Carbon footprint - Calculation for aluminium production processes

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Aachen, 23.03.2023

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Carbon Accounting – Product Carbon Footprint and Corporate Carbon Footprint

Product Carbon Footprint

One specific product is evaluated throughout its life cycle.

Norms and standards:
- PAS 2050
- GHG Protocol: Product Accounting and Reporting standard
- DIN ISO EN 14067
- DIN ISO EN 14027

Carbon Accounting

Corporate Carbon Footprint

All production processes of a company are evaluated, together with upstream and downstream processes following a life cycle approach.

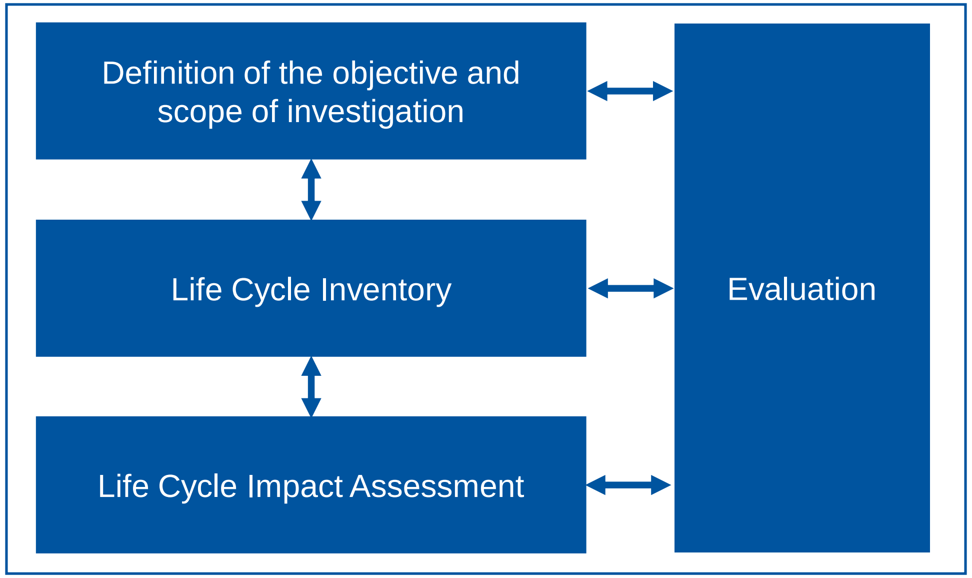
Norms and standards:
- GHG Protocol: Corporate Accounting and Reporting standard
- DIN ISO EN 14064

Based on Life Cycle Assesments (LCA) and Material Flow Analysis (MFA)

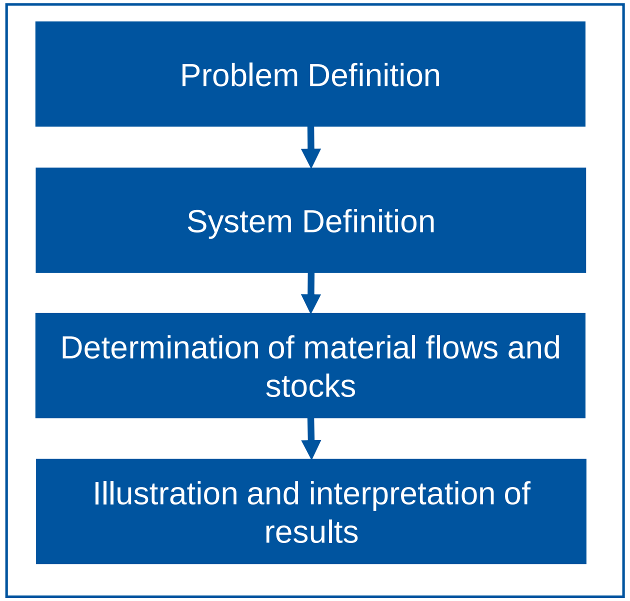
Foundations of Life Cycle Assesments (LCA) and Material Flow Analysis (MFA)

- LCA: Compilation and assessment of input and output flows and potential environmental impacts of a product system during its life cycle.
- MFA: Systematic assessment of the state and changes of flows and stocks of materials within a system defined in space and time.

Phases of a life cycle assessment [1]



Phases of a material flow analysis [2]

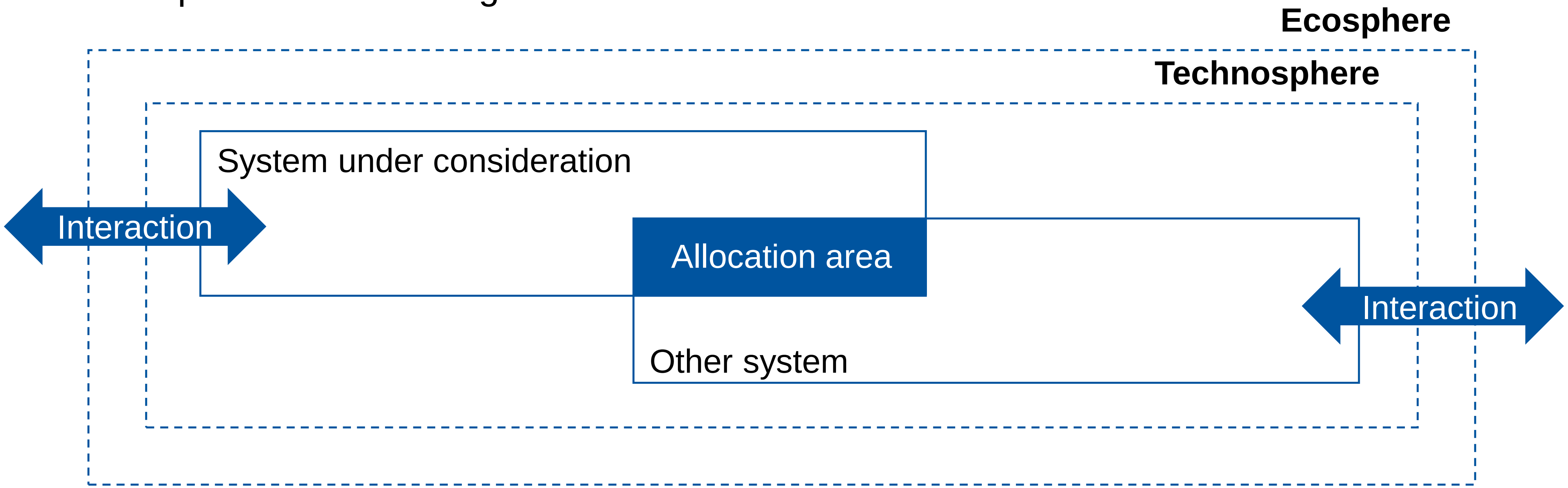


Source: [1] DIN EN ISO 14040, DIN EN ISO 14044, [2] Brunner et al. 2004

Methodology of Product Carbon Footprint (PCF) calculation

Definition of the problem/objective and the scope of the investigation

- Definition of objectives
- Definition of the product system, functional unit and reference flow
- Definition of the scope and methodologies



Source: DIN EN ISO 14040, Klöpffer (2017); Sundmacher (2002)

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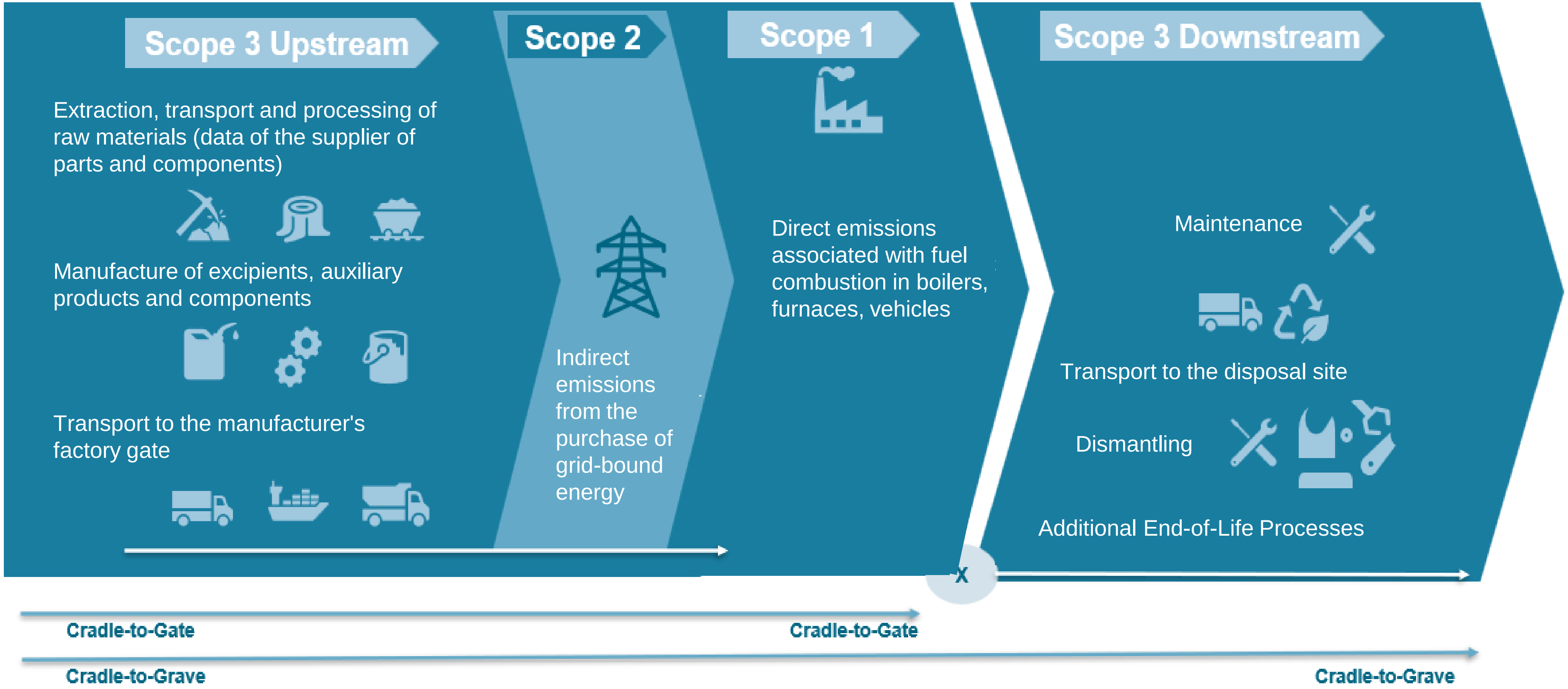
Methodology of Product Carbon Footprint (PCF) calculation

Definition of different Scopes



Source: VDMA 2022

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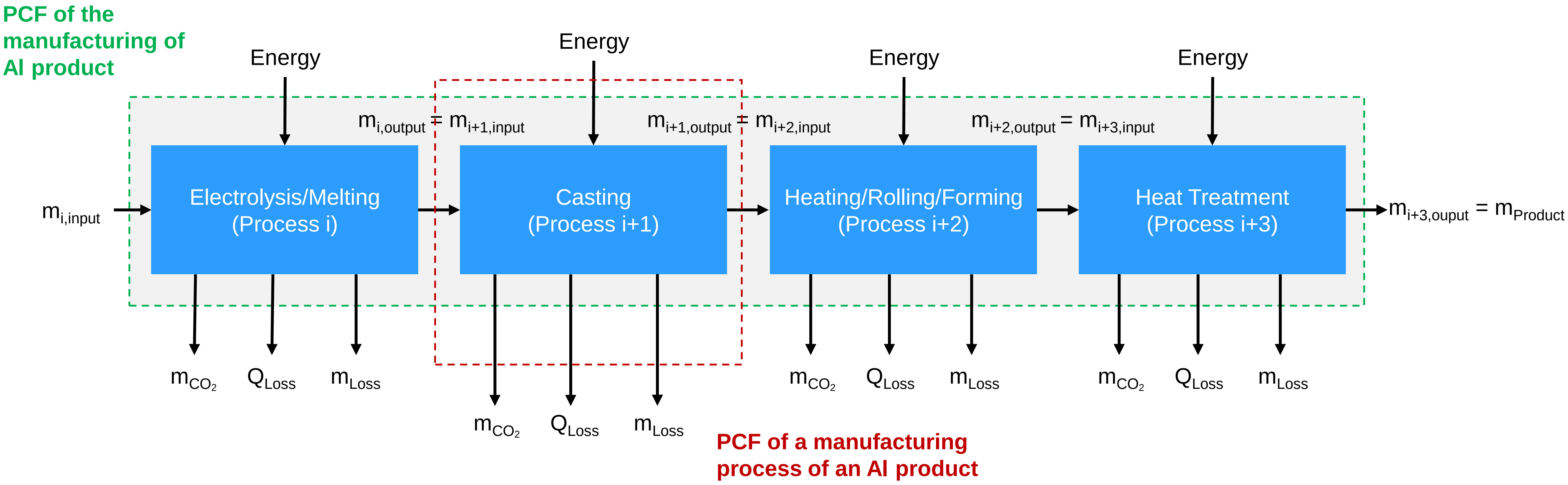
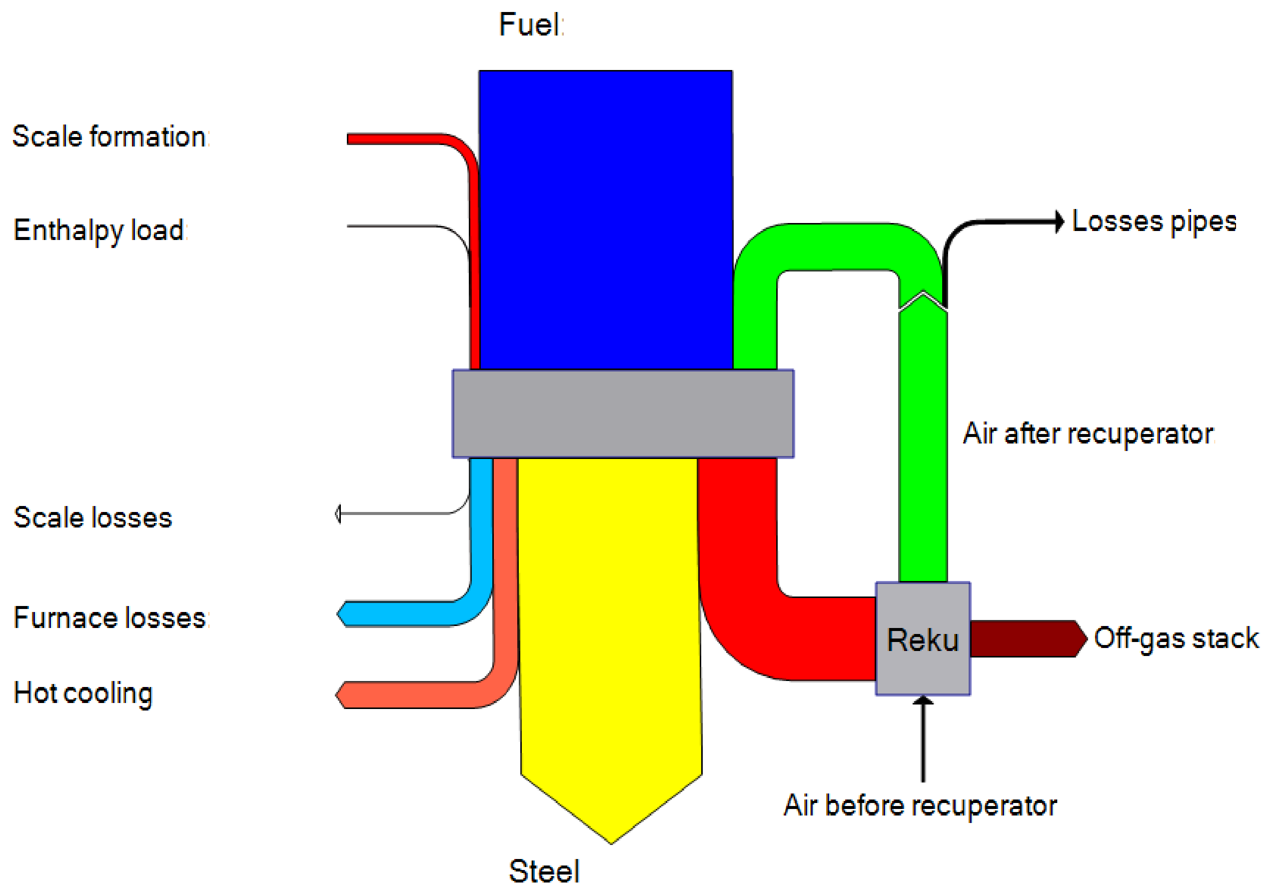
Exemplary product systems and system boundaries of aluminium manufacturing



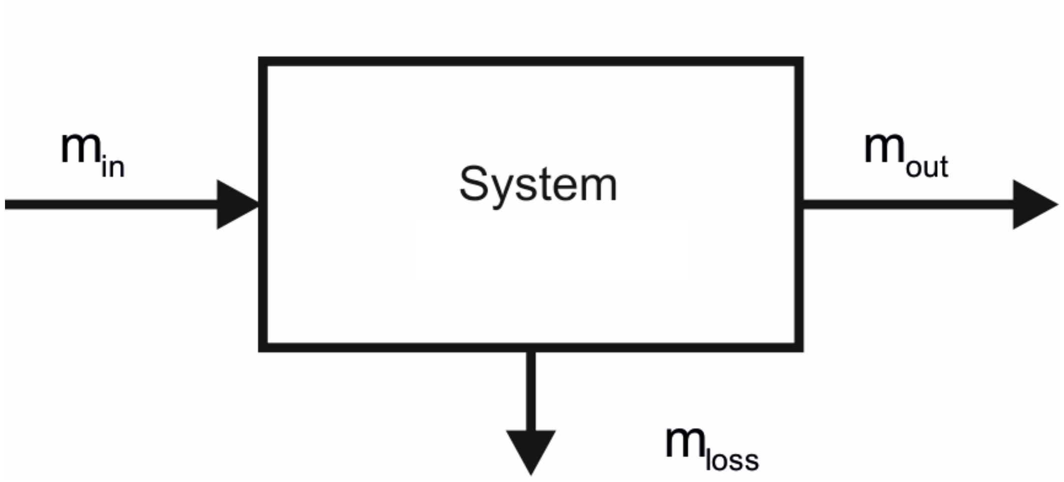
Methodology of Product Carbon Footprint (PCF) calculation

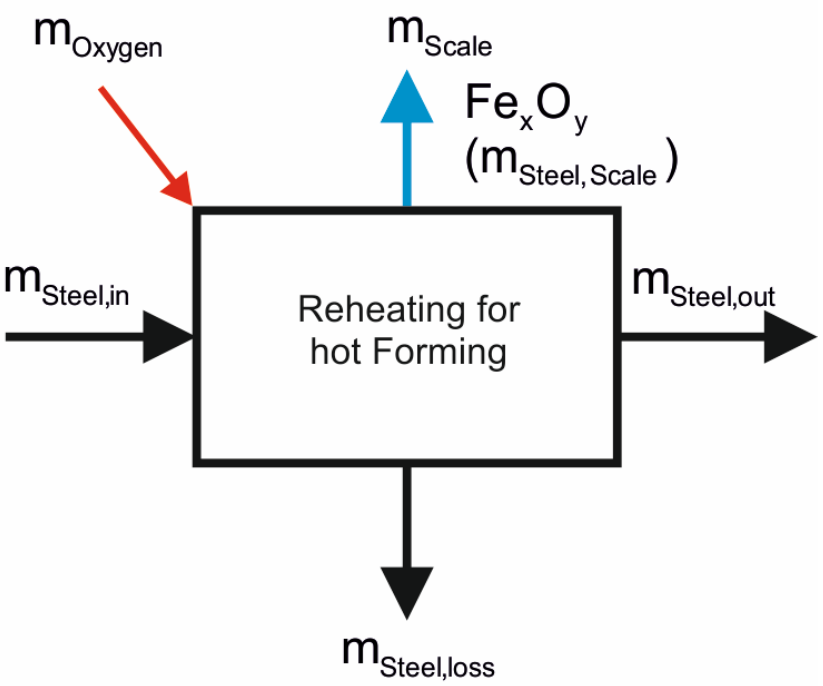
Life Cycle Inventory and determination of material flows and stocks

- Data collection
- Data calculation
- Assignment to Process Modules
- Modeling of the product system



Principle of mass balances (with and without chemical reactions)

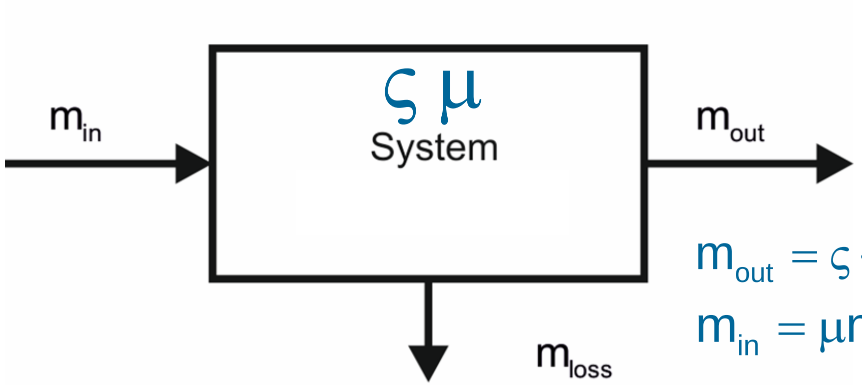




$$m_{in} = m_{out} + m_{loss}$$

$$m_{Steel,in} + m_{Oxygen} = m_{Steel,out} + \Delta m_{Steel,Scrap} + \Delta m_{Scale}$$

Mass balance – Yield and excess input



$$m_{out} = \varsigma \cdot m_{in}$$

$$m_{in} = \mu m_{out}$$

$$m_{loss} = (1-\varsigma) m_{in}$$

$$m_{loss} = (\mu - 1) m_{out}$$

Yield

$$\varsigma = \frac{m_{out}}{m_{in}} = \frac{m_{in} - m_{loss}}{m_{in}} = 1 - \frac{m_{loss}}{m_{out}}$$

Excess input

$$\mu = \frac{m_{in}}{m_{out}} = \frac{m_{in}}{m_{in} - m_{loss}} = \frac{1}{1 - \frac{m_{loss}}{m_{in}}} = \frac{1}{\varsigma}$$

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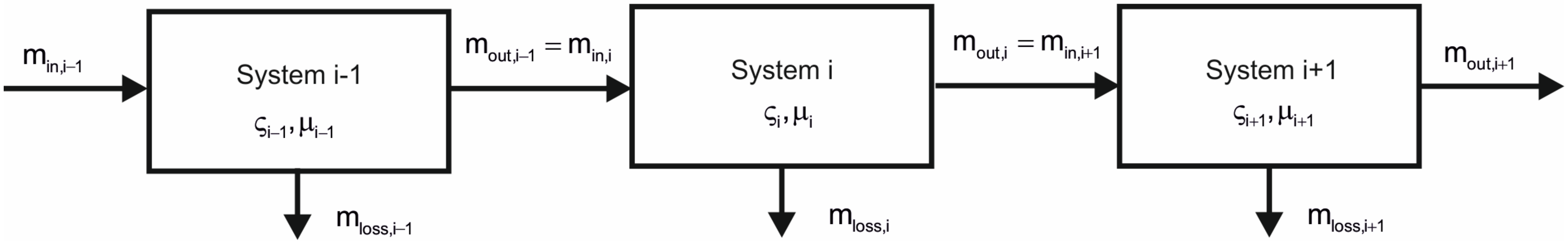
Mass balance – Combination of process modules

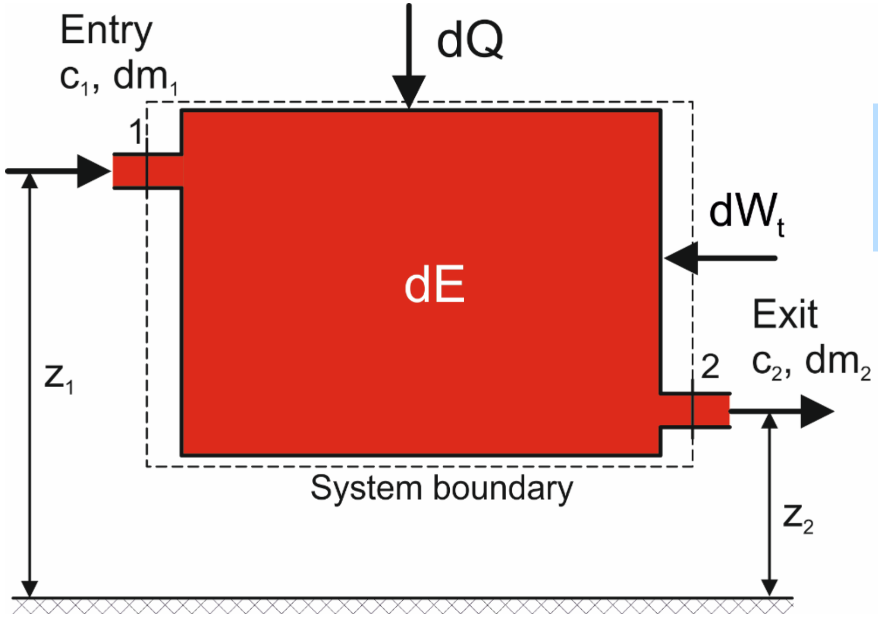


$$\varsigma_{tot} = \frac{m_{out,1}}{m_{in,1}} \frac{m_{out,2}}{m_{in,2}} \frac{m_{out,3}}{m_{in,3}} \ldots = \varsigma_1 \cdot \varsigma_2 \cdot \varsigma_3 \cdot \ldots = \prod_{i=1}^{n} \varsigma_i$$

$$\mu_{tot} = \frac{m_{in,1}}{m_{out,1}} \frac{m_{in,2}}{m_{out,2}} \frac{m_{in,3}}{m_{out,3}} \ldots = \mu_1 \cdot \mu_2 \cdot \mu_3 \cdot \ldots = \prod_{i=1}^{n} \mu_i$$

Energy balance principles

Sum of the entering energy flows	-	Sum of the outgoing energy flows	=	Time depended change of the stored energy in the control volume

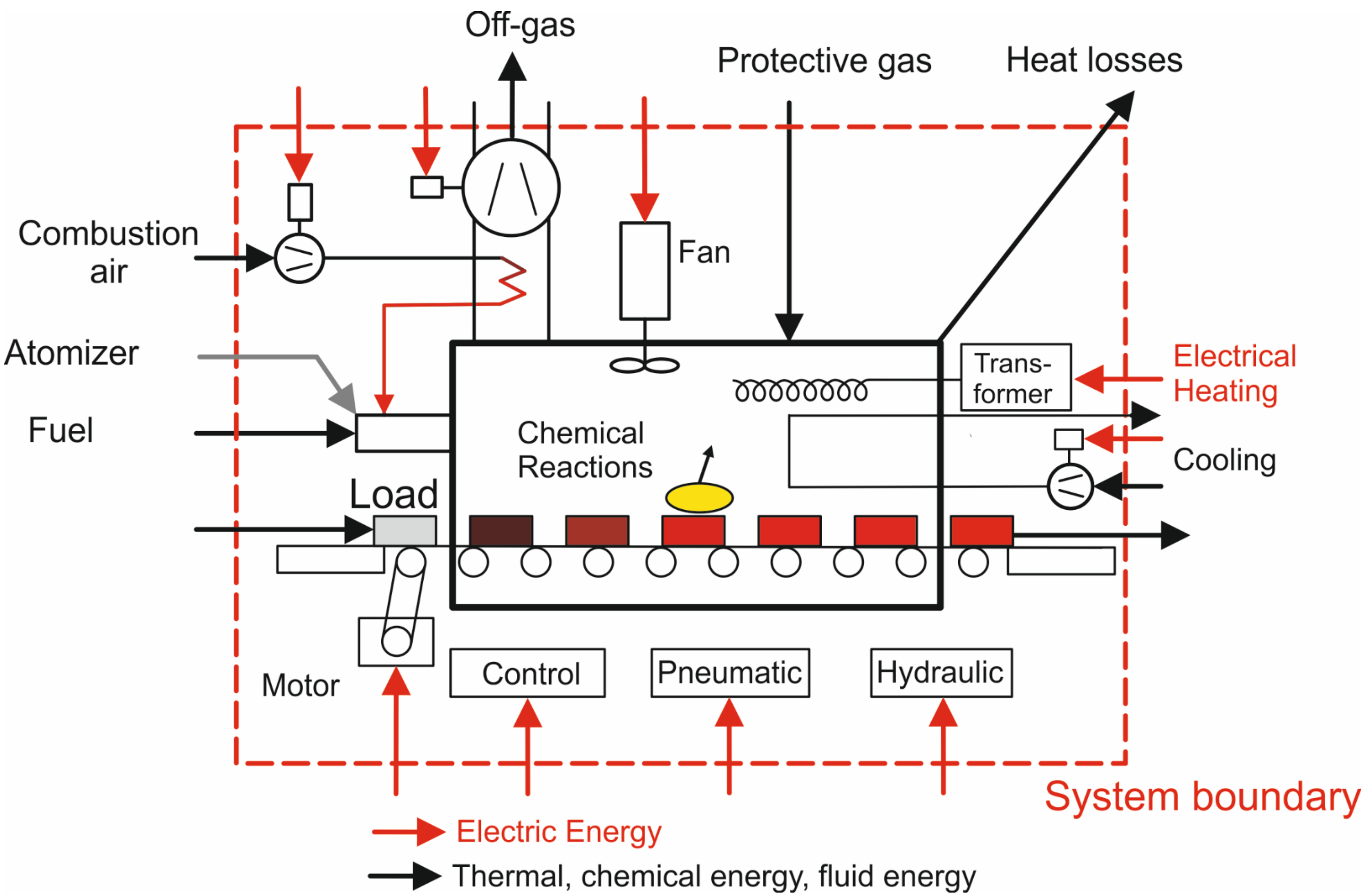


$$dQ + dW_t + \left(h_1 + \frac{c_1^2}{2} + gz_1\right)dm_1 - \left(h_2 + \frac{c_2^2}{2} + gz_2\right)dm_2 = dE$$

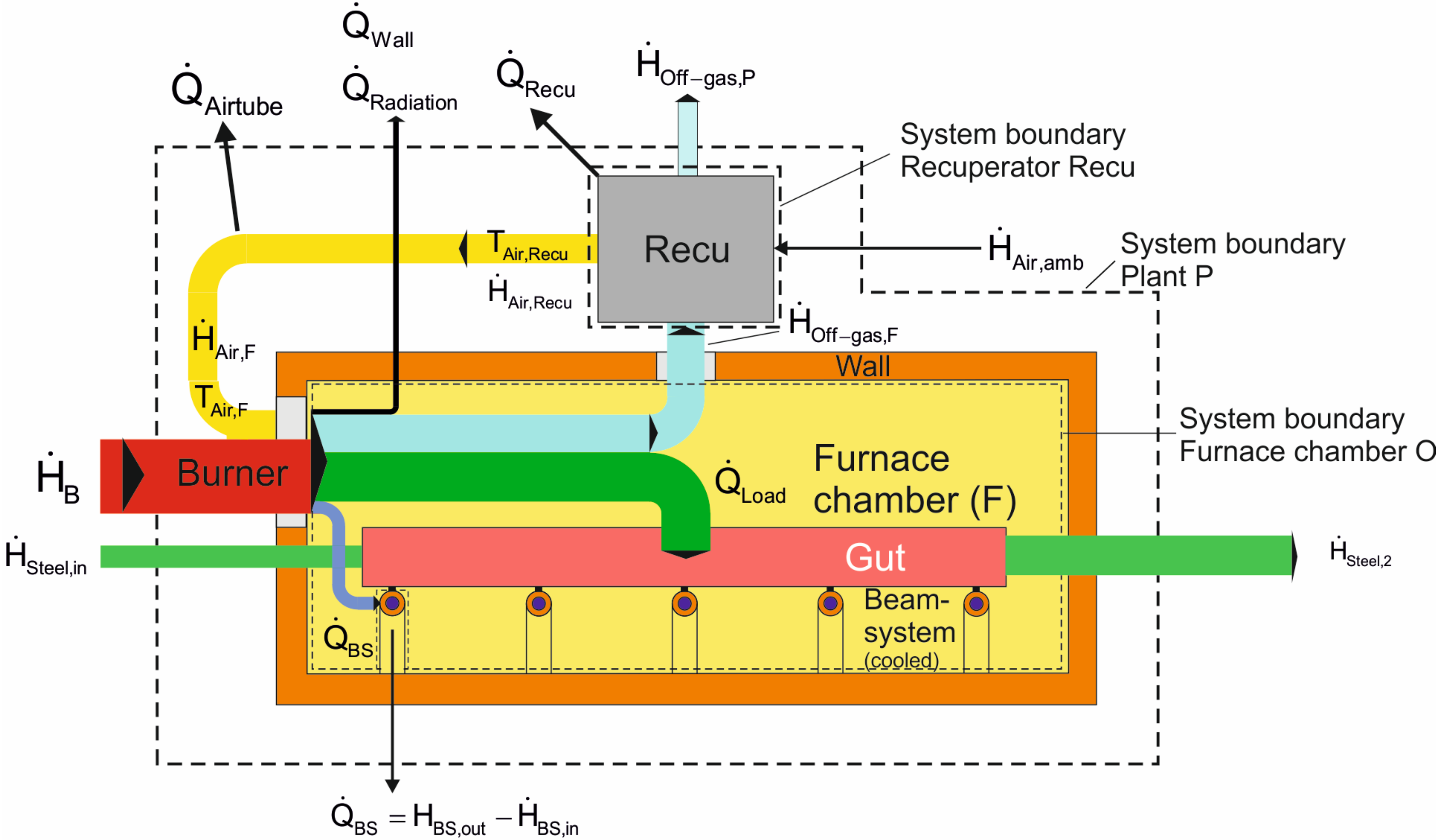
Q	Heat	W_t	Technical work
h_i	Specific enthalpy	c_i	Velocity
g	Gravity	z_i	Geodetic hight
m_i	Mass	E	Energy

1 ≙ in 2 ≙ out

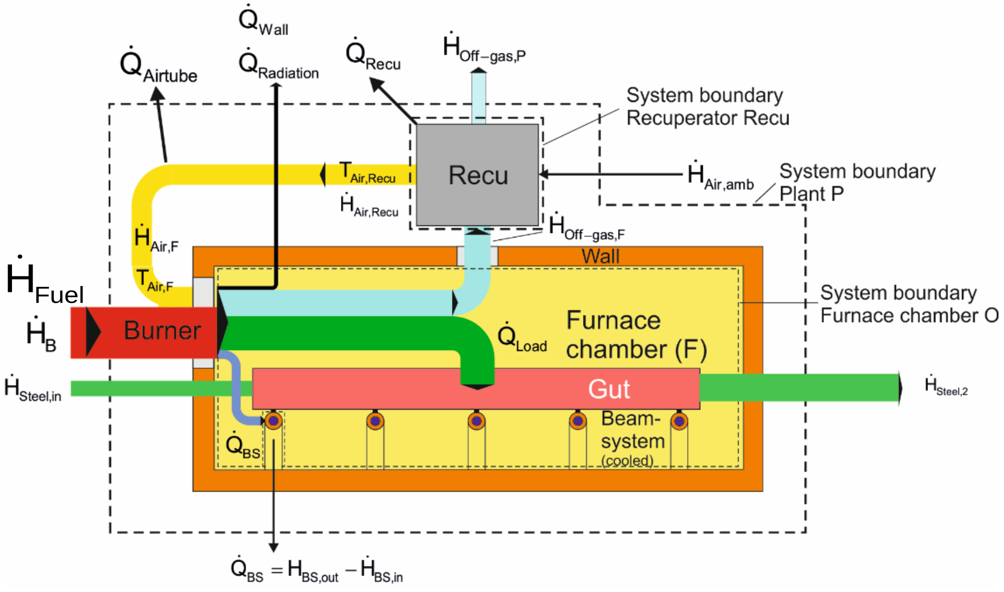
Mass- and energy balances of industrial processes



Mass- and energy balances of industrial processes



Energy balance – Definition of key parameters



Total system (P)

$$\dot{H}_{Fuel} + \dot{H}_{Air,amb} - \dot{H}_{Steel,2} + \dot{H}_{Steel,1} - \dot{H}_{Off-gas,P} - \sum_i \dot{Q}_{i,P} = 0$$

Furnace chamber (F)

$$\dot{H}_{Fuel} + \dot{H}_{Air,F} - \dot{H}_{Steel,2} + \dot{H}_{Steel,1} - \dot{H}_{Off-gas,F} - \sum_i \dot{Q}_{i,F} = 0$$

Recuperator (Recu)

$$\dot{H}_{Off-gas,F} - \dot{H}_{Off-gas,P} + \dot{H}_{Air,amb} - \dot{H}_{Air,Recu} - \sum_i \dot{Q}_{i,Recu} = 0$$

Energy balance – Definition of key parameters

Overall system - plant (P)

$$\dot{H}_{Fuel} + \dot{H}_{Air,amb} - \dot{H}_{Steel,2} + \dot{H}_{Steel,1} - \dot{H}_{Off-gas,P} - \sum_i \dot{Q}_{i,P} = 0$$

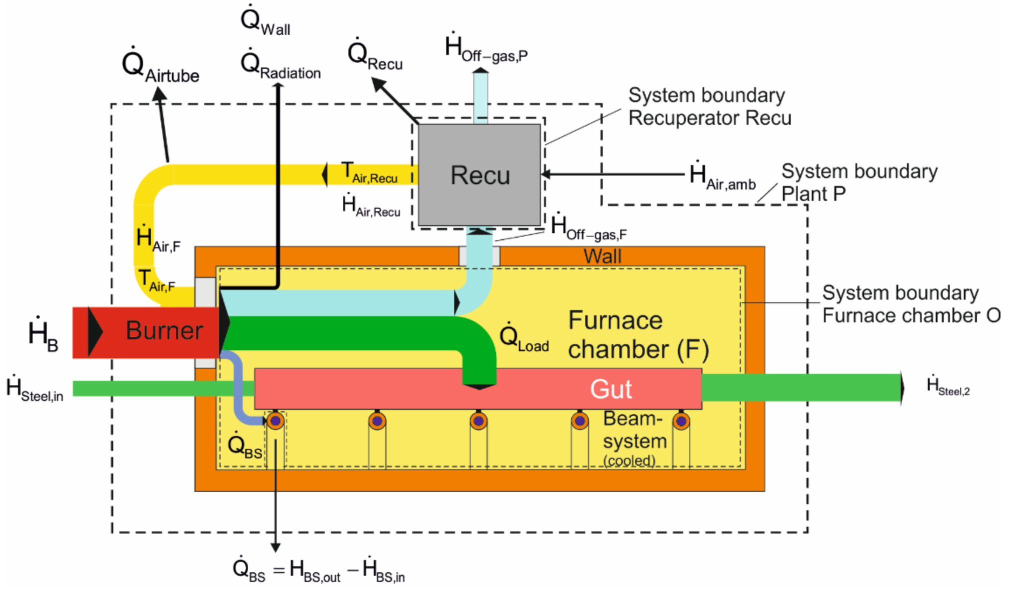
Combustion or heating medium (fuel) efficiency

$$\eta_{c,P} = \frac{\dot{H}_{Fuel} - \dot{H}_{Off-gas,P}}{\dot{H}_{Fuel}} = 1 - \frac{\dot{H}_{Off-gas,P}}{\dot{H}_{Fuel}}$$

$$\dot{H}_{Air,amb} = 0$$

Reactor efficiency

$$\eta_{r,P} = \frac{\dot{H}_{Steel,2} - \dot{H}_{Steel,1}}{\dot{H}_{Fuel} - \dot{H}_{Off-gas,P}} = \frac{\dot{H}_{Steel,2} - \dot{H}_{Steel,1}}{\dot{H}_{Steel,2} - \dot{H}_{Steel,1} + \sum_i \dot{Q}_{i,P}} = \frac{1}{1 + \frac{\sum_i \dot{Q}_{i,P}}{\dot{H}_{Steel,2} - \dot{H}_{Steel,1}}}$$



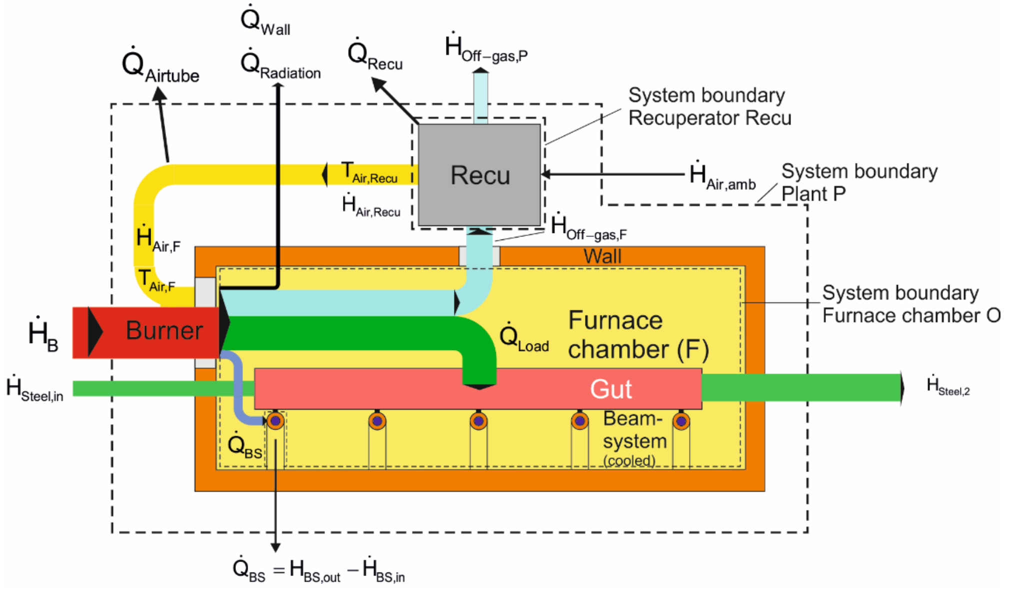
Energy balance – Definition of key parameters

Overall system - plant (P)

$$\dot{H}_{Fuel} + \dot{H}_{Air,amb} - \dot{H}_{Steel,2} + \dot{H}_{Steel,1} - \dot{H}_{Off-gas,P} - \sum_i \dot{Q}_{i,P} = 0$$

Relations of the efficiencies

$$\eta_{tot,P} = \frac{\dot{H}_{Steel,2} - \dot{H}_{Steel,1}}{\dot{H}_{Fuel}} = \eta_{c,P}\,\eta_{r,P}$$



Energy balance – Combustion efficiency

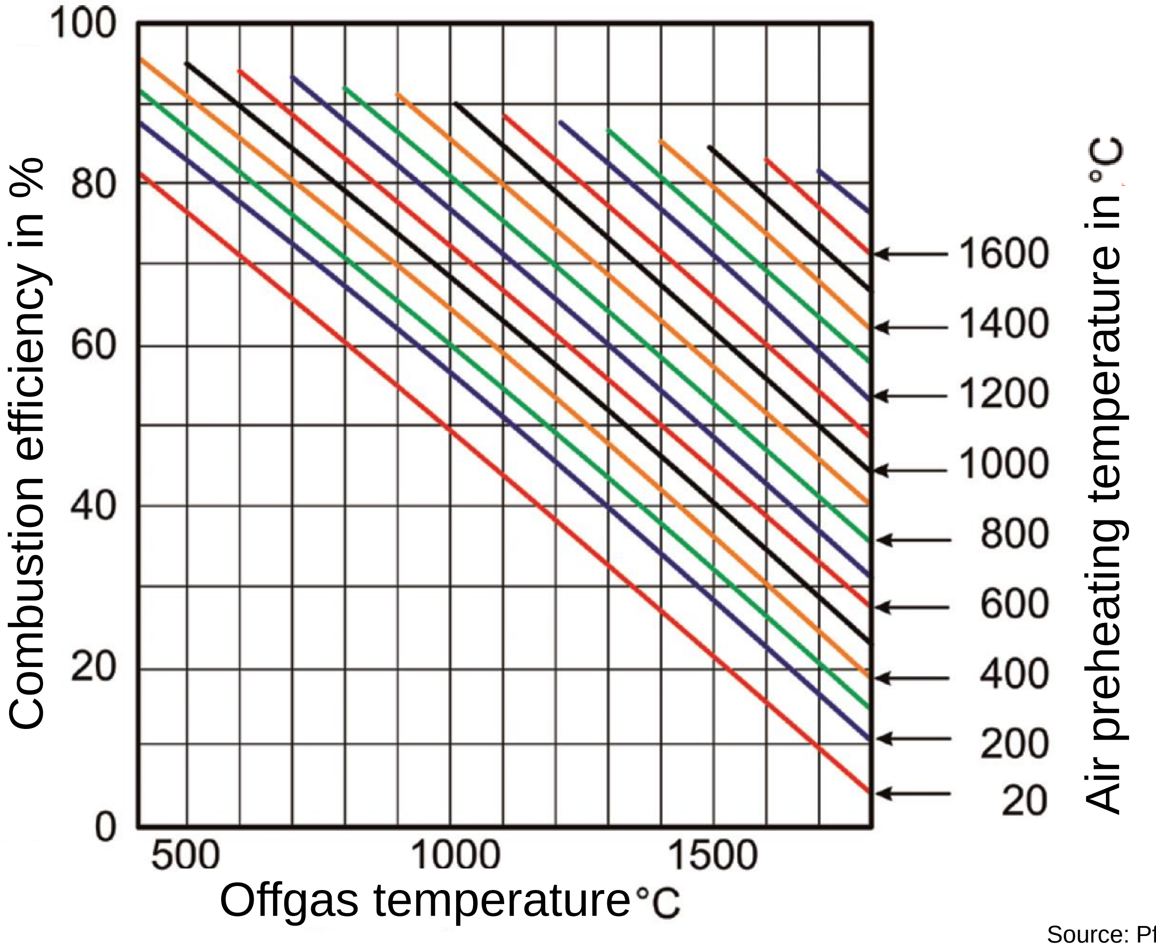
$$\eta_c = 1 - \frac{H_{Off-gas}}{H_{Fuel}}$$

$H_{off\text{-}gas}/H_{Fuel}$ = f (fuel, off-gas temperature $T_{off\text{-}gas}$, air temperature T_{air}, air ratio λ resp. o_2)

$$\frac{H_{Off-gas}}{H_{Fuel} + H_{Air}} = C_1 T_{Off-gas} - C_2 T_{Air} + C_3 \left(T_{Off-gas} - T_{Air}\right) o_{2,dry}$$

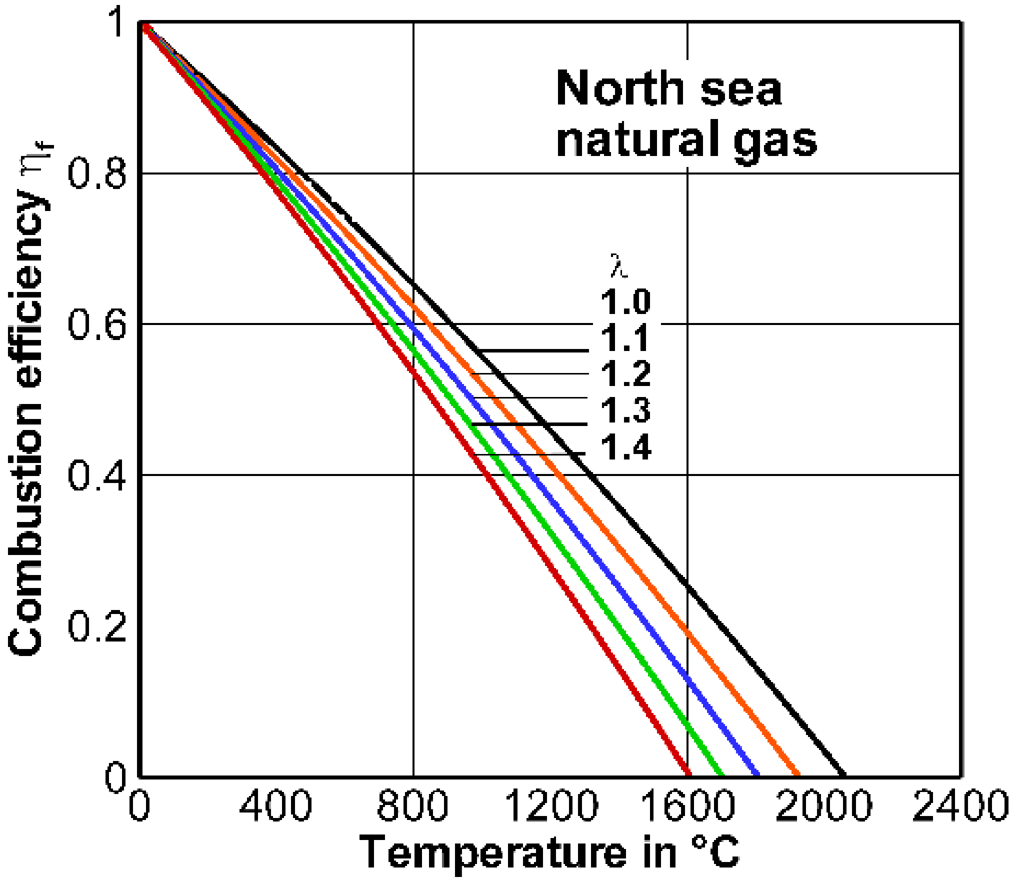
Fuel	C_1 in °C^{-1}	C_2 in °C^{-1}	C_3 in °C^{-1}
CH_4 (Natural gas)	$4.43 \cdot 10^{-4}$	$1.34 \cdot 10^{-4}$	$2.70 \cdot 10^{-3}$
C_3H_8 (Propane)	$4.25 \cdot 10^{-4}$	$1.26 \cdot 10^{-4}$	$3.11 \cdot 10^{-3}$
H_2 (Hydrogen)	$401 \cdot 10^{-4}$	$1.04 \cdot 10^{-4}$	$2.81 \cdot 10^{-3}$
Blast furnace gas	$7.69 \cdot 10^{-4}$	$1.78 \cdot 10^{-4}$	$3.90 \cdot 10^{-3}$
Coke oven gas	$4.26 \cdot 10^{-4}$	$1.18 \cdot 10^{-4}$	$2.50 \cdot 10^{-3}$
BOF gas	$4.46 \cdot 10^{-4}$	$1.02 \cdot 10^{-4}$	$2.86 \cdot 10^{-3}$

Energy balance – Combustion efficiency



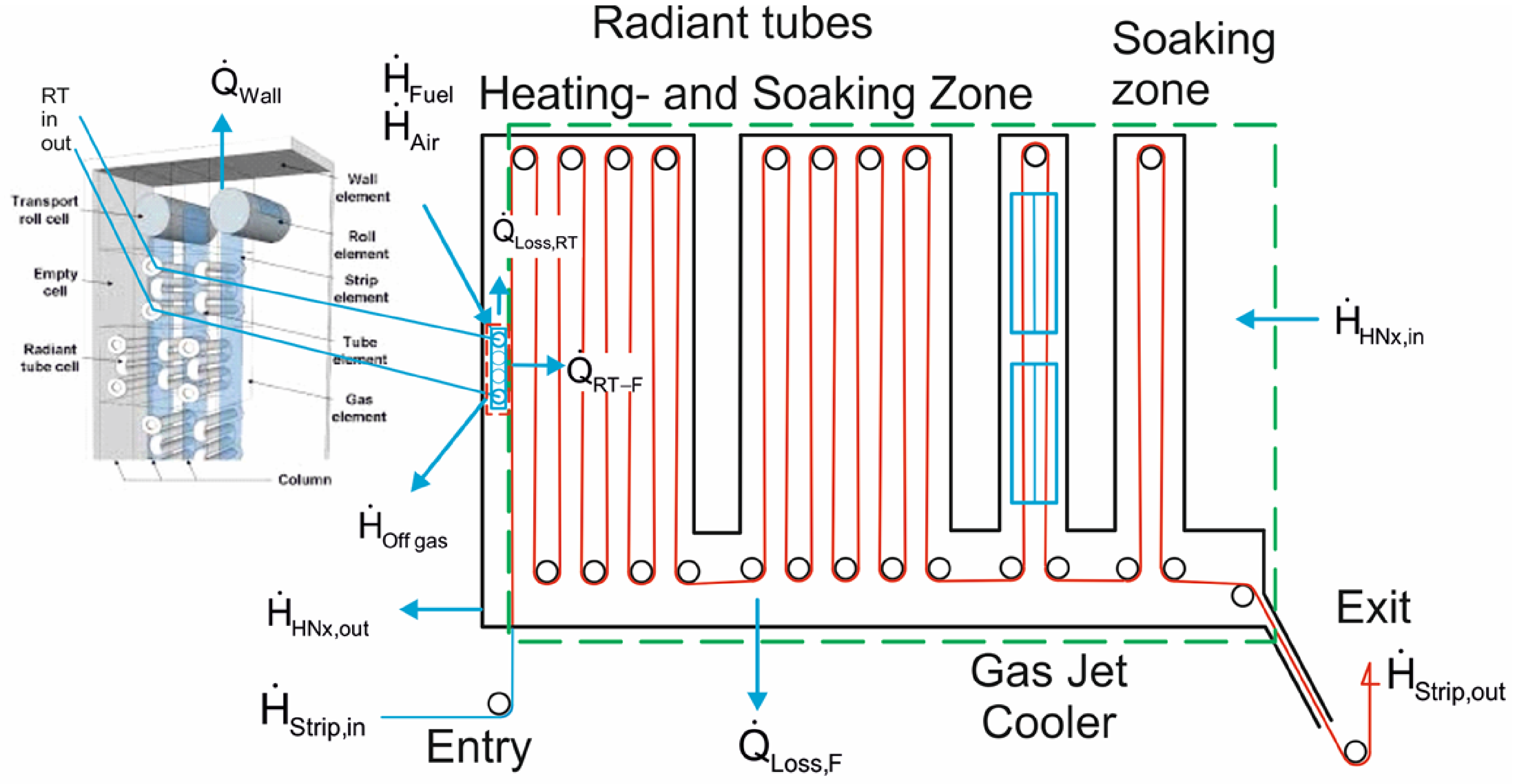
Source: Pfeifer – Handbuch Industrielle Wärmetechnik (2013)

Energy balance – Combustion efficiency



Source: Pfeifer – Handbuch Industrielle Wärmetechnik (2013)

Energy balance – Different system boundaries



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Mass- and energy balances of industrial processes

Data gathering

TRANSPORT (From storage to furnace)			
Transport medium (Truck, conveyor belt, forklift…)	**DISTANCE**	**UNIT**	**COMMENT**

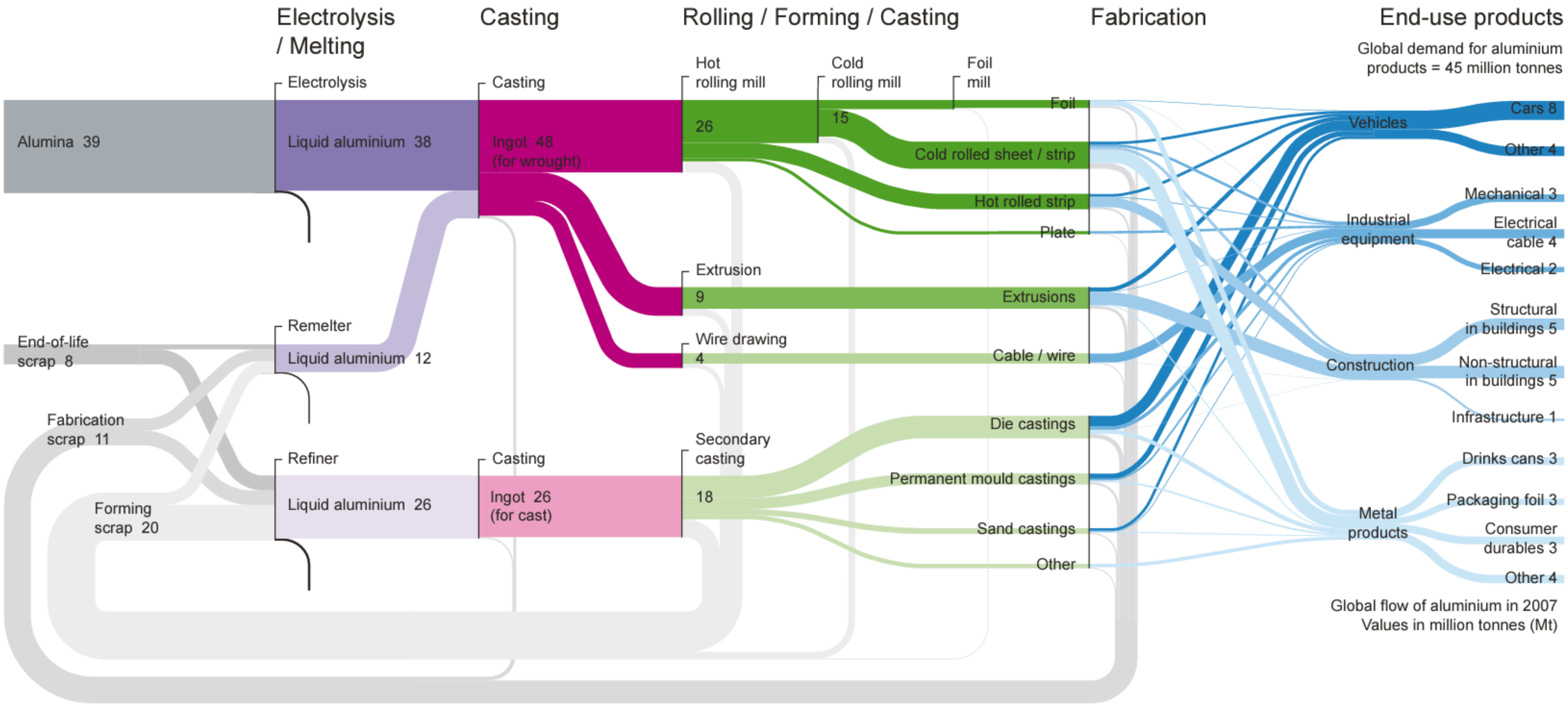
ENERGY SOURCE (Energy source to provide heat)	**CONSUMPTION**	**UNIT**	**ORIGIN** (Where is this energy coming from? e.g. 100% Renewable, Nuclear, coal…)
Natural gas			
Electricity			
Other			

INPUT	QUANTITY	UNIT	COMMENT
Raw materials (materials entering the furnace)			
Consumables (Electrodes, oil, lubricants…)			
Water (cooling water, distilled water..)			

OUTPUT	QUANTITY	UNIT	COMMENT
Product (Material leaving the furnace)			
Co-product (Valuable material generated during the production of other material)			
product			
Emissions to air			
Emissions to water			
Emissions to soil			
Other			

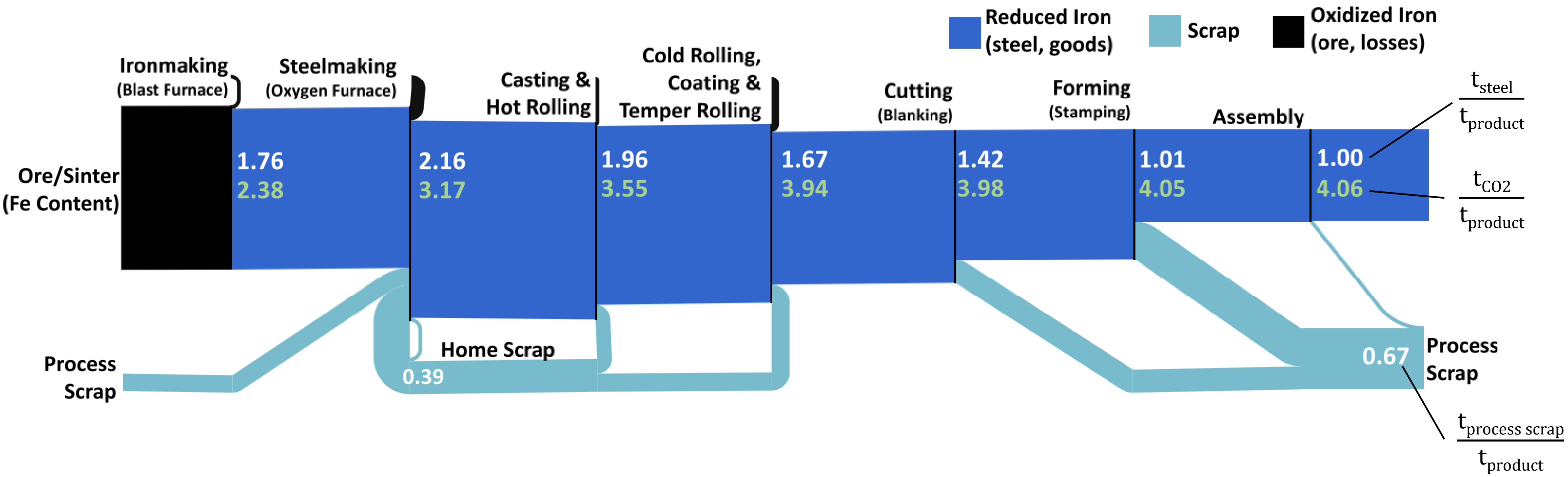
- Data often based on ranges
- Depending on the product, data has to be converted to fit the format x/product or $x/t_{product}$

Mass- and energy balances of industrial processes



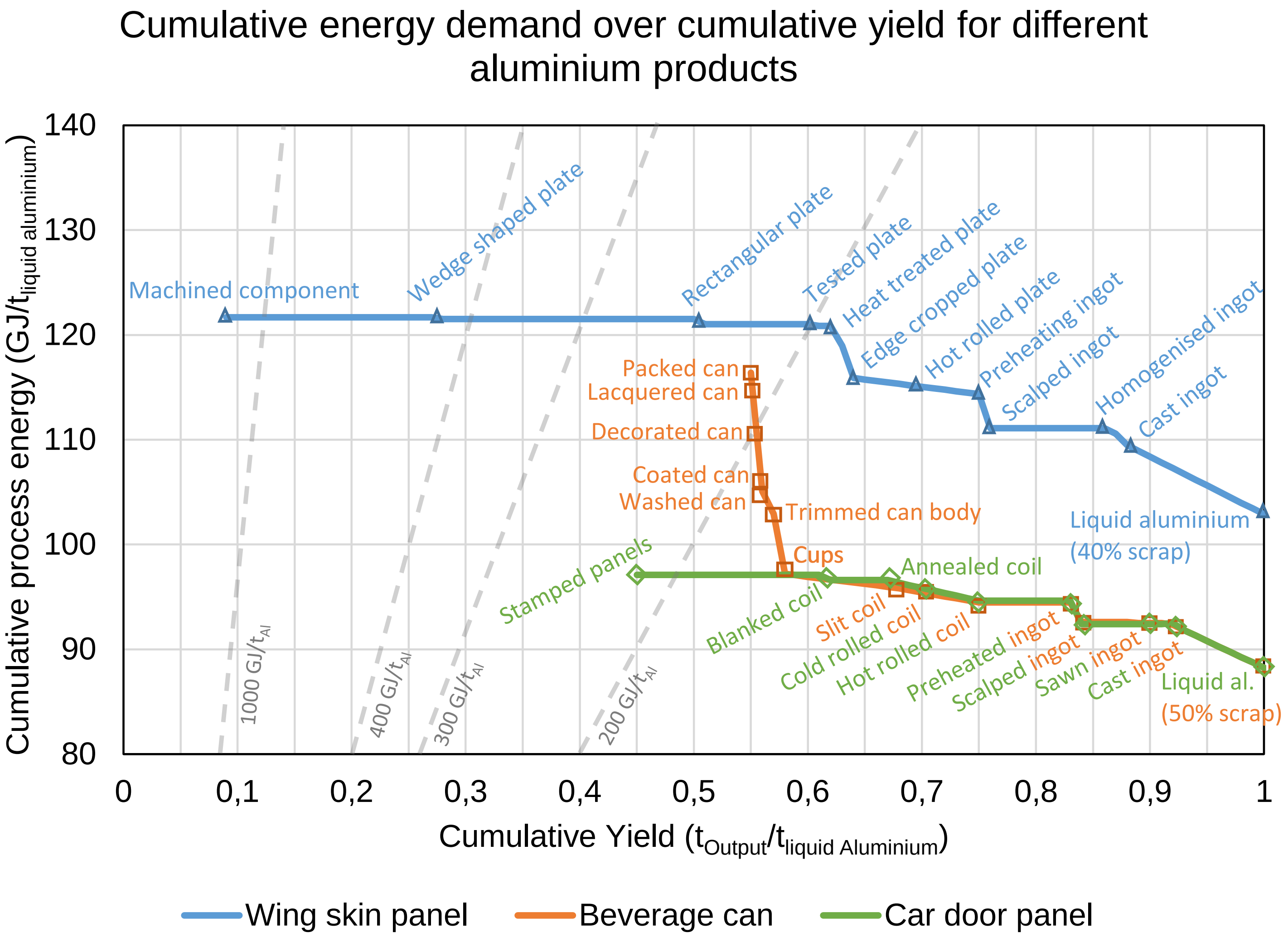
Source: Allwood, Cullen, et al – Going on a metal diet (2011)

Influence of combining KPIs in a process chain



Source: Flint et al – Scrap, carbon and cost savings from the adoption of flexible nested blanking (2019)

Mass- and energy balances of industrial processes



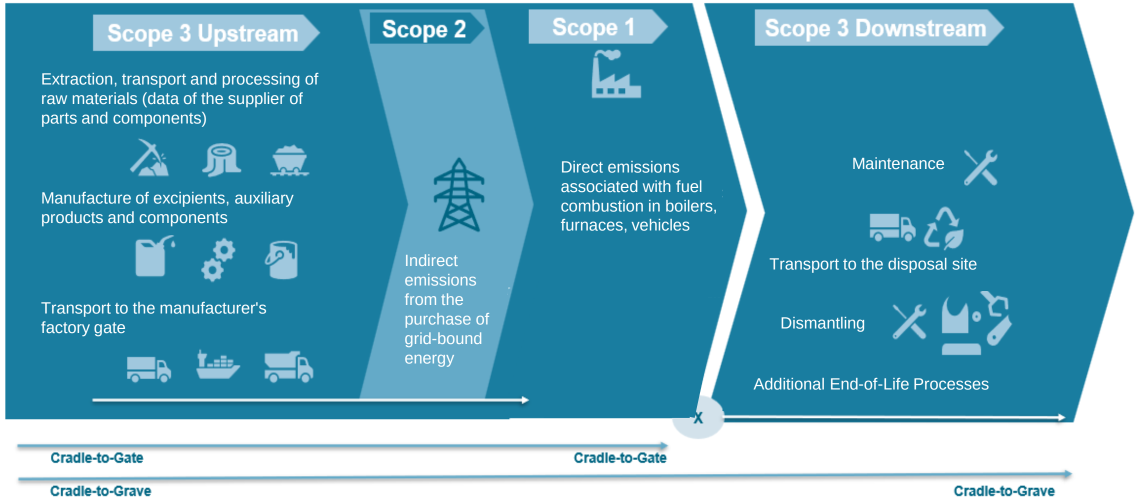
Source: Milwood et al. 2011

Mass- and energy balances of industrial processes

CO_2-Emissions

Scope 1: Direct emissions from fuel combustion

$$\gamma_{fuel,CO_2} = \frac{m_{CO_2}}{m_{product}} = e_{fuel} \cdot f_{fuel,CO_2} \qquad in \left[\frac{t_{CO_2}}{t_{product}}\right]$$



Scope 2: Indirect CO_2-emissions from the electricity grid

$$\gamma_{electricity,CO_2} = \frac{m_{CO_2\,(indirect)}}{m_{product}} = e_{el} \cdot f_{electricity,CO_2} \qquad in \left[\frac{t_{CO_{2,indirect}}}{t_{product}}\right]$$

Calculation software, databases and emission factors

Energy emission factors (Scope 1 and 2)

Constant emission factor of natural gas

Fuel	f_{fuel} according to UBA/DEHSt in in kg_{CO2}/kWh [1]	Calculated f_{fuel} in kg_{CO2}/kWh according to [2]
Russian Natural Gas H	0.201	0.197
Holland Natural Gas L	0.201	0.202

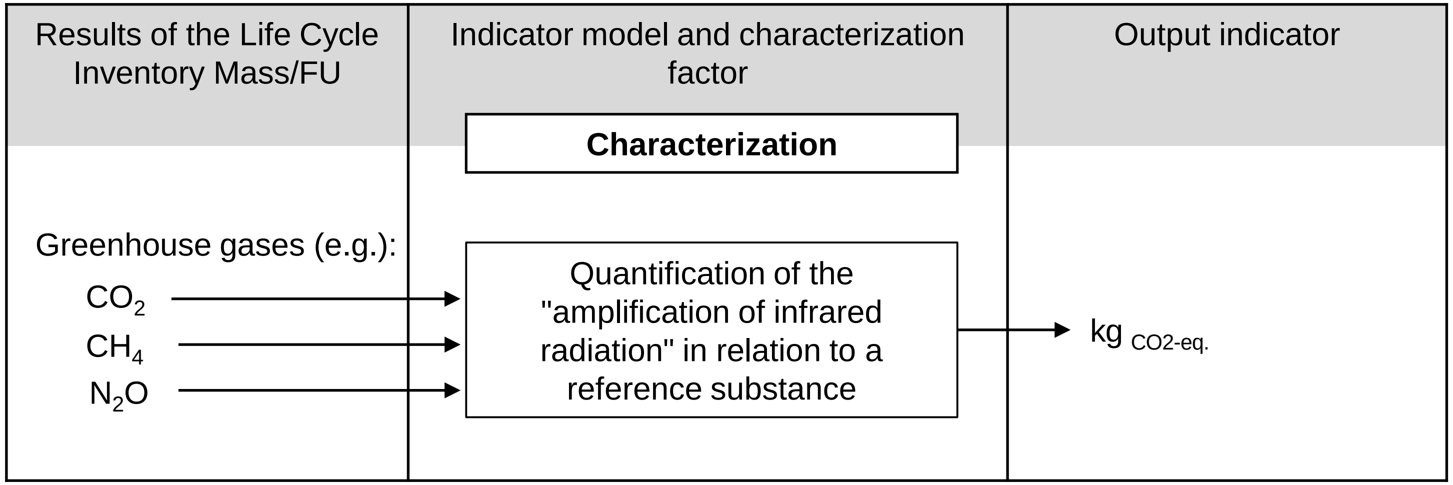
Dynamic emission factor developement of the general electricity mix (ger)

Year	Ø $f_{electricity}$ of the ger. electricity mix in $kg_{CO2\text{-}eq.}$/kWh
2020	0.375
2030 - 2040	0.230
2040 - 2050	0.154
2050	0.017

Source: [1] UBA (2022), DEHSt (2006); [2] nach Pfeifer et al. (2018)

Life Cycle Impact Assessment

- Calculation of impact indicator values (characterization)
- Standard characterization is the global warming potential for the next 100 years (GWP100) in $kg_{CO2\text{-}eq.}$



If an activity emits simultaneously 1 kg CO_2 (GWP100 = 1) and 1 kg methane (GWP100 = 28), the total emissions in the form of GWP100 is 29 $kg_{CO2\text{-}eq.}$

Source: Klöpffer (2017)

Calculation software, databases and emission factors

Software and Databases

Name	Homepage	License	Language	Access	Subject area
Stichting Sustainability Impact Metrics (SSIM)	https://www.ecocostsvalue.com/	Without fee	English	Export as Excel file	LCA database, Eco Cost Database
ISOPA	https://www.isopa.org/	Without fee	English	web-based; Export as pdf or Excel file	LCA database
GaBi (Sphera)	sphera.com	With fee	English	web-based	LCA database
Ecoinvent	http://www.ecoinvent.org/	With fee	English	web-based	LCA database
SimaPro	https://simapro.com/	With fee	English	web-based	LCA database
ELCD	https://eplca.jrc.ec.europa.eu/ELCD3/index.xhtml?stock=default	Without fee	English	web-based; Export as pdf or Excel file	PEF
IEA	https://www.iea.org/	Without fee	English	web-based	Power and heat generation (country-specific)
DEFRA	GOV.UK	Without fee	English	webbasiert	
GEMIS	http://www.gemis.de/	Without fee	German	Integrated into your own software tool	
Probas	http://www.probas.umwelt/	Without fee	German	web-based; Export as pdf or Excel file	
DIN EN 16258:2013-03	https://www.beuth.de/de/norm/din-en-16258/152888035	With fee	Multilingual	Standard	Transport
sustamize	www.sustamize.com	With fee	English	Web-based API	
Umberto LCA+	https://www.ifu.com/de/umberto/oekobilanz-software/	With fee	Multilingual	Integrated into your own software tool	
ecoCockpit	https://ecocockpit.de/	Without fee	German	Web-based	LCA database
Fred	https://www.fred-footprint.de/	With fee	Multilingual	Integrated into your own software tool	Massive forming

Source: according to VDMA 2022

Calculation software, databases and emission factors

Examplary material emission factors (Scope 3)

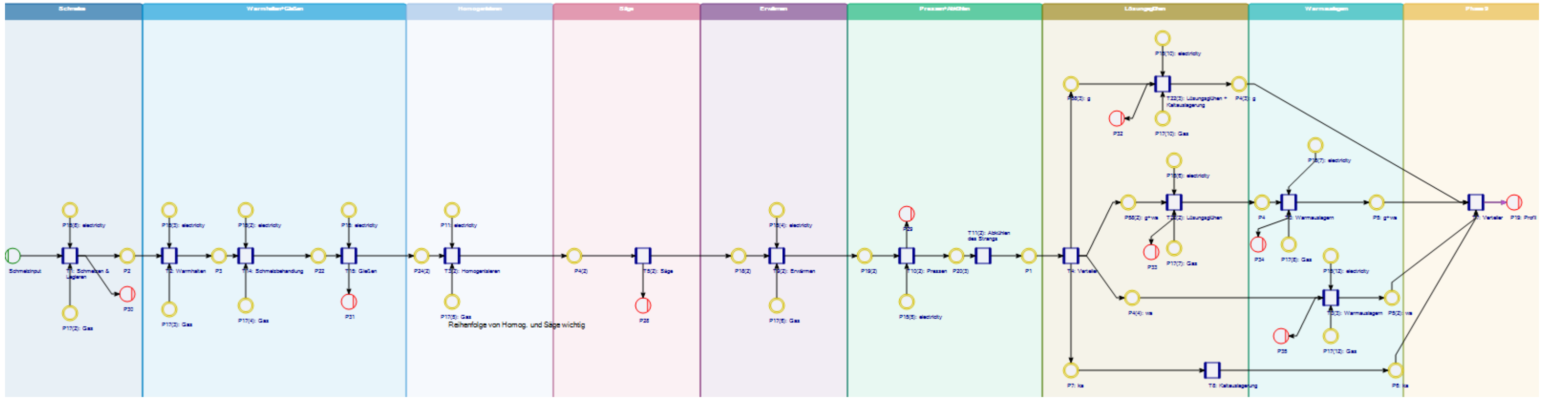
Materials	Emission factor in $t_{CO2\text{-}eq.}/t_{Material}$
Aluminium ingots (87.5 % prm. & 12.5 % sec.)	7.63
Aluminium ingot (60 % prm. & 40 % sec.)	5.73

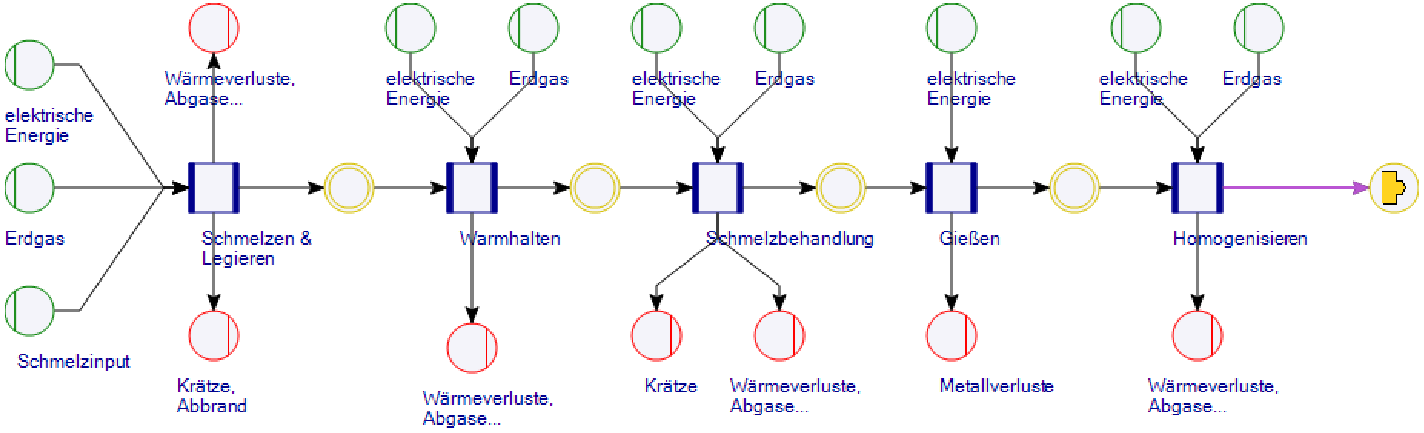
Aluminum processes	Emission factor in $t_{CO2\text{-}eq.}/t_{Material}$
Bauxite extraction	0,01
Alumina production	0,77
Anode manufacture	0,62
Smelting	6.78
Ingot casting	0.13
Remelting	0.27
Sawing	0.00 - 0.03
Scalping	0.01
Preheating	0.01 - 0.25
Hot rolling	0.08 - 0.12
Cold rolling	0.08
Annealing	0.077
Blanking	0.02

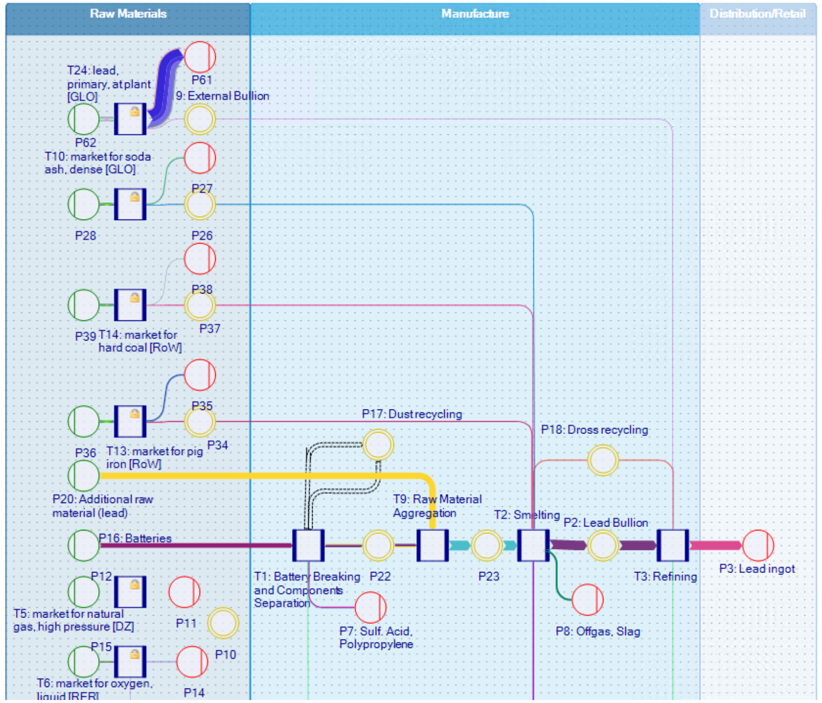
Datenbank: Stichting Sustainability Impact Metrics (SSIM), Milford et al. 2011

Calculation software, databases and emission factors

Modelling example in Umberto LCA+







Calculation example for aluminium reheating process

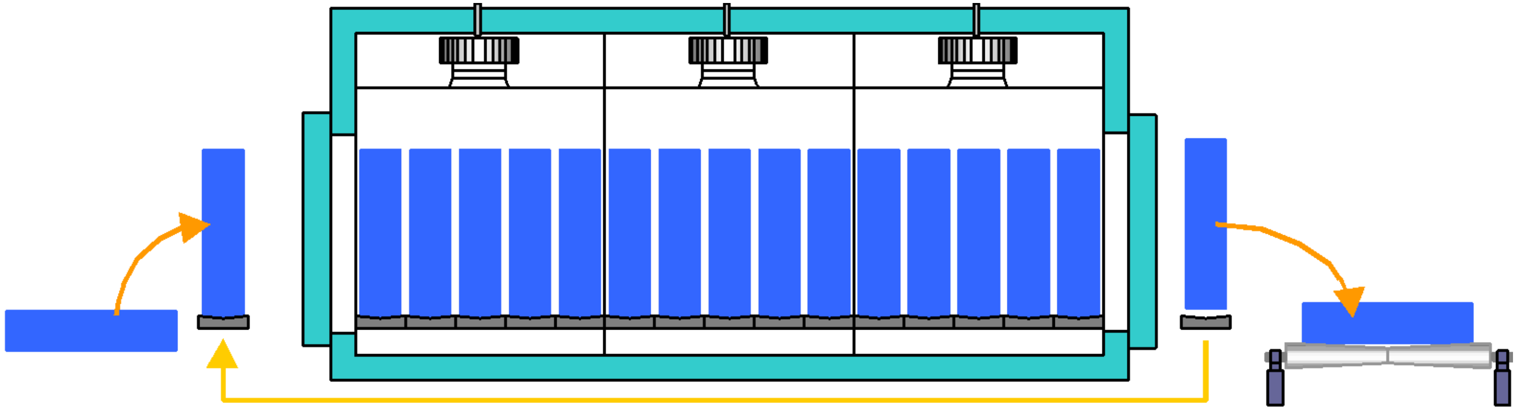
Evaluation and interpretation of results

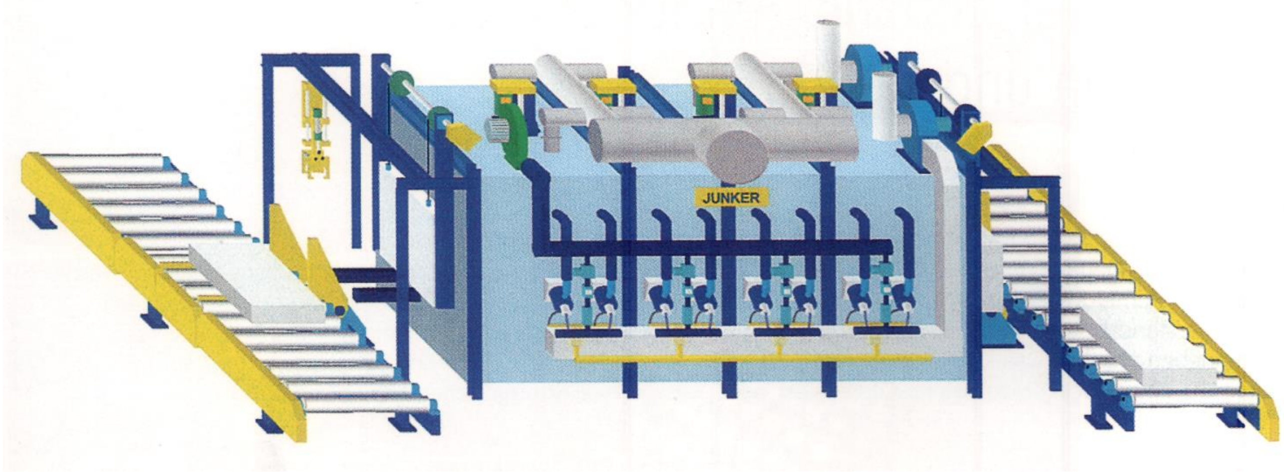
- Identification of significant parameters
- Assessment of the method
  - Sensitivity analysis
  - Consistency analysis
- Conclusions and summary
- Optional: Validation and verification of the PCF

Source: DIN EN ISO 14040

Calculation example for aluminium reheating process – Slab reheating furnace

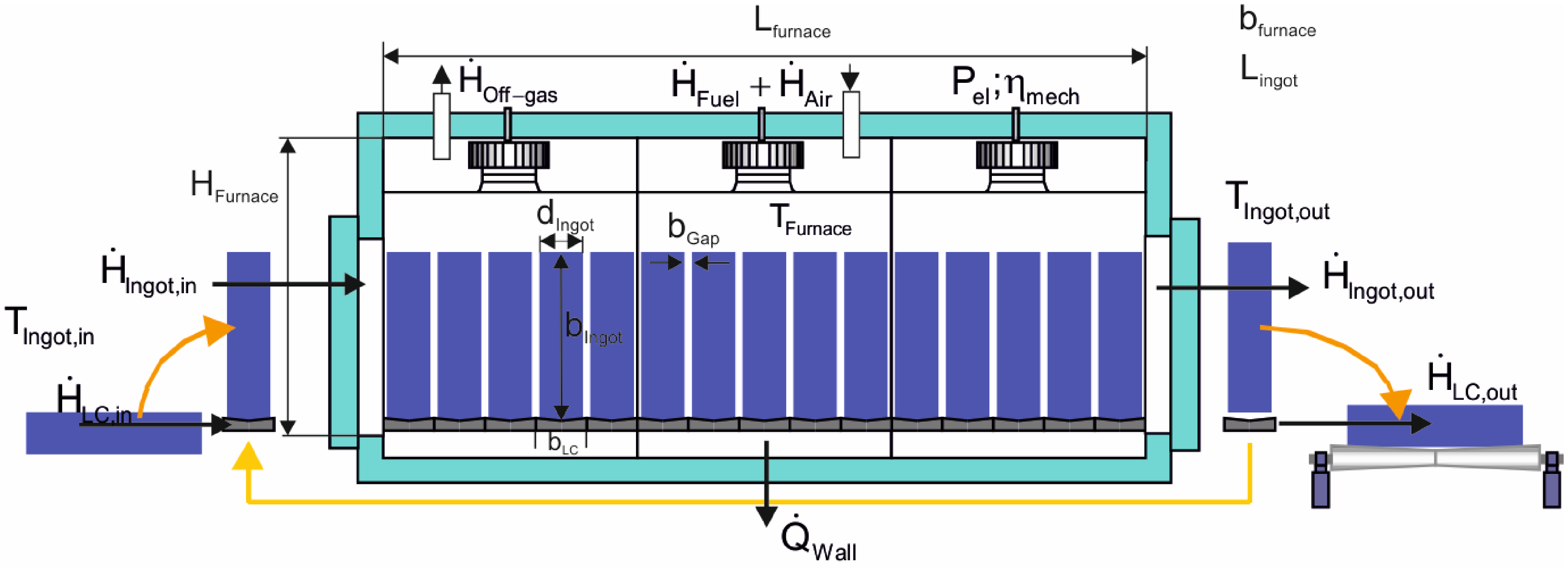
Direct gas heated pusher-type furnace for pre-heating/homogenization of Al-slabs





Calculation example for aluminium reheating process – Slab reheating furnace

Pusher-type furnace – Key figures



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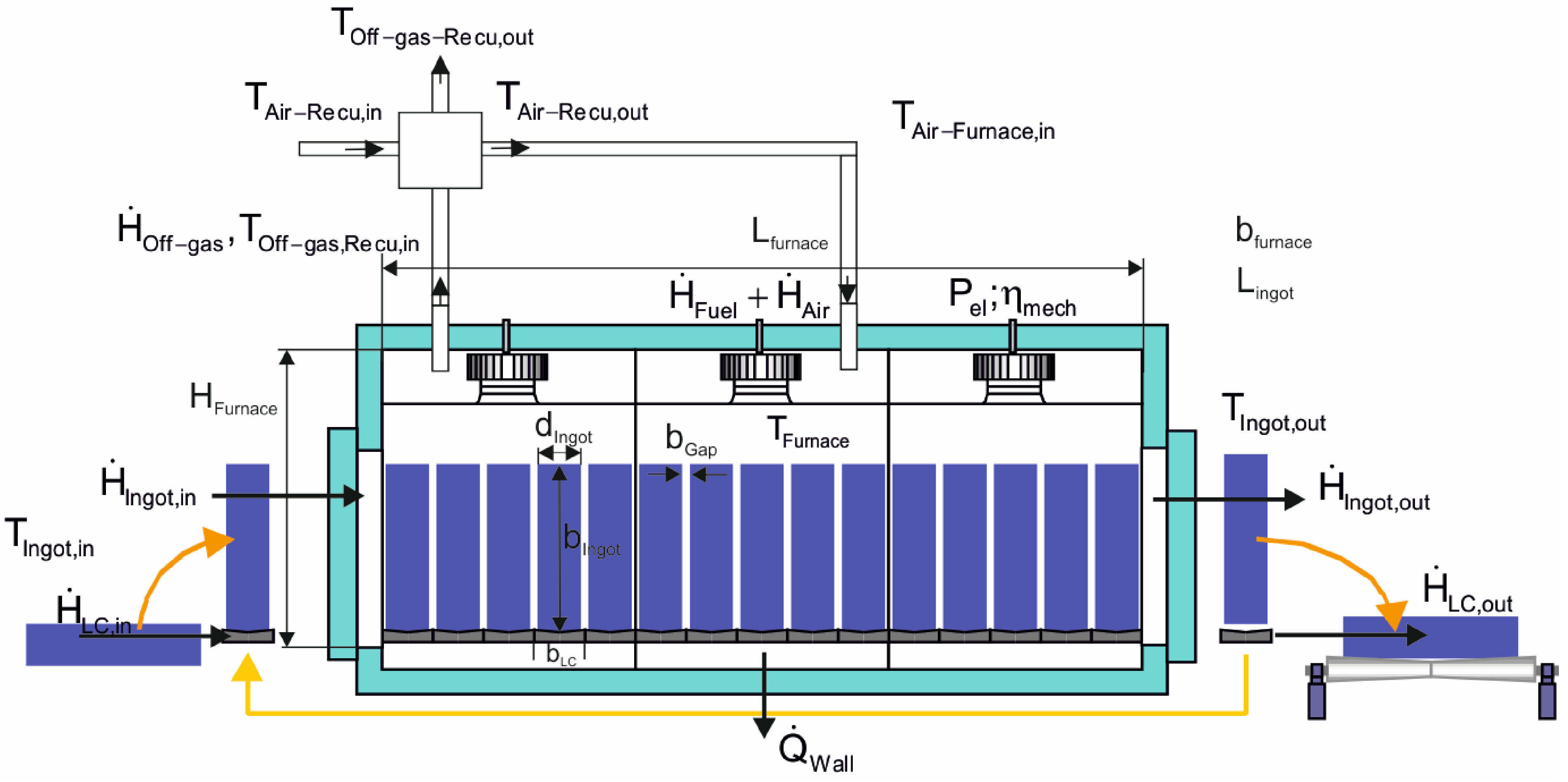
Calculation example for aluminium reheating process – Slab reheating furnace



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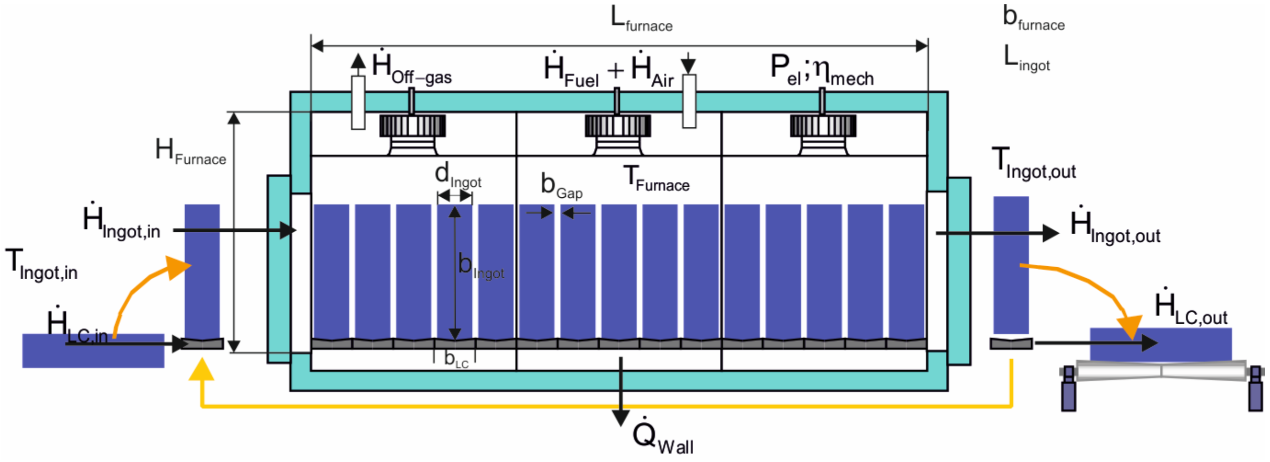
Calculation example for aluminium reheating process – Slab reheating furnace



$$\dot{H}_{Fuel} + \dot{H}_{Air,Furnace\,chamber} + P_{Fan} + \dot{H}_{Ingot,in} + \dot{H}_{LC,in} - \dot{H}_{Ingot,out} - \dot{H}_{LC,out} - \dot{H}_{Off-gas,Furnace\,chamber} - \dot{Q}_{Wall} = 0$$

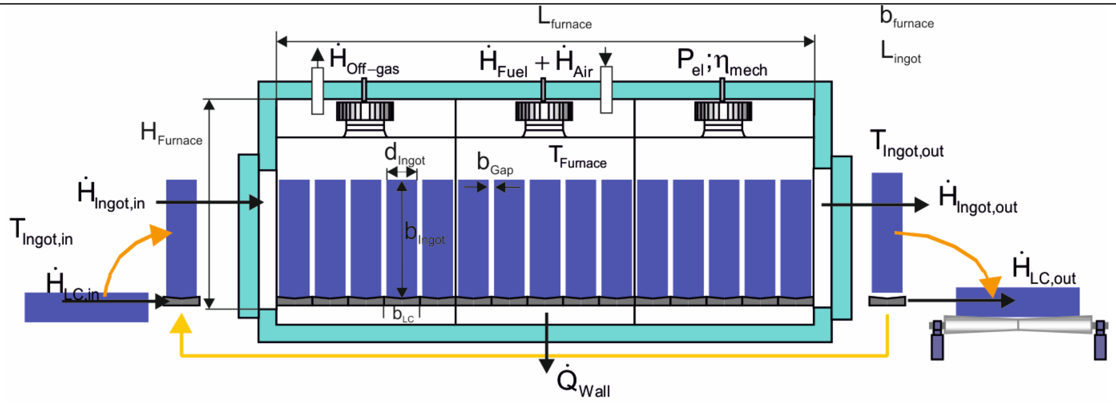
$$\dot{H}_{Air,Furnace\,chamber} = 0$$

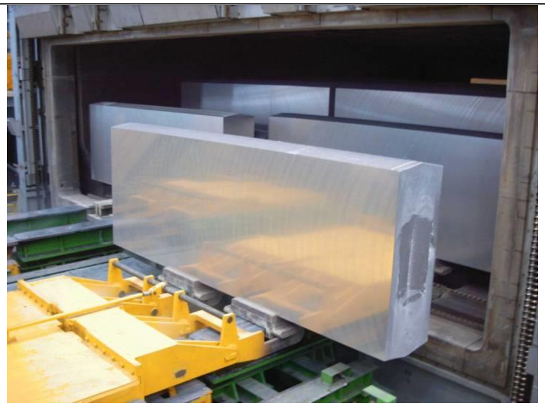
Load flow (Al-bar blanks) - inlet temperature is ambient temperature $T_{Ingot,in} = T_{amb}$

$$\Delta\dot{H}_{Ingot} = \dot{H}_{Ingot,out} - \dot{H}_{Ingot,in} = \dot{m}_{Ingot}\left[h_{Ingot}(T) - h\left(T_{amb}\right)\right]$$

$$h_{Ingot}(T) - h\left(T_{amb}\right) = \bar{c}_{Ingot}\left(T_{Ingot,out} - T_{Ingot,in}\right)$$

Calculation example for aluminium reheating process – Slab reheating furnace





Mass flow of charge carriers

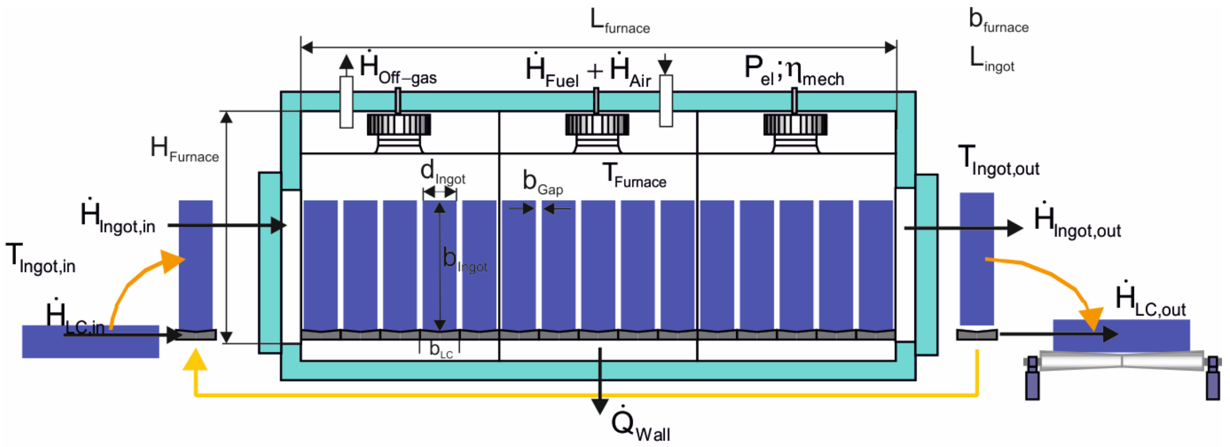
$$\Delta\dot{H}_{LC} = \dot{H}_{LC,out} - \dot{H}_{LC,in} = \dot{m}_{LC}\left[h_{LC}(T_{LC,out}) - h_{LC}\left(T_{LC,in}\right)\right]$$

$$x_{LC} = \frac{\dot{m}_{LC}}{\dot{m}_{Ingot}} = \frac{m_{LC}}{m_{Ingot}}$$

$$\Delta\dot{H}_{LC} = \dot{H}_{LC,out} - \dot{H}_{LC,in} = x_{LC} \cdot \dot{m}_{Ingot}\left[h_{LC}(T_{LC,out}) - h_{LC}\left(T_{LC,in}\right)\right]$$

$$h_{LC}(T_{LC,out}) - h_{LC}\left(T_{LC,in}\right) = \bar{c}_{Steel}\left(T_{LC,out} - T_{LC,in}\right)$$

Calculation example for aluminium reheating process – Slab reheating furnace



Wall heat losses

$$\dot{Q}_{Loss,Wall} = A_W \dot{q}''_{Loss,Wall} = 2\left(h_{Furnace} + b_{Furnace}\right) L_{Furnace} \dot{q}''_{Wall}$$

Off-gas losses

$$\dot{H}_{Off-gas,Furnace\,Chamber} = \dot{V}_{Fuel} v_{Off-gas} \left[h_{Off-gas}\left(T_{Furnace}\right) - h_{Off-gas}\left(T_{amb}\right) \right]$$

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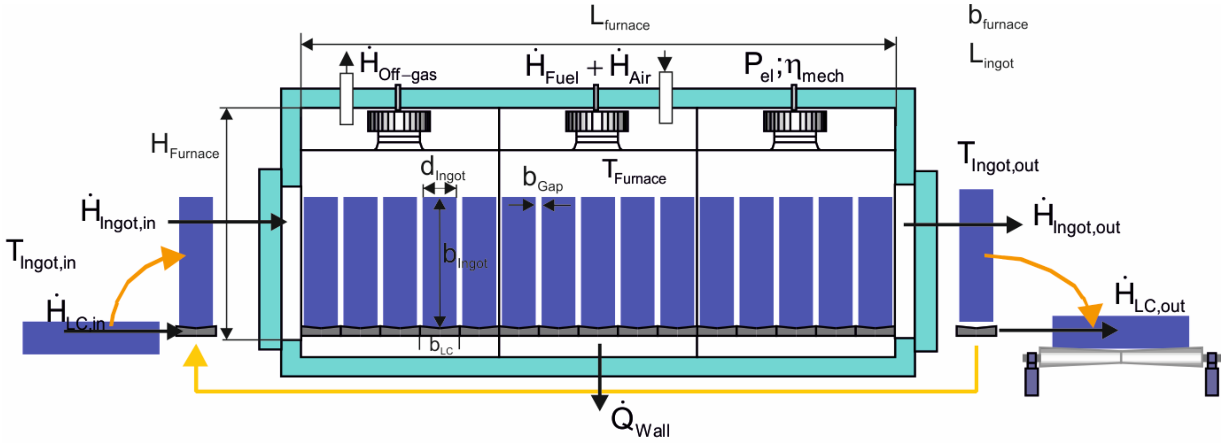
Calculation example for aluminium reheating process – Slab reheating furnace



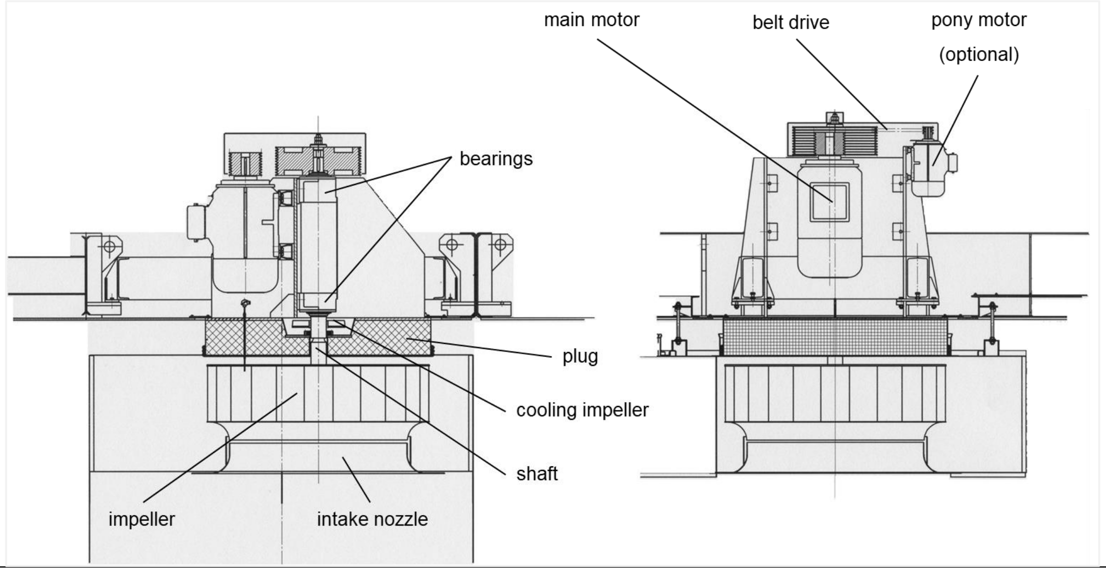
Power of the Fan

$$P_{Fan} = \dot{V}\Delta p = P_{el}\eta_{el+mech}$$

$$x_{P/\dot{H}} = \frac{P_{el}}{\dot{H}_{Fuel}}$$

$$P_{el} = x_{P/\dot{H}} \cdot \dot{H}_{Fuel}$$

$$P_{Fan} = x_{P/\dot{H}} \cdot \dot{H}_{Fuel}\eta_{el+mech}$$



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Calculation example for aluminium reheating process – Slab reheating furnace

Energy flow balance

$$\dot{H}_{Fuel} + \dot{H}_{Air,Furnace\,chamber} + P_{Fan} + \dot{H}_{Ingot,in} + \dot{H}_{LC,in} - \dot{H}_{Ingot,out} - \dot{H}_{LC,out} - \dot{H}_{Off-gas,Furnace\,chamber} - \dot{Q}_{Wall} = 0$$

$$\dot{H}_{Fuel} + x_{P/\dot{H}} \cdot \dot{H}_{Fuel}\eta_{el+mech} = \Delta\dot{H}_{Ingot} + \Delta\dot{H}_{LC} + \dot{Q}_{Wall} + \dot{H}_{Off-gas,Furnace\,chamber}$$

$$\dot{H}_{Fuel} = \dot{V}_{Fuel}h_u = \Delta\dot{H}_{Ingot} + \Delta\dot{H}_{LC} + \dot{Q}_{Wall} + \dot{H}_{Off-gas,Furnace\,chamber} - P_{Fan}$$

Specific fuel and electric power consumption

$$e_{Fuel} = \frac{\dot{H}_{Fuel}}{\dot{m}_{Ingot}} = \frac{\dot{V}_{Fuel}}{\dot{m}_{Ingot}}h_u = \frac{\Delta\dot{H}_{Ingot} + \Delta\dot{H}_{LC} + \dot{Q}_{Wall} + \dot{H}_{Off-gas,Furnace\,chamber}}{\dot{m}_{Ingot}x_{P/\dot{H}}\eta_{el+mech}}$$

$$e_{el} = \frac{P_{el}}{\dot{m}_{Ingot}} = x_{P/\dot{H}}\frac{\dot{H}_{Fuel}}{\dot{m}_{Ingot}} = x_{P/\dot{H}}e_{fuel}$$

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Calculation example for aluminium reheating process – Slab reheating furnace

Pusher type furnace – Key figure values

KPI	Value	Unit
Specific energy demand – Fuel energy – Electr. energy	220 180 40	kWh/t
Total efficiency η_{tot}	64,38	%
Share of electric energy input	18	%
Mass throughput	17,2	t/h
Ingot temperature – Start – Finish	 15 538	°C
No air preheating		

Source: Values taken from ranges according to: Neumeister – CO_2-Prozessanalyse von Aluminium Walzprodukten und Ansätze für eine CO_2 arme Produktion (2007)

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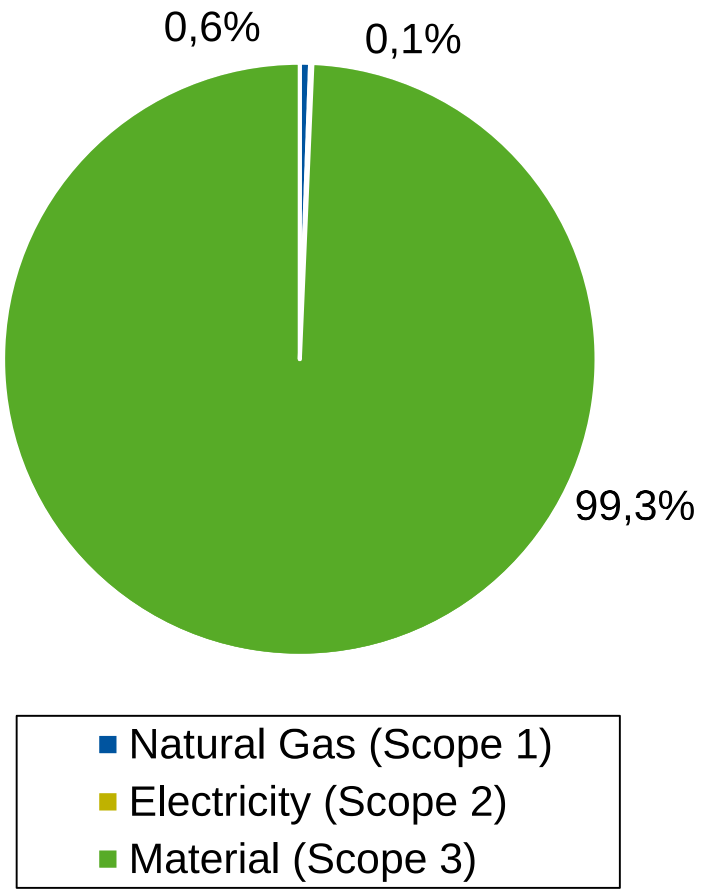
Calculation example for aluminium reheating process – Slab reheating furnace

Pusher type furnace – Scope 1, 2 and 3 emissions

Scope	Spezific emissions in $t_{CO2\text{-}eq.}/t_{output}$	Cumulativ emissions in tsd. $t_{CO2\text{-}eq.}$
Natural Gas (Scope 1)	0,20	135
Electricity (Scope 2)	0,38 - 0,01	29
Material (Scope 3)	5,73	24 136
Sum	5,94 - 6,31	24 300

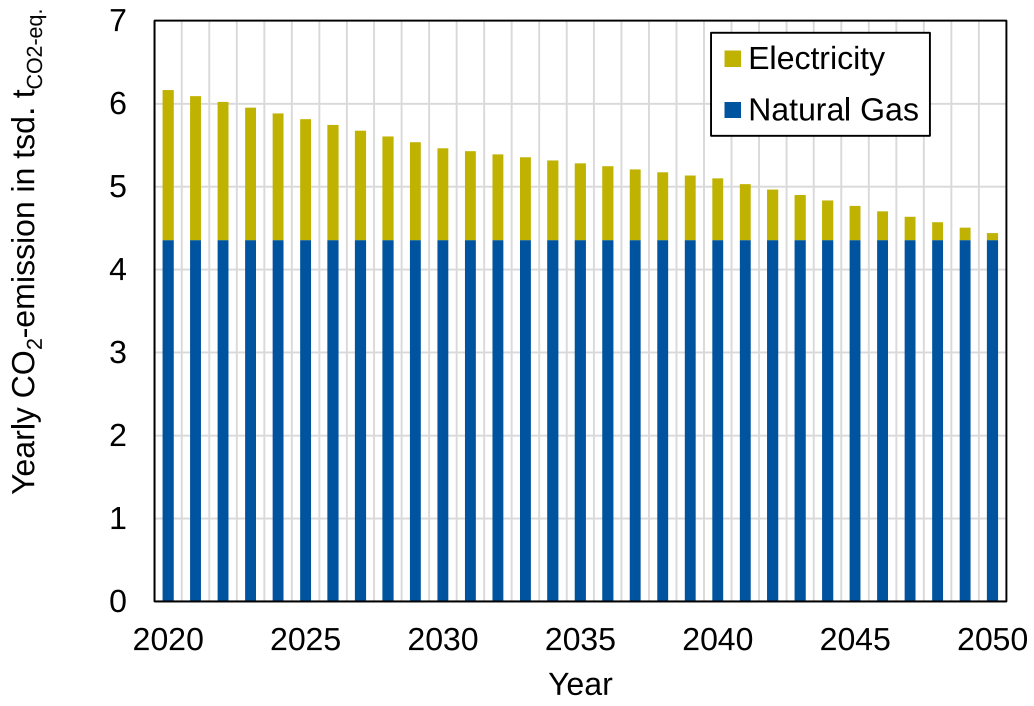
Operating time from 2020 - 2050

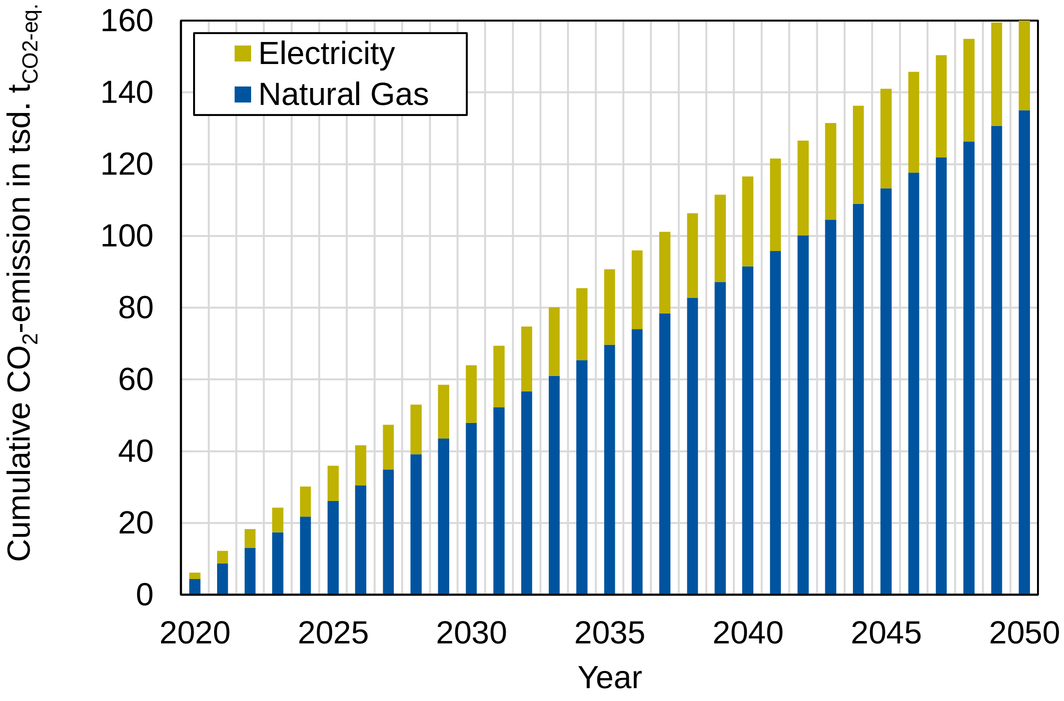


Carsten Gondorf, M.Sc. | Felix Kaiser, M.Sc.
Aachen | 23.03.2023

Calculation example for aluminium reheating process – Slab reheating furnace

Pusher type furnace – Scope 1 and 2



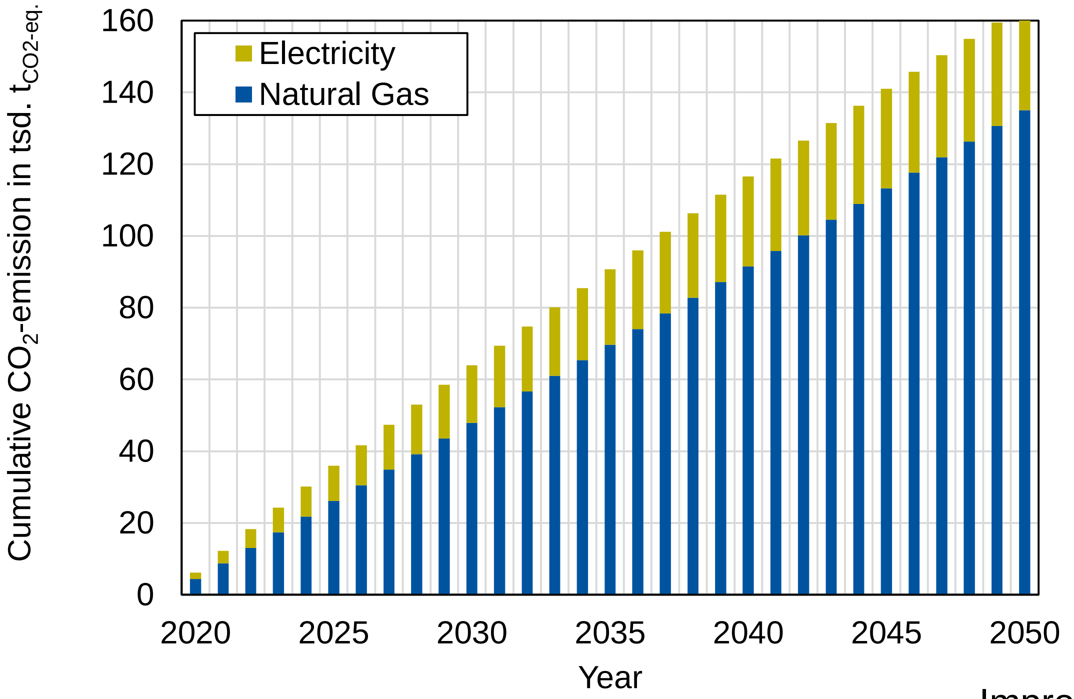


Specific energy demand:
- 180 kWh_{fuel}/t_{output}
- 40 $kWh_{el.}/t_{output}$

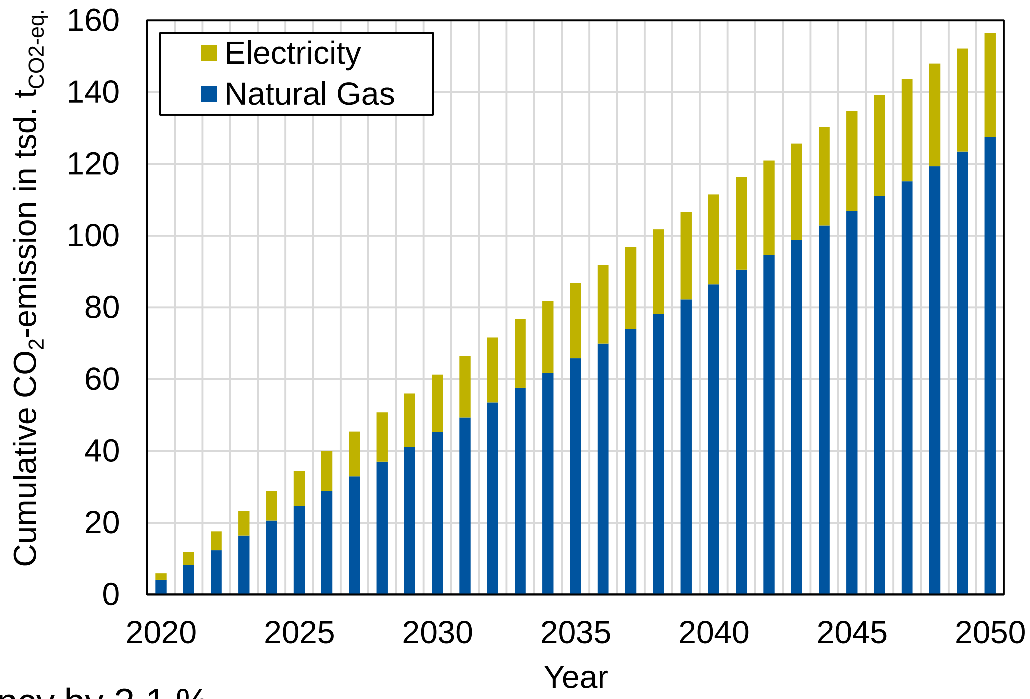
Mass throughput:
- 17.2 t_{output}/h
- 120,400 t_{output}/a

Calculation example for aluminium reheating process – Slab reheating furnace

Pusher type furnace – Scope 1 and 2 with improved total efficiency (+3,1 %)



Reduction of 7502 $t_{CO2\text{-}eq.}$



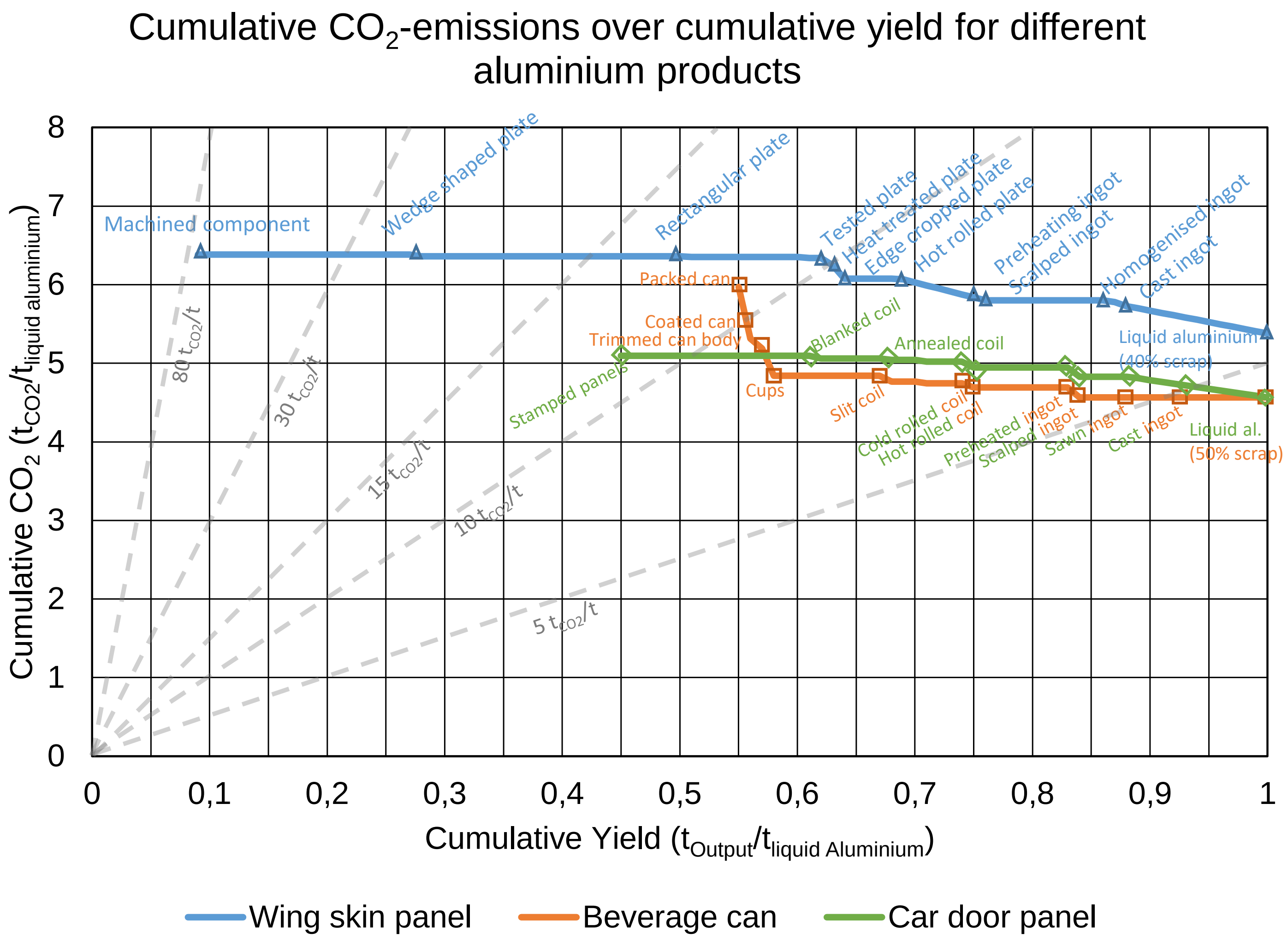
Improved total efficiency by 3,1 %

Specific energy demand:
- 180 kWh_{fuel}/t_{output}
- 40 $kWh_{el.}/t_{output}$

Specific energy demand:
- 170 kWh_{fuel}/t_{output}
- 40 $kWh_{el.}/t_{output}$

Mass throughput:
- 17.2 t_{output}/h
- 120,400 t_{output}/a

Calculation example for aluminium reheating process – For different aluminium products



Source: Milwood et al. 2011

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Summary

- Significant influence on the results of the life cycle assessment
  - Dynamic factors
- Biggest limitations of the life cycle assessment
  - Supplier transparency
  - Influence of the databases used
  - Partly simplification
- Comprehensive mass and energy balance for the process as an important foundation
- Knowledge of carbon footprints of upstream processes necessary (but responsibility on respective companies)

Thank you
for your attention

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