

A systemic study for enhanced waste heat recovery and renewable energy integration towards decarbonizing the aluminium industry

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- Large heating/cooling demands → Waste heat is an important byproduct
- More stringent regulations ($> 100 \text{ EUR/t}_{\text{CO}_2}$) → Need for decarbonization
- Power-to-gas for grid-scale energy storage

▪ Aluminium remelting

Remelting $0.5 \text{ t}_{\text{CO}_2}/\text{t}_{\text{Al}}$

Reduction $18 \text{ t}_{\text{CO}_2}/\text{t}_{\text{Al}}$



▪ Urban Agglomeration

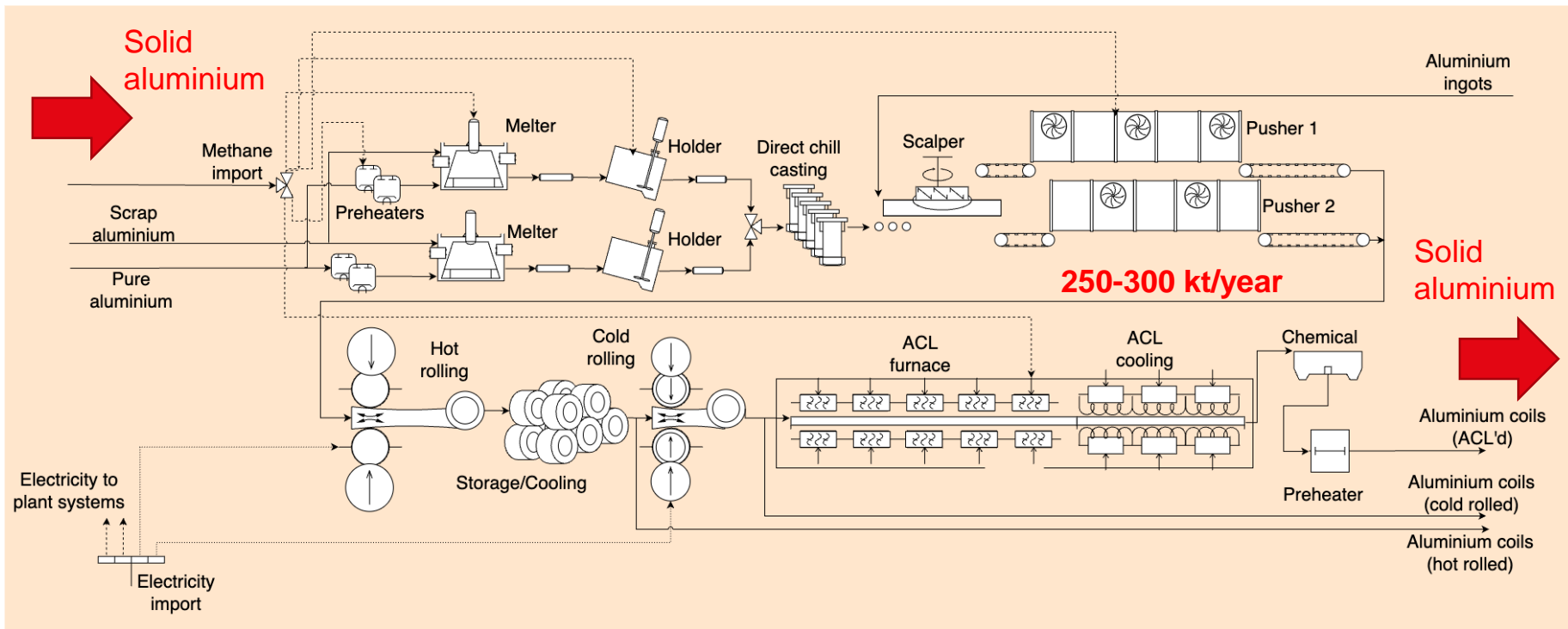
Seasonal requirements:

- space heating
- air conditioning
- refrigeration
- domestic hot water



Power consumption:
~ 50-80 GWh/y





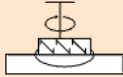


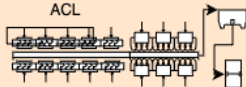
Natural gas consumption:
~ 190-210 GWh/y



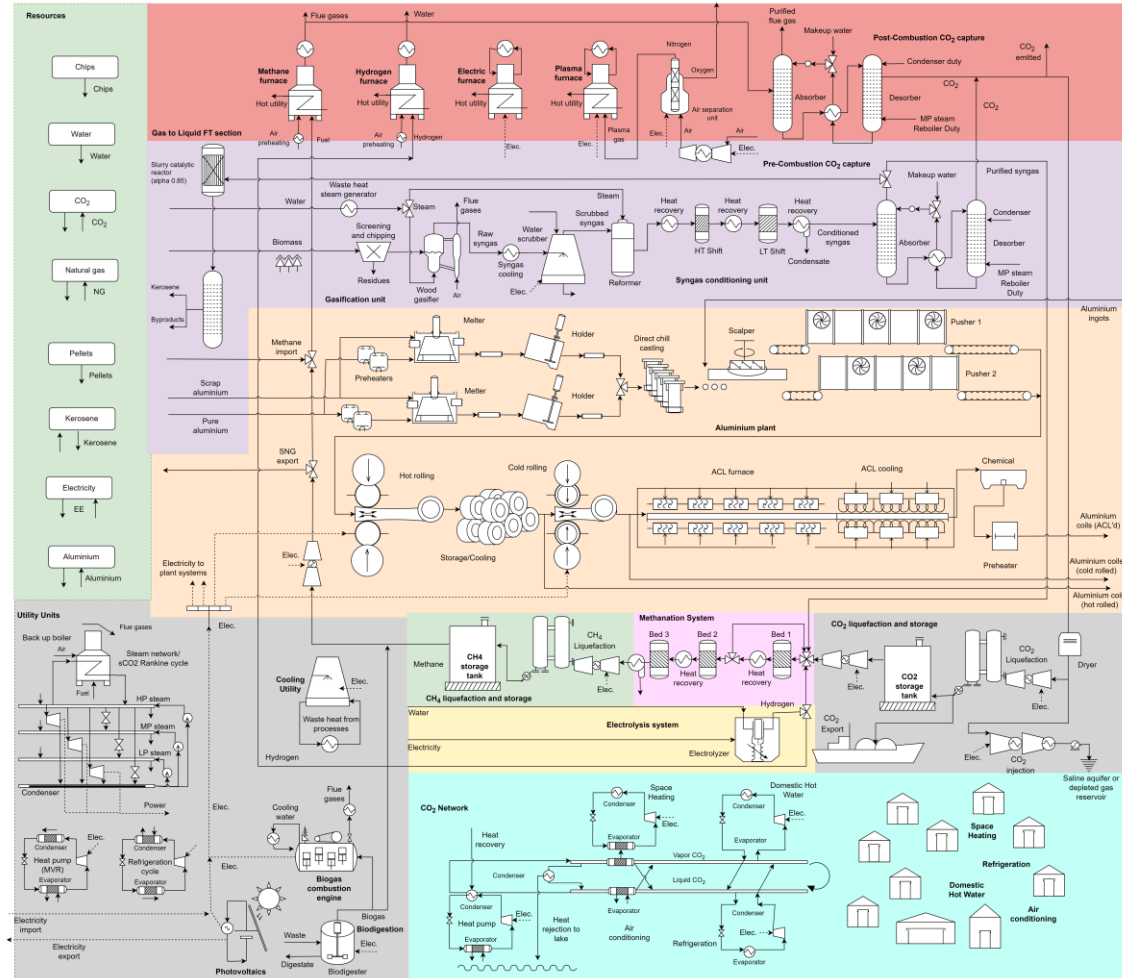
Aluminium processing units

Base case operation:

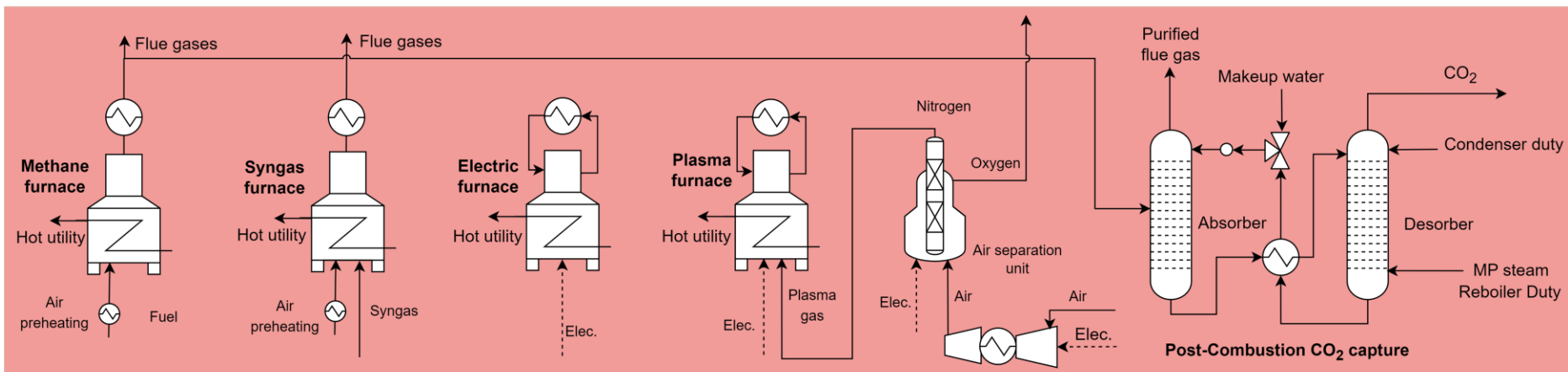
Heating and cooling loads and temperature levels per equipment.

Unit	Energy consumption (kWh/tAl BSO)	Temperature level (°C)
Preheater 	33.3	230°C
Melter 	355.1	730 - 750 °C
Holder 	27.0	750 °C
Casting 	178.4	750 - 60° C
Scalper 	--	--
Pushers 1 & 2 	186.8	570 °C
Hot rolling	48.6	400 °C
Storage /Cooling 	85.9	400 - 80 °C
Cold rolling	49.2	130 °C
ACL 	129.0	570, 130 °C

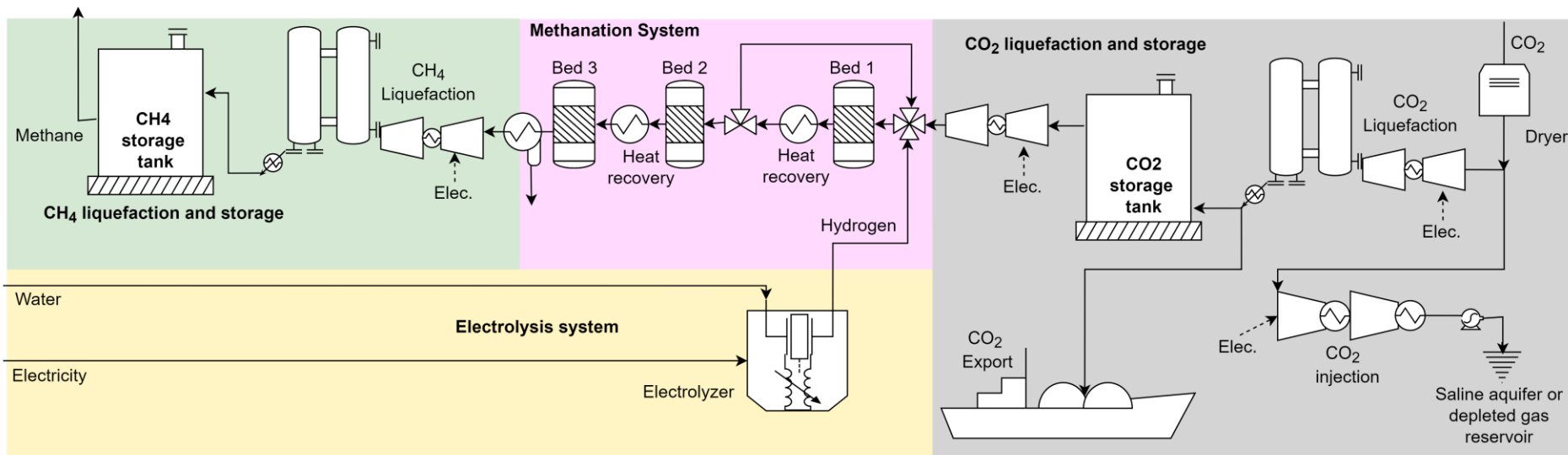
- Aluminium remelting plant
- Space heating (city, plant)
- Domestic hot water (city)
- Air conditioning (city)
- Refrigeration (city)
- Furnaces (fired, electrical, oxycomb.)
- Biomass conversion systems
- Cooling systems
- Carbon abatement units
- Power-to-gas systems (electrol./methan.)
- Storage units (liquids CH_4 , CO_2)
- Waste heat recovery network
- Additional: Biodigestion, Cogeneration, Heat Pump, Fuels



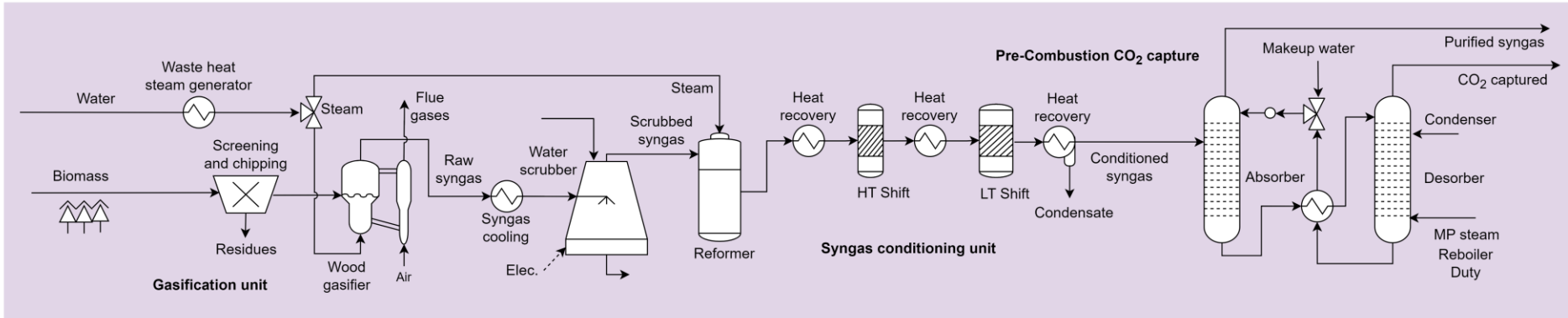
- Heating and cooling utilities, transcritical CO₂ cycle for power generation
- Post-combustion CO₂ capture unit



- Liquid fuels storage.
- CO₂ import, injection or venting (subject to taxation).

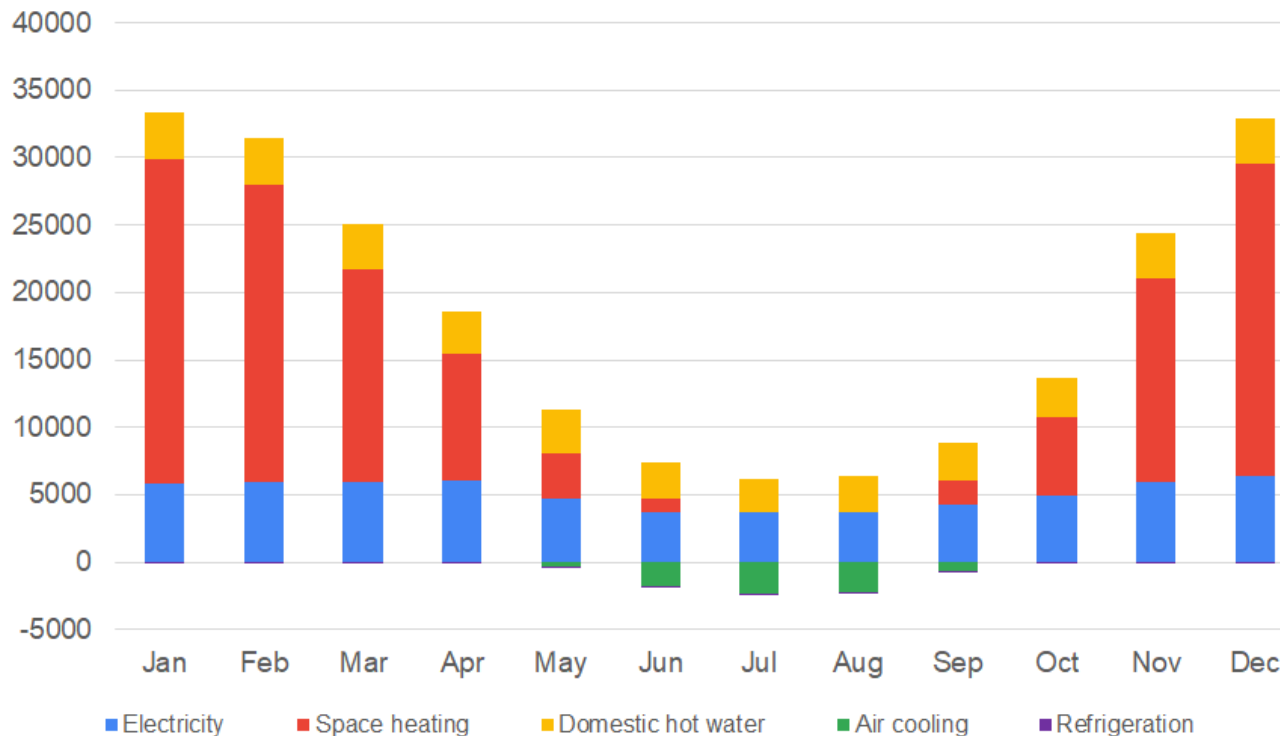


- Biomass gasification unit produces syngas that can be either used as gaseous fuel directly or converted into synthetic natural gas for storage, export and consumption.



- Space heating, domestic hot water, air conditioning, refrigeration.

Heating or cooling demand (kW)

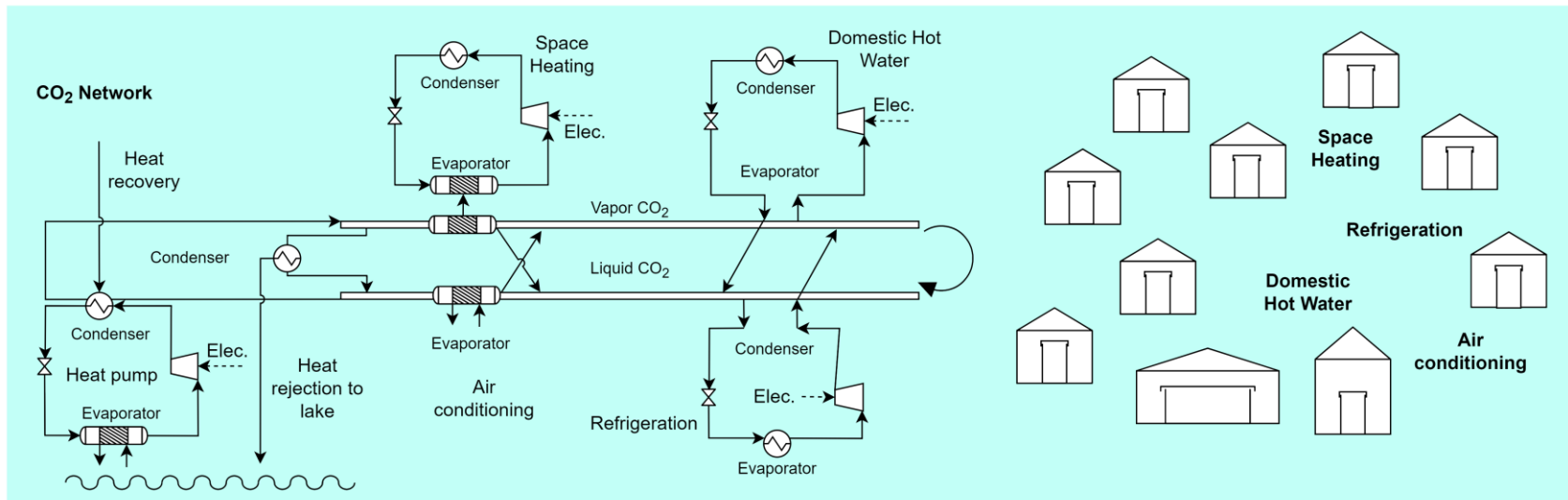


20000 cap.

0.682 kW/capita

$\sim 2.0 \text{ kW}_{\text{th}}/\text{dwelling}$

- Space heating, domestic hot water, air conditioning, refrigeration.
- CO₂ district heating network.



$w = \{\text{utility units, resources}\}$, y_w existence (binary) and f_w load factor variables

Optimization problem: minimum operating cost or maximum revenue:

$$\text{Min}_{f_{\omega}, y_{\omega}, R_r, W} \left[f_{Biomass} (m \cdot c)_{Biomass} + f_{NatGas} (B \cdot c)_{NatGas} \pm f_{Elec} (W \cdot c)_{Elec} + f_{EnvEm} (m \cdot tax)_{EnvEm} + f_{Water} (m \cdot c)_{Water} \right. \\ \left. + f_{CO_2}^{Imported} (m \cdot c)_{CO_2}^{Imported} + \frac{Z_{equip} \times Ann_factor}{N_{hours\ per\ year}} - f_{Aluminium} (B \cdot c)_{Aluminium} - f_{heat, biofuel, CO_2}^{Exported} (m \cdot c)_{heat, biofuel, CO_2}^{Exported} \right]$$

Subject to:

$$\sum_{\omega=1}^{N_{\omega}} f_{\omega} q_{\omega, r} + \sum_{i=1}^N Q_{i, r} + R_{r+1} - R_r = 0 \quad \forall r = 1 \dots N \quad \sum_{\omega=1}^{N_{\omega}} f_{\omega} W_{\omega} + \sum_{chemical\ units} W_{net} + W_{imp} - W_{exp} = 0$$

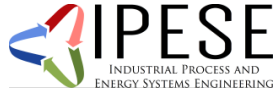
$$f_{min, \omega} y_{\omega} \leq f_{\omega} \leq f_{max, \omega} y_{\omega} \quad \forall \omega = 1 \dots N_{\omega} \quad W_{imp} \geq 0, W_{exp} \geq 0 \quad R_1 = 0, R_{N+1} = 0, R_r \geq 0$$

$c_{NG} = 0.45 \text{ EUR/kWh}$; $c_{Biom} = 0.014 \text{ EUR/kWh}$; $c_{EE} = 0.15 \text{ (Nov-Feb) or } 0.001 \text{ (Mar-Oct) EUR/kWh}$; $c_{CO_2 import} = 0.0084 \text{ EUR/kg}$; $c_{CO_2, tax} = 100 \text{ EUR/t}$

Process Modeling and Simulation:

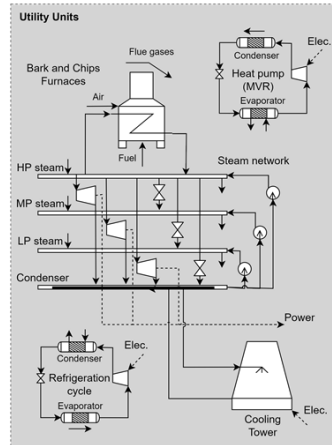


**Sequential
Modular
Simulation**



Energy integration framework: OSMOSE Lua / Refprop

**Equation
Oriented
Modeling and
Simulation**



**Minimum
Energy
Requirement**

$$\min_{R_r} R_{N_r+1}$$

Subject to

Heat balance of temperature intervals

$$\sum_{i=1}^N Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1 \dots N$$

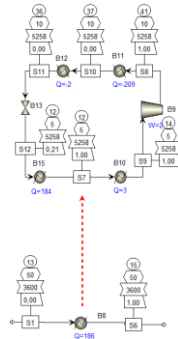
Feasibility of the solution $R_r \geq 0$

- Tanks cycling:** $Storage\ Level_t = f_{\text{tank},t}$

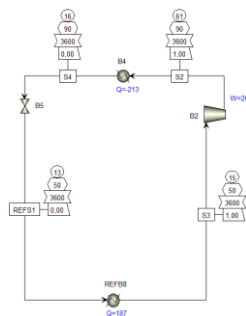
$$Storage\ Level_{t+1} - Storage\ Level_t = Mass\ or\ Energy\ Inlet_t - Mass\ or\ Energy\ Outlet_t$$

CH₄ stored at -162°C and 1bar (423 kg/m³) and CO₂ stored at -50°C and 7bar (1155 kg/m³)

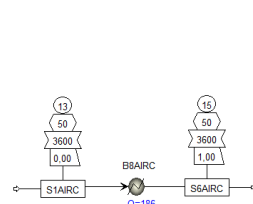
- CO₂ network (Aspen Plus and Coolprop):**



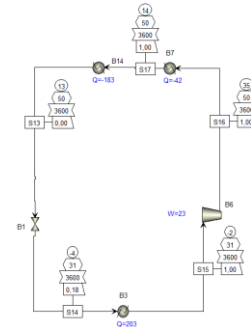
Space heating



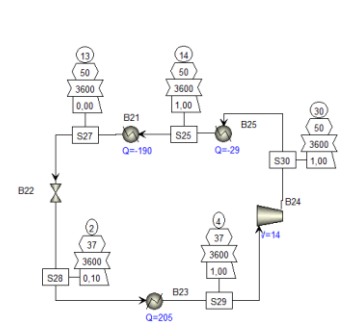
Hot water production



Air conditioning



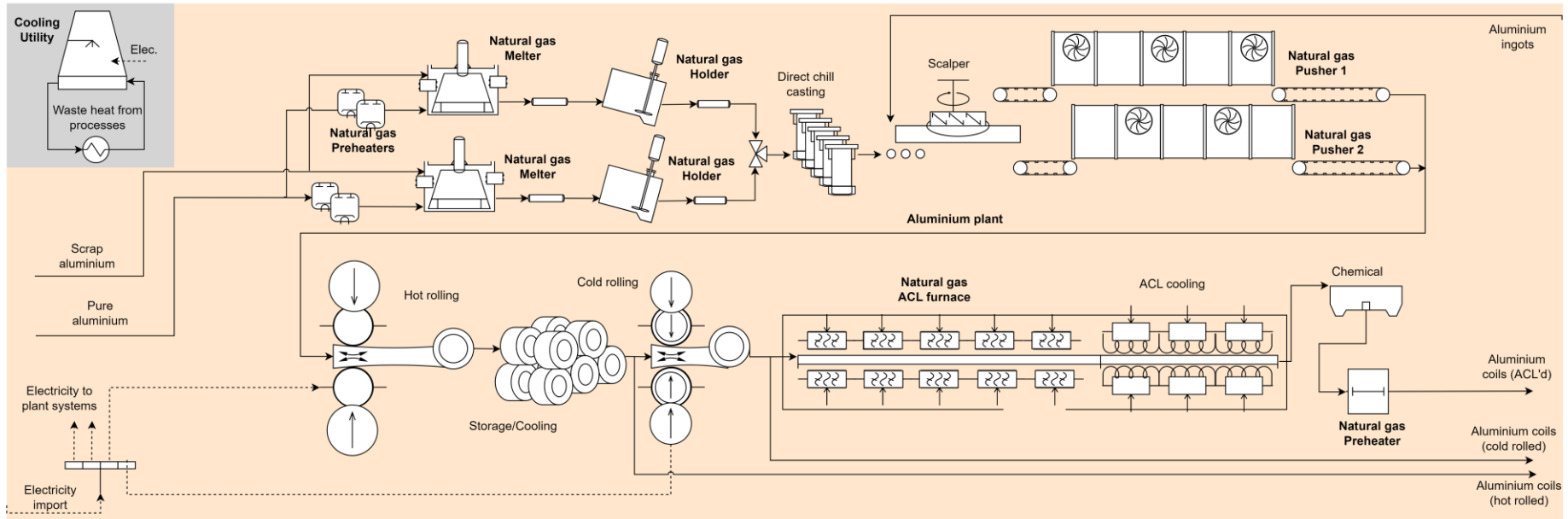
Refrigeration



Central plant

Base case solution

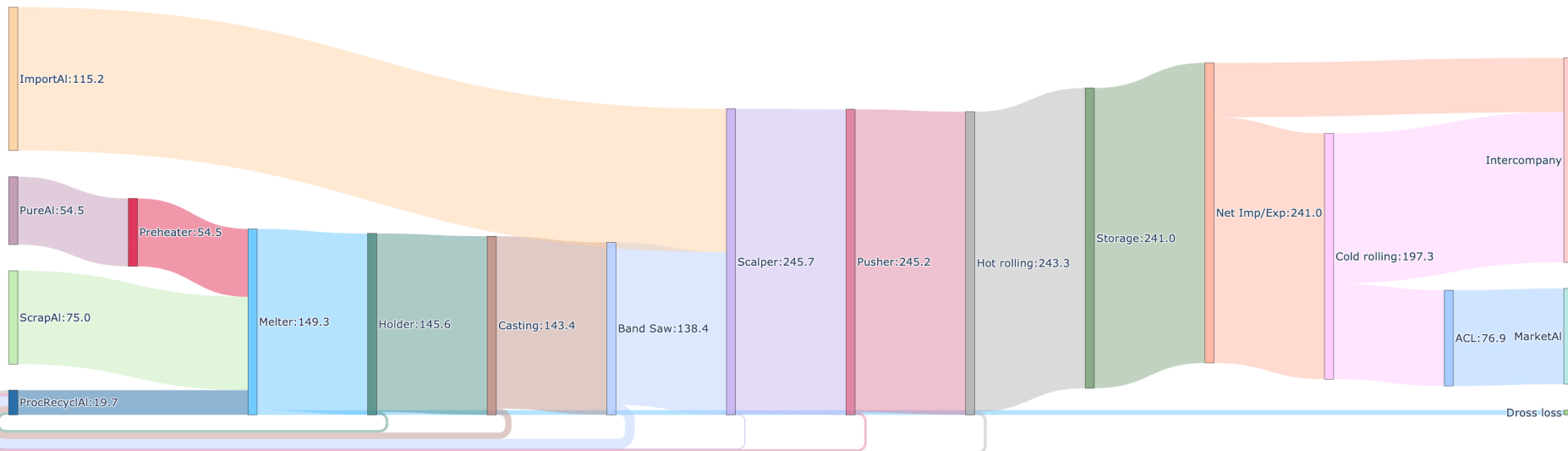
The heating needs are provided by natural gas and electricity is imported from the grid to be used in different appliances of the plant (rolling, fans, doors etc.).



Base case solution

Aluminium remelting process: Mass balance

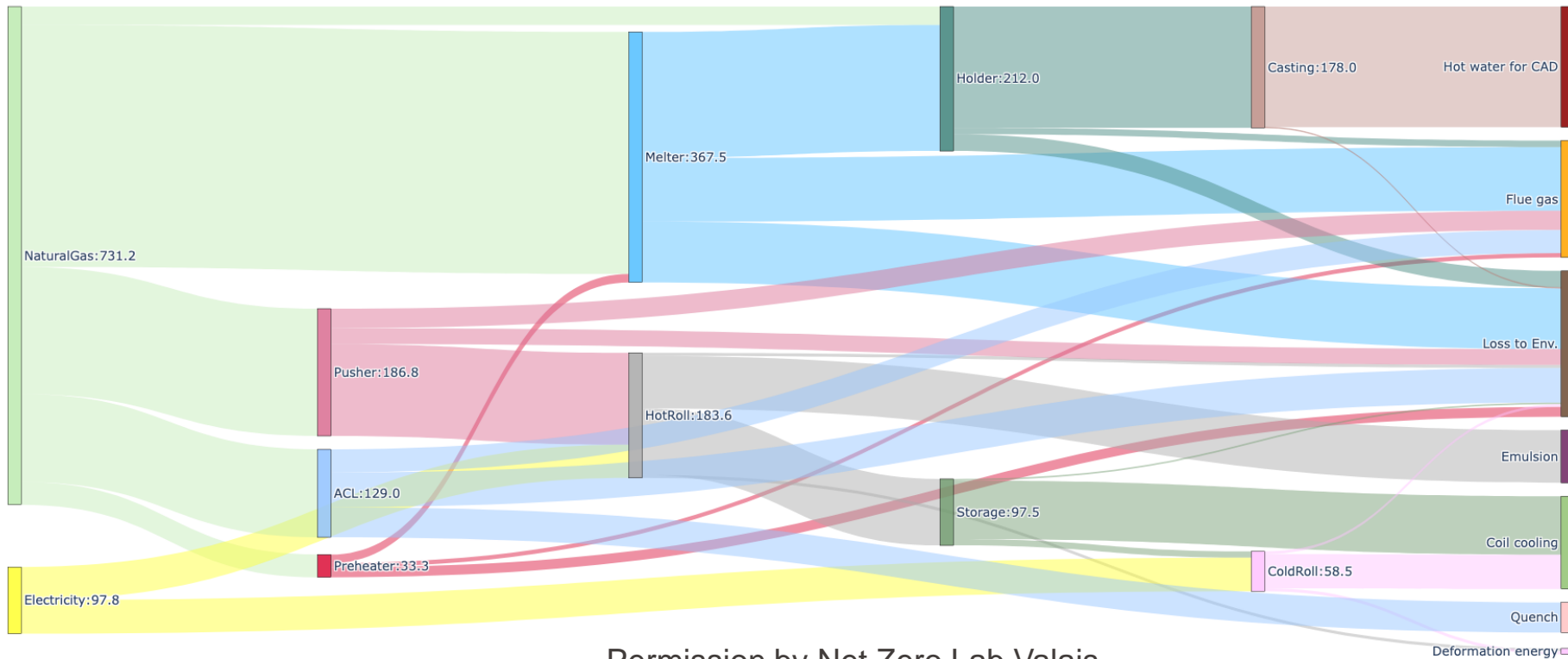
Values are reported in kilo tonnes of Aluminium/year



Base case solution

Aluminium remelting process: Energy balance

Values are reported in kWh/tonne of Aluminium at the Pusher



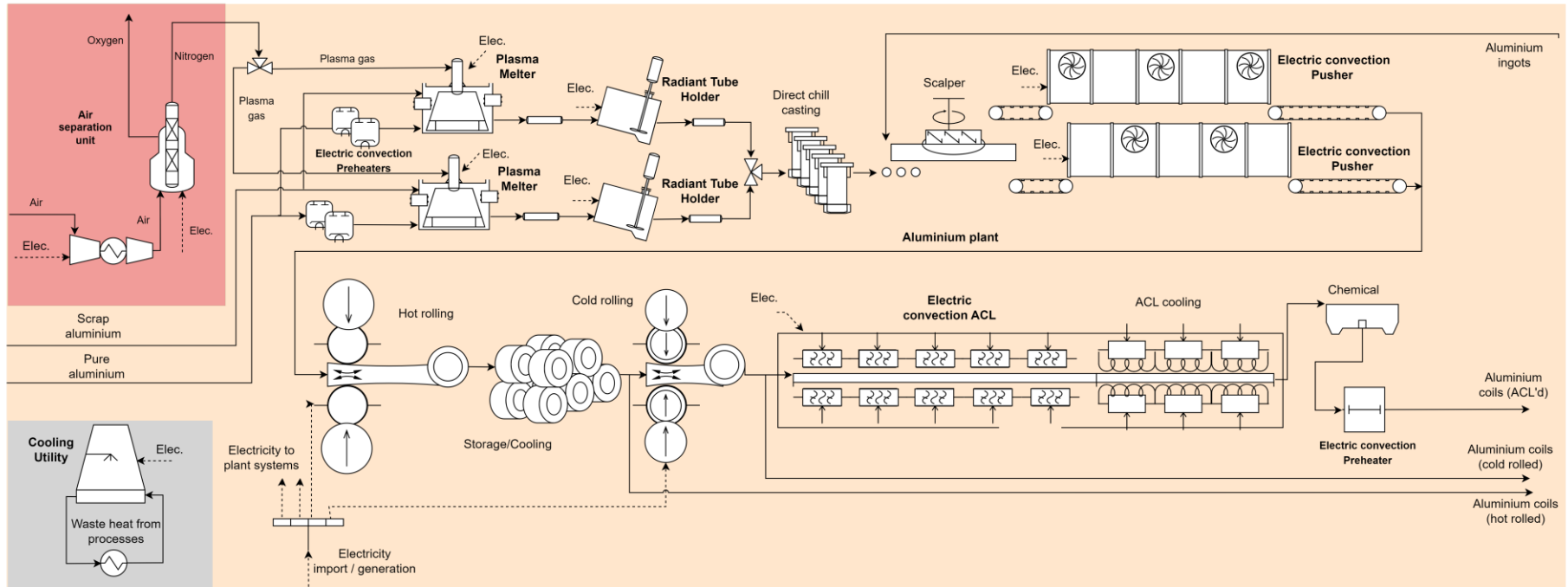
Base case solution

- Natural gas consumption 252.61 GWh/y (includes aux boiler NG cons. 59.67 GWh/y, 11.81 kt/y CO₂)
- Biomass consumption: 0 GWh/y
- Electricity consumption: 68.86 GWh/y
- Electricity air conditioning: 0.95 GWh/y
- Electricity refrigeration city: 0.03 GWh/y
- Electricity self-generation: 0 GWh/y
- Diesel consumption 0.23 kt/y
- Total emissions: **58.79 kt/y (only fossil)**
- Indirect emissions: NG cons. 4.46 kt/y, EE cons. 4.31 kt/y

CAPEX: 1,492,560 EUR/y
OPEX: -1,077,183,970 EUR/y

Fully electrified solution

Plasma-driven melters, radiant tubes in holders, electrically heated pushers and ACL furnaces are considered. All the heating processes are electrified. Nitrogen production for plasma. The CO₂ network imports electricity to drive heat pumps.

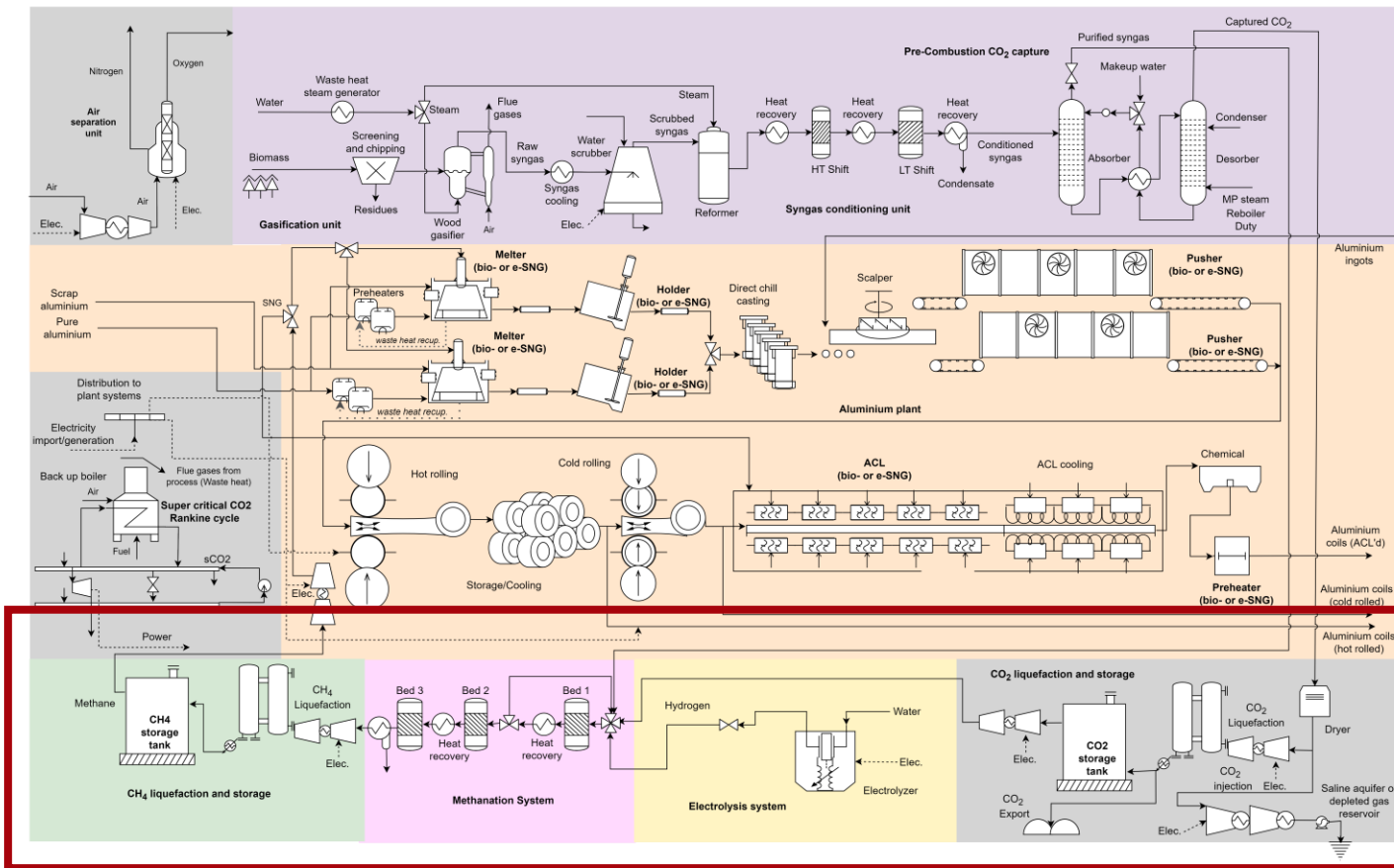


- Natural gas consumption: 0 GWh/y
- Biomass consumption: 0 GWh/y
- Electricity consumption: 311.62 GWh/y (Incl. initial aluminum plant 67.88 GWh/y)
- Electricity self-generation: 0 GWh/y
- Diesel consumption: 0.23 kt/y
- Direct emissions: 0 kt/y
- Total indirect emissions: 19.52 kt/y
- Nitrogen to plasma: 46.21 kt/y
- Oxygen to export: 0 kt/y
- Nitrogen to export: 0 kt/y
- Air separation unit power consumption: 3.24 GWh/y

CAPEX: 5,745,440 EUR/y
OPEX: -1,181,612,791 EUR/y

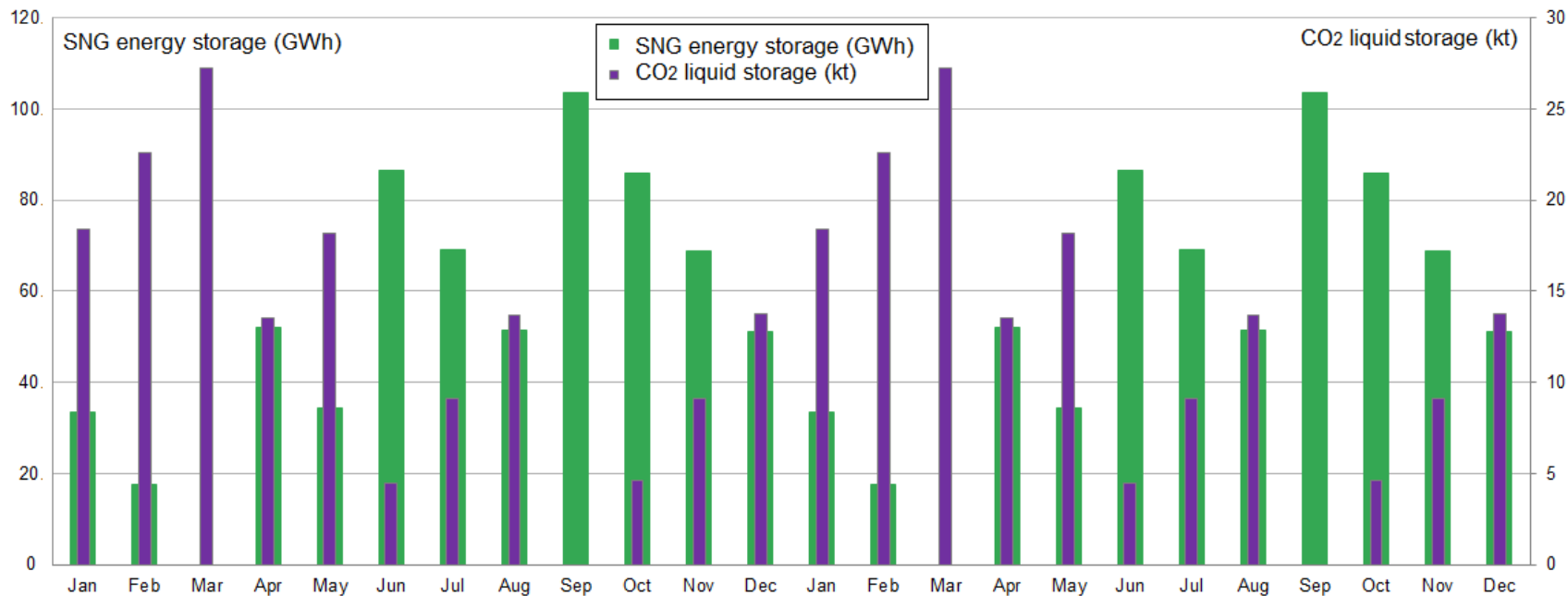
Power-to-gas SNG fuelled solution with seasonal storage

Importation of CO₂ is
necessary to
compensate for the
gas escaping.



Monthly variation of CH₄ and CO₂ storage

Frozen-earth or double-wall storage systems



- Natural gas consumption: 0 GWh/y
- Biomass consumption: 0 GWh/y
- Electricity consumption: 1370 GWh/y
- (Electrolyzer installed capacity: 200 MW)
- Electricity generation: 0 GWh/y
- Diesel consumption: 0.23 kt/y

- Aluminum plant power consumption: 67.88 GWh/y

- Total emissions: 92.87 kt/y
- Direct emissions: 7.55 kt/y
- Indirect emissions: from EE 85.83 kt/y

- O₂ production rate in electrolyzer: 183.05 kt/y
- H₂ production electrolyzer: 22.88 kt/y
- Methanation SNG production: 207.91 GWh/y
- H₂ export: 15.40 kt/y

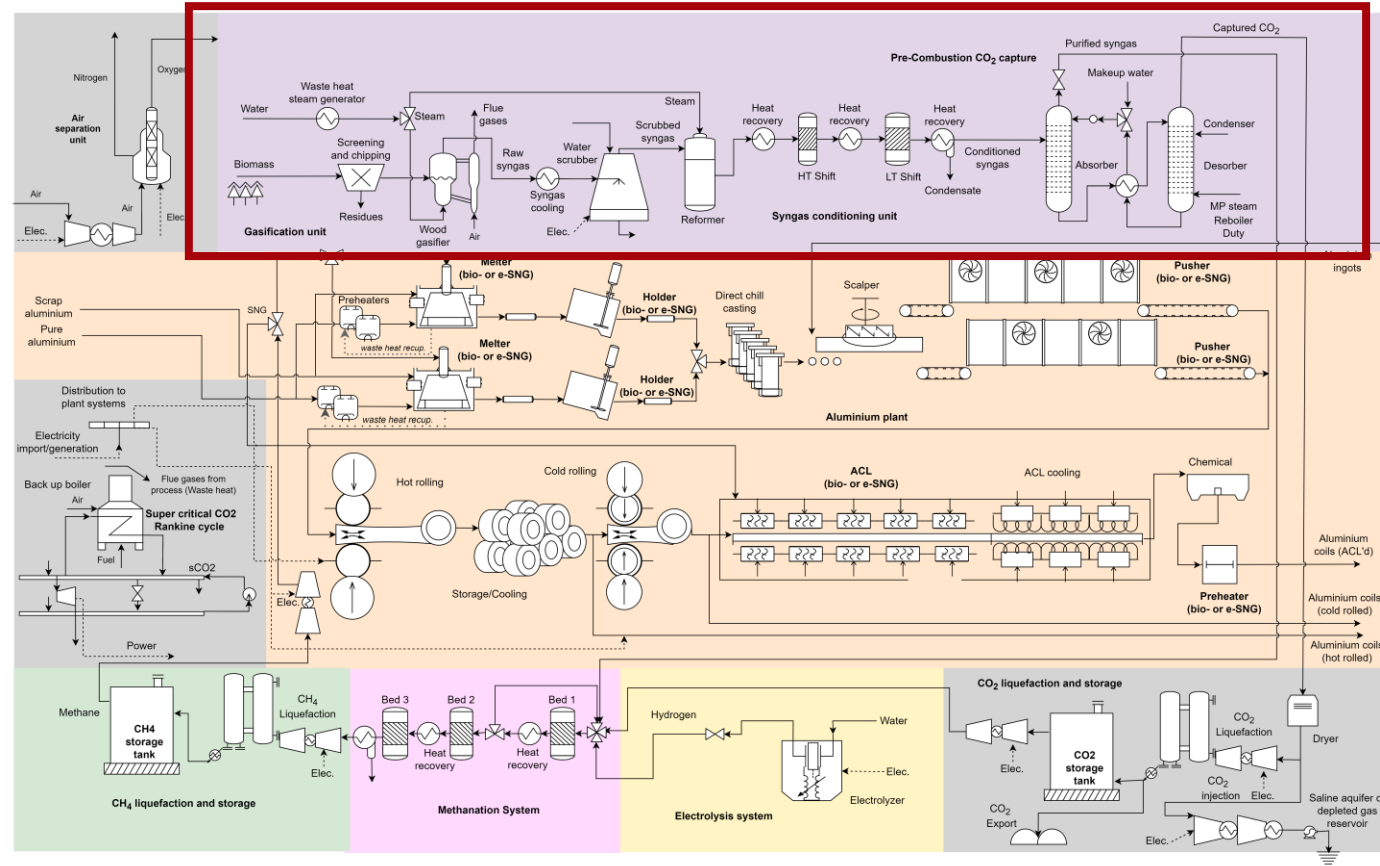
- Import CO₂ (compensate loss): 7.55 kt/y

CAPEX: 33,282,585 EUR/y
OPEX: -1,172,990,841 EUR/y

Biomass-derived SNG fuelled solution

Electricity is generated in a supercritical CO₂ cycle.

Large amount of waste heat available from biomass conversion units and stack gases.



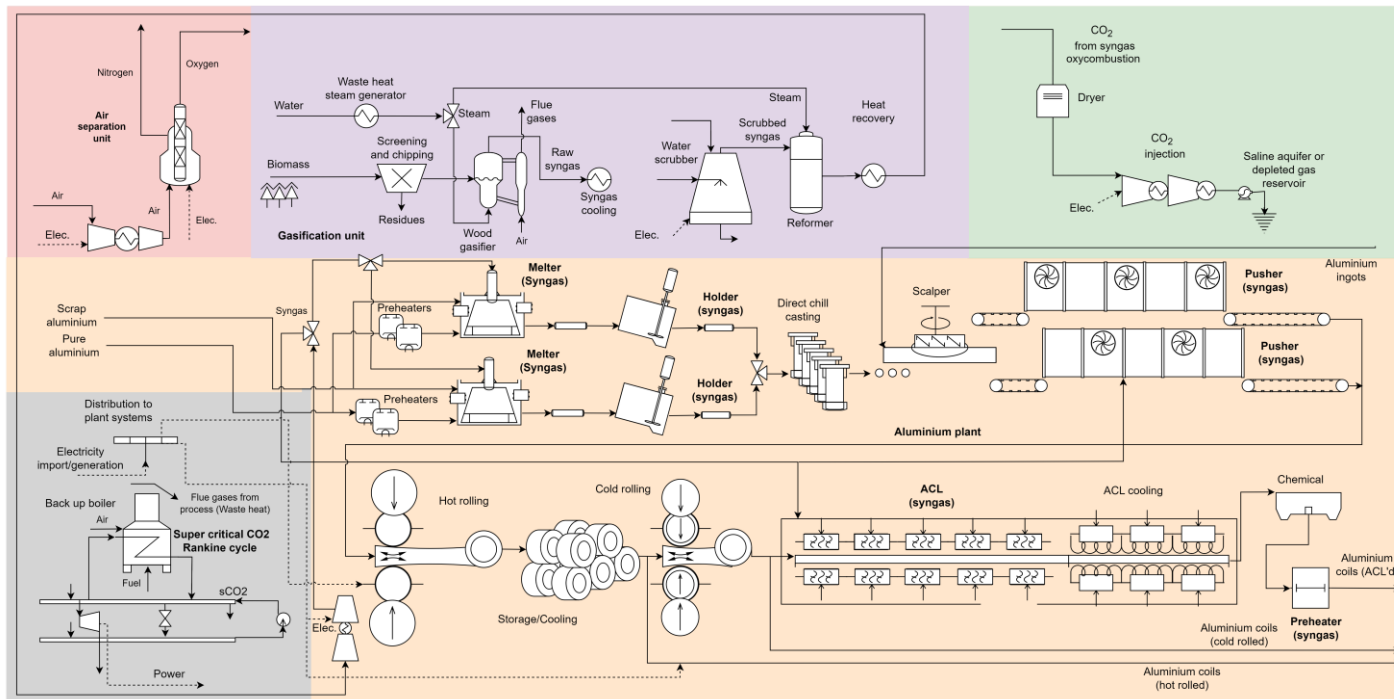
- Natural gas consumption: 0 GWh
- Biomass consumption: 333.25 GWh/y
- Electricity import: 100 GWh/y
- Electricity self-generation: 38 GWh/y
- Al plant power consumption 67.88 GWh/y
- Total direct biogenic emissions: 55 kt/y
- Indirect emissions EE grid 6.27 kt/y, Biom grid 4.68 kt/y
- CO2 injection: 73 kt/y (7.67 GWh/y)
- Diesel consumption: 0.23 kt/y
- SNG production in gasifier/methanation section: 208.04 GWh/y
- Pure CO2 production in gasifier/methanation section : 39.46 kt/y
- Flue stack CO2 emit in gasifier/methanation section : 36.72 kt/y
- Gasification section power consumption: 20 GWh/y
- Power consumption ASU: 17.56 GWh/y
- ASU oxygen production: 60.98 kt/y,
- ASU nitrogen production: 250 kt/y
- Oxygen export: 0 kt/y

CAPEX: 6,916,005 EUR/y
OPEX: -1,183,965,030 EUR/y

Biomass-derived syngas fuelled solution

Electricity is generated in a supercritical CO₂ cycle.

Large amount of waste heat available from biomass conversion units and stack gases.



- Natural gas consumption: 0 GWh/y
- Biomass consumption: 319.28 GWh/y
- Electricity import: 94 GWh/y
- Electricity self-generation: 28.71 GWh/y
- Power consumption ASU 17.28 GWh/y
- Power consumption injection 6.28 GWh/y
- Power consumption gasification unit: 6.39 GWh/y
- Oxygen production ASU 60 kt/y
- Nitrogen production ASU 246.64 kt/y
- Syngas from biomass: 232.57 GWh/y
- CO₂ in flue stack from gasifier emitted: 35.18 kt/y
- Al plant power consumption 67.88 GWh/y
- Total emissions (biogenic): 59.08 kt/y
- Indirect emissions: EE 5.91 kt/y, Biom 4.48 kt/y
- Diesel consumption: 0.23 kt/y
- Power consumption CO₂ injection: 59.85 GWh/y
- CO₂ injected: 59.85 kt/y

CAPEX: 6,305,551 EUR/y
OPEX: -1,183,894,335 EUR/y

Conclusions

	Base case	All electric	Power to Gas	SNG sCO ₂	Syngas sCO ₂
NG (GWh/y)	252	0	0	0	0
Biom (GWh/y)	0	0	0	333	319
EE import (GWh/y)	69	312	1,370	100	94
Self EE (GWh/y)	0	0	0	38	29
Total emissions (kt/y)	59 (fossil)	19 (fossil)	93	55	59
Indirect emissions					
NG (kt/y)	4.5	0	0	0	0
EE (kt/y)	4.3	19	86	6.3	5.9
Biom (kt/y)	0	0	0	4.68	4.48
CAPEX (EUR/y)	1,494,560	5,745,440	33,282,585	6,916,055	6,305,551
OPEX (EUR/y)	-1,077,183,970	-1,181,612,791	-1,172,990,841	-1,183,965,030	-1,183,894,335

Conclusions

- Hard to decarbonize heavy industries require **breakthrough approaches** for a proper management of waste heat recovery, cogeneration and carbon abatement technologies.
- Higher costs of natural gas will favor **electrification of heating supply** in a more efficient and environmentally friendly way.
- The carbon tax is an important factor that may boost the **deployment of carbon abatement** technologies and more efficient energy conversion systems, although may not be enough for **reducing the risk perception**.
- Electricity imported is used in the plant to **drive the auxiliary aluminium remelting processes**. A fraction of **electricity can be stored in a seasonal way** (short and long term) so that it can be used in a power-to-gas-to-heat approach. This process is more expensive capex-wise though.
- Installing a novel **CO₂-based district heating network** may increase efficiency, as the amount of power consumed is much lower than the heat supply using fired heaters (harvest energy from environment).

Acknowledgments

The authors would like to thank the Swiss Federal Office of Energy for funding this research work in the frame of the Net Zero Lab, through the project grants “Sustainable natural gas (SNG) and aluminium production via biomass gasification and enhanced waste heat recovery in Novelis plant in Sierre City” and “Enhanced waste heat recovery approach for the reduction of fuel consumption in the aluminium industry”.

Thanks for your attention

Gracias por su atención