Decarbonisation of the industry
An overview …

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Defossilizing industry : systemic analysis and decision support

Heat valorisation
Heat pumping
Waste heat to electricity

Efficiency
Materials recovery
Heat recovery

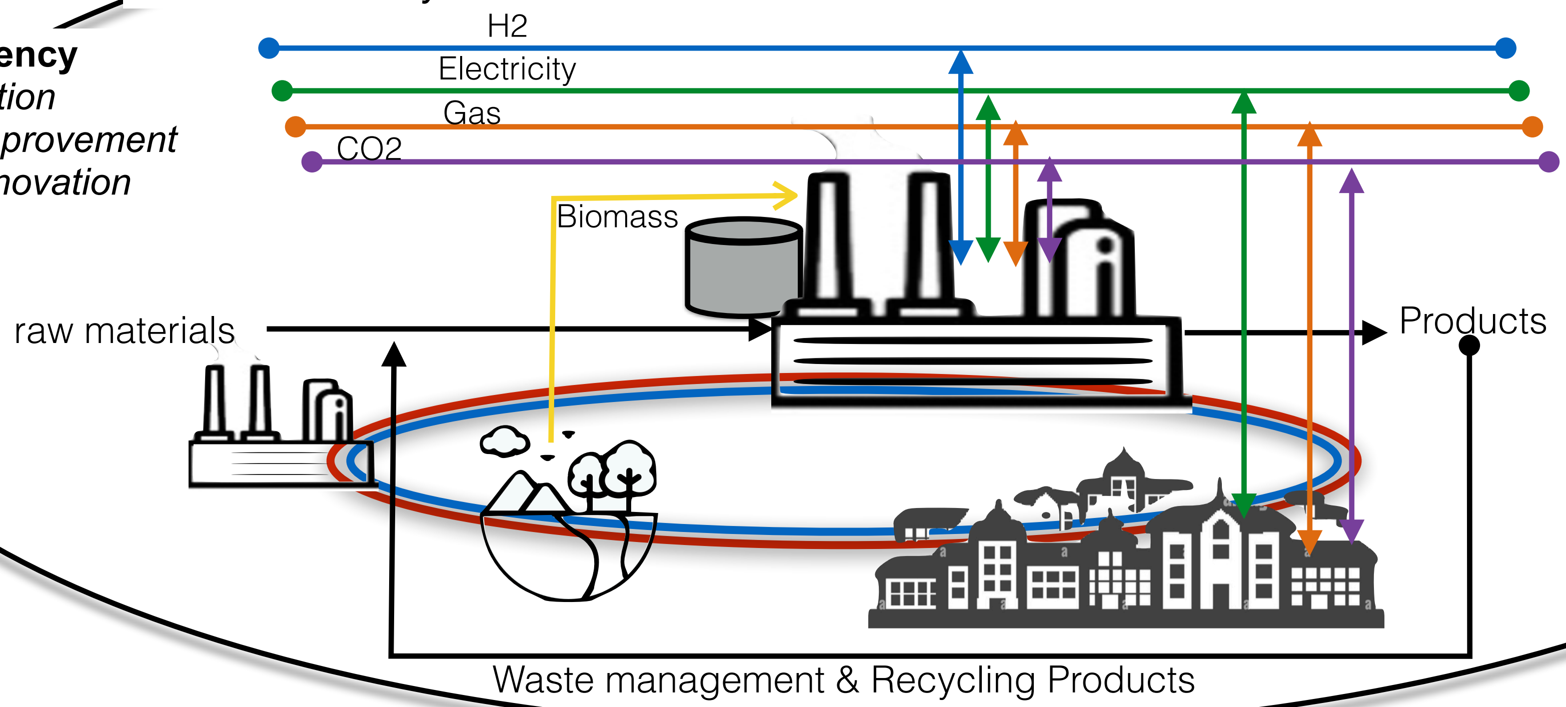
Energy conversion
Renewable energy sources
Combined Heat and Power
Combined Heat and Fuel

Technology efficiency
Optimal operation
Technology improvement
Technology innovation

CO2
Capture, reuse, sequestrate

Energy system integration
Energy grids
Heat and electricity storage
Hydrogen
Power2Tanks2Power

Energy Audits
Energy Drivers
Efficiency KPI
Monitoring



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

ESG - T

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

Energy efficiency : understanding the use of energy

Audit : flows & energy

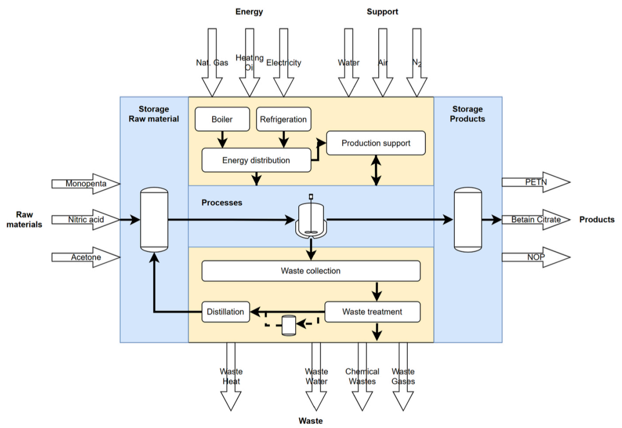


FIGURE 2.1—Mass and energy flows of the main units

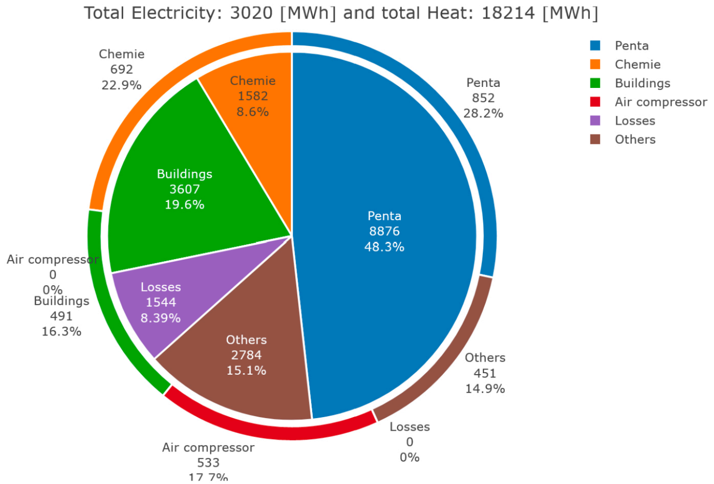


FIGURE 2.4—Energy consumption by type and consumer

Recovery

Heat recovery targeting

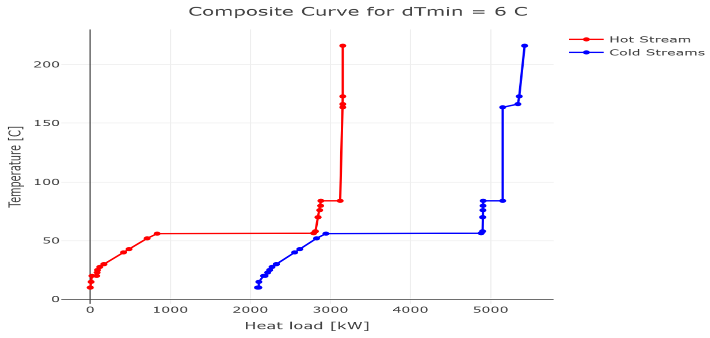
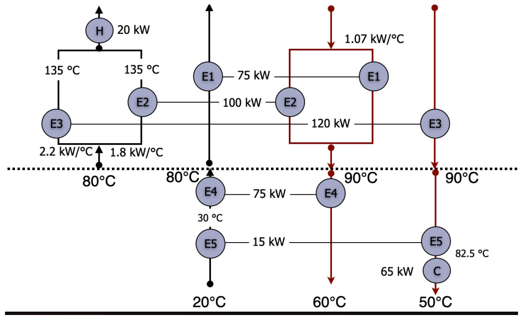


FIGURE 6.2—Composite curve for MER

Heat exchangers



Conversion

- Heat pumps
- MVR
- Cogeneration
- Waste - Water

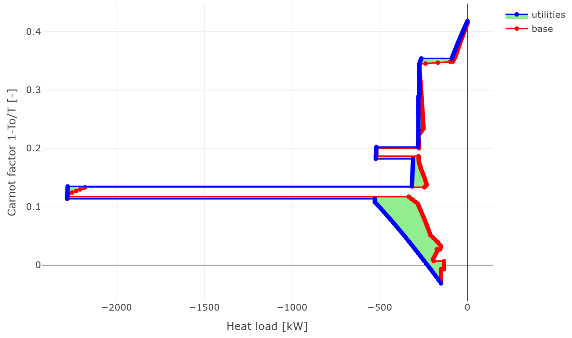


FIGURE 9.5—Carnot Composite Curve for optimized utilities

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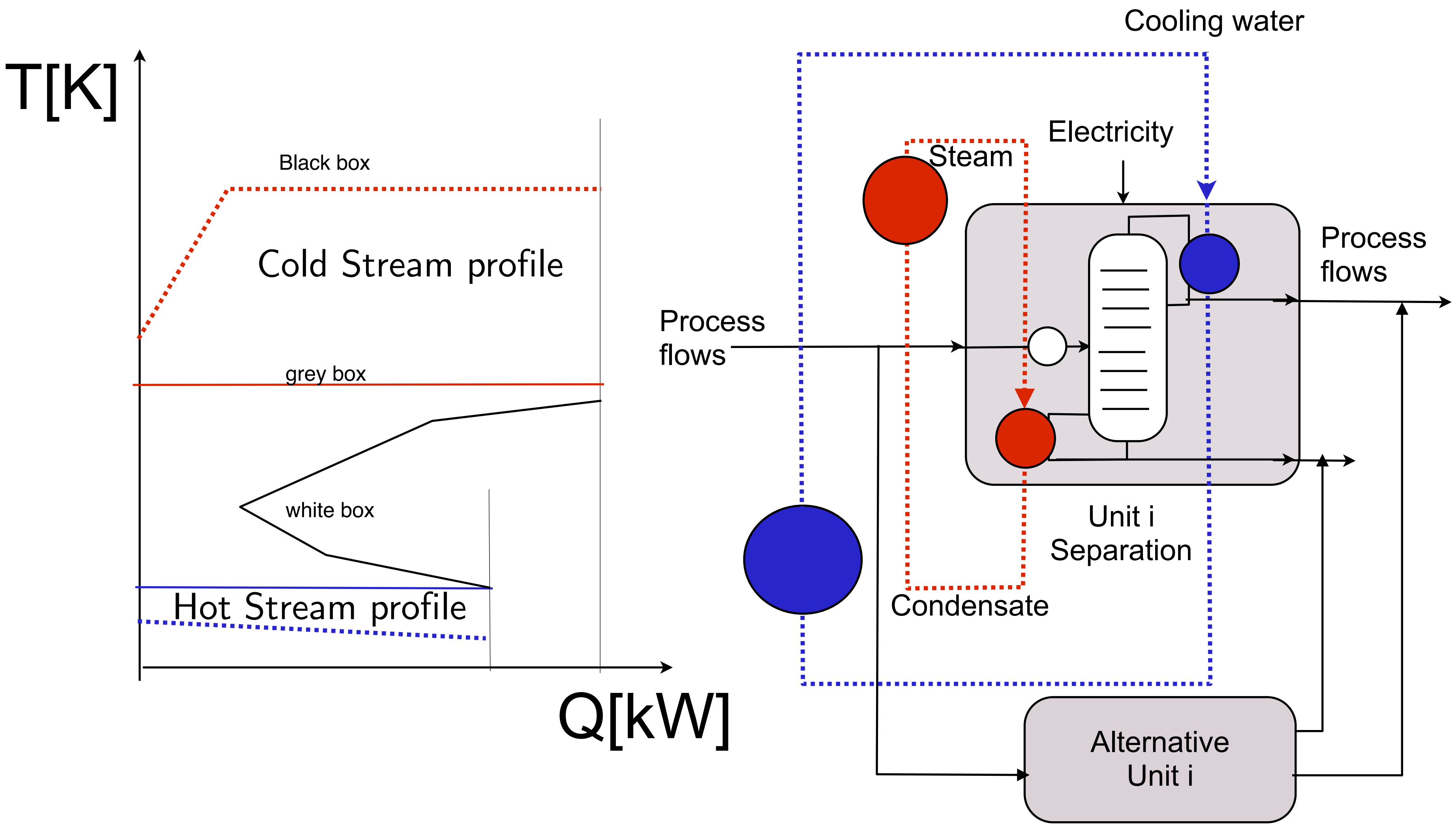
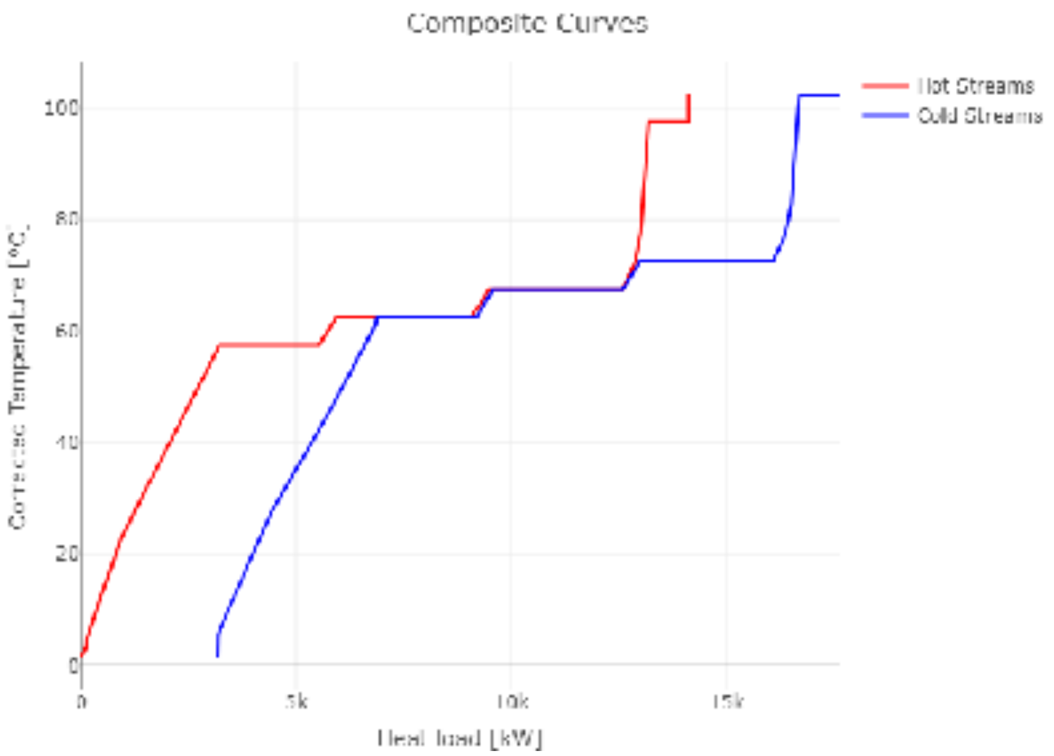
Heat transfer Interfaces

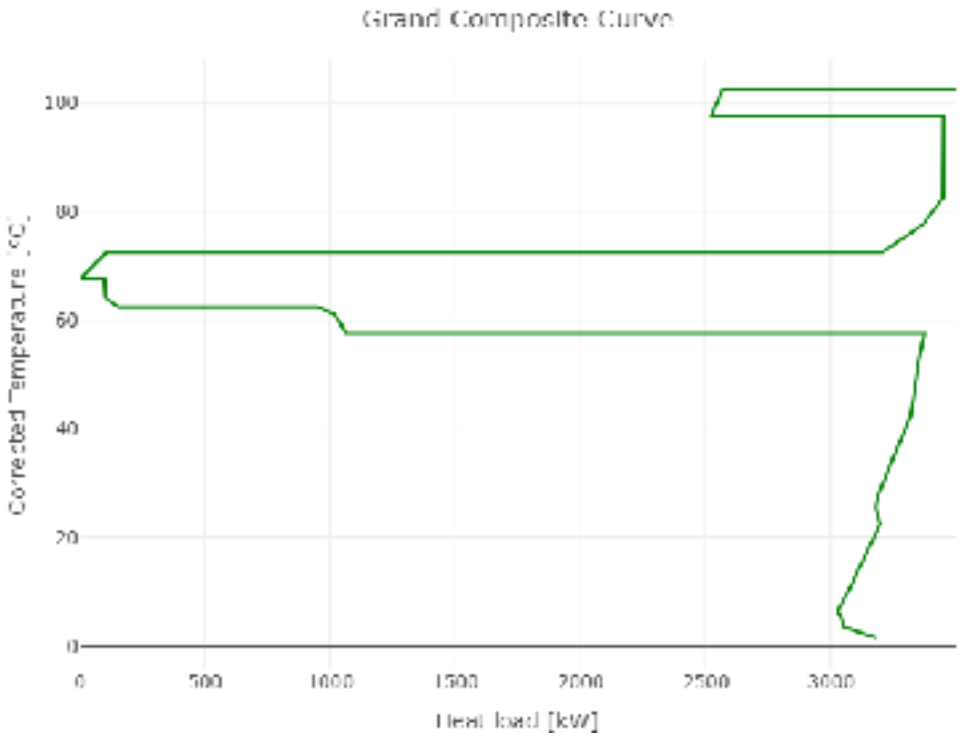
- Energetics of unit operations



Heat recovery and heat cascade

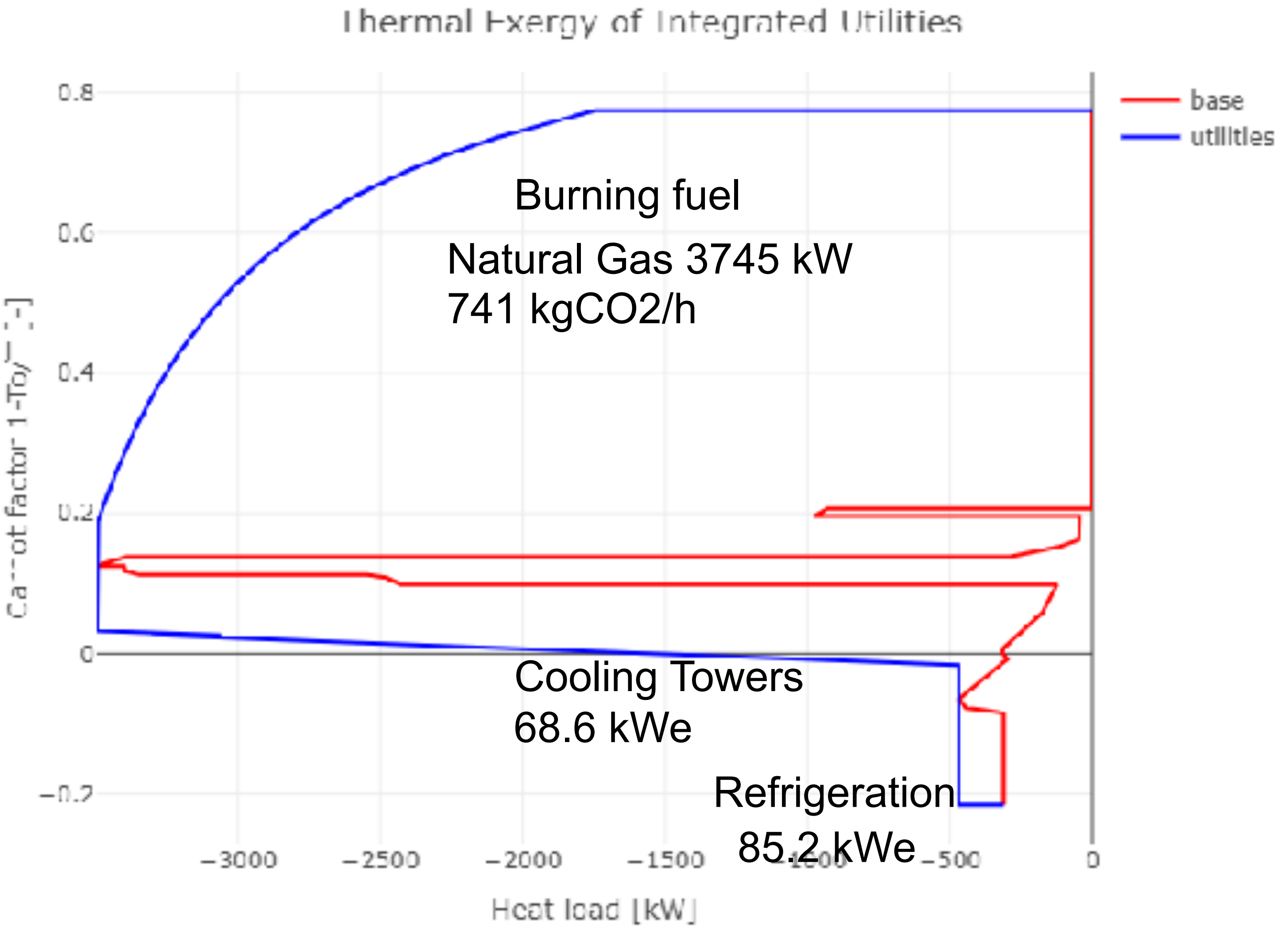
- Corrected temperature $T^* = T +/- (\Delta T_{min}/2)$
- Graphical plot of the heat cascade : [R_r, T^*_r] r=1,n_r





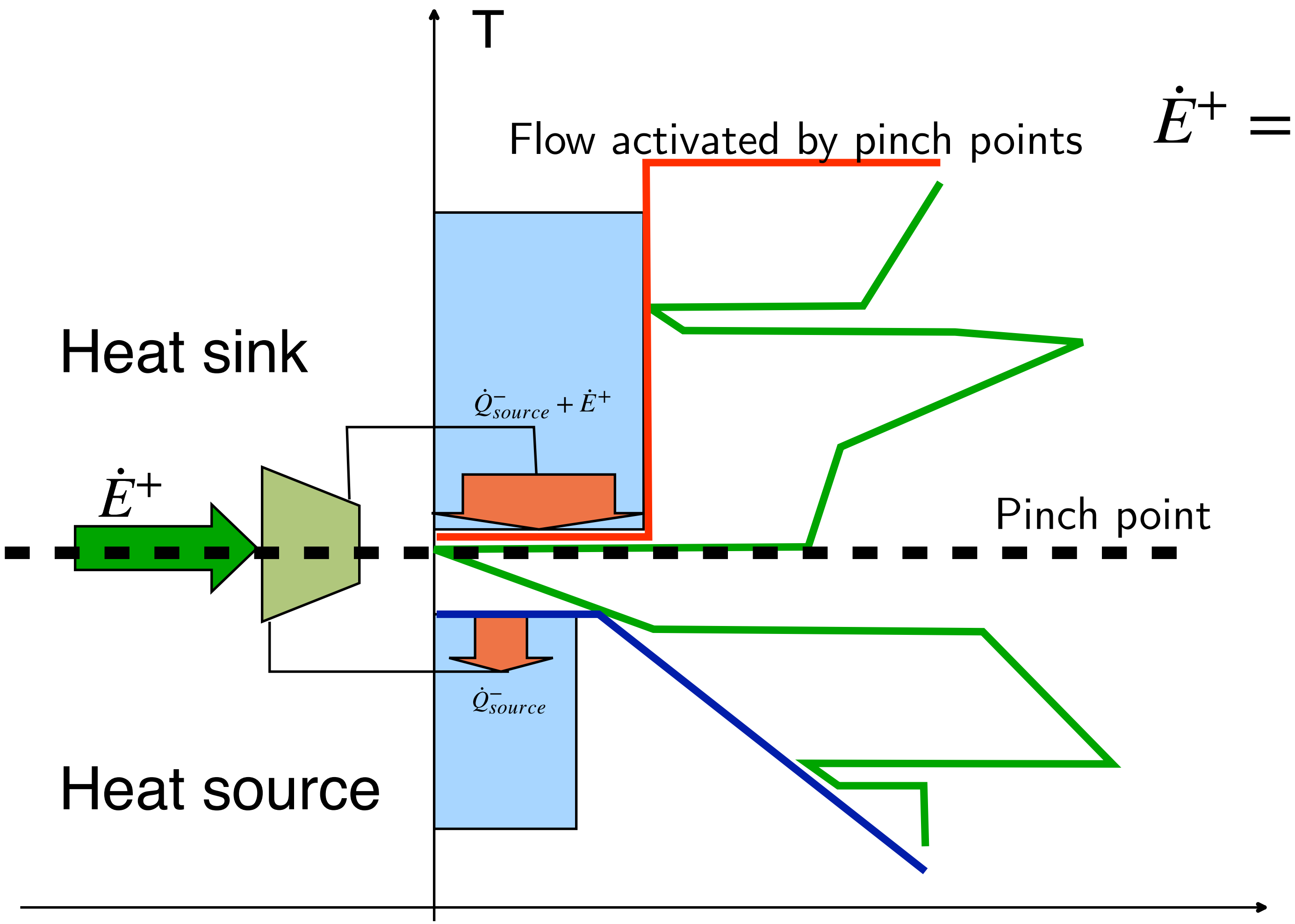
The Grand composite is the heat cascade representation in the corrected temperature domain. it represents the flow of energy in the system from higher temperatures to lower temperature. Above the pinch point is also represents the heat-temperature profile of the heat to be supplied to the system and below the pinch it represents the heat-temperature profile of the heat available in the process and to be removed from the system.

Closing the energy balance : energy conversion integration

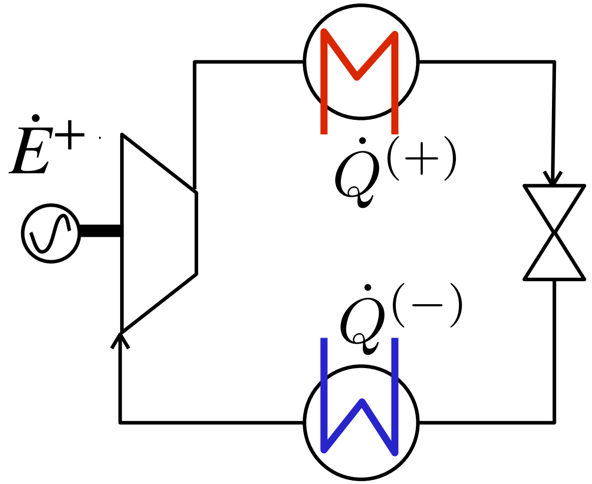


Integrating heat pumps from heat source to heat sink

$$\text{Savings Hot Utility} = c^+_{heat} \cdot (\dot{Q}^-_{source} + \dot{E}^+) - c^+_{elec} \cdot \dot{E}^+$$



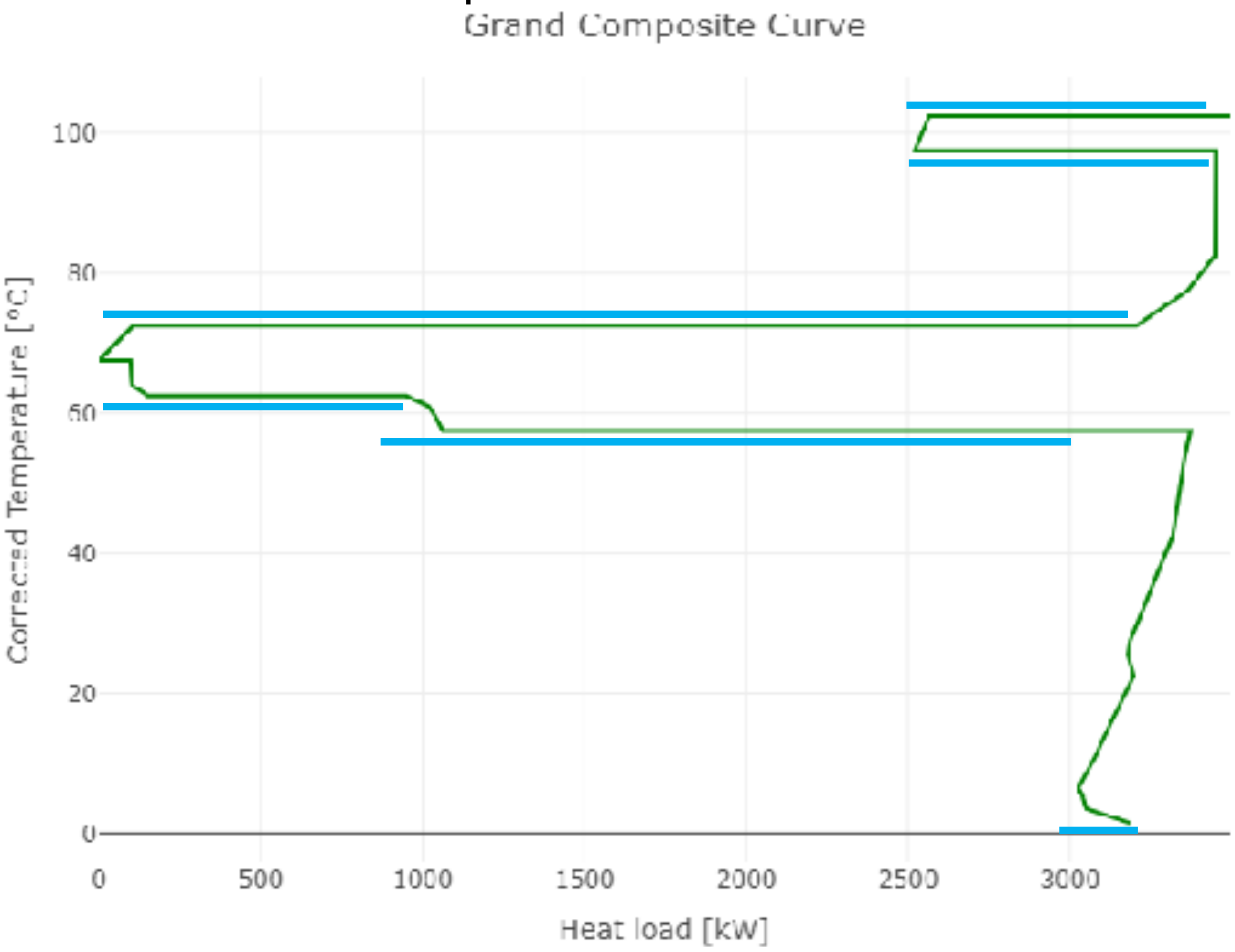
$$\dot{E}^+ = \dot{Q}^+_{sink} \cdot \frac{1}{\eta_{Carnot}} \cdot \frac{\tilde{T}_{sink} - \tilde{T}_{source}}{\tilde{T}_{sink}}$$

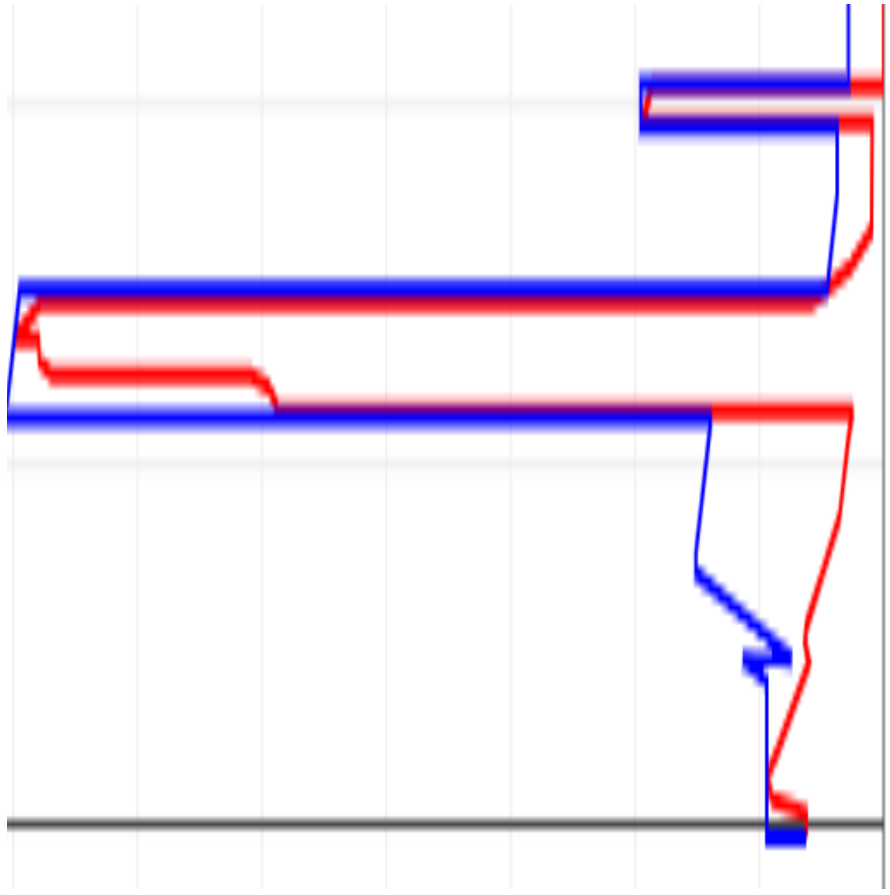


$$\text{Savings Cold Utility} = c^+_{cold} \cdot \dot{Q}^-_{source}$$

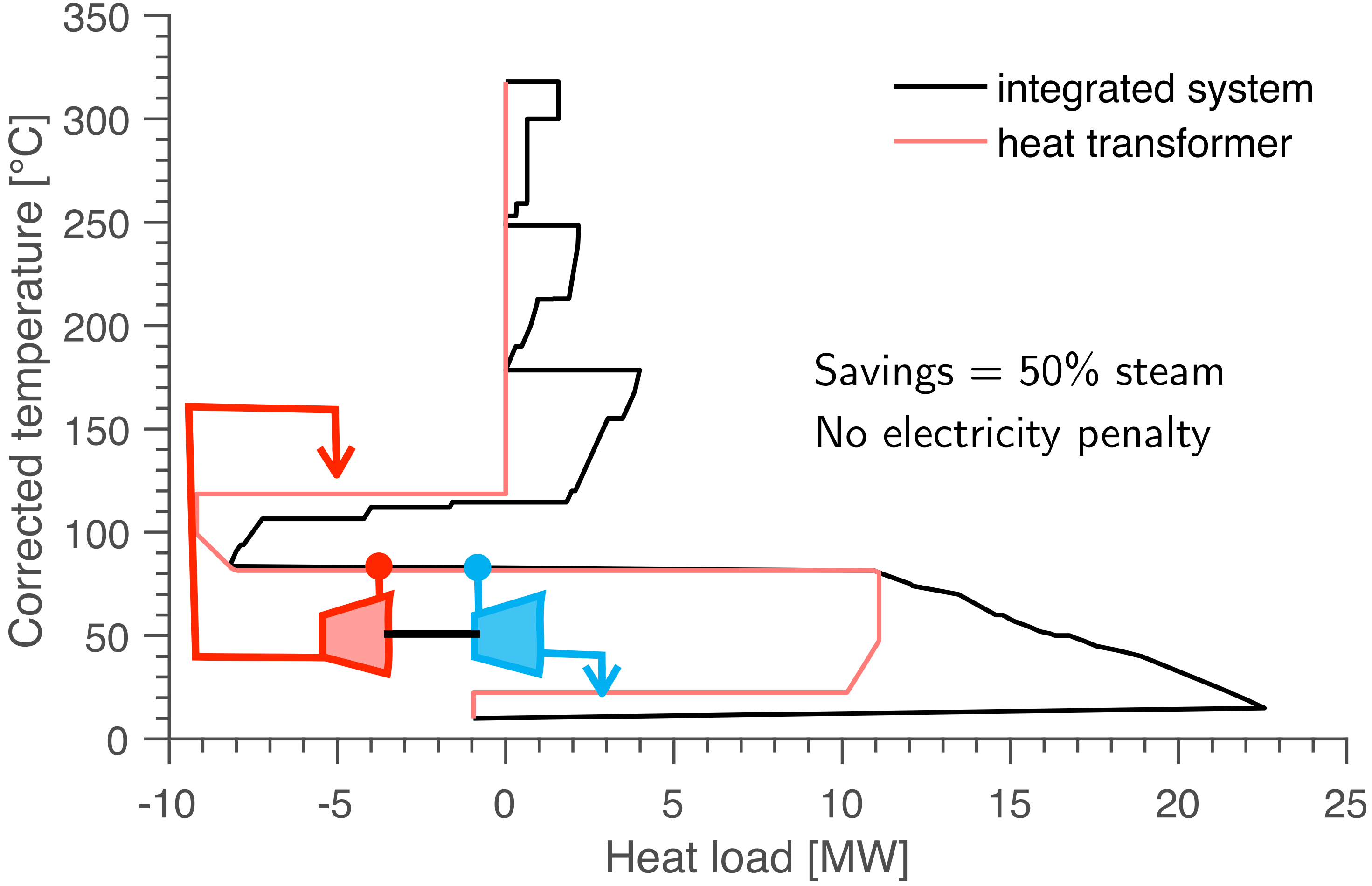
Identify temperature levels

Temperature levels → Multi-stage heat pumps





Heat pumps and waste heat valorisation



Heat pump + ORC

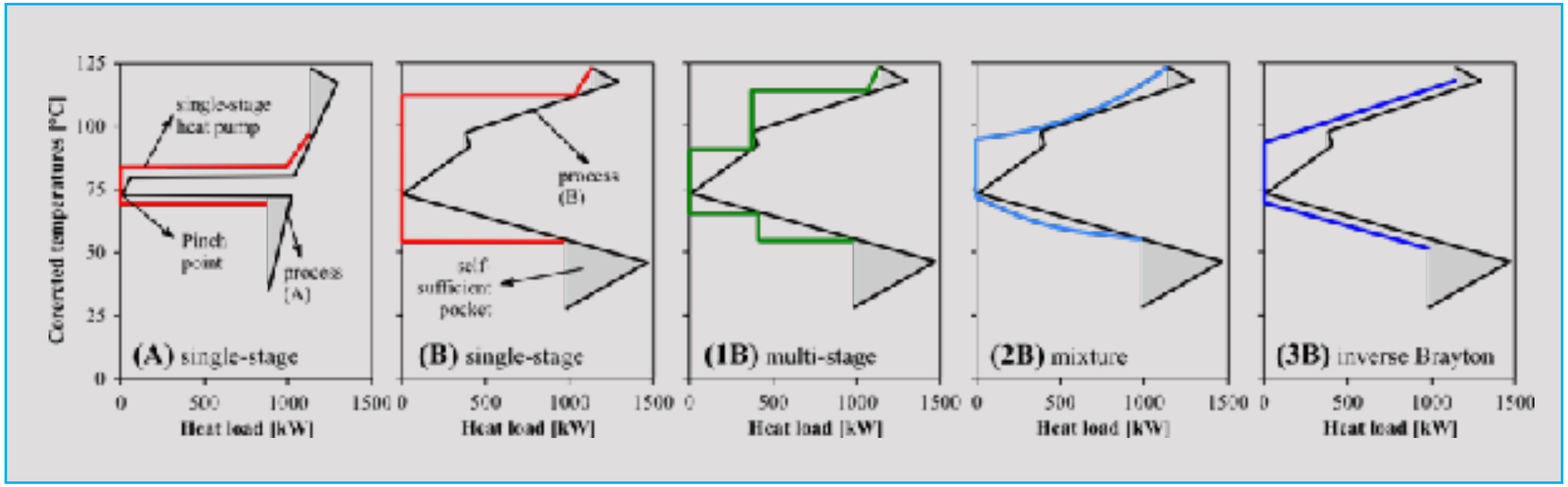
- Superstructure
- Fluids
- Turbines
- Optimisation

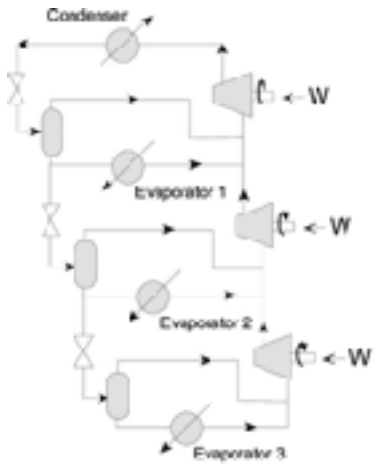
Kermani et al., Applied Energy, 2019

Heat pump integration : problem statement

A.S. Wallerand 2018. EPFL Thesis

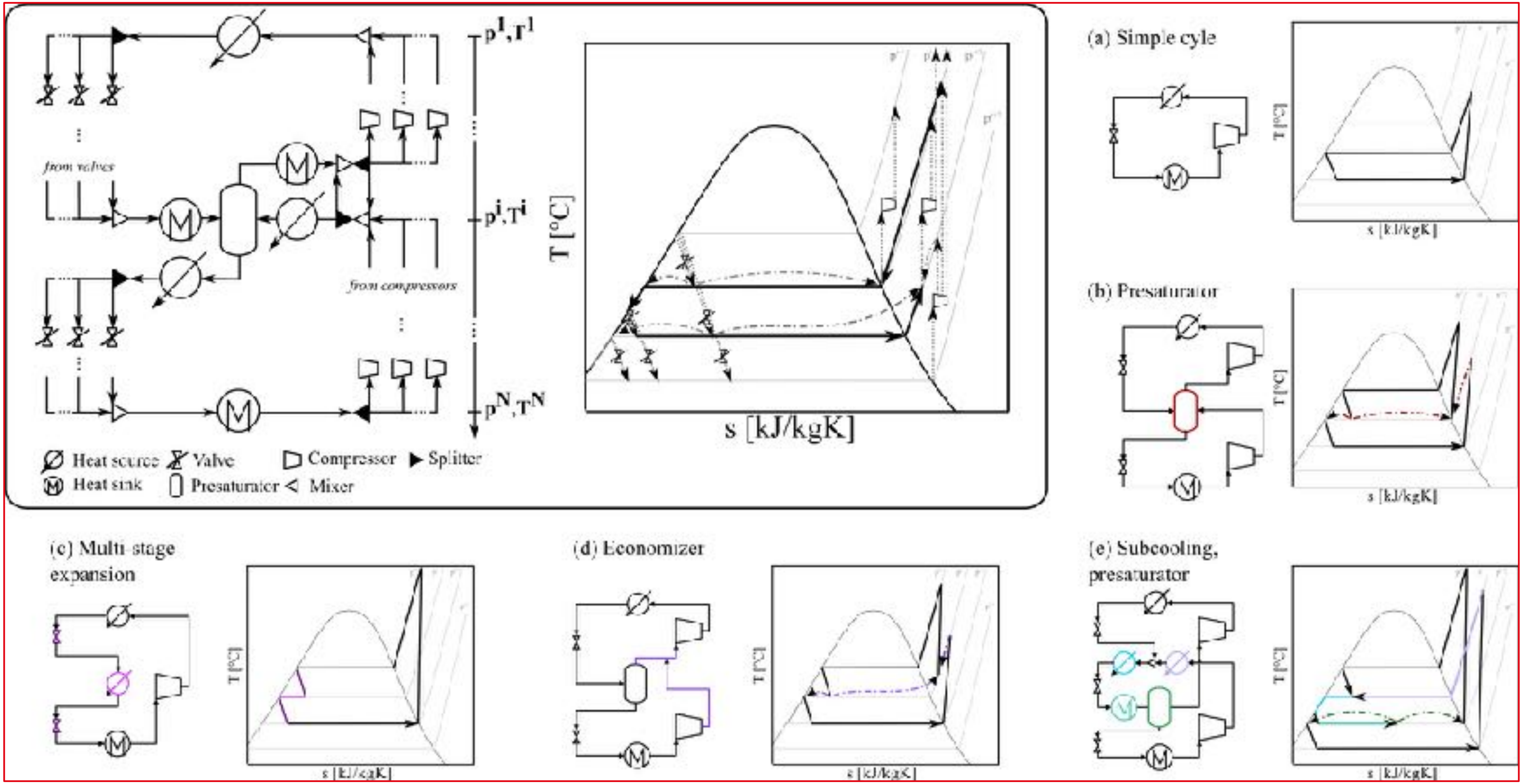
- Heat pump type ?
- Working fluid ?
- Operating conditions ?
- Multi-stage compression / expansion ?
- Subcooling/preheating ?
- Flash drums ?
- Compressor types ?





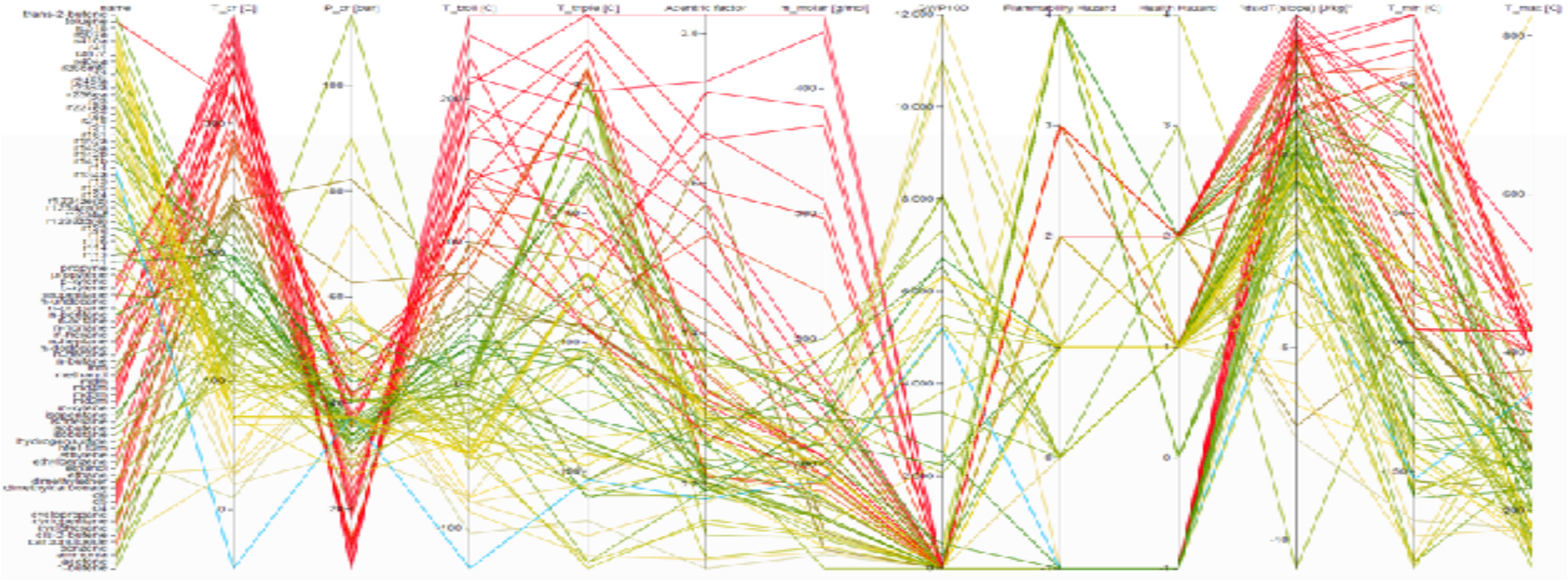
All adapted from: Del Nogal et al. (2008)

Systematic approach: superstructure model



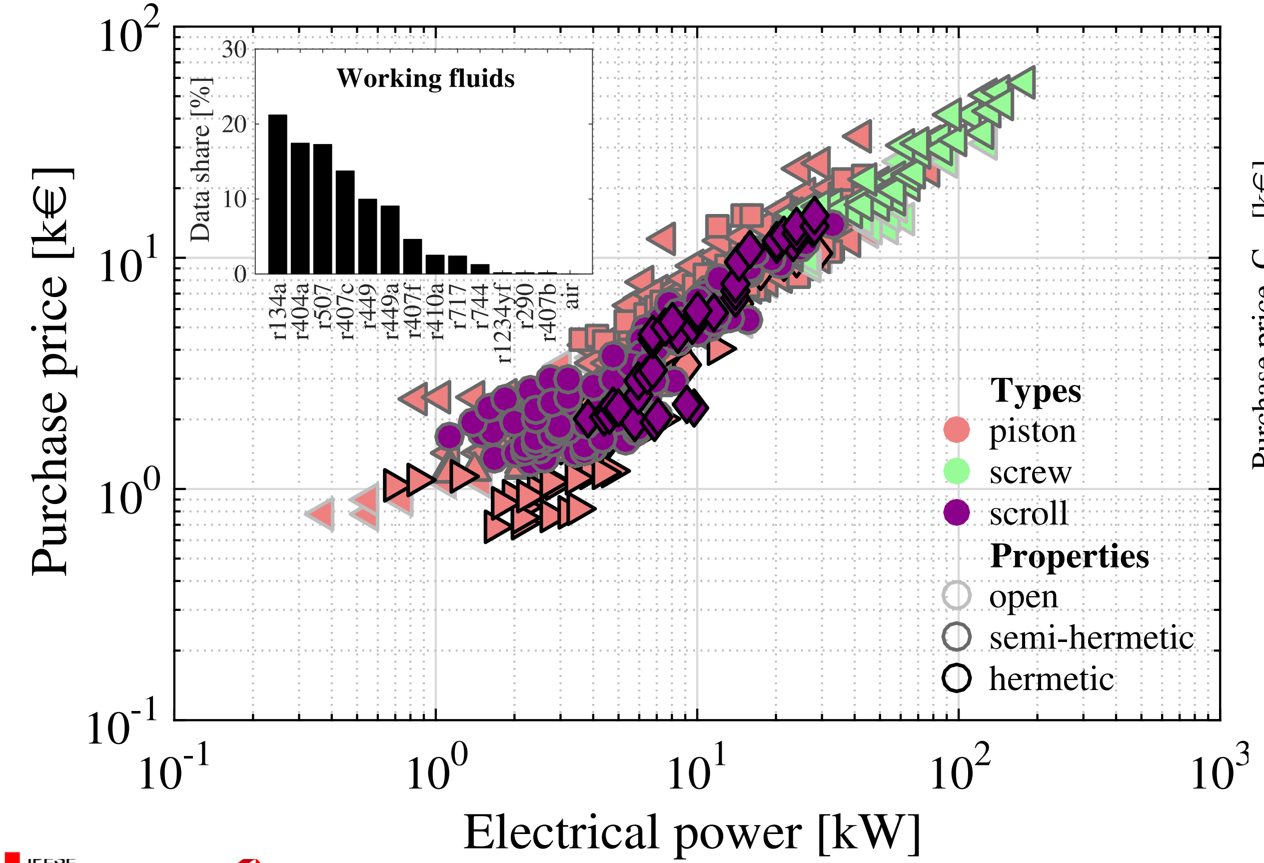
Fluid data base

working fluids and their thermo-physical properties

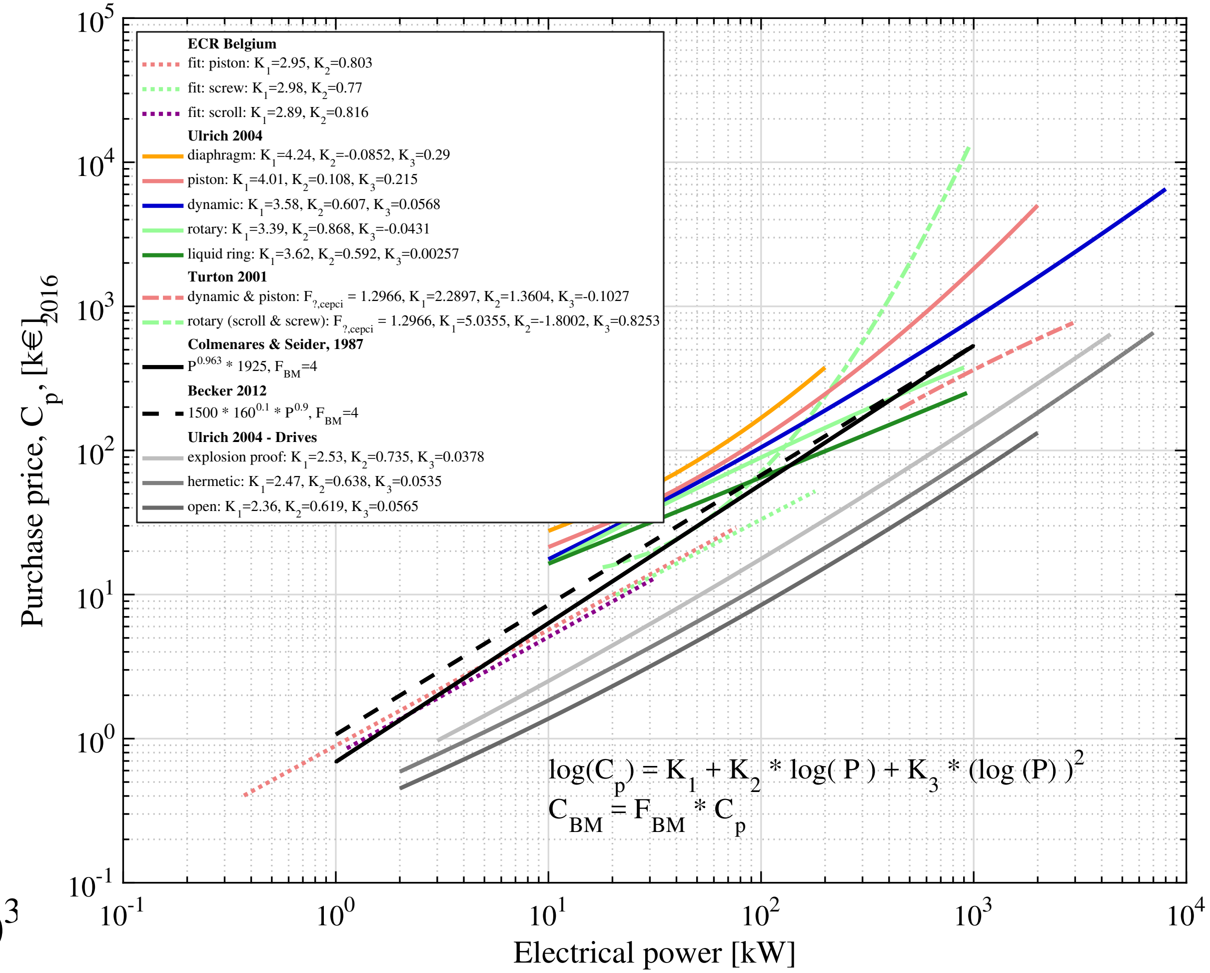


Technology data base : compressors

Figure 2: Tree diagram of compressor types, adapted from Wikipedia [8] with inspiration from Favrat [9]. Novel technologies are marked with asterisk (*).



Cost function review



[1] A.Wallerand, BFE 2019
[2] Kantor et al., ECOS proceedings, 2018

Optimisation to select and calculate flows in the system

$$\min_{R_r, y_w, f_w, E^+, E^-} \left(\sum_{w=1}^{n_w} C2_w f_w + C_{el+} E^+ - C_{el-} E^- \right) * t$$

Operating cost

$$+ \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau} \left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w) \right)$$

Fixed maintenance

Investment

Subject to : Heat cascade constraints

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, ..., n_r$$

Feasibility

$$R_r \geq 0 \qquad \forall r = 1, ..., n_r; R_{n_r+1} = 0; R_1 = 0 \qquad E^+ \geq 0; E^- \geq 0$$

Electricity consumption

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

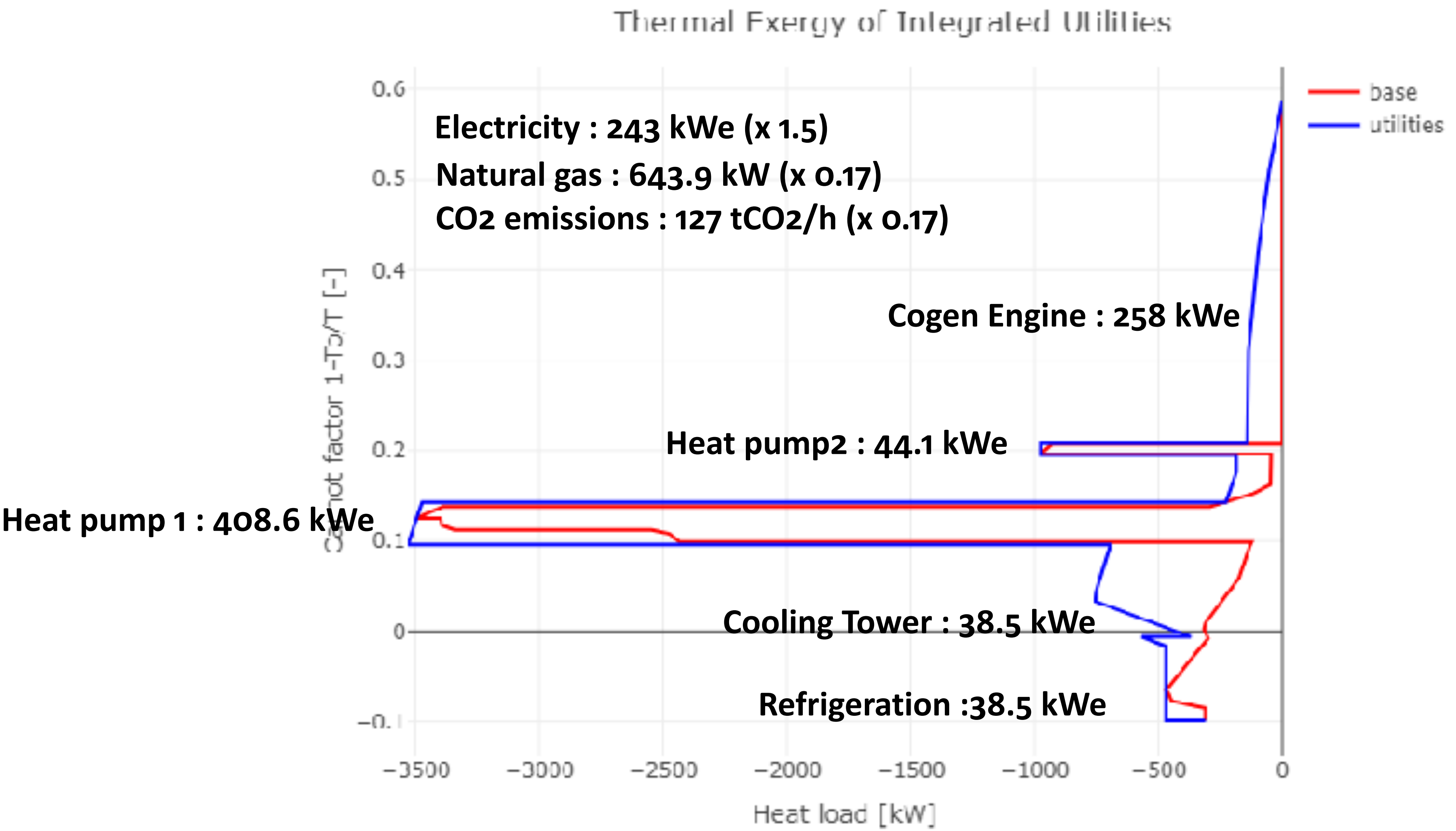
Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0, 1\}$$

System integration results



Carnot Integrated Composite Curve before fluid selection

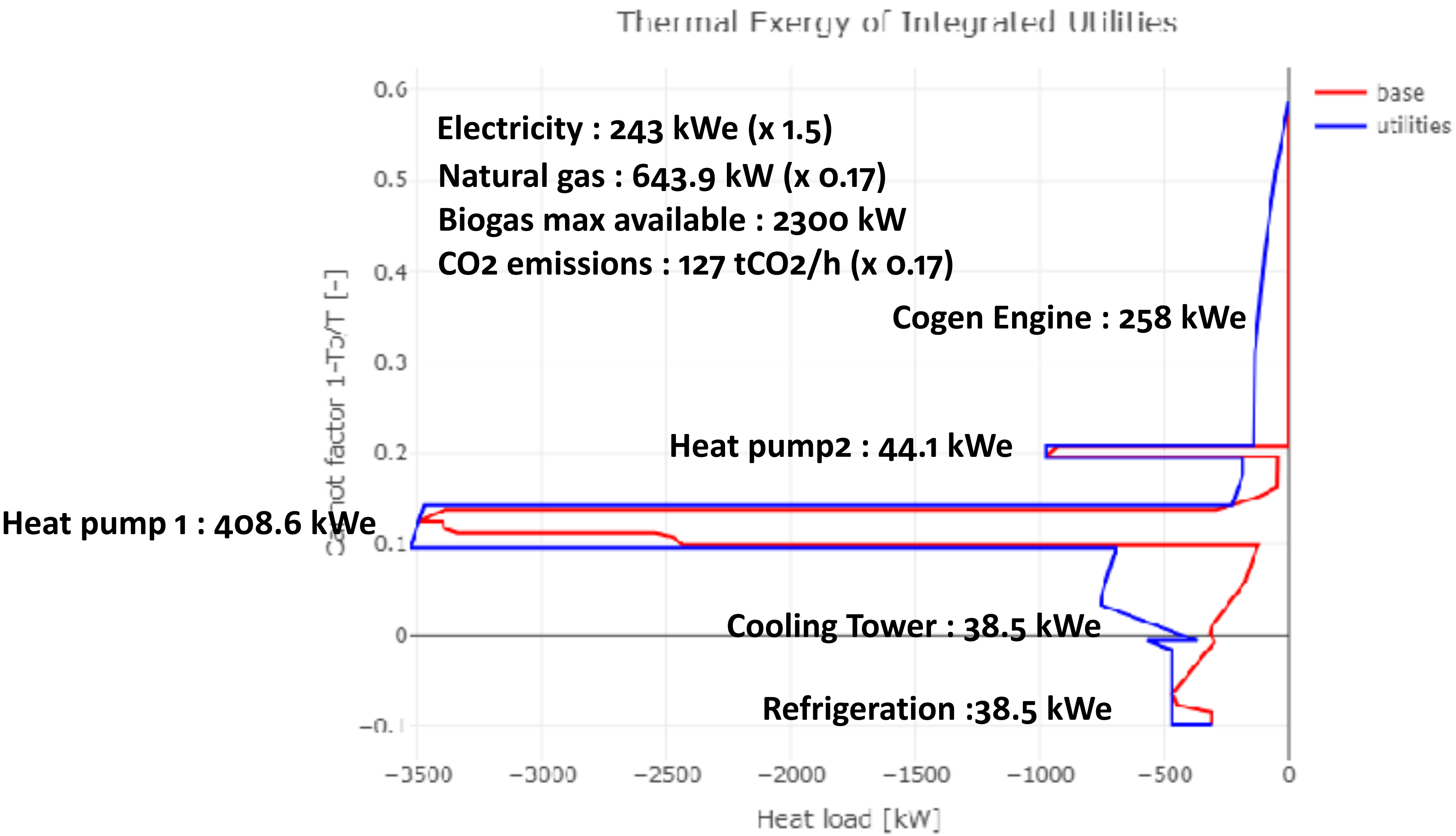
Energy saving potential through heat pumps in Swiss industry

Method[1]: based on *sector blueprints*[2]
- Heat pump design for *sector blueprints*
- Preliminary results scaling based percentage that sector profile covers of the sector

Sector	Maximum energy recovery						Additional direct energy efficiency measures						Total					
	Electricity			*Primary Thermal*			*Electricity*			*Primary Thermal*			*Electricity*			*Primary Thermal*		
	Opt.	*Techn.*	*Cons.*	*Opt.*	*Techn.*	*Cons.*	*Opt.*	*Techn.*	*Cons.*	*Opt.*	*Techn.*	*Cons.*	*Opt.*	*Techn.*	*Cons.*	*Opt.*	*Techn.*	*Cons.*
Food and beverage	*9%*	*8%*	*1%*	*37%*	*30%*	*10%*	*3%*	*5%*	*1%*	*32%*	*30%*	*10%*	*12%*	*13%*	*1%*	*69%*	*59%*	*16%*
Pulp and paper	*N/A*			*28%*	*22%*	*21%*	*N/A*			*N/A*			*N/A*			*28%*	*22%*	*21%*
Chemicals	*0%*			*69%*	*41%*	*25%*	*N/A*			*N/A*			*0%*			*69%*	*41%*	*25%*
Cement	*0%*			*0%*			*50%*	*15%*	*12%*	*0%*			*50%*	*15%*	*12%*	*0%*		
Steel	*0%*			*87%*	*9%*	*8%*	*23%*	*2%*	*2%*	*0%*			*23%*	*2%*	*2%*	*87%*	*9%*	*8%*
Non-ferrous metals	*0%*			*52%*	*5%*	*2%*	*N/A*			*N/A*			*N/A*			*52%*	*5%*	*2%*
Total industry (weighted)	**1%**	**1%**	**0%**	**36%**	**19%**	**11%**	**27%**	**6%**	**1%**	**5%**	**5%**	**1%**	**28%**	**7%**	**1%**	**42%**	**24%**	**12%**

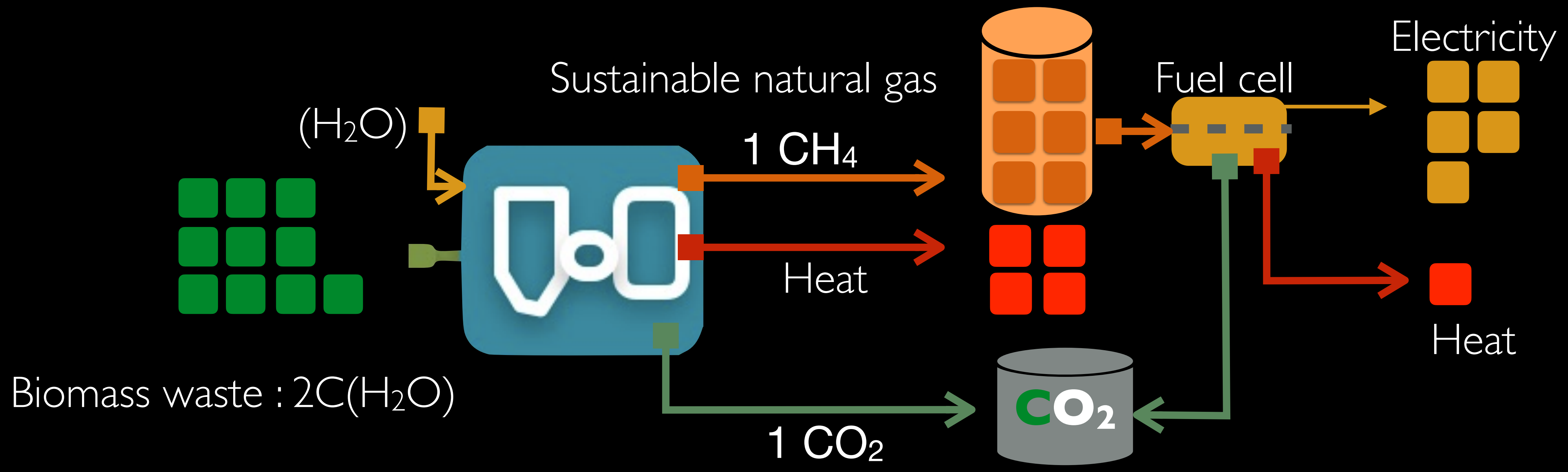
[1] Wallerand et al., 2019, in preparation
[2] Kantor et al., ECOS proceedings, 2018

System integration results



Carnot Integrated Composite Curve before fluid selection

BIOMASS CONVERSION ?



50% : Biomethanisation

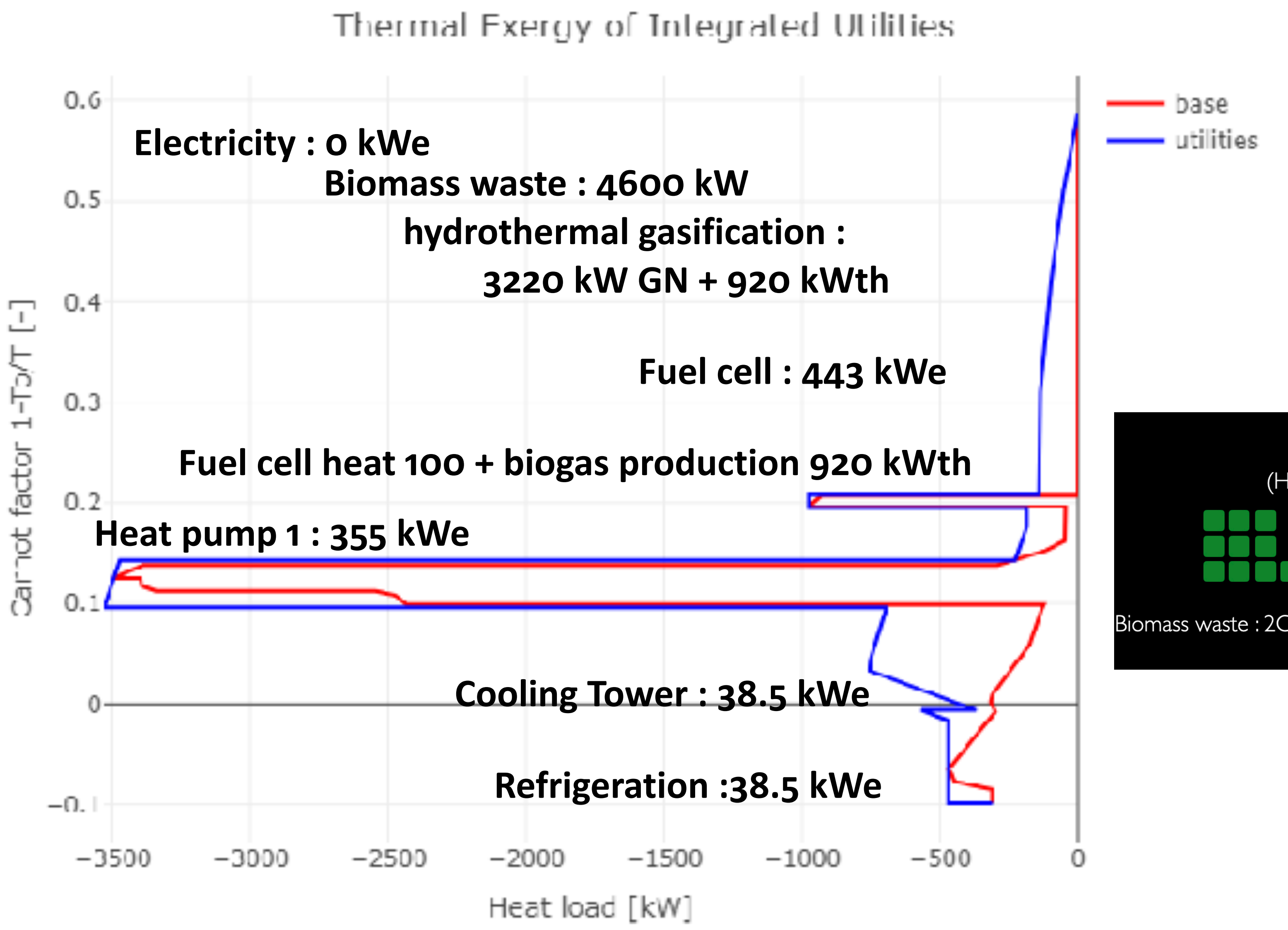
70% : Hydrothermal gasification (http://trea-tech.com)

70% : Synthetic Natural Gas

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

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

System integration Waste valorisation + Fuel cell + Biogaz export



Electricity : 0 kWe

Biomass waste : 4600 kW

hydrothermal gasification :

3220 kW GN + 920 kWth

Fuel cell : 443 kWe

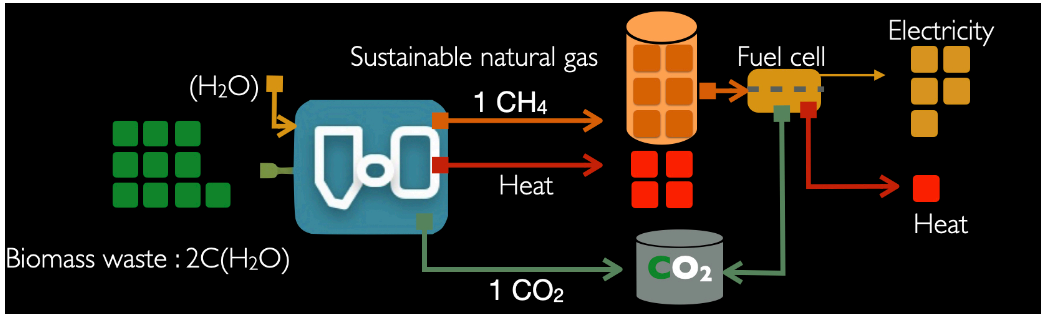
Fuel cell heat 100 + biogas production 920 kWth

Heat pump 1 : 355 kWe

Cooling Tower : 38.5 kWe

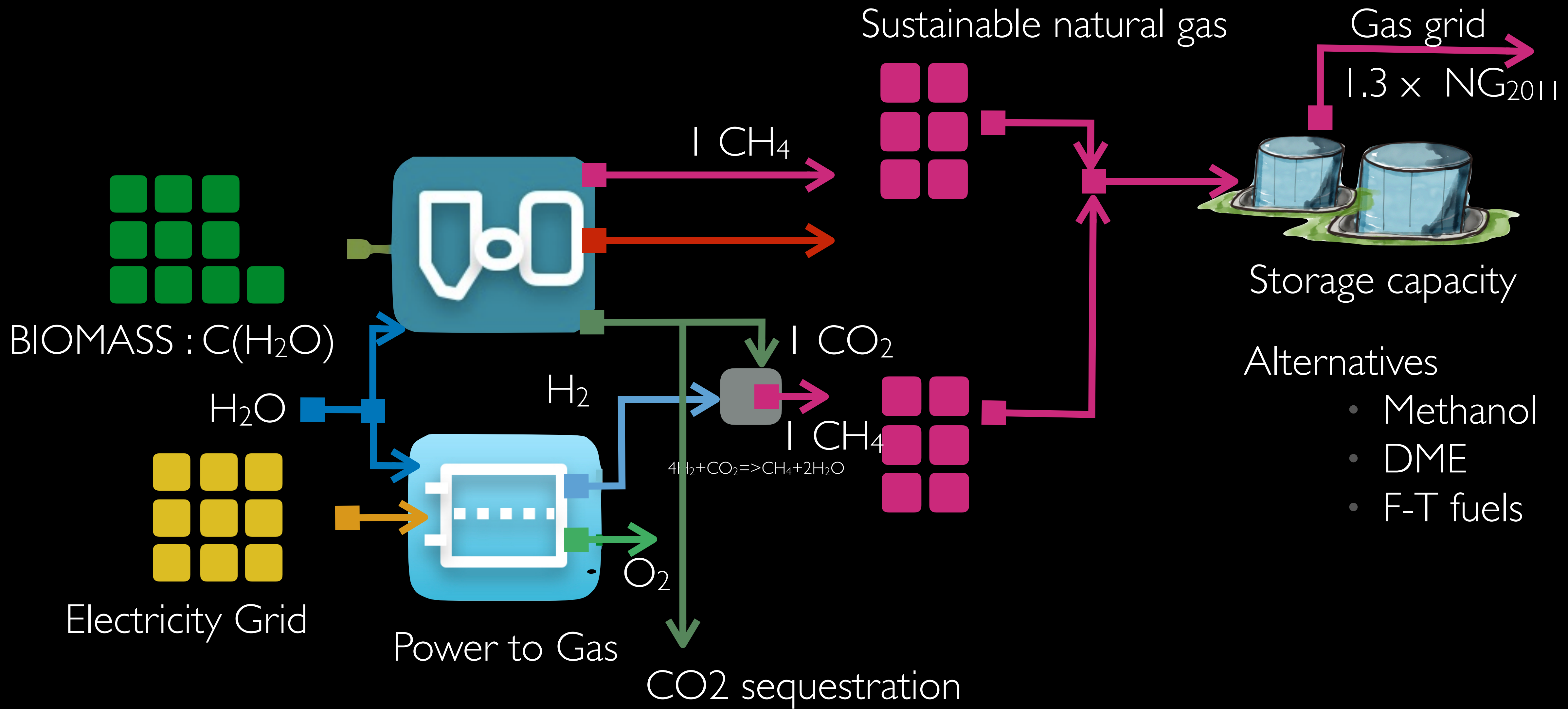
Refrigeration :38.5 kWe

Biogas export : 2582 kW



Carnot Integrated Composite Curve before fluid selection

COMBINING BIOMASS CONVERSION AND ELECTROLYSIS



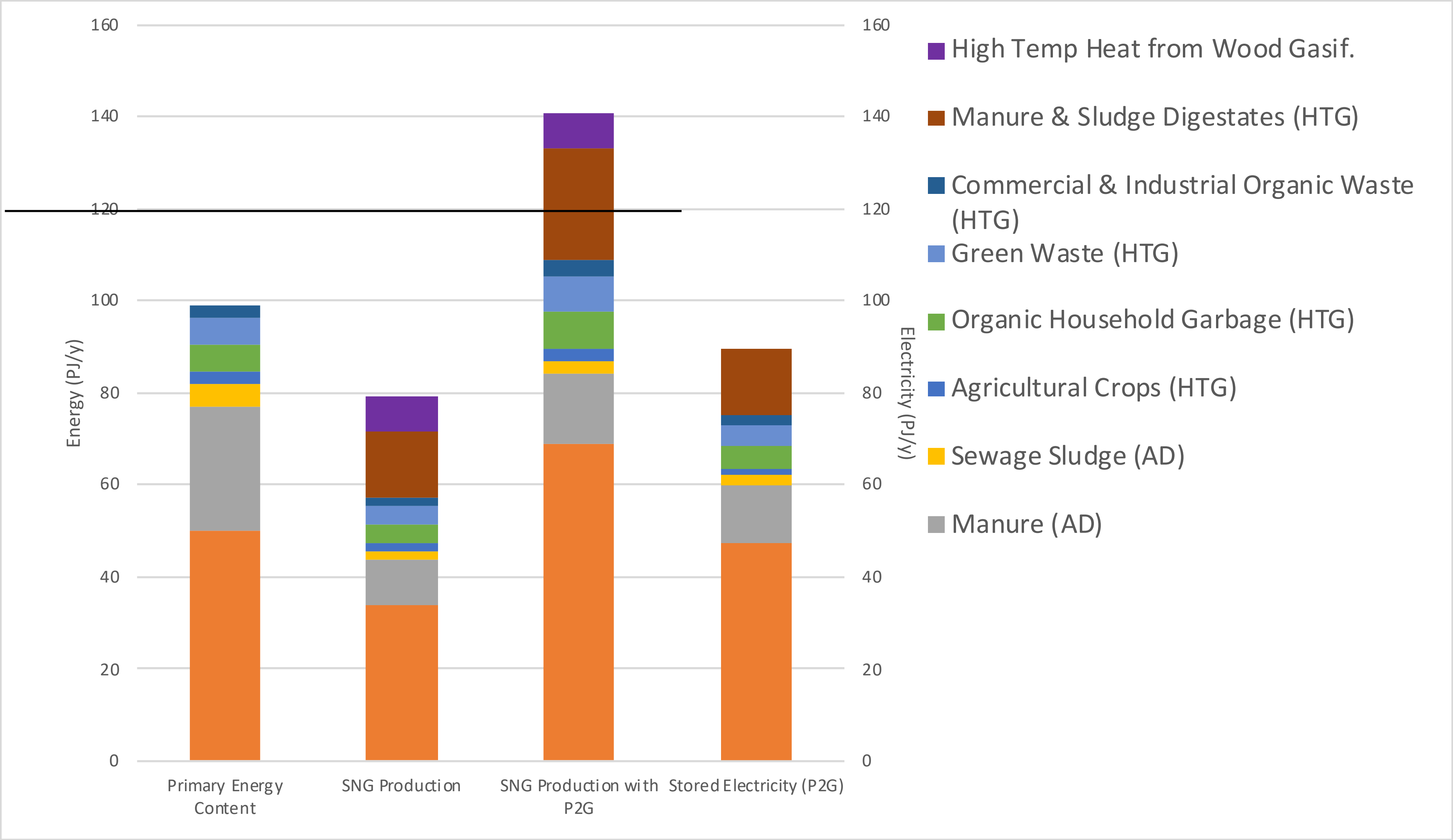
Alternatives

- Methanol
- DME
- F-T fuels

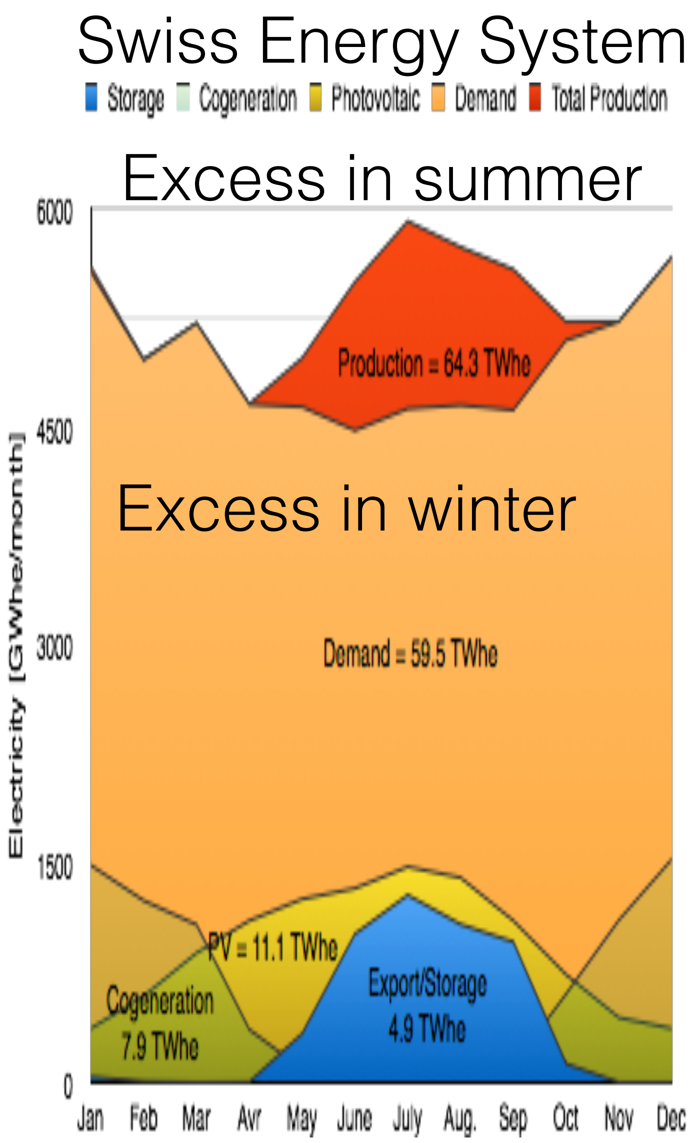
Gassner, Martin, and François Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." Energy 33.2 (2008): 189-198.

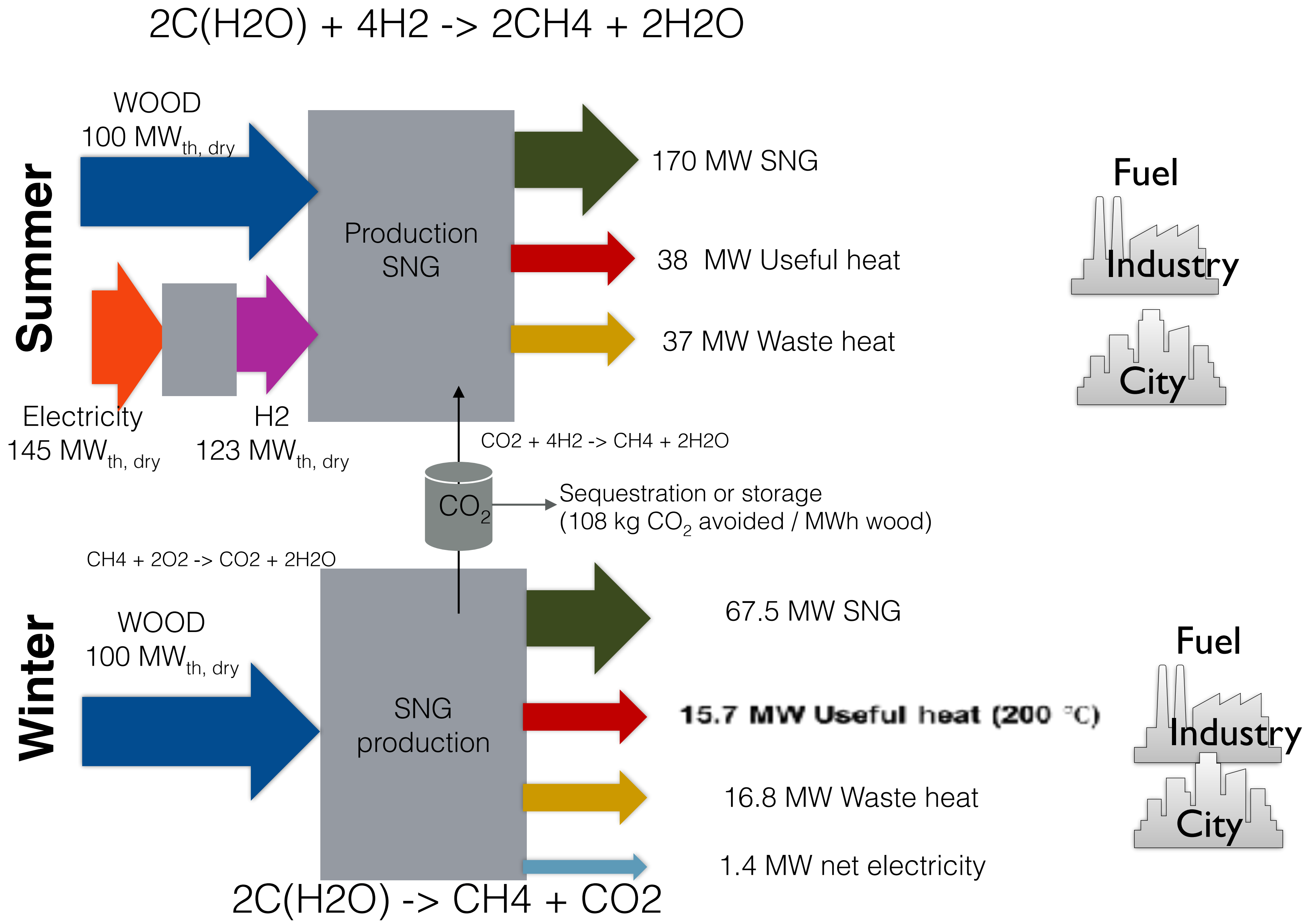
BIOMASS RESOURCE AND CONVERSION

Natural gas 2011



Integrating synthetic natural gas production in the energy system : Combined heat and fuel production





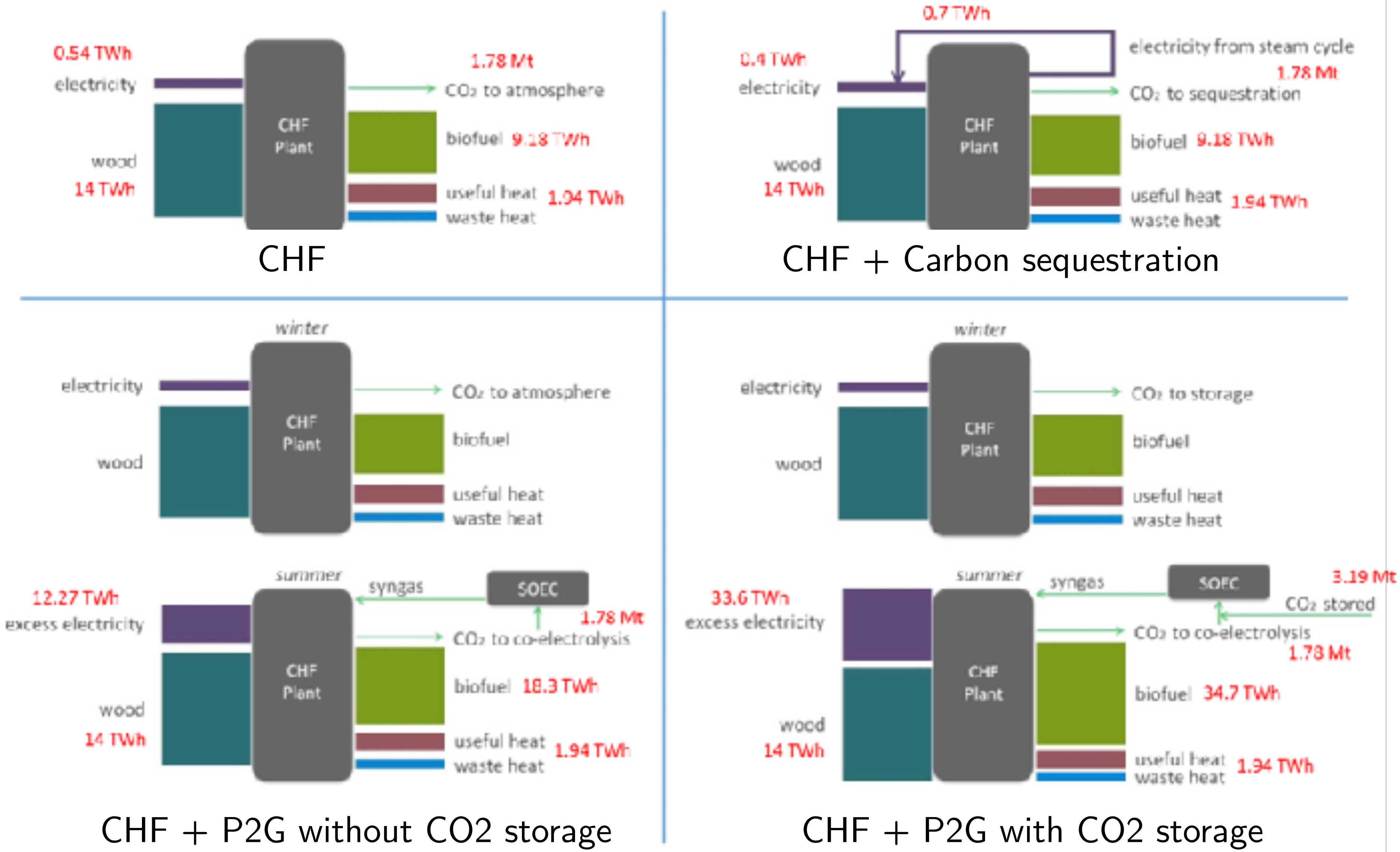
Combined Heat and Fuel (CHF) production
Substituted fossil carbon per unit of biogenic carbon in wood

1.6
wood boiler

2.8
wood boiler

2.1
wood boiler

3.0
wood boiler



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

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

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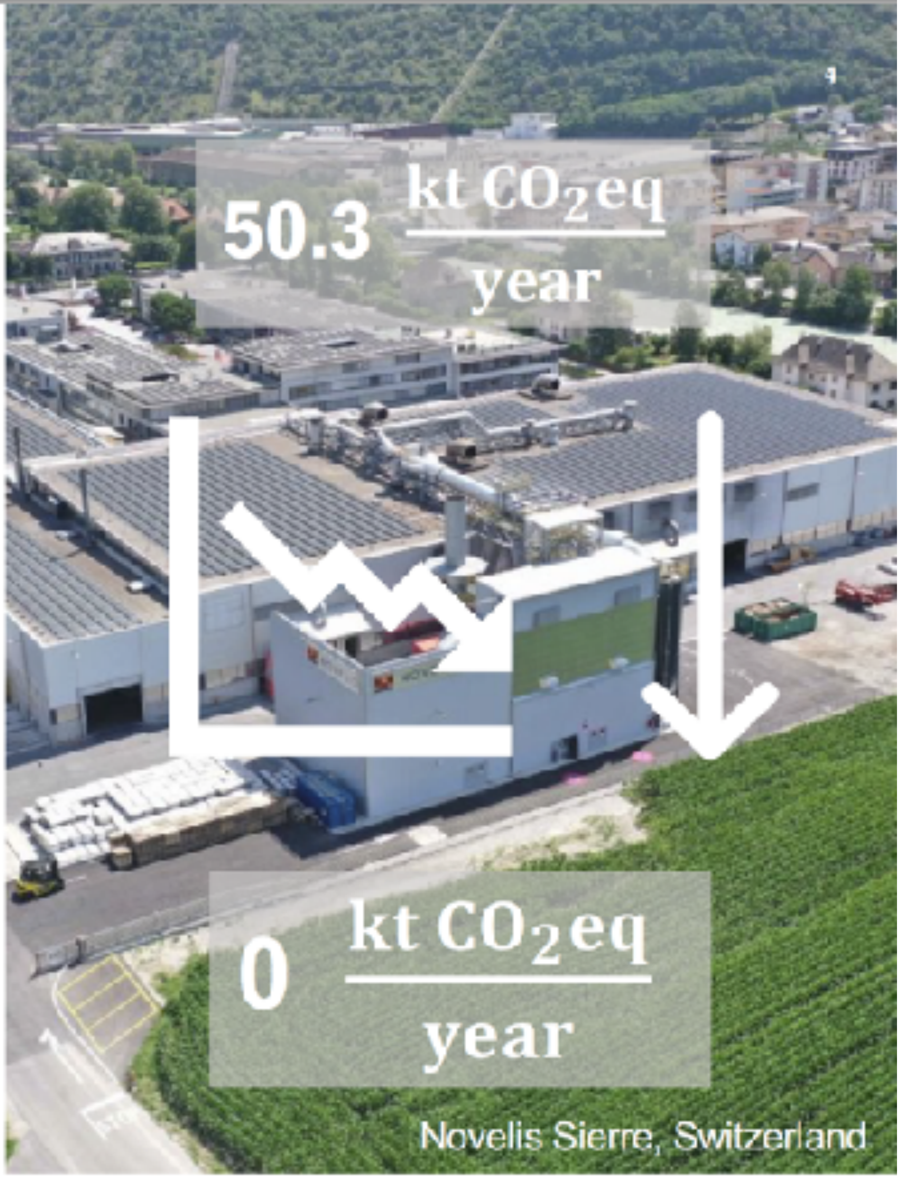
NetZero LAB

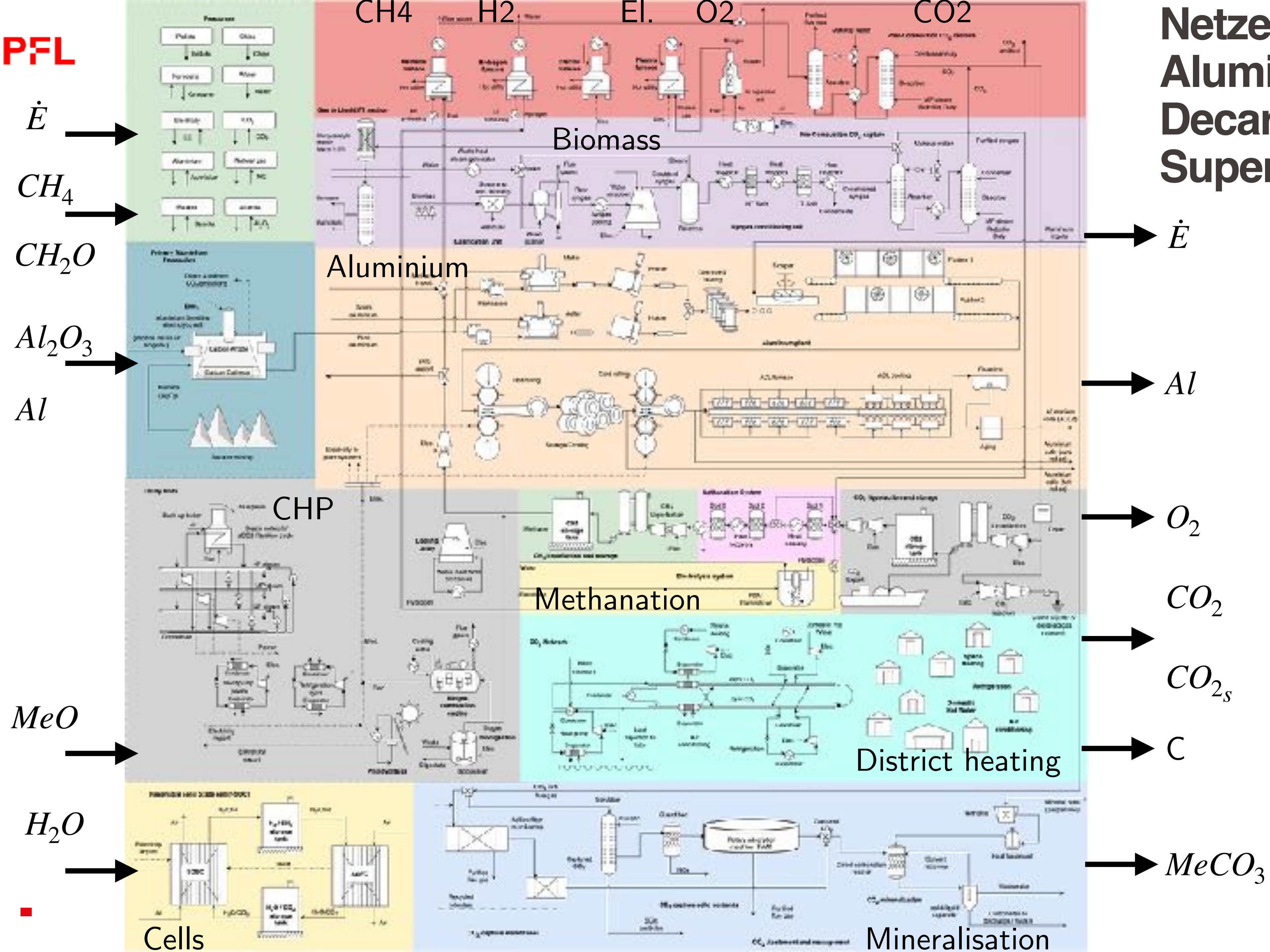
NET ZERO LAB valais

- Launched to develop carbon neutral solutions for Aluminium manufacturing at Novelis – Sierre
- Net zero for scope 1 and 2 emissions at the plant by 2030
- Integration with city district heating demands
- Providing global solutions for Novelis operations and other aluminium producers

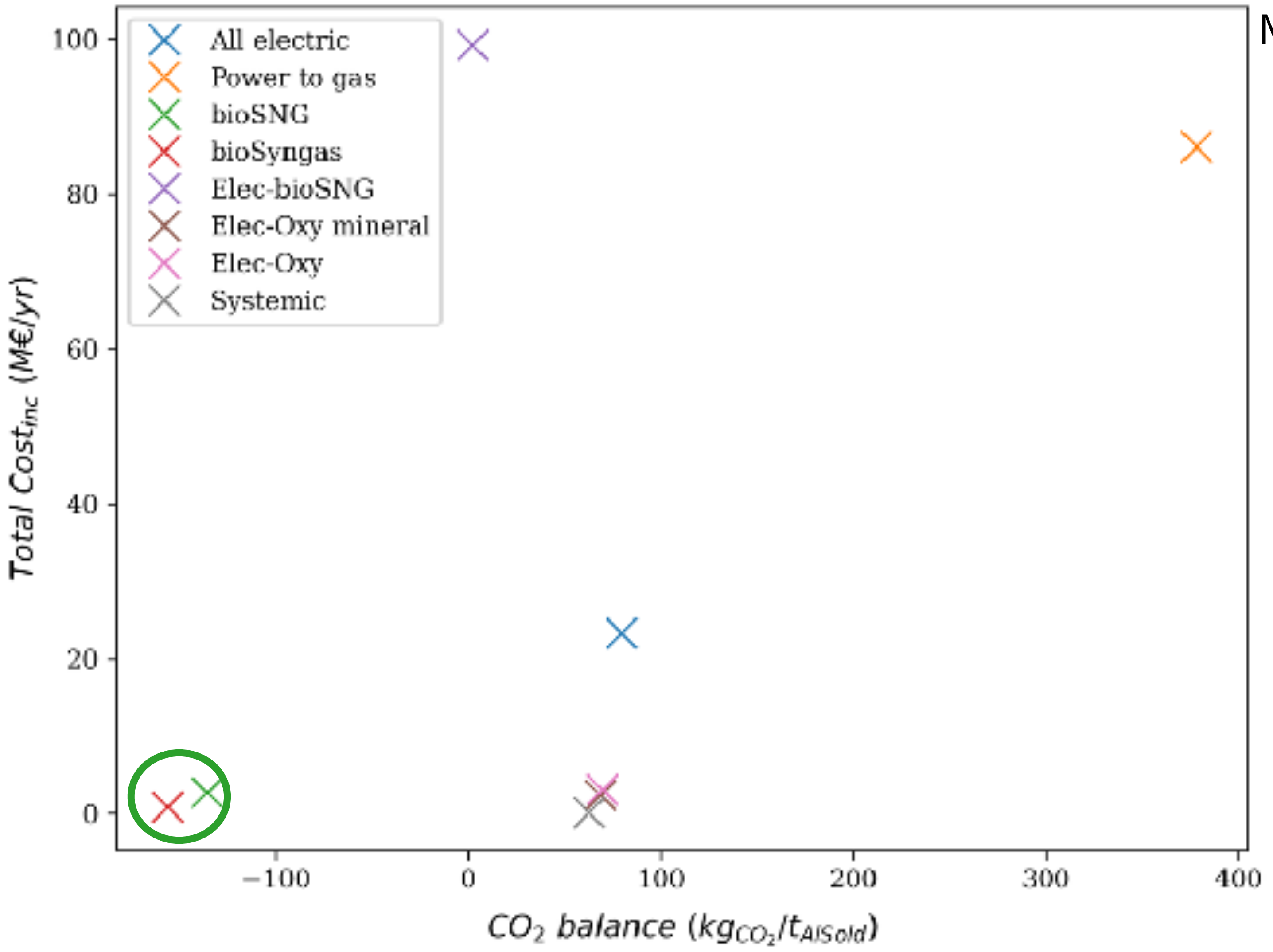


Novelis Hes·so VALAIS WALLIS EPFL OIKEN

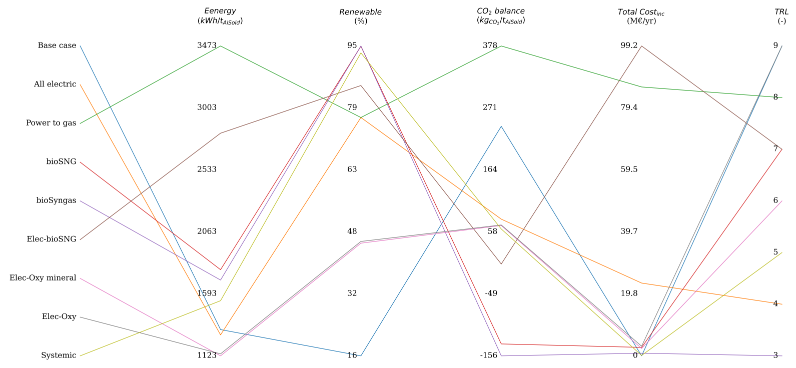
Netzerolab Aluminium Decarbonization Superstructure



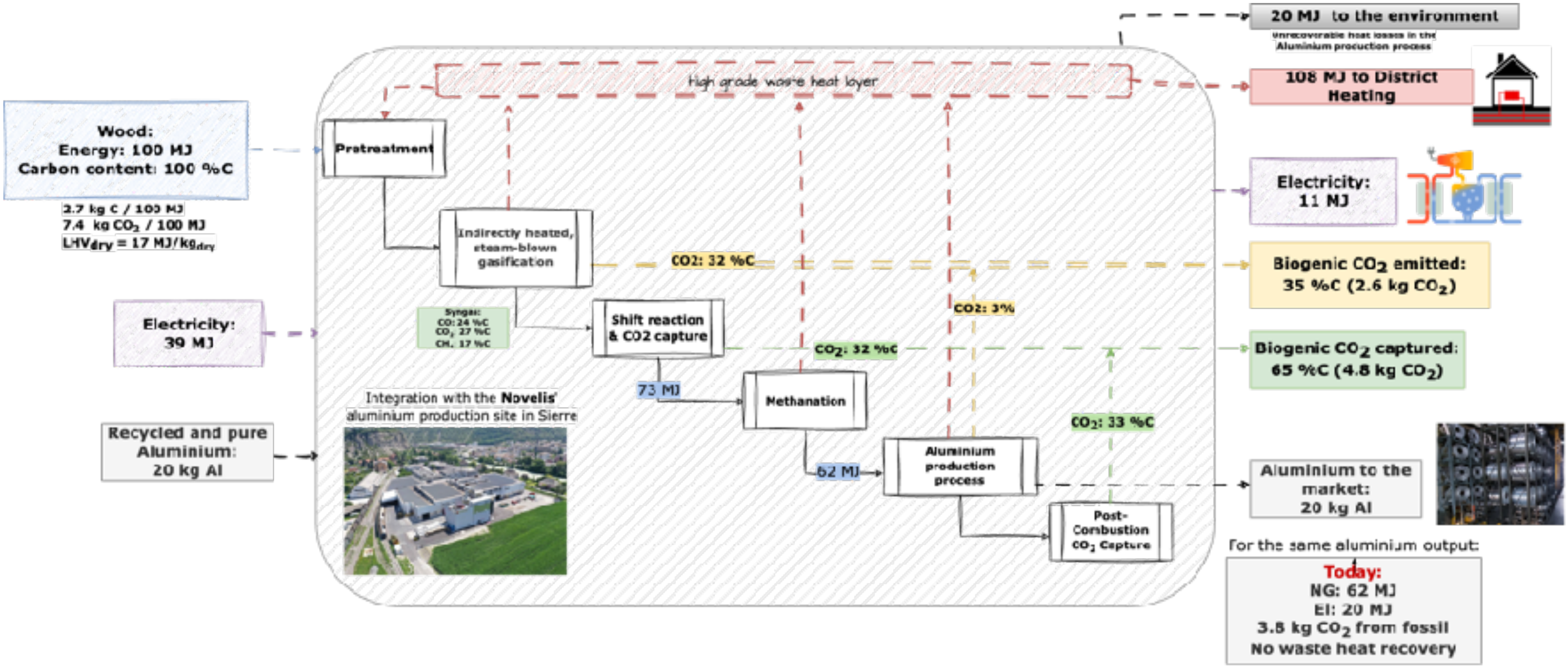
Generating process configurations
Pareto: Environmental impacts vs. Total Cost



Multiple KPI : Environmental Governance

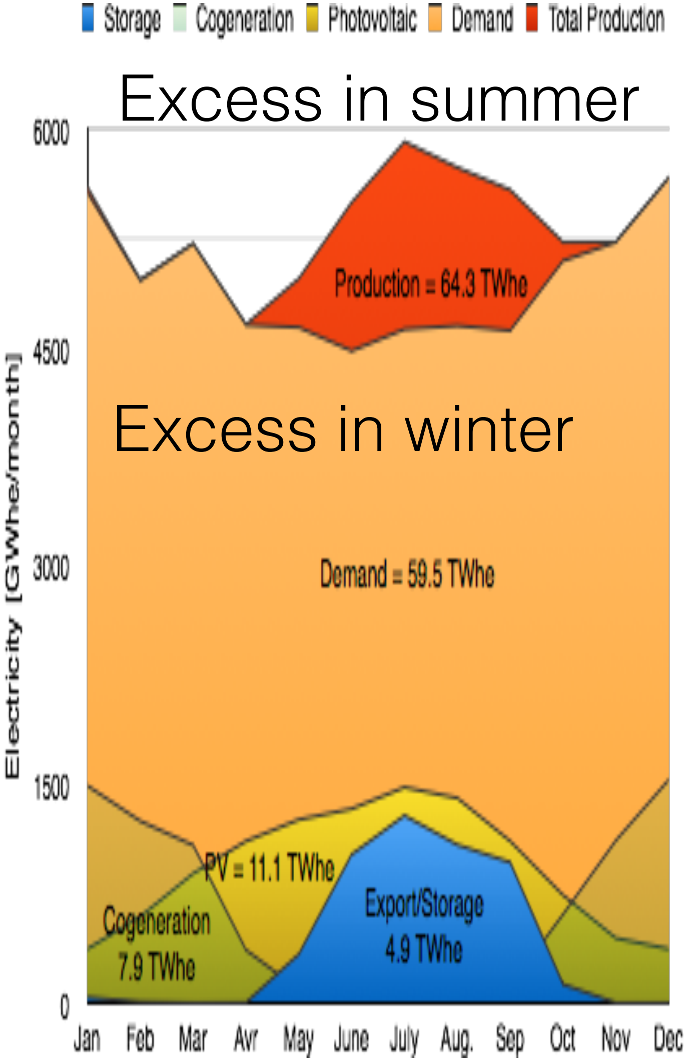


Example of configurations

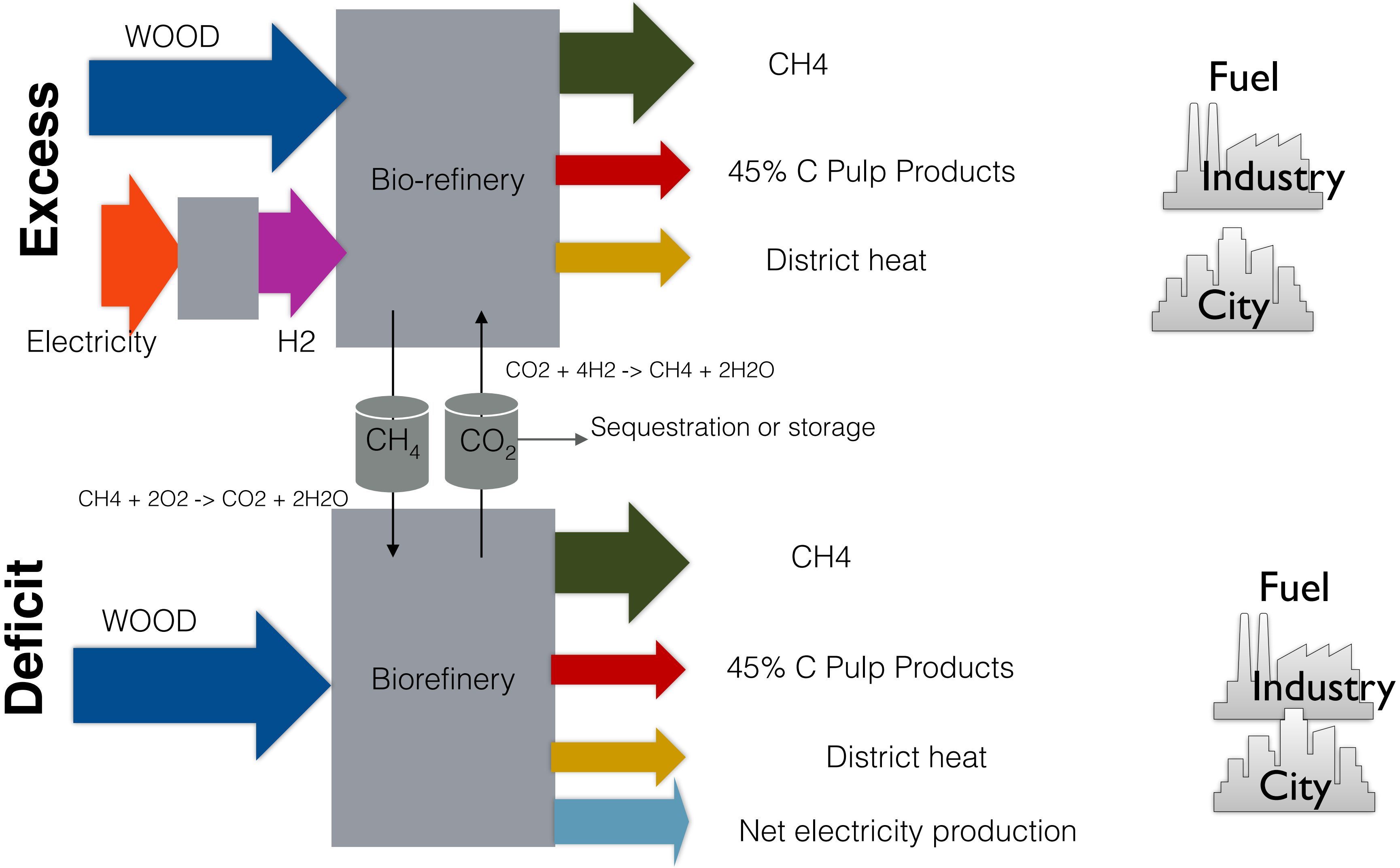


Integrating with the energy system : Combined products - fuel production & electricity management

Swiss Energy System

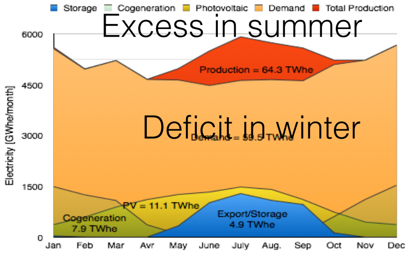


2C(H2O) + 4H2 -> 2CH4 + 2H2O

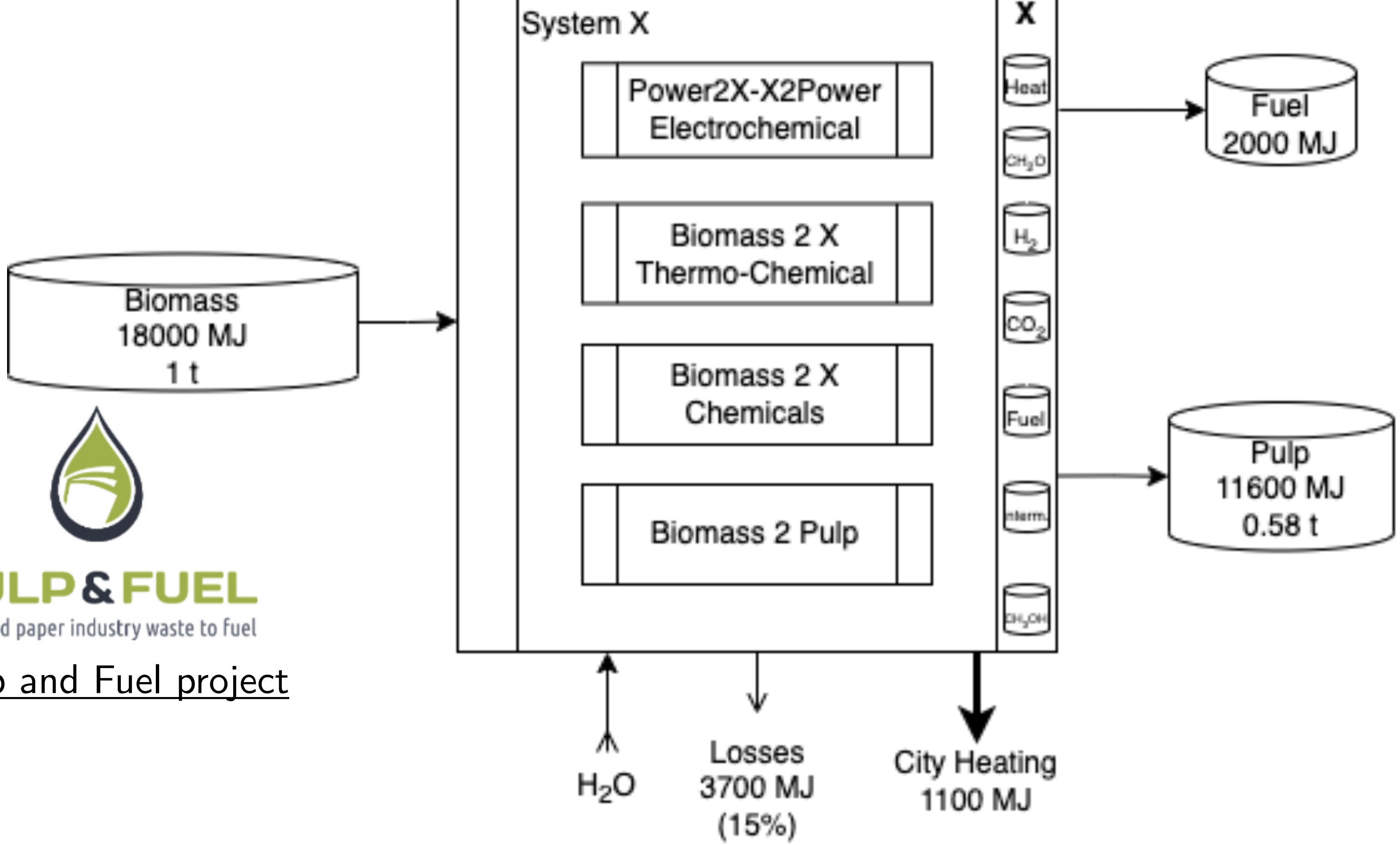


2C(H2O) -> CH4 + CO2

Integrated biorefineries renewable energy hub



Up to 90 % Biogenic carbon efficiency



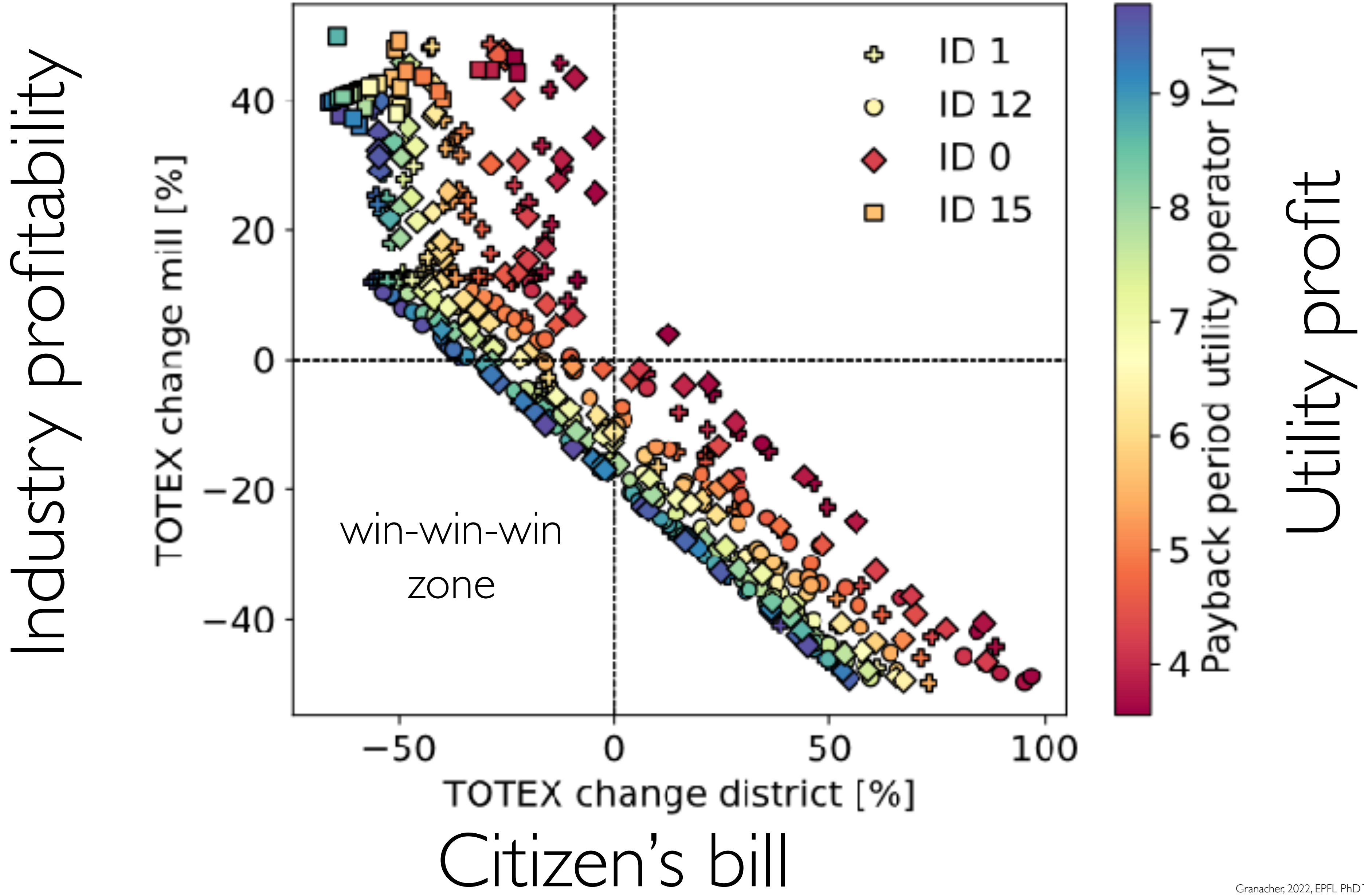
PULP & FUEL
pulp and paper industry waste to fuel

Pulp and Fuel project

Front. Energy Res., 23 November 2022
Sec. Bioenergy and Biofuels
Volume 10 - 2022 | https://doi.org/10.3389/fenrg.2022.979502

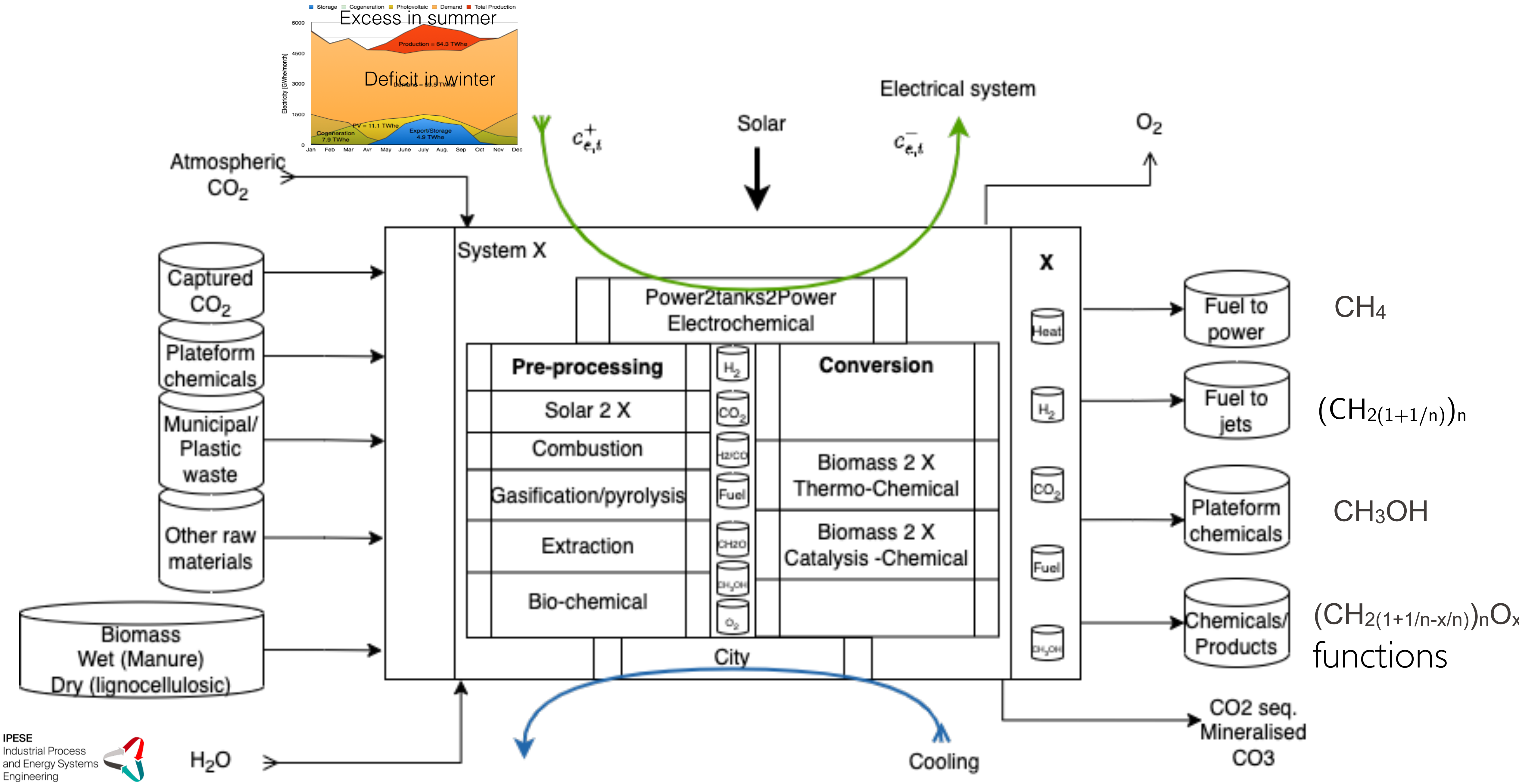
Multi-stakeholders problem by multi-objective optimisation problem

Julia Granacher



Granacher, 2022, EPFL PhD Thesis

Industrial clusters as a circular renewable energy hub



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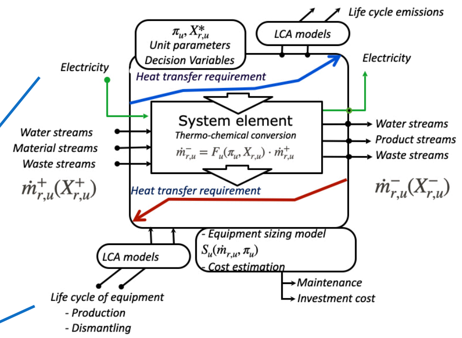
Defining decarbonisation routes for the industry (AIDRES-EU)

Blueprint **models** per sector

Decarbonisation options

- Process models
- Integration models assembling the bricks

Decarbonisation Pathways



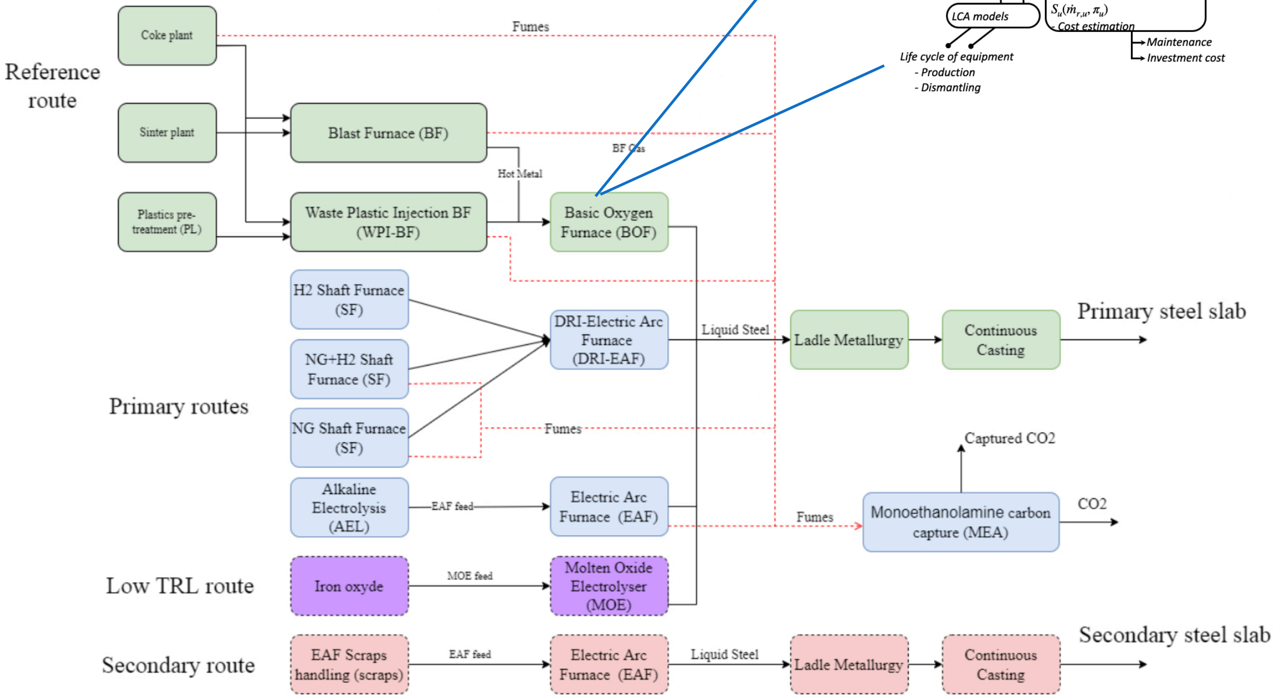


Figure 2.3: steel production routes schematic.

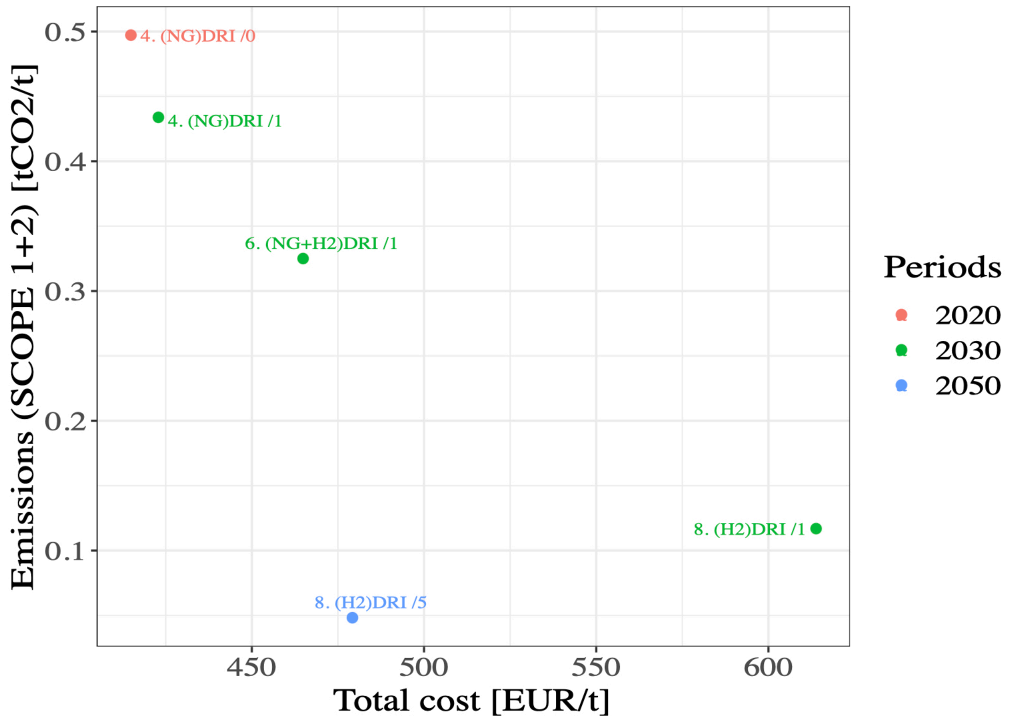


Figure 2.1: Pareto front of total cost and SCOPE 1+2 emissions for primary steel production.

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

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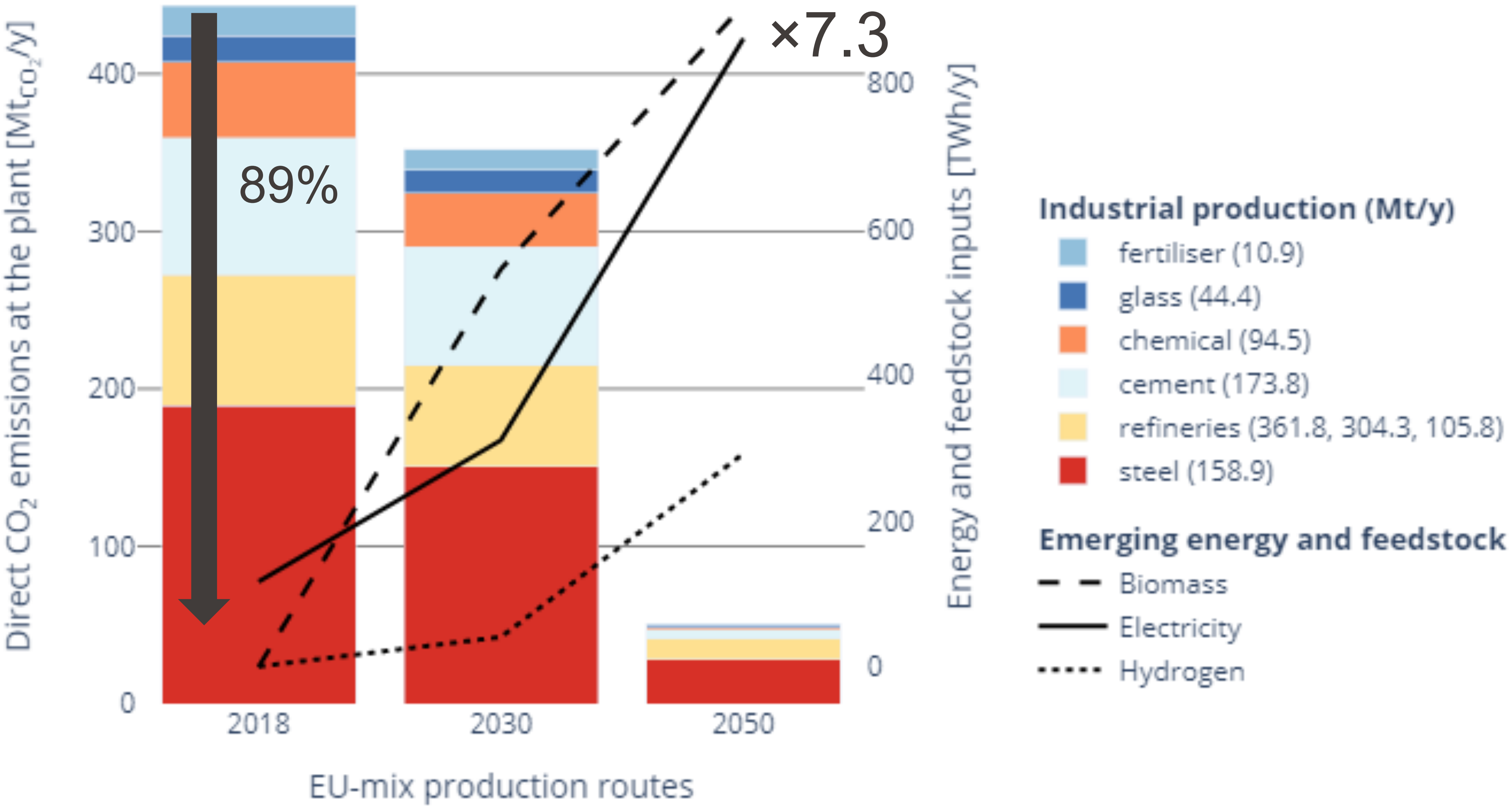
AIDRES - RESULTS - OVERALL
Direct emissions & emerging energy and feedstock



Industry decarbonation pathways

- Efficiency
- Waste heat valorisation
- Electrification
  - Heat pumps
  - High temperature heat ?
- Renewable energy
  - Combined heat and fuel production via co-electrolysis
  - Electricity storage
  - Biogenic CO_2 mineralisation
- CO_2 capture
  - When fossil carbon is in the raw materials and not in the product
  - H_2 storage by carbon circularity
  - Negative emissions from biomass
- Hydrogen from RES and Water
  - As a reducing agent (removes O_2) : Steel - Aluminium
  - H_2 as an atom : Plastics/chemicals

La recherche est là pour aider

- Questions ?

References

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