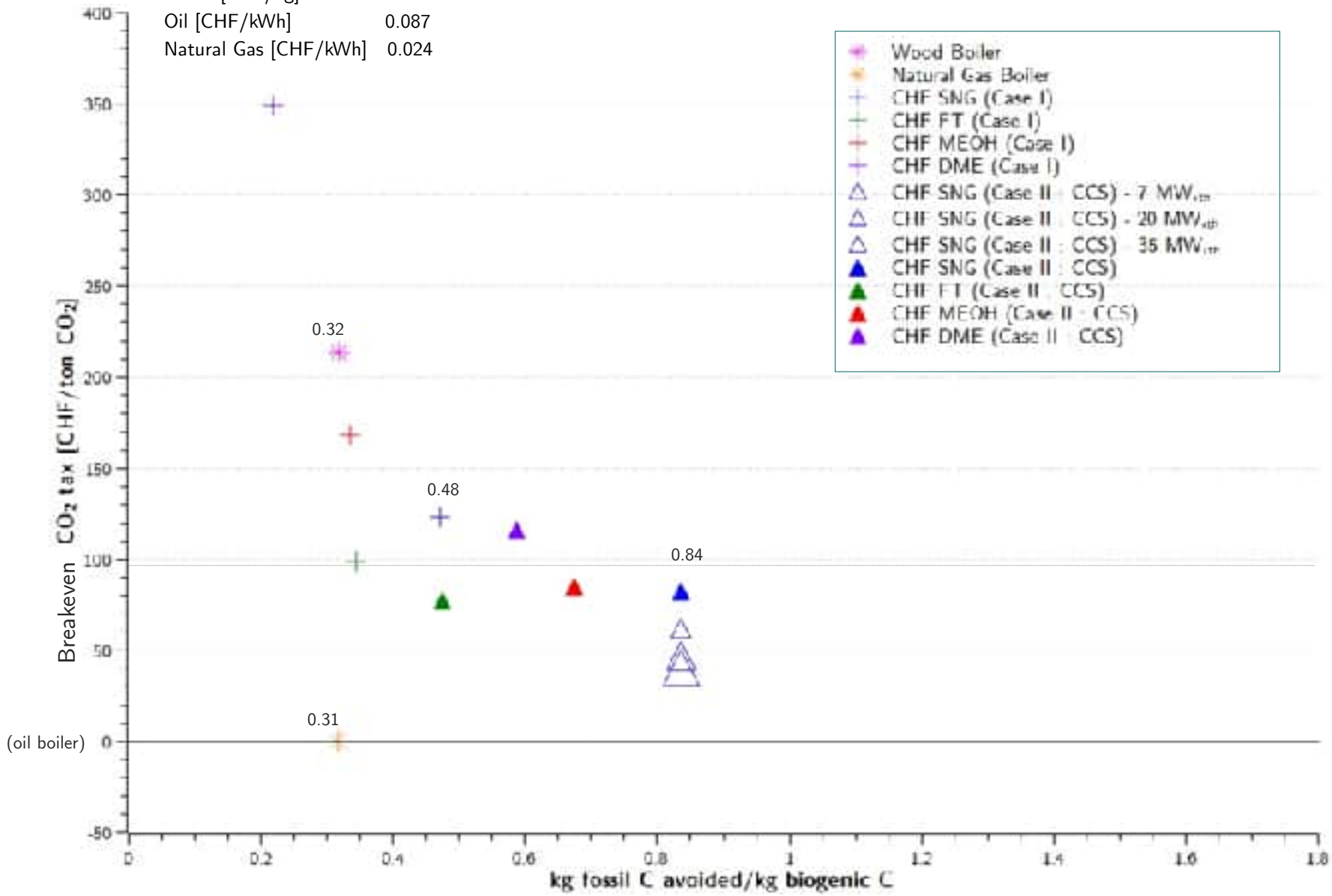
EPFL

CIRCULAR ECONOMY



Fossil carbon substitution per unit of biogenic carbon

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

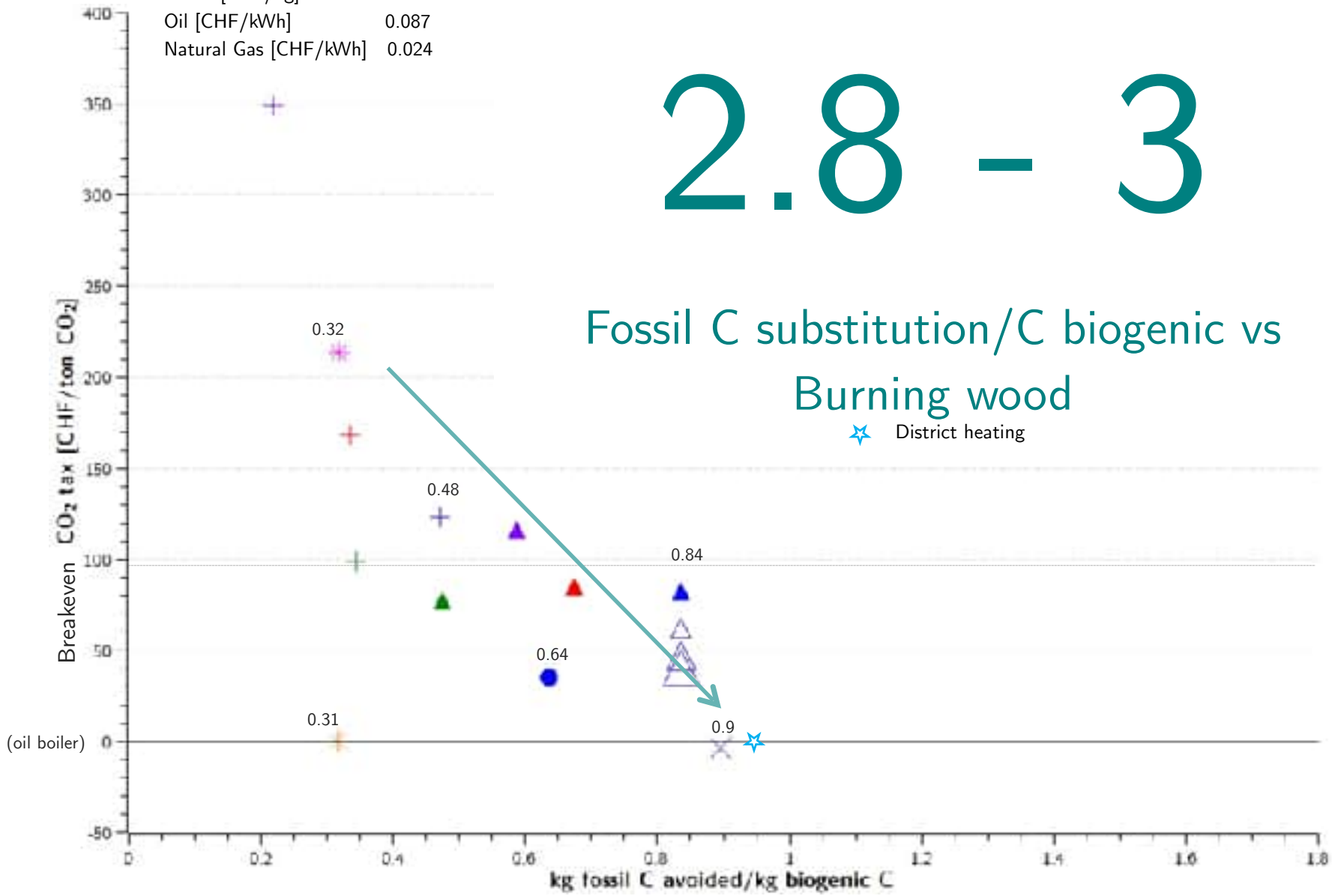


Fossil carbon substitution per unit of biogenic carbon

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

2.8 - 3

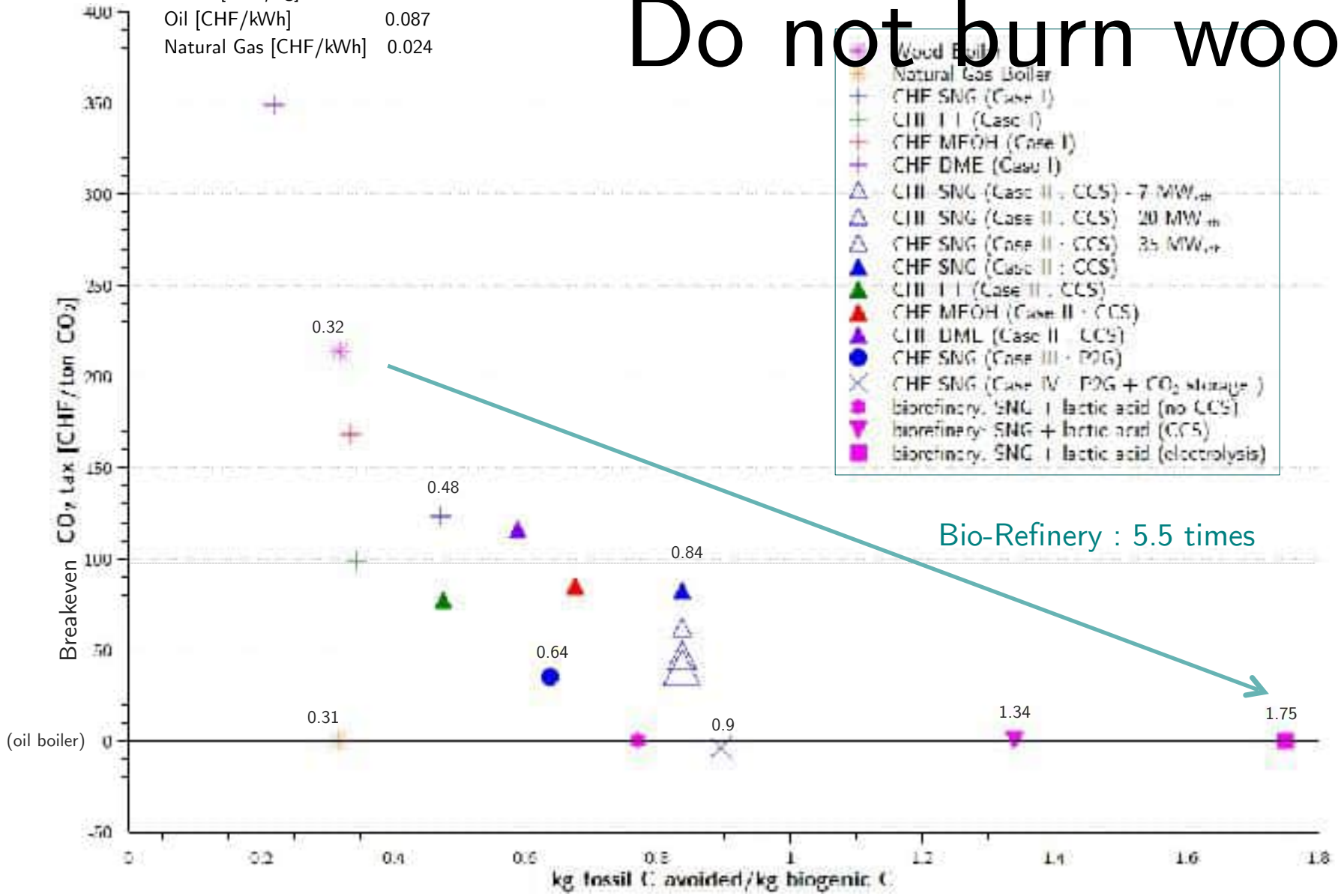
Fossil C substitution/C biogenic vs Burning wood



Fossil carbon substitution per unit of biogenic carbon

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

Do not burn wood !

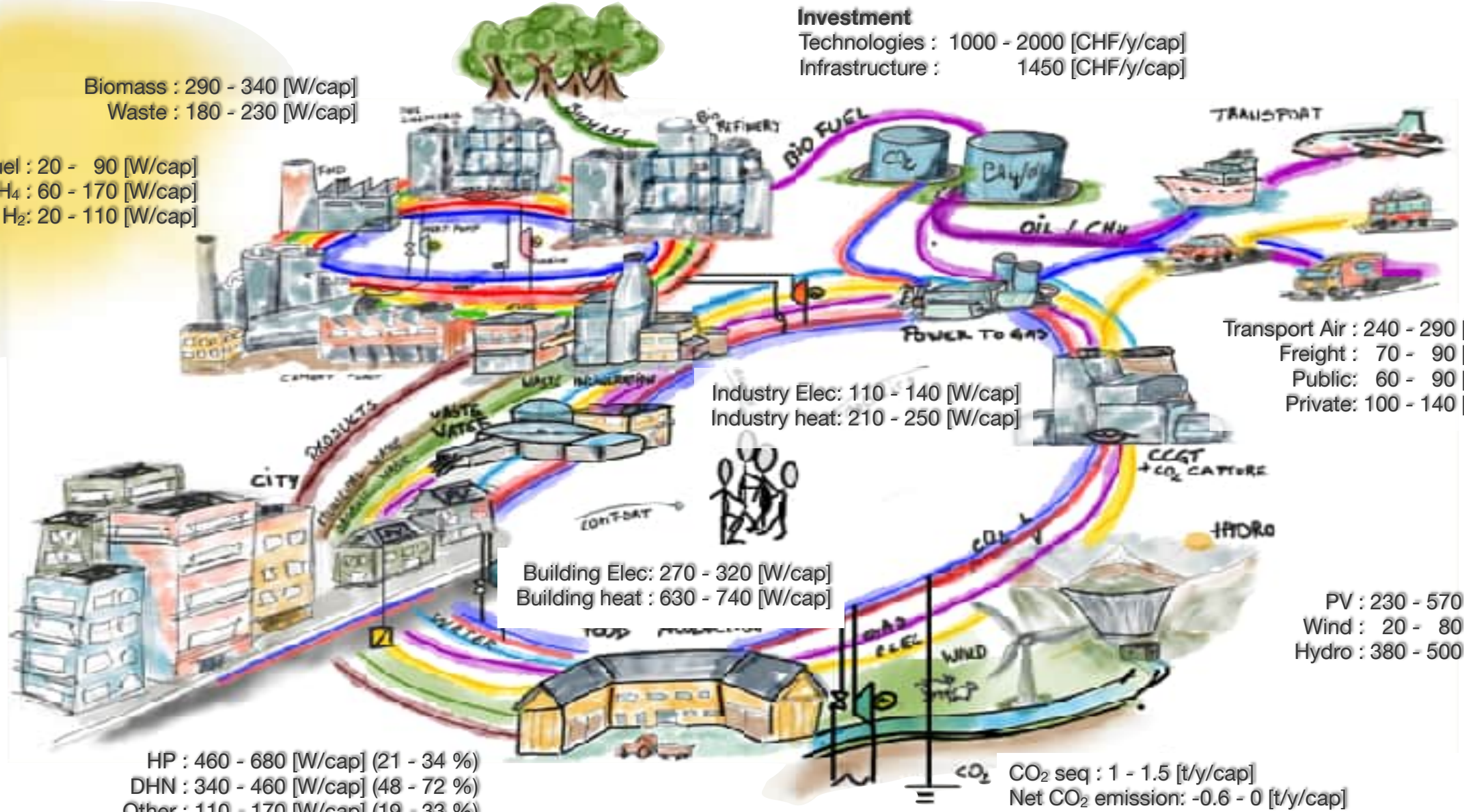


energyscope.ch : Systemic vision of independent and neutral Switzerland

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

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

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

Conclusions : net zero city

- **Renewable energy hubs**
  - Efficacité
  - Energie renouvelable
  - Autoconsommation
  - Intégration système
- **Réseaux de chaleur**
  - Anergie
  - Collecte de l'inefficacité
  - Symbiose système
  - Resources locales
  - Retrofit et evolution
- **Intégration système énergétique**
  - Gestion de l'énergie (multi-énergie)