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Materials Science and Technology

Charting the path to Net-Zero

A case study of the Bündner Rheintal including CCUS pathways and fuel production opportunities

Arijit Upadhyay, Matthias Sulzer, Mathias Giesbrecht, Binod Koirala, Barton Chen, Robin Mutschler

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Current situation, requirements and objectives

Rheintal energy system: An urban-industrial cluster!

Industry sector

546 GWh/a unused low-temp heat (ThLt)

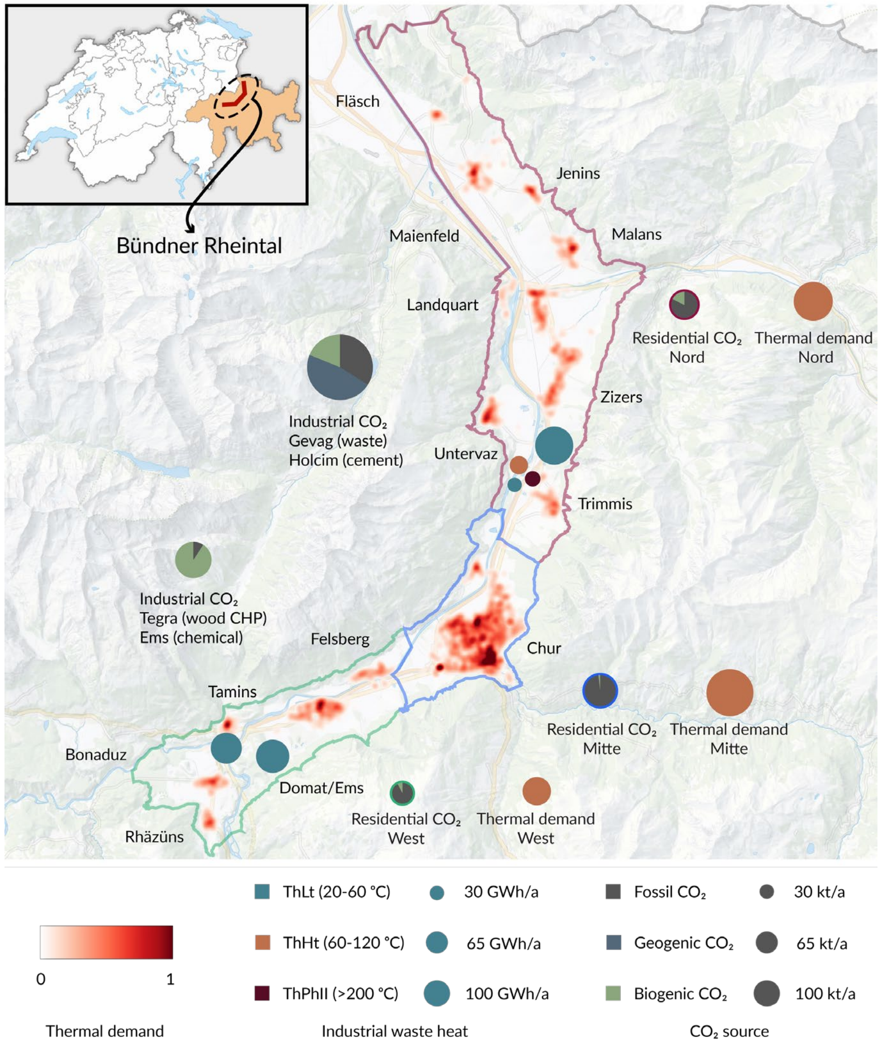
49 GWh/a unused high-temp heat (ThHt)

35 GWh/a unused process heat (ThPhII)

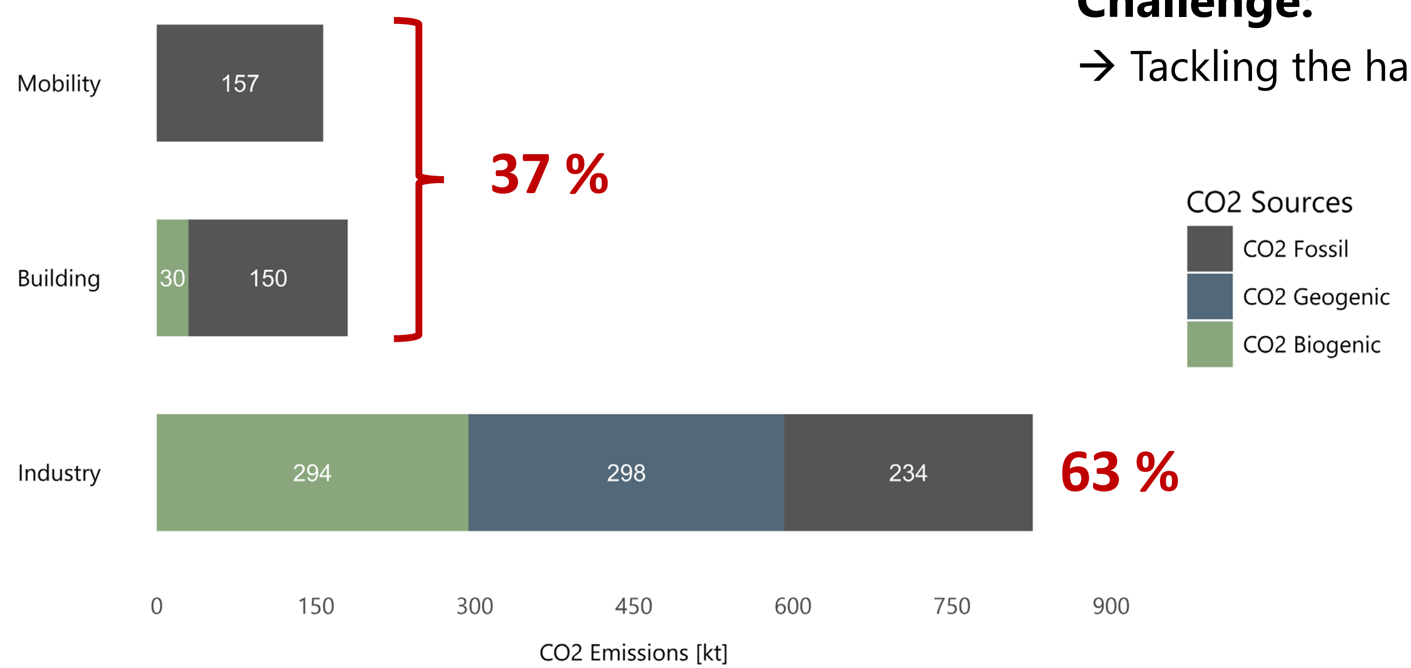
Urban sector

Thermal demand: Ca. 670 GWh/a (ThHt)

- Holistic system analysis spanning all sectors
- High spatial and temporal resolution
- Potential for waste heat integration between the industrial and urban sectors



Current situation: CO_2 emissions in Bündner Rheintal



Challenge:

→ Tackling the hard-to-abate emissions

Switzerland: **4 t_{CO2}/ capita**

Bündner Rheintal: 11 t_{CO2}/ capita

Objectives of the project

- Developing a **spatially resolved energy system model** for the Rheintal valley for “status quo” und 2050, involving the **various partners** at the **RoundTable**.
- Evaluating the **cost-effective, holistic solution**, that meets the **2050 Net-Zero** emissions target.

The Rhine Valley photographed from Montalin, 2266 meters above sea level. Photo: Lino Schmid

RoundTable“Netto-Null Rheintal 2050”

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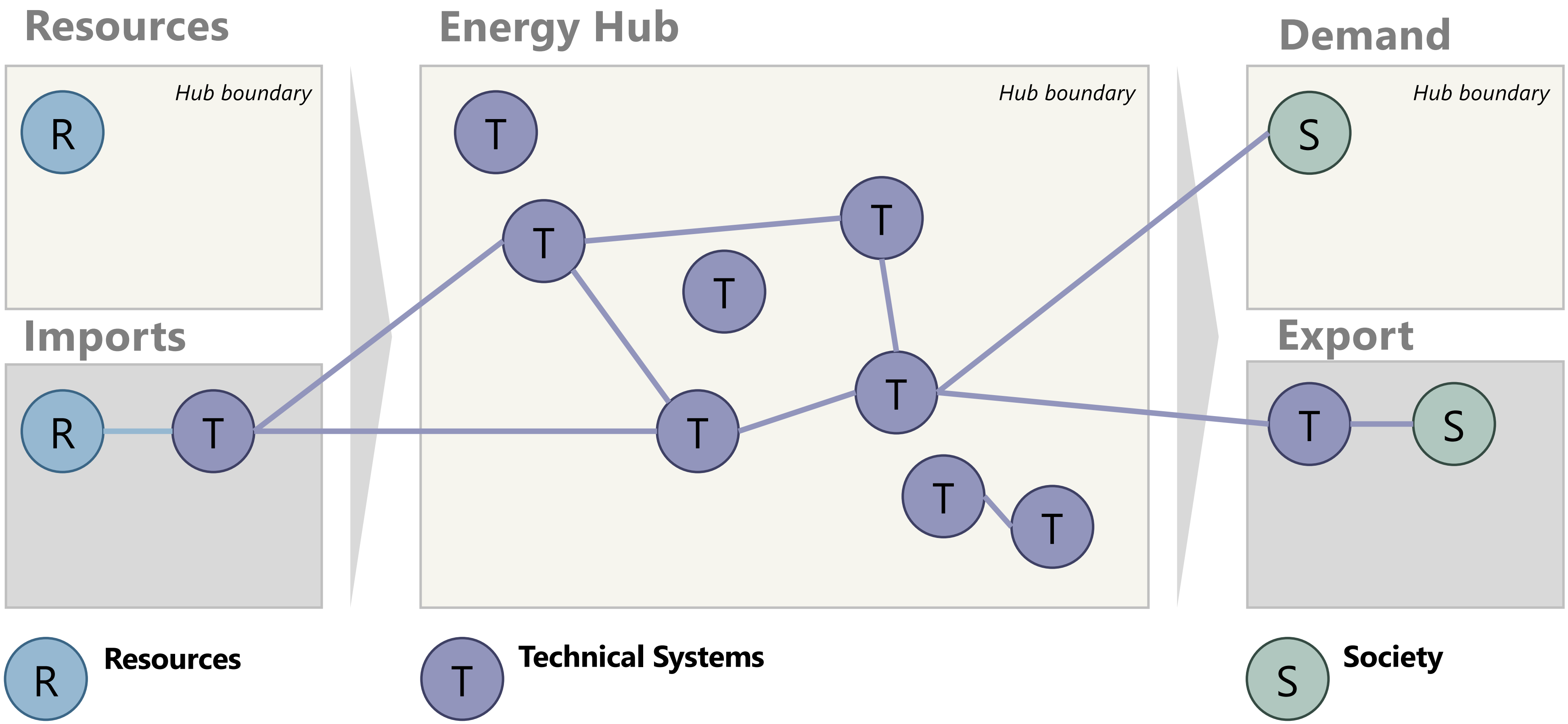
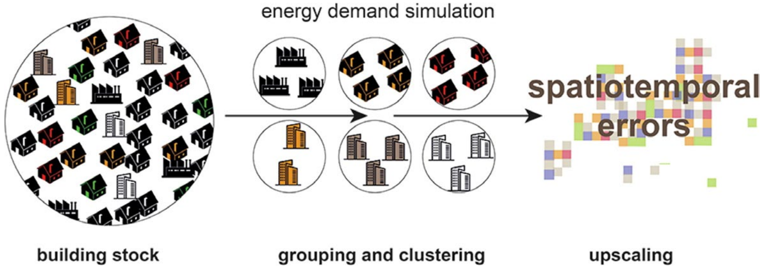
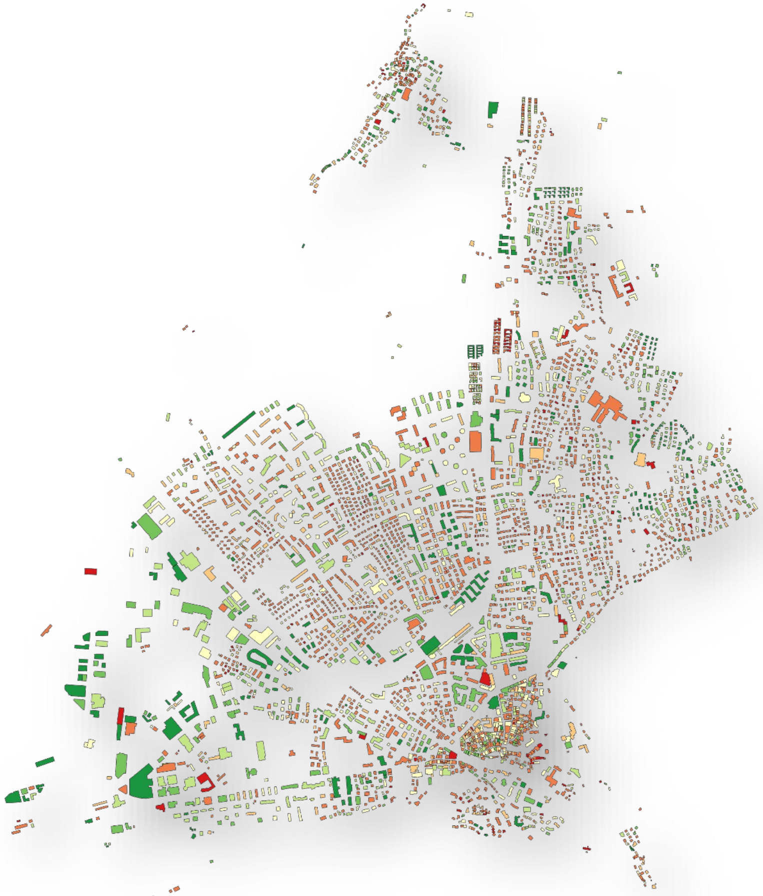
Methodology

The energy hub concept



Bottom-up urban demand analysis (example: Chur)





Specific energy demand
Energy Reference Area
[kWh/m²]

- 0 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100
- 100 - 200
- 200 - 700

Reference

[1] Spatiotemporal upscaling errors of building stock clustering for energy demand simulation, S. Eggimann et. al, 2022

The Rheintal in “Hubs”
Hub = Energy Balance Zone

Urban settlement hubs in the Rheintal

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H2: West

Buildings: ~ 4,000
Residents: ~ 17,000
Vehicles: ~ 14,000

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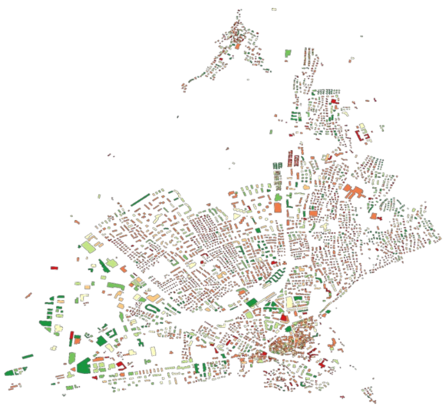
H1: Mitte

Buildings: ~ 4,000
Residents: ~ 37,000
Vehicles: ~ 30,000



Chur

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H3: Nord

Buildings: ~ 6,000
Residents: ~ 26,000
Vehicles: ~ 21,000

Landquart

Industry hubs in the Rheintal

H4: Gevag

Waste to Energy
Trimmis

https://gevag.ch/

H5: Holcim

Cement plant
Untervaz

https://www.holcim.ch/de/zementwerk-untervaz

H6: Tegra

Wood CHP
Domat/Ems

https://www.axpo.com

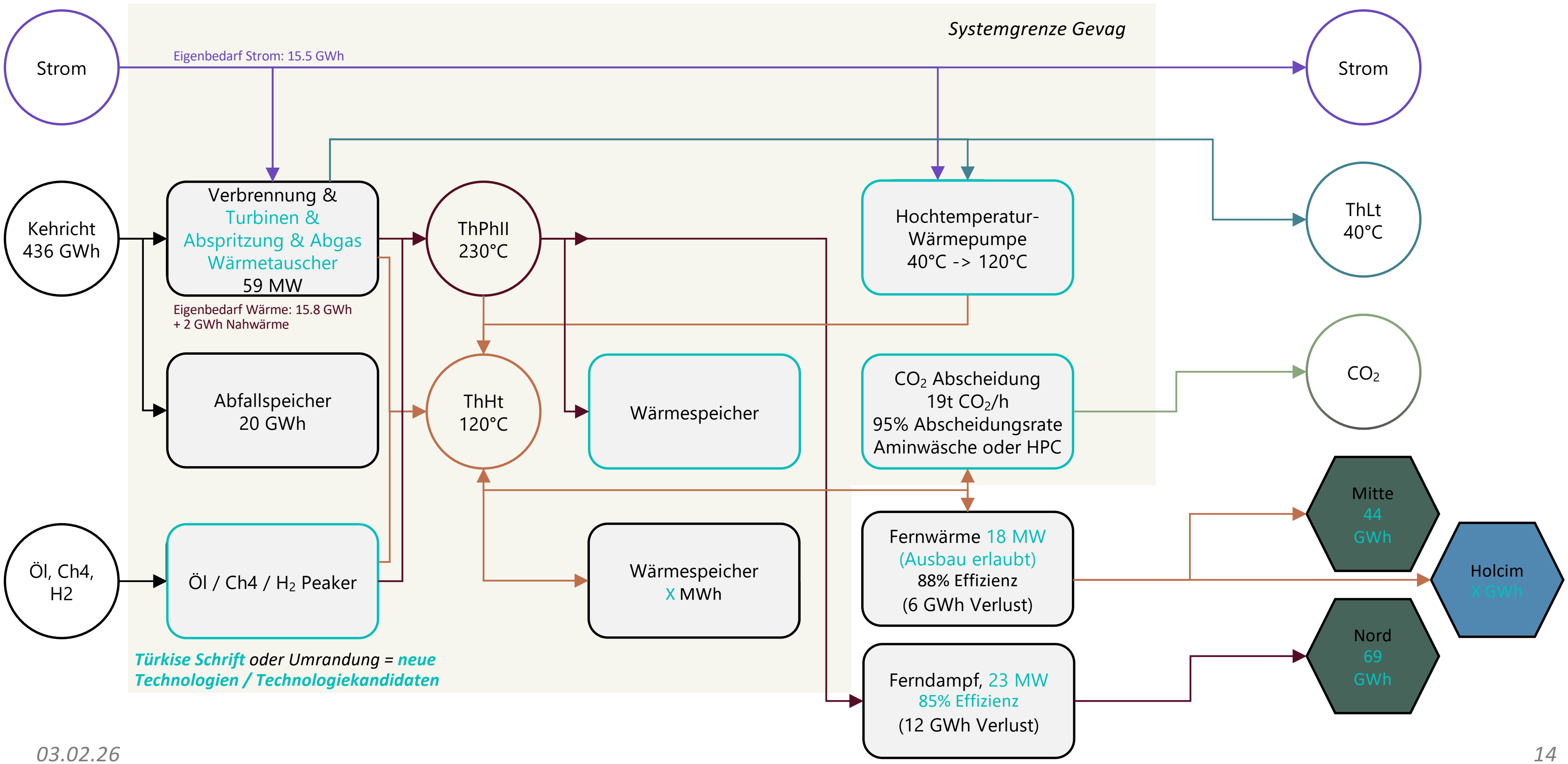
H7: Ems

Chemical plant
Domat/Ems

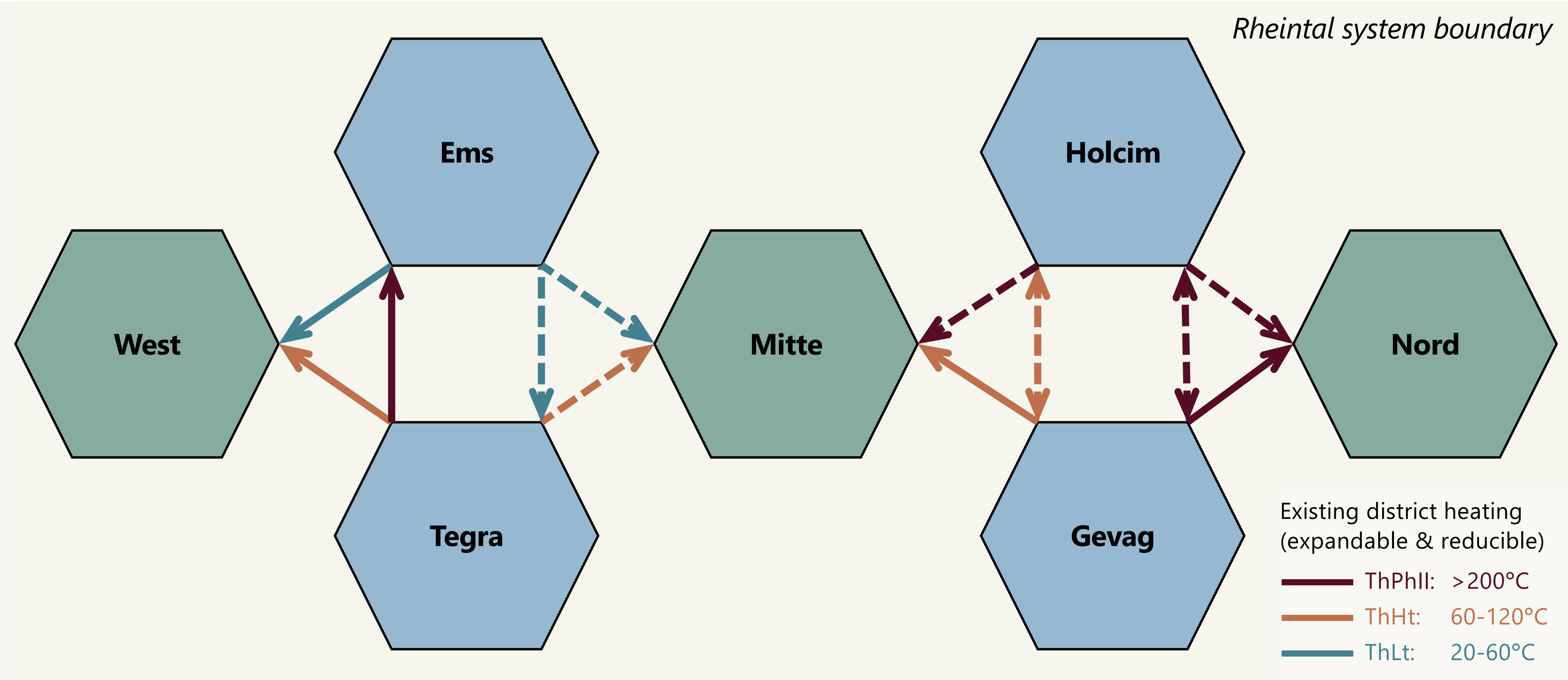
https://www.ems-group.com


gevag
ENERGIE AUS ABFALL

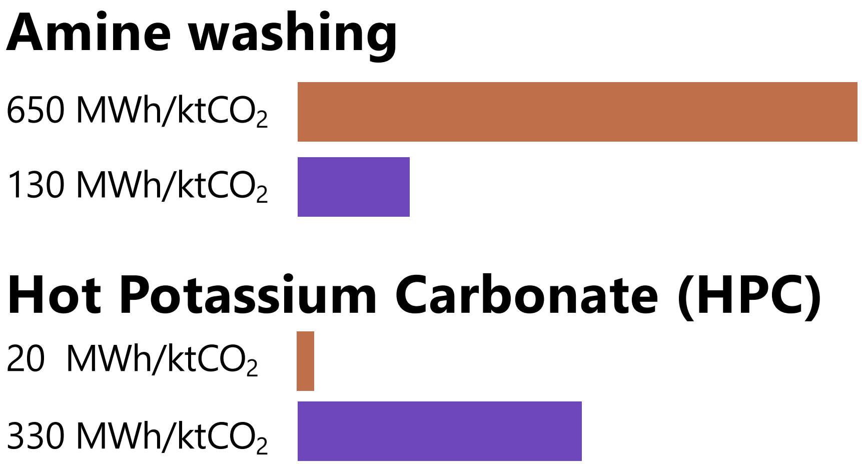
GEVAG Modell, 2050

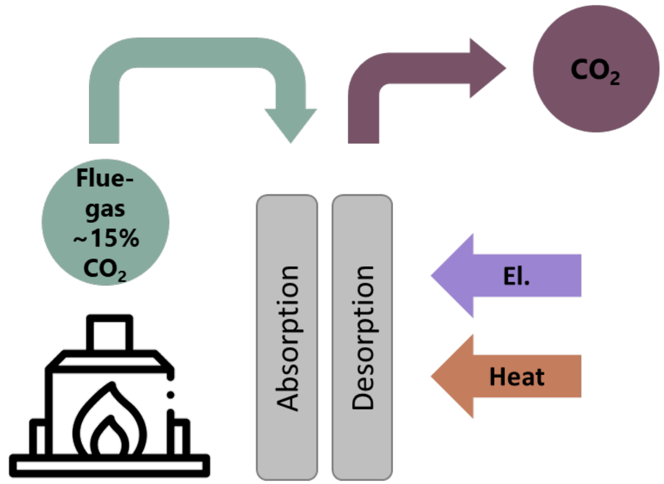


Heat integration of the hubs via district heating



Energy demand for CO_2 capture

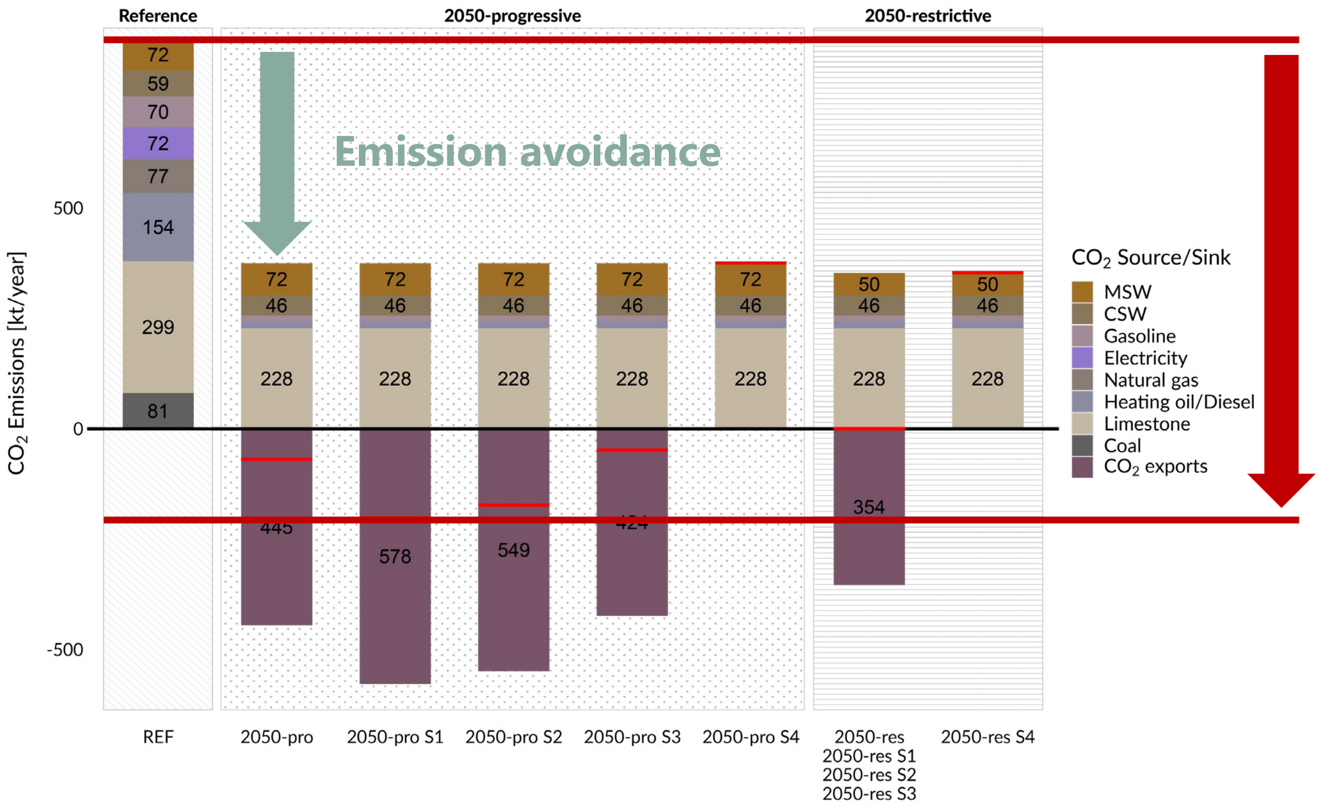




Amine washing requires predominantly high temperature **heat** (~120 °C) while **HPC** requires predominantly **electricity** to capture CO_2

Key results

Result I: The Net-Zero target can be achieved!



2050 Net-Zero and net-negative emissions can be achieved via:

- Emission avoidance
- CO_2 capture and storage (CCS)
- Net-negative solutions via CCS of biogenic emissions from wood, MSW
- Assumption: CO_2 ETS price 175 CHF/t

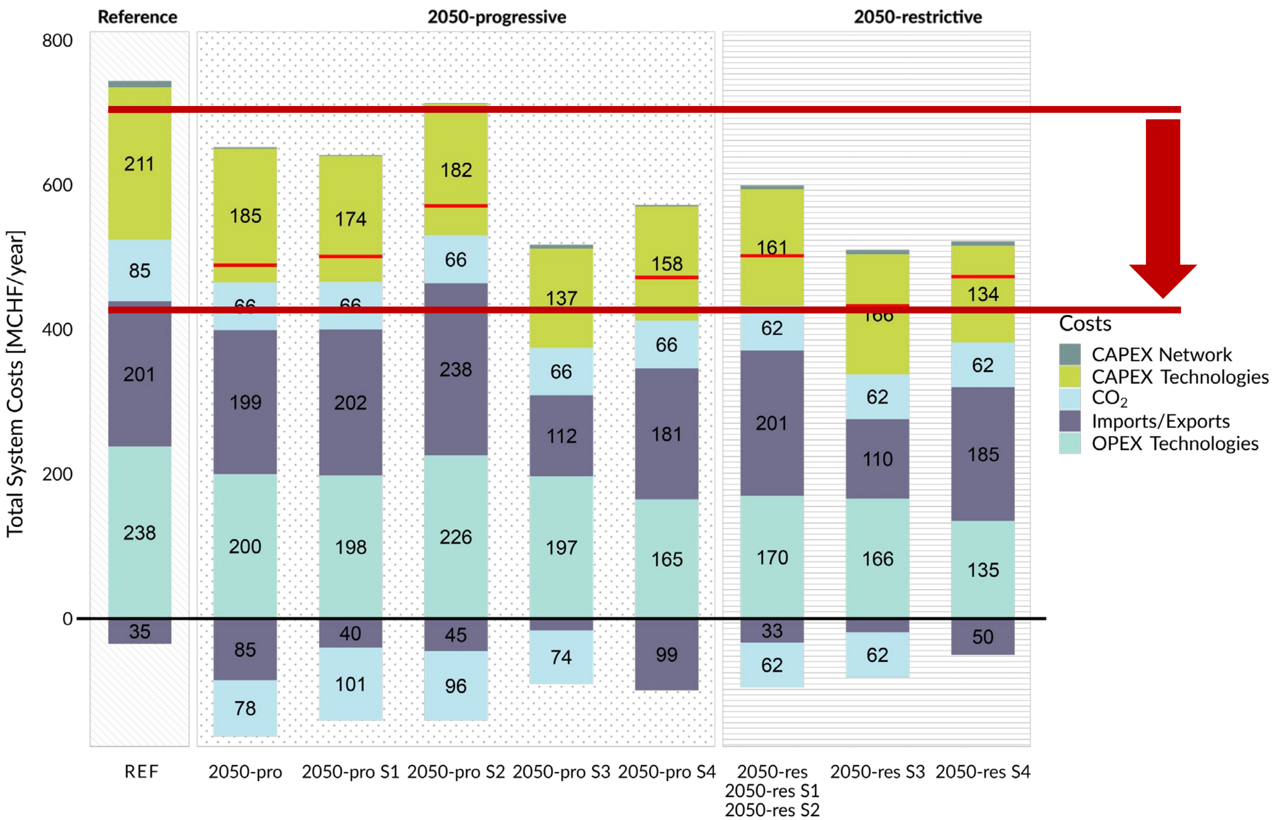
Pro: Progressive scenario
- Low H_2 cost (2.5 CHF/kg), No El. restrictions, El. price 3x REF (2018)

Res: Restrictive scenario
- High H_2 cost (6 CHF/kg), Max. +20% El. imports compared to today, El. Price 3x REF

S1-S4 Sensitivity analysis
- S1: Capped H_2 imports to 400 GWh/a
- S2: No H_2 and synfuel imports. Open-field PV.
- S3: Electricity price of REF (2018)
- S4: No Net-Zero target

Reference
[1] Charting the path to Net-Zero: A Case Study of Integrated Energy Systems, A. Upadhyay et. al, 2025

Result II: System cost can be lower in the future



Reference

[1] Charting the path to Net-Zero: A Case Study of Integrated Energy Systems, A. Upadhyay et. al, 2025

Reduced annual system costs are possible - including CCS!

- Decreased heating demands
- Increased system efficiency through electrification
- Local resources and less imports
- Waste heat utilization and optimized system integrations
- Electricity is a critical cost driver

Pro: Progressive scenario

- Low H_2 cost (2.5 CHF/kg), No El. restrictions, El. price 3x REF (2018)

Res: Restrictive scenario

- High H_2 cost (6 CHF/kg), Max. +20% El. imports compared to today, El. Price 3x REF

S1-S4 Sensitivity analysis

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- S4: No Net-Zero target

Conclusions

1. The net-zero target in the Rheintal can only be achieved with CCS
2. The annualized system costs in the Rheintal valley can reduce by 2050
3. The valley's dependence on imports will decline by 2050
4. District heating can make an important contribution to heat supply and relieve the burden on the electricity grid
5. Hydrogen and renewable fuels can play an important role in the 2050 system

Collaboration leads to successful system transformation!

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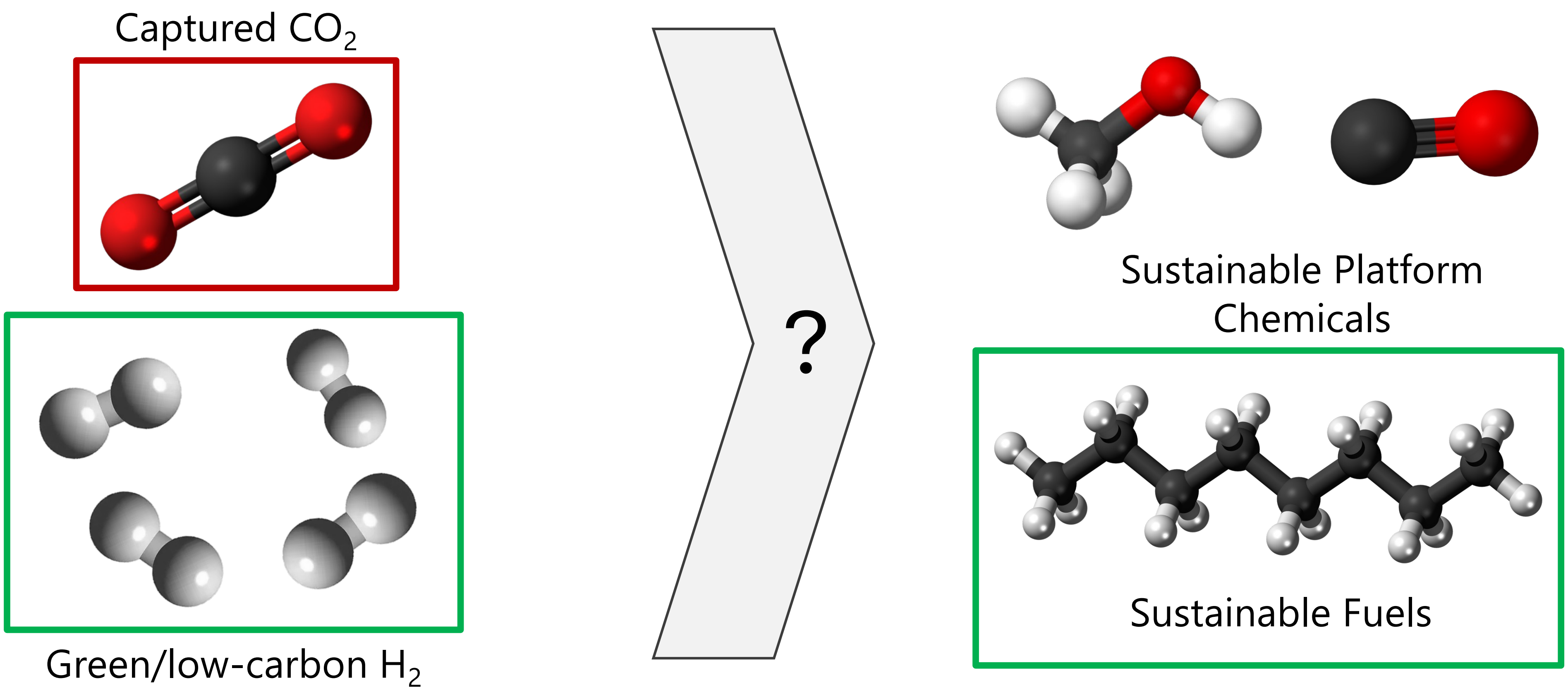
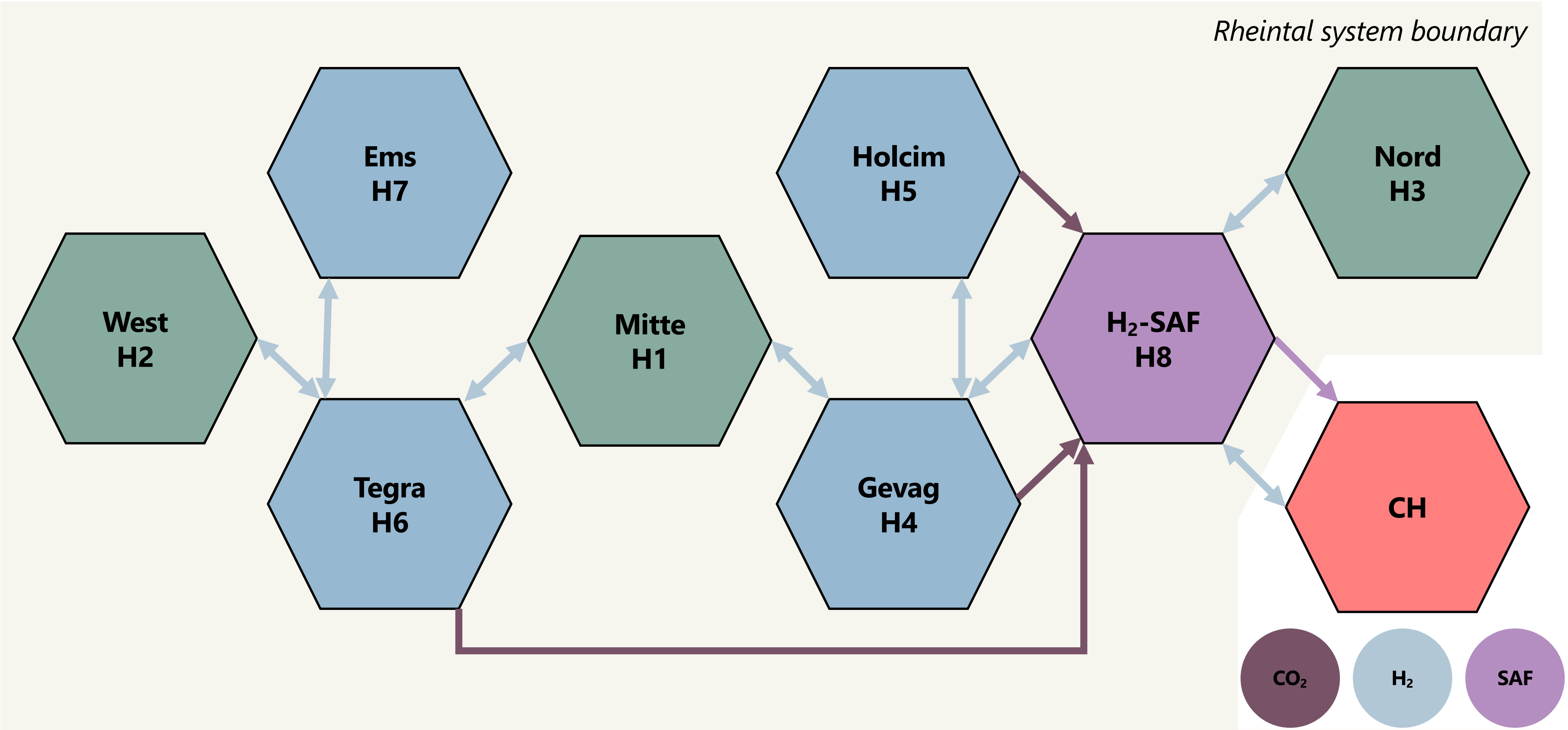
The partners, ANU and Empa are deriving a concrete action plan towards the implementation of solutions between 2025 and 2027.

Fuel production opportunities

Various conversion paths exist for SFs and SPCs



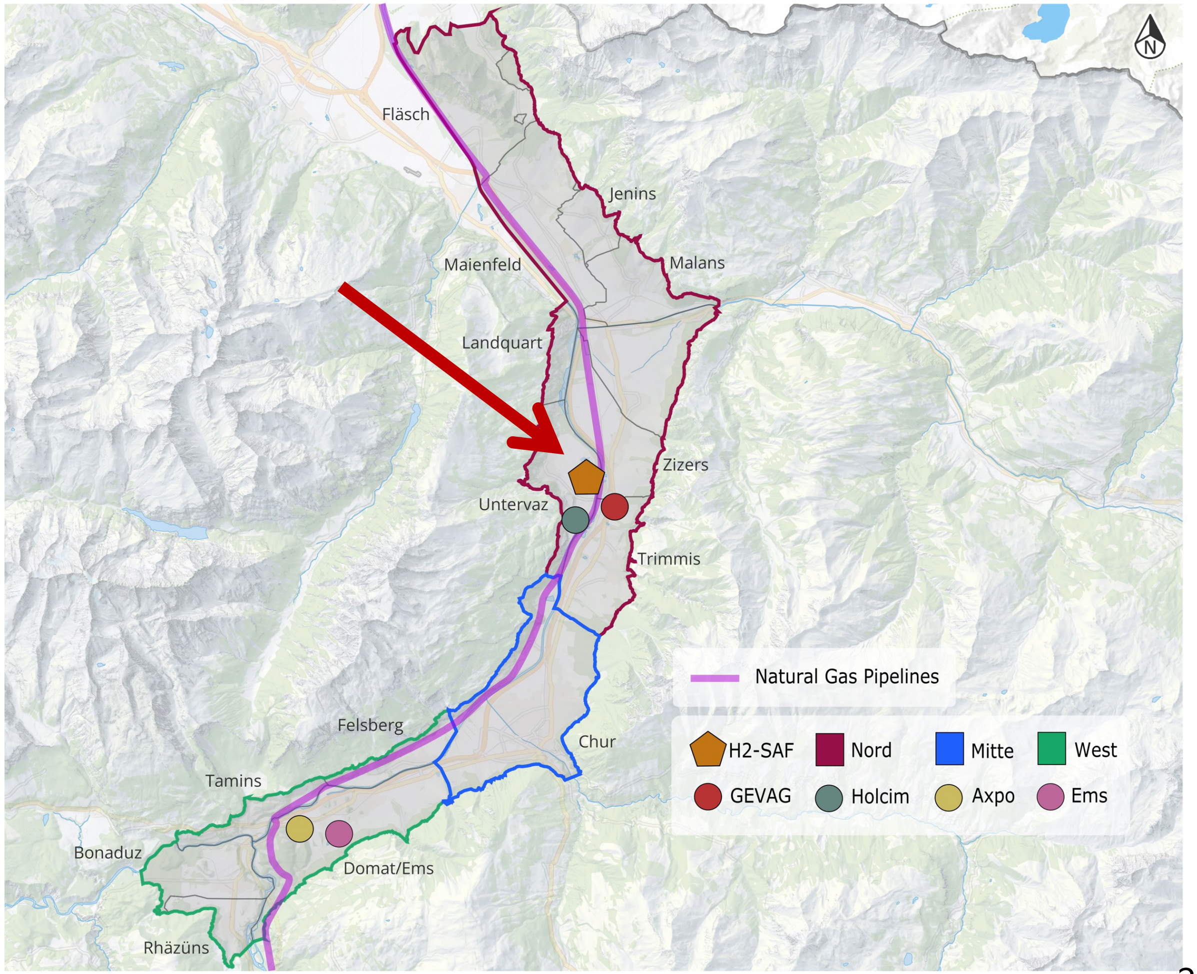
CO_2 and H_2 network in Rheintal for SAF production



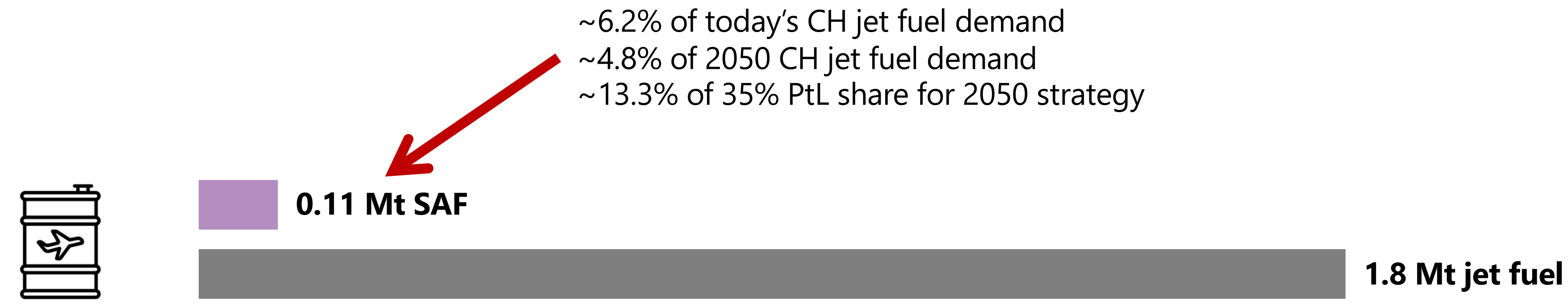
Existing gas pipeline in Rheintal

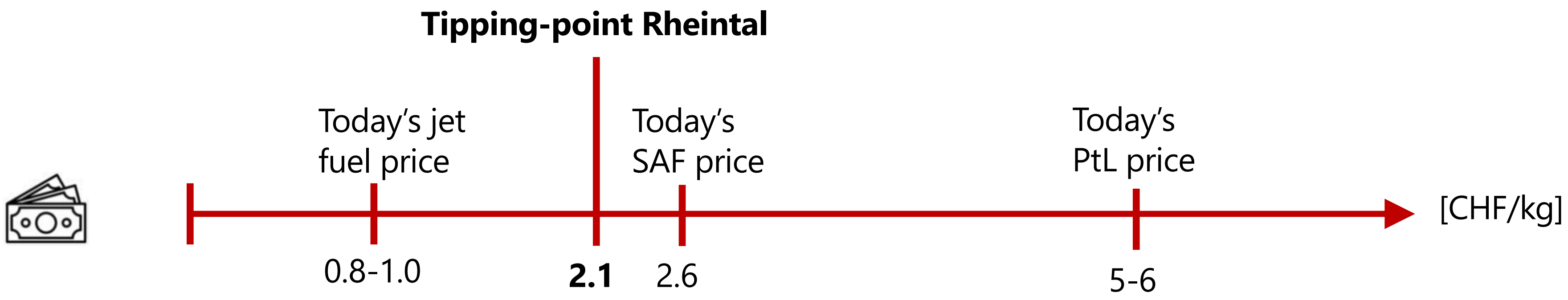
- Hydrogen network location:
  - Based on current NG pipelines
  - Repurposed/new built

- Location of H2-SAF hub:
  - At the entry of valley
  - Next to the pipeline
  - Close to CO_2 sources



How much sustainable fuel can be produced in Rheintal?





Conclusions: A Hydrogen Valley is feasible!

Hydrogen Tipping Points

- 2.8 CHF/kg for process heat
- 5.3 CHF/kg for fuel cells due to higher electricity price
- Today's blue hydrogen price around 2.9 CHF/kg

SAF Tipping Point

- 2.1 CHF/kg for SAF production
- Max production at 111 kt limited by utilisable biogenic CO_2 (excl. DAC)
- Carbon tax increases may enhance competitiveness

System Cost

- Reduction of overall system cost with hydrogen
- SAF production augment export revenues

Acknowledgement “Netto-Null Rheintal 2050”

Partners of the round table

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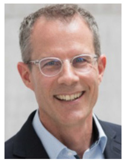
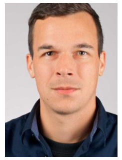

Matthias Sulzer


Mathias Giesbrecht


Michel Obrist

Outlook

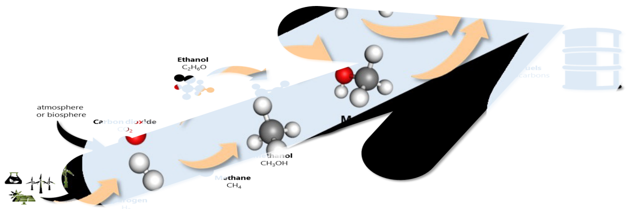
The SWEET reFuel.ch project

Christian Bach,
Empa
Co-Coordinator
reFuel.ch

Regina Betz,
ZHAW
Co-Coordinator
reFuel.ch

Aim of reFuel.ch: Develop robust pathways and synthesis methods for sustainable fuels (SF) -and platform chemicals (SPC).

Aim of WP3: Determine robust transition paths for the Swiss energy system including SF and SPC**.**



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Robin Mutschler


Barton Chen


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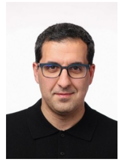
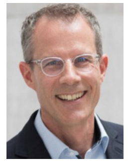

Arash Samani


Matthias Sulzer

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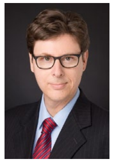
Evangelos Panos

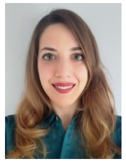

Das Partha

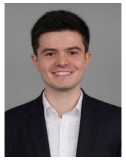

Christian Moretti

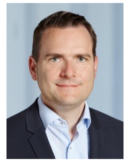

Christian Bauer

ETH


Gianfranco Guidati


Eleonora Bargiacchi


Marvin Volkmer


André Bardow

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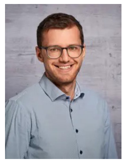
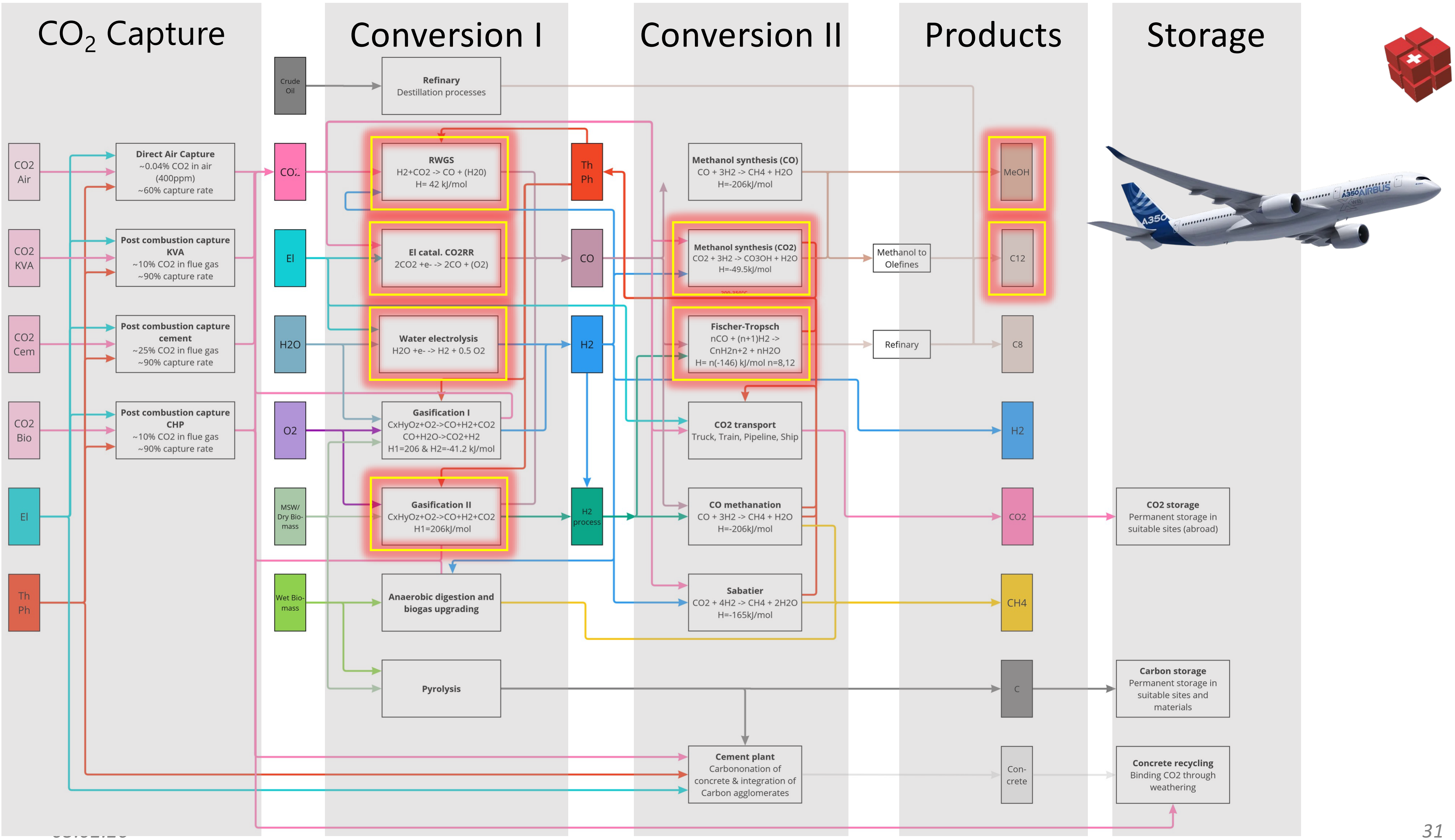
Viola Rühlin


Marco Aebi


Maike Scherrer



CO2 Capture
Conversion I
Conversion II
Products
Storage
CO2 Air
CO2 KVA
CO2 Cem
CO2 Bio
El
Th Ph
Direct Air Capture
~0.04% CO2 in air (400ppm)
~60% capture rate
Post combustion capture KVA
~10% CO2 in flue gas
~90% capture rate
Post combustion capture cement
~25% CO2 in flue gas
~90% capture rate
Post combustion capture CHP
~10% CO2 in flue gas
~90% capture rate
Crude Oil
CO2
El
H2O
O2
MSW/ Dry Bio-mass
Wet Bio-mass
Refinary
Destillation processes
RWGS
H2+CO2 -> CO + (H20)
H= 42 kJ/mol
El catal. CO2RR
2CO2 +e- -> 2CO + (O2)
Water electrolysis
H2O +e- -> H2 + 0.5 O2
Gasification I
CxHyOz+O2->CO+H2+CO2
CO+H2O->CO2+H2
H1=206 & H2=-41.2 kJ/mol
Gasification II
CxHyOz+O2->CO+H2+CO2
H1=206kJ/mol
Anaerobic digestion and biogas upgrading
Pyrolysis
Th Ph
CO
H2
H2 process
Methanol synthesis (CO)
CO + 3H2 -> CH4 + H2O
H=-206kJ/mol
Methanol synthesis (CO2)
CO2 + 3H2 -> CO3OH + H2O
H=-49.5kJ/mol
Fischer-Tropsch
nCO + (n+1)H2 ->
CnH2n+2 + nH2O
H= n(-146) kJ/mol n=8,12
CO2 transport
Truck, Train, Pipeline, Ship
CO methanation
CO + 3H2 -> CH4 + H2O
H=-206kJ/mol
Sabatier
CO2 + 4H2 -> CH4 + 2H2O
H=-165kJ/mol
Cement plant
Carbononation of concrete & integration of Carbon agglomerates
Methanol to Olefines
Refinary
MeOH
C12
C8
H2
CO2
CH4
C
Con-crete
CO2 storage
Permanent storage in suitable sites (abroad)
Carbon storage
Permanent storage in suitable sites and materials
Concrete recycling
Binding CO2 through weathering
A350 AIRBUS

Empa – The Place where Innovation Starts

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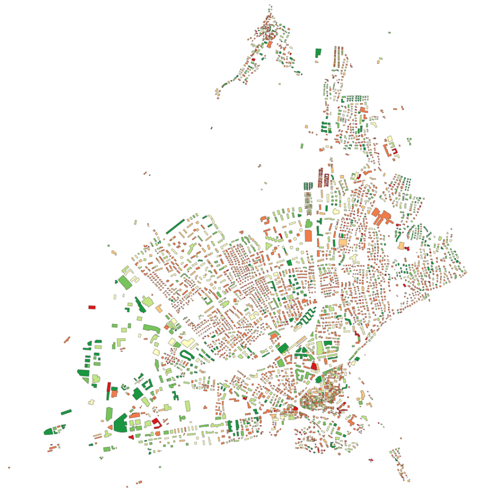
Supplementary

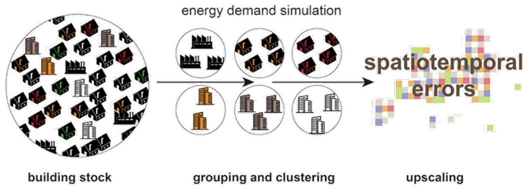
Vorgehen zur Berechnung des Gebäudeenergieverbrauchs

1. GIS Analyse



Analyse pro Siedlungs Hub durchgeführt.
Gebäudedaten werden an Simulation übergeben.

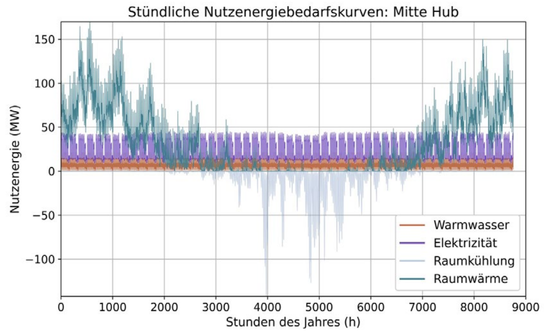
2. Gebäude Simulation



Referenz: [Spatiotemporal upscaling errors of building stock clustering for energy demand simulation, S. Eggimann et. al., 2021]

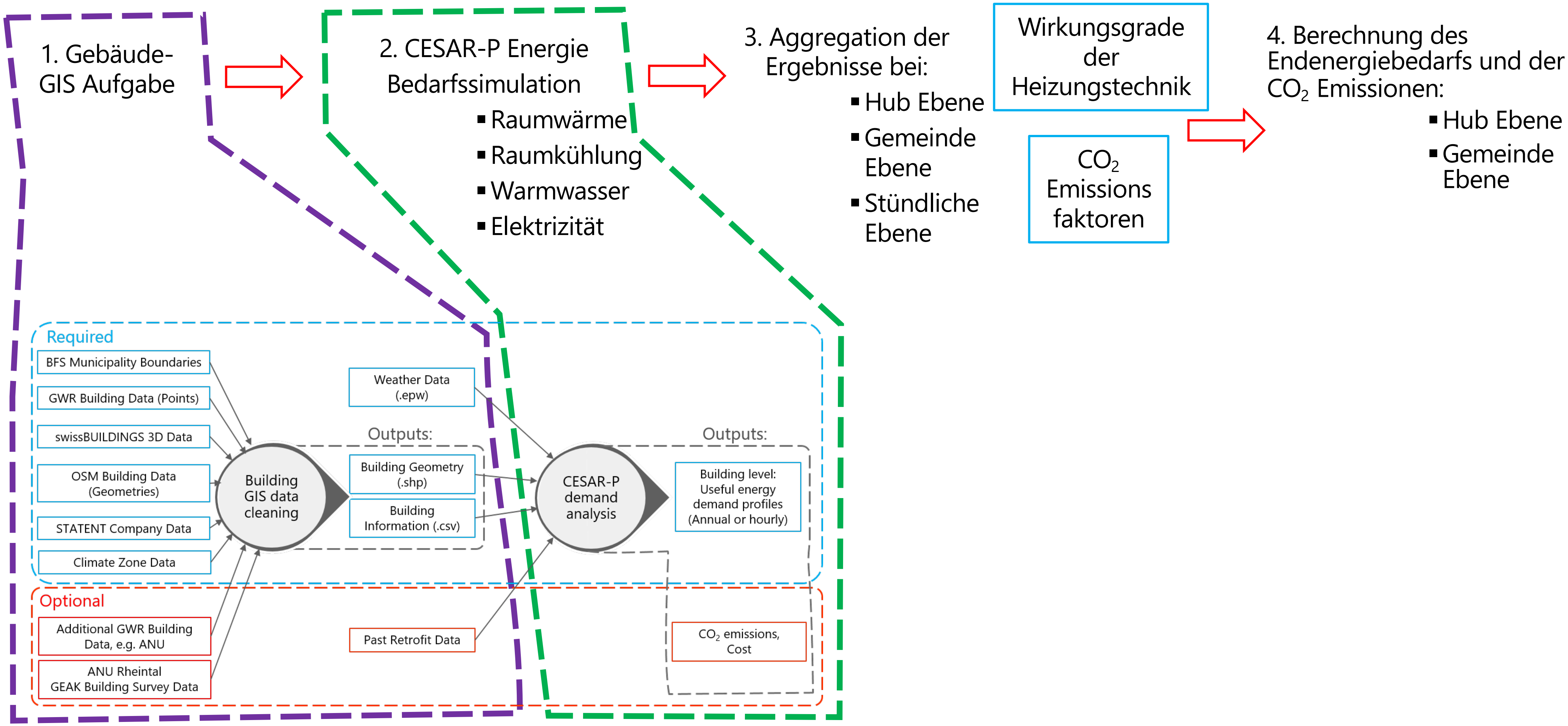
Die Gebäude Simulation ermittelt den Energiebedarf des Gebäudes anhand einer Klassifizierung basierend auf Gebäudealter und Typ- neben weiteren Kriterien. Siehe Referenz.

3. Nutzenergiebedarf

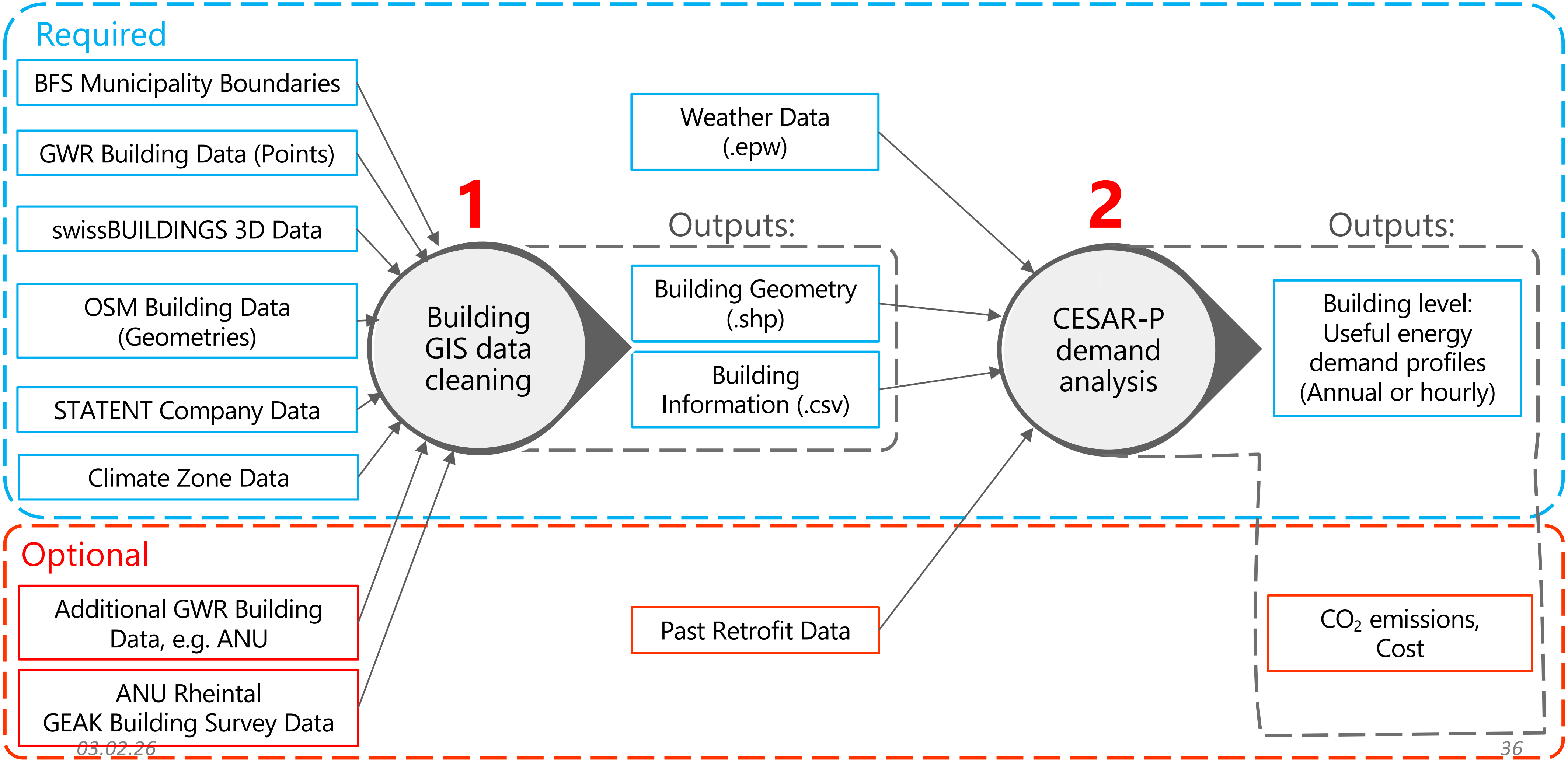


Bedarfskurven wurde pro Hub erstellt -> Profile als Eingabe für Energiesystem Optimierung

Arbeitsabläufe



Schritte der Gebäudeanalyse



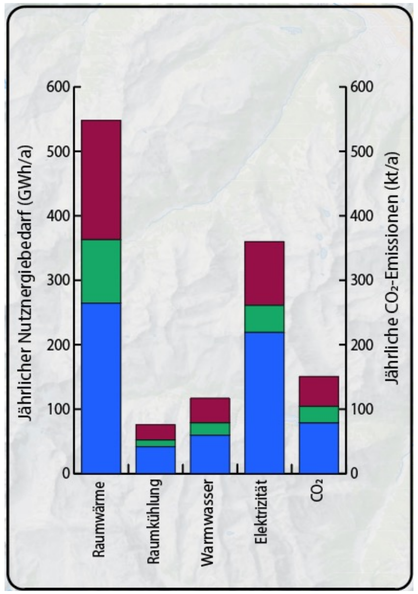
Sanierungsraten

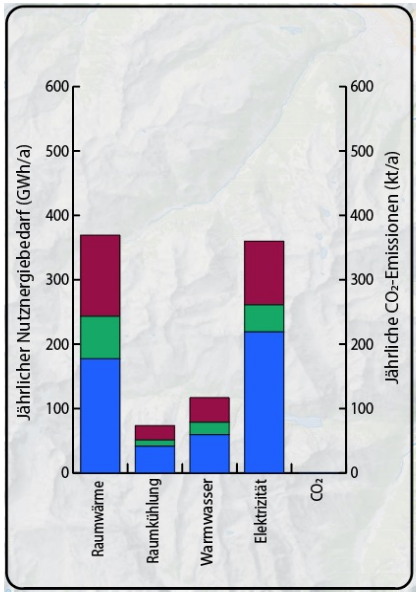
Die Sanierungsraten beeinflussen den Endenergiebedarf der Gebäude.
Nicht jedoch die Heiztechnologien! Diese werden durch das Modell entschieden.

Die Sanierungsrate wurde für das gesamte Rheintal auf 2,7 %/Jahr festgelegt. Diese Raten basieren auf dem Muken-Bericht:

- Ohnehin-Sanierungsrate: 1%. Von den 1 % der sanierten Gebäude werden 40 % einer Vollsanierung unterzogen (Fenster & Dach & Wand & Boden) vorgenommen. 20 % der Gebäude werden einer Fenster & Wand & Dach Sanierung unterzogen und bei 40 % der Gebäude wird eine Fenster & Dach Sanierung durchgeführt.
- Bei den zusätzlichen Sanierungen (alles was 1% übersteigt) wird angenommen, dass die Sanierung an Fenster & Dach Sanierungen vorgenommen wird.

Energieverbrauch und Emissionen Gebäude





Jährlicher Wärmeenergiebedarf

<u>REF</u>: 665 GWh
Mitte: 324 GWh
West: 118 GWh
Nord: 223 GWh

<u>2050</u>: 486 GWh (-27%)
Mitte: 237 GWh
West: 85 GWh
Nord: 164 GWh

Spitzen Wärmeenergiebedarf

<u>REF</u>: 364 MW
Mitte: 179 MW
West: 64 MW
Nord: 121 MW

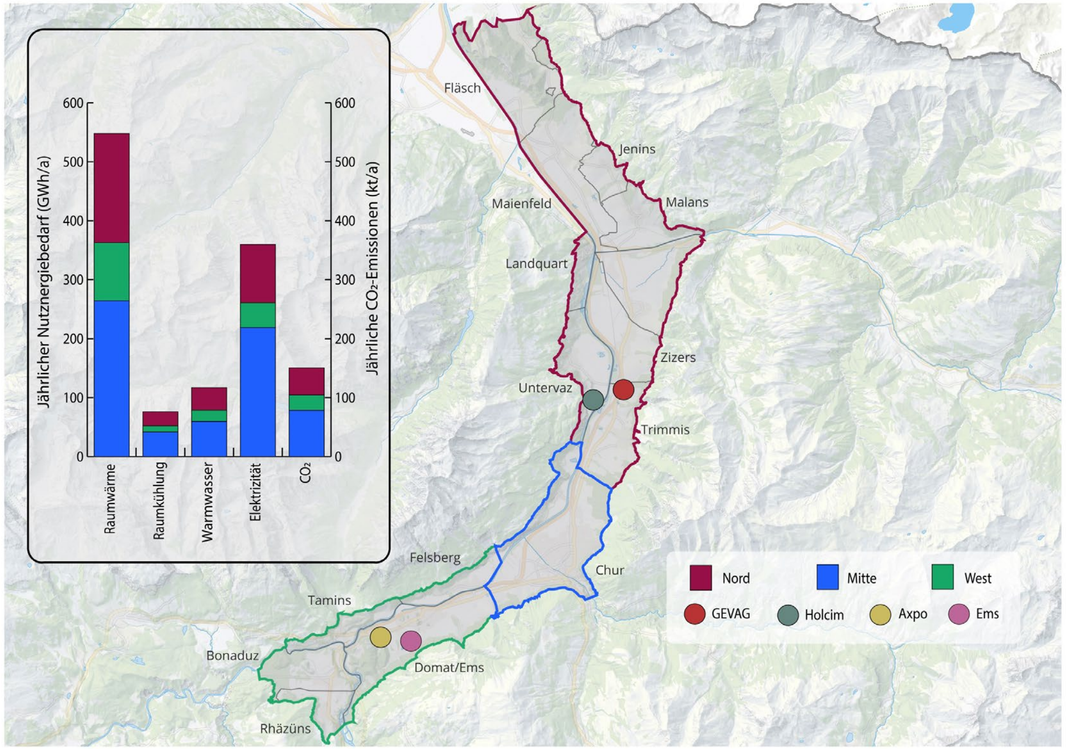
<u>2050</u>: 252 MW (-31%)
Mitte: 122 MW
West: 45 MW
Nord: 85 MW

<u>REF Fahrzeuge:</u>
Total: 66 k: (65'110 Fossil + 1'011 EV). Diesel: 36'050 (Mitte: 16'822, West: 7'781, Nord: 11'446), Benzin: 29'060 (Mitte: 13'561, West: 6'273, Nord: 9'227), EV: 1'011 (Mitte: 448, West: 187, Nord: 376)
Total Fahrzeuge in GR: 162'452 (2020). Bevölkerung: 200'096 (2020).
Quelle: Kanton GR. Anzahl Fahrzeuge pro Hubs ist Proportional zum Kantonalen Durchschnitt.
<u>2050 Fahrzeuge:</u>
Total: 62 k (12'365 Fossil + 49'460 EV). Diesel: 6'846 (Mitte: 3195, West: 1478, Nord: 2174), Benzin: 5519 (Mitte: 2575, West: 1191, Nord – 1752), EV*: 49'460* (Mitte: 23'080, West: 10'676, Nord: 15'704)
Energieverbrauch pro Fahrzeuge:
Diesel: 9085 kWh/a, Benzin: 9085 kWh/a, Strom[3]: 2862 kWh/a
[1] Im Jahr 2050 werden 80 % der Fahrzeugflotte aus Elektrofahrzeugen bestehen. Die Fahrzeugflotte in GR reduziert sich um 5% (Bevölkerungsrückgang) Quelle: EBP.
[3] Eigenen Annahmen

Elektrizitätsbedarf für Elektrofahrzeuge (EV)

2050: 142 GWh
Mitte: 66 GWh
West: 31 GWh
Nord: 45 GWh

Energieverbrauch und Emissionen der Gebäude im Rheintal, REF

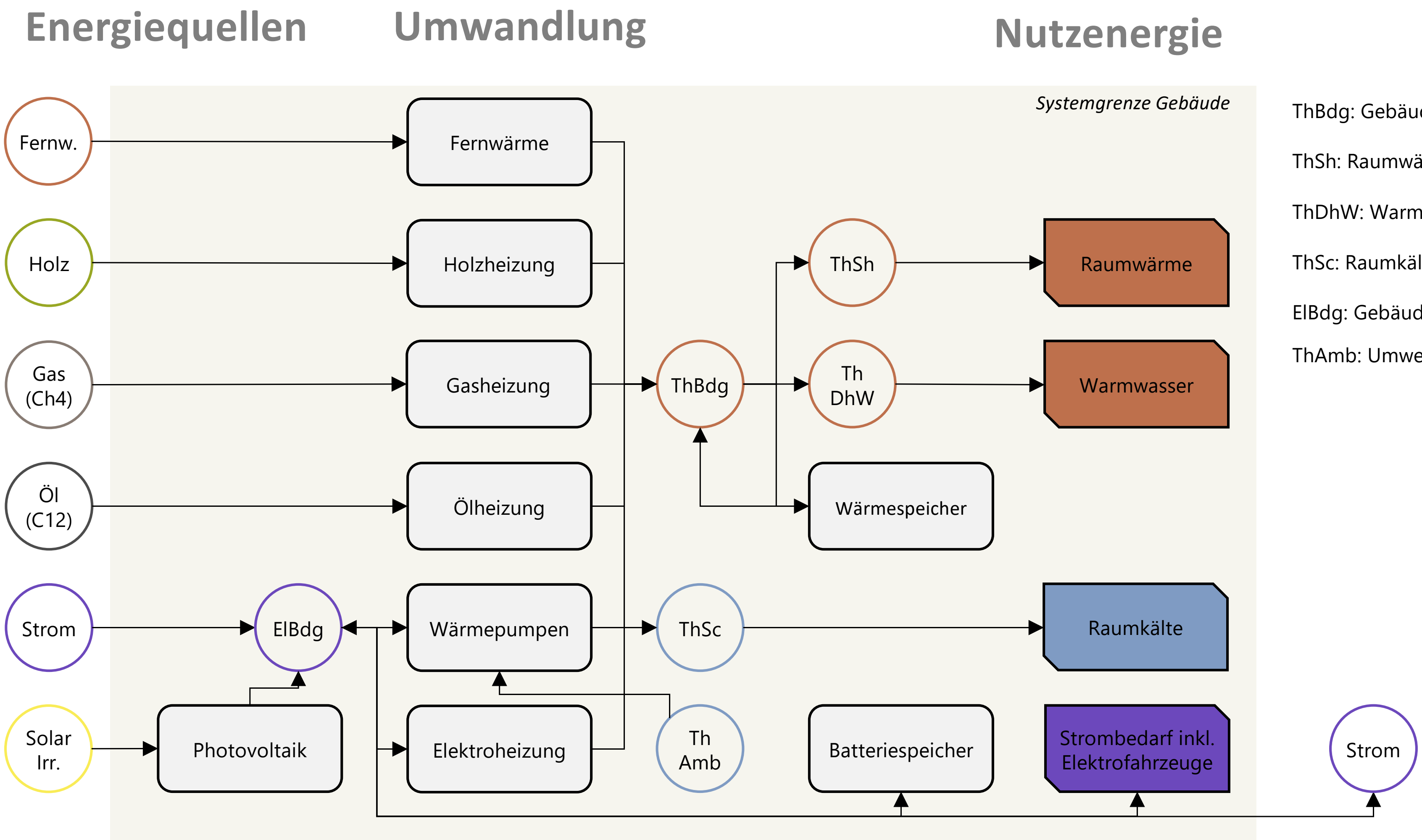


Heizungssysteme im Rheintal
Gebäudewärme –und Warmwasser wird vor allem durch **fossile Gebäudeheizungen** bereitgestellt. Die Heizungssystem sind wie folgt verteilt:

- 37% Gasheizungen
- 32% Ölheizungen
- 14% Wärmepumpen
- 8% Holzheizungen
- 7% Fernwärmeanschlüsse
- 2% elektrische Widerstandsheizungen

*Grossverbraucher-Bedarf ist hier nicht enthalten

Gebäudemodell Rheintal. Pro Hub. Ohne H_2 Techs.



ThBdg: Gebäudewärme

ThSh: Raumwärme

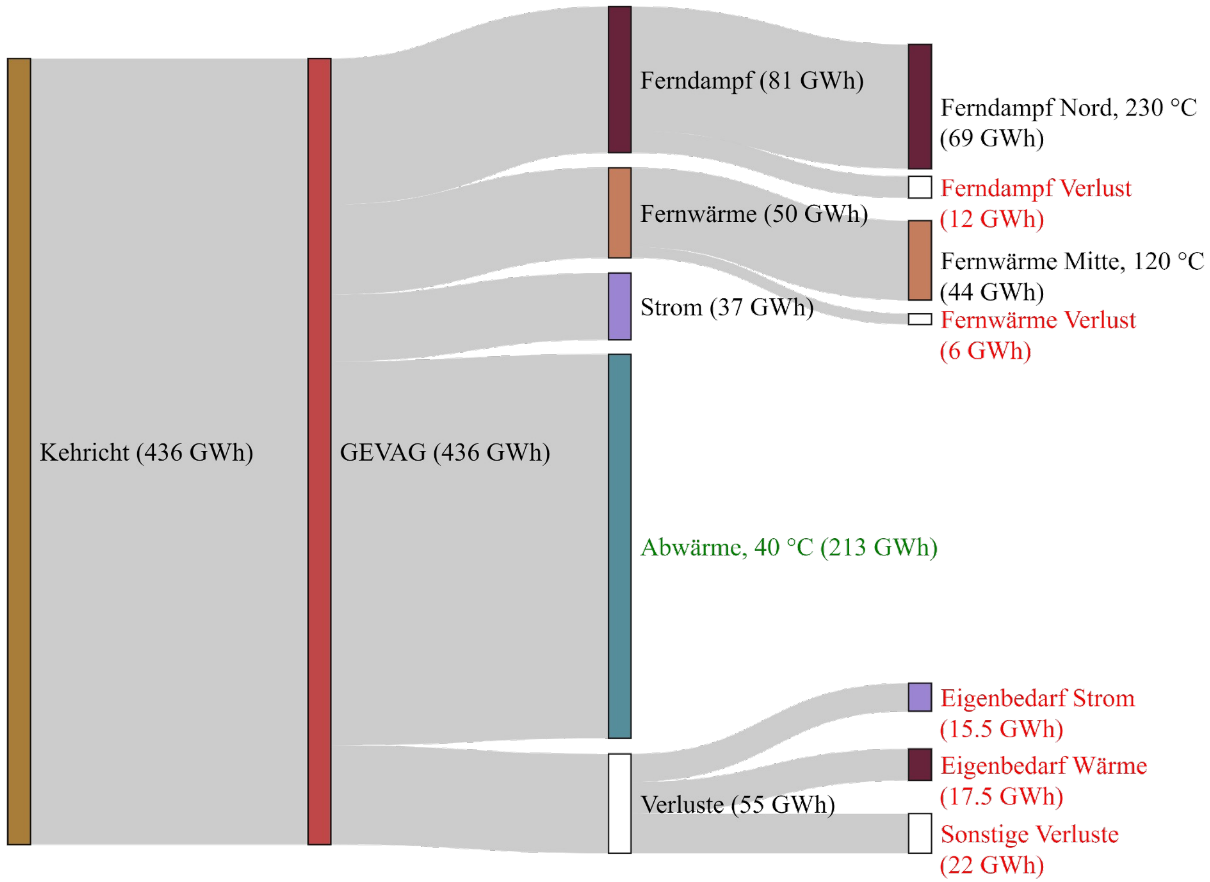
ThDhW: Warmwasser

ThSc: Raumkälte

ElBdg: Gebäude Elektrizität

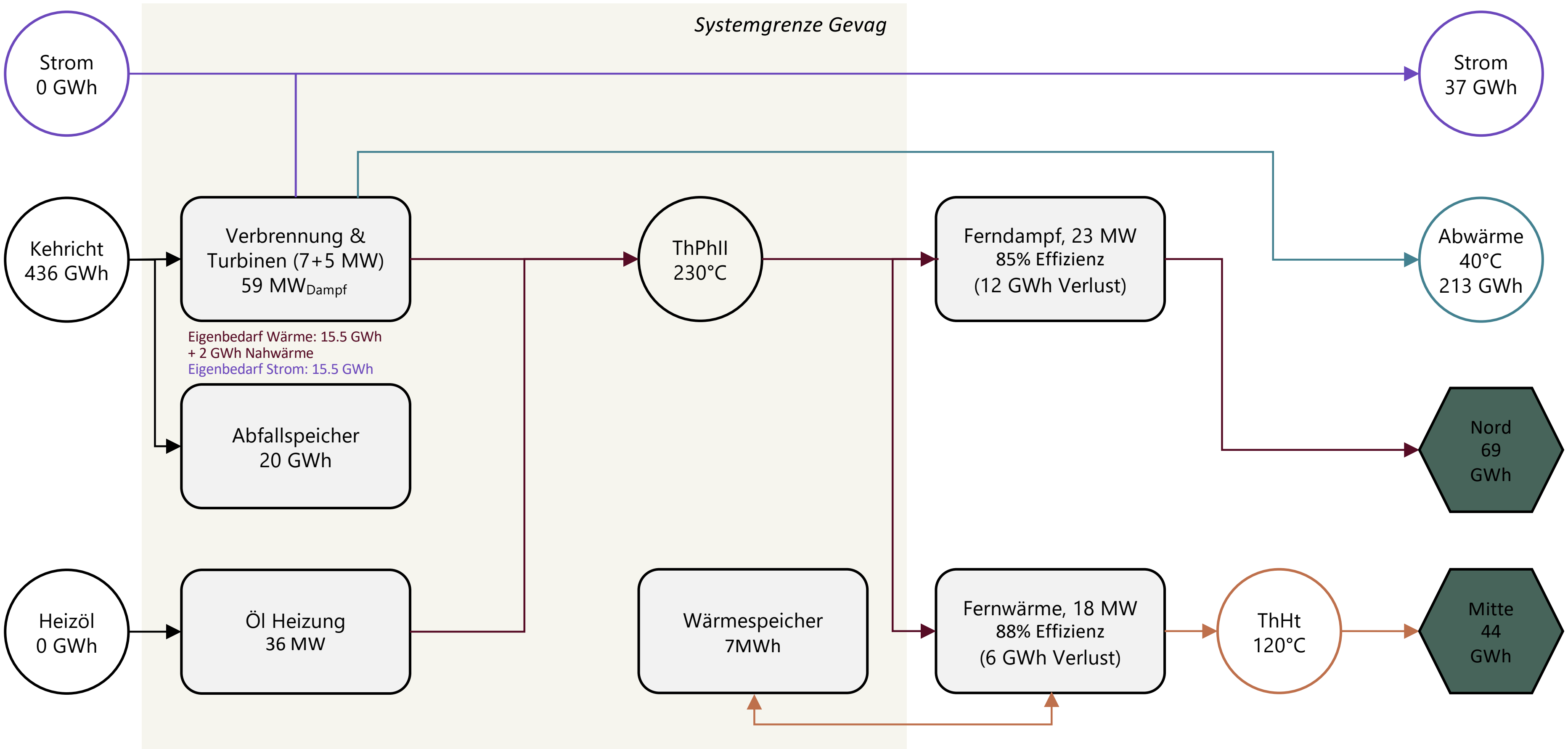
ThAmb: Umweltwärme

Energieflüsse GEVAG, REF



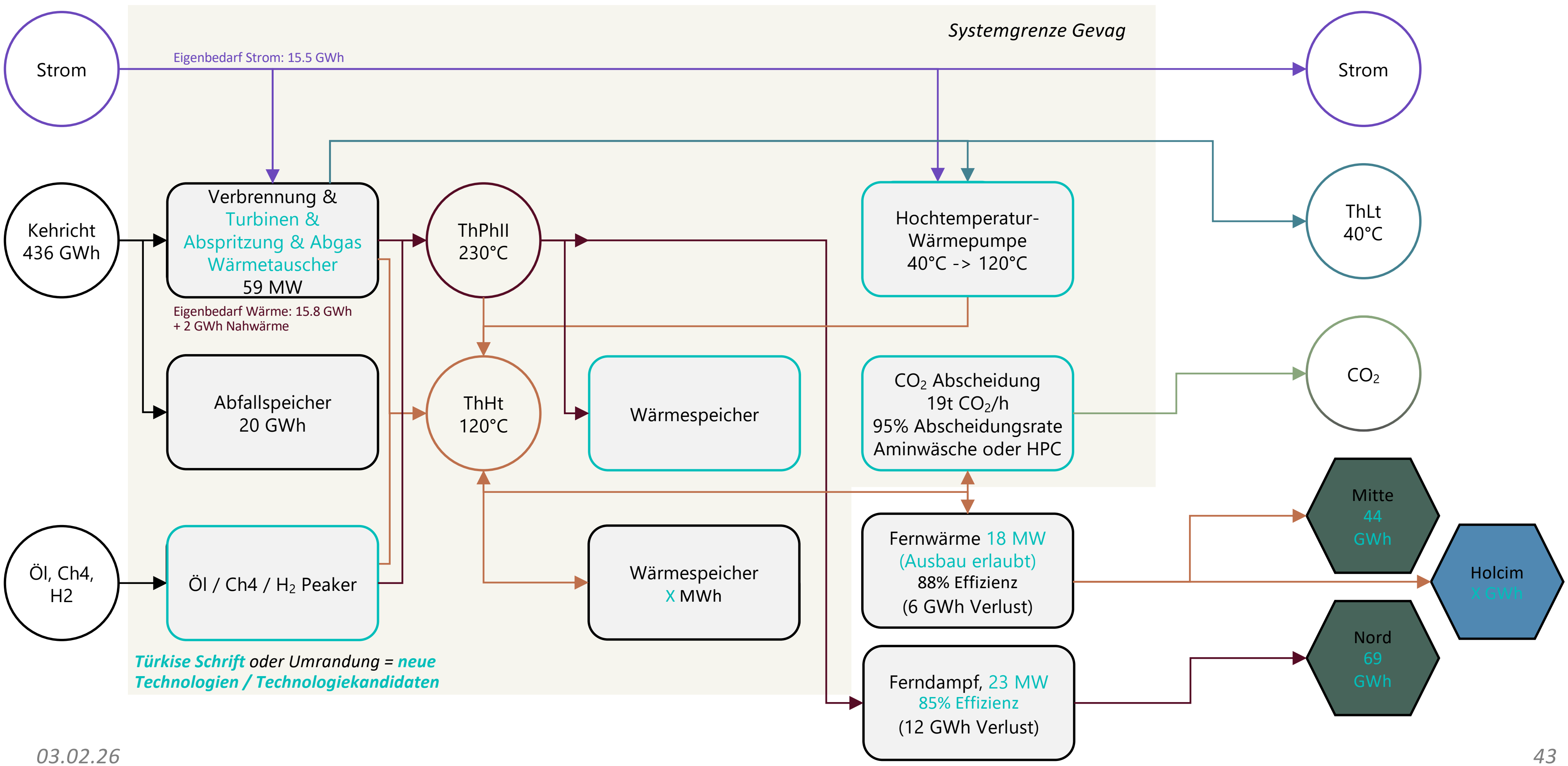
Erklärung Schriftfarbe
Schwarzer Text: Genutze Energie
Grüner Text: Freie Energie
Roter Text: Verluste/Eigenbedarf

GEVAG Modell, REF+

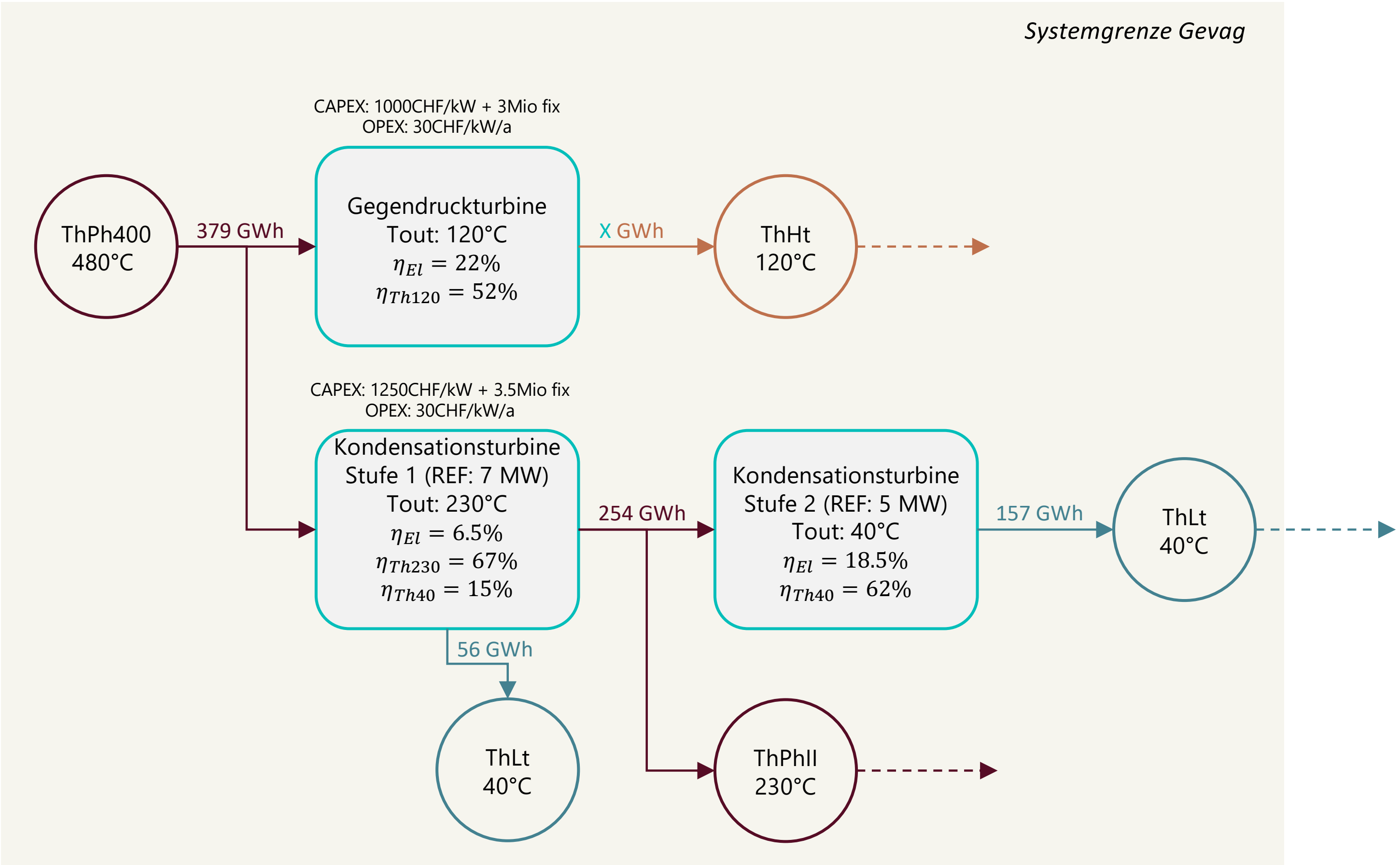


Anmerkung: Dampfturbinen (5+7 MW), Dampf Abspritzung, Abgaswärmetauscher (2.7MW) und Eigenverbrauch sind in "Verbrennung und Turbinen" Element eingerechnet. Die Kesseltemperatur beträgt 480°C. REF+ berücksichtigt Anlagenerweiterungen, welche in naher Zukunft Umgesetzt werden.

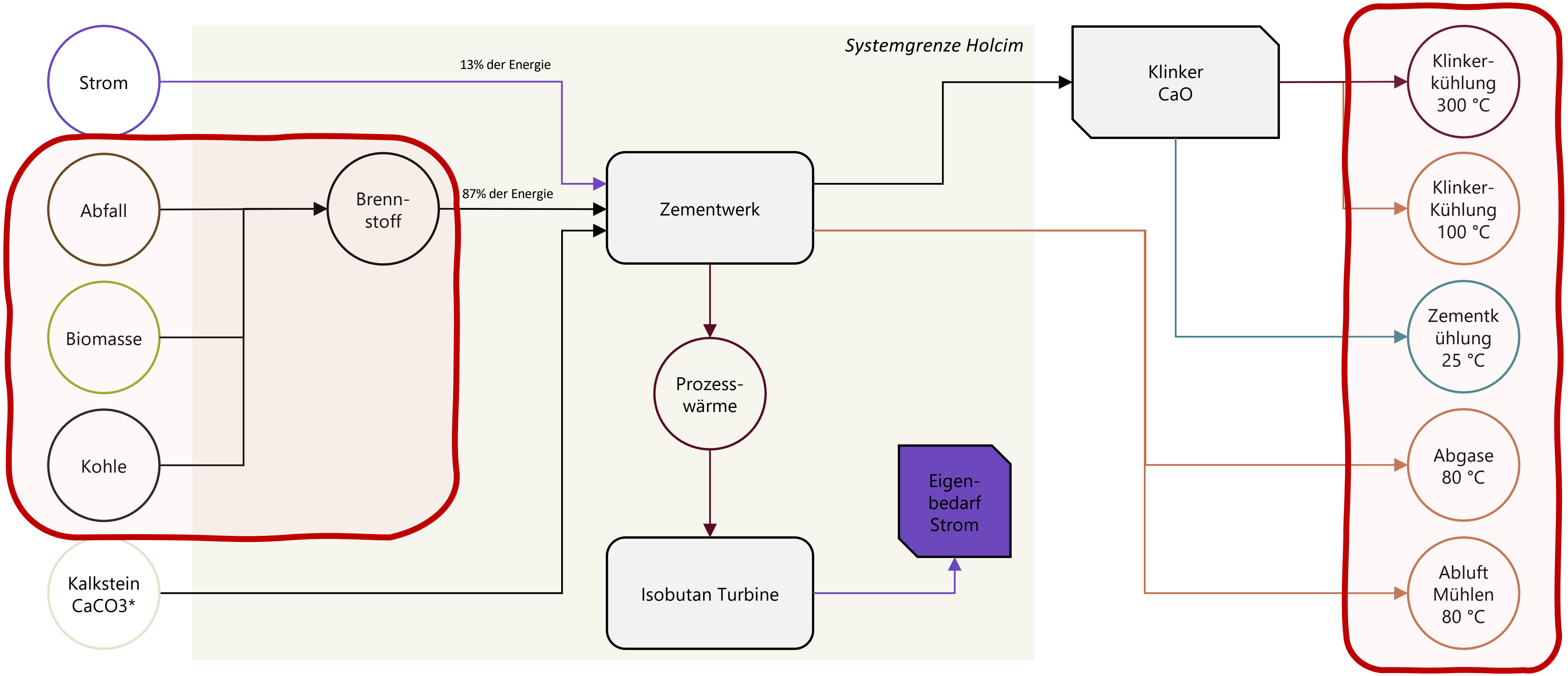
GEVAG Modell, 2050



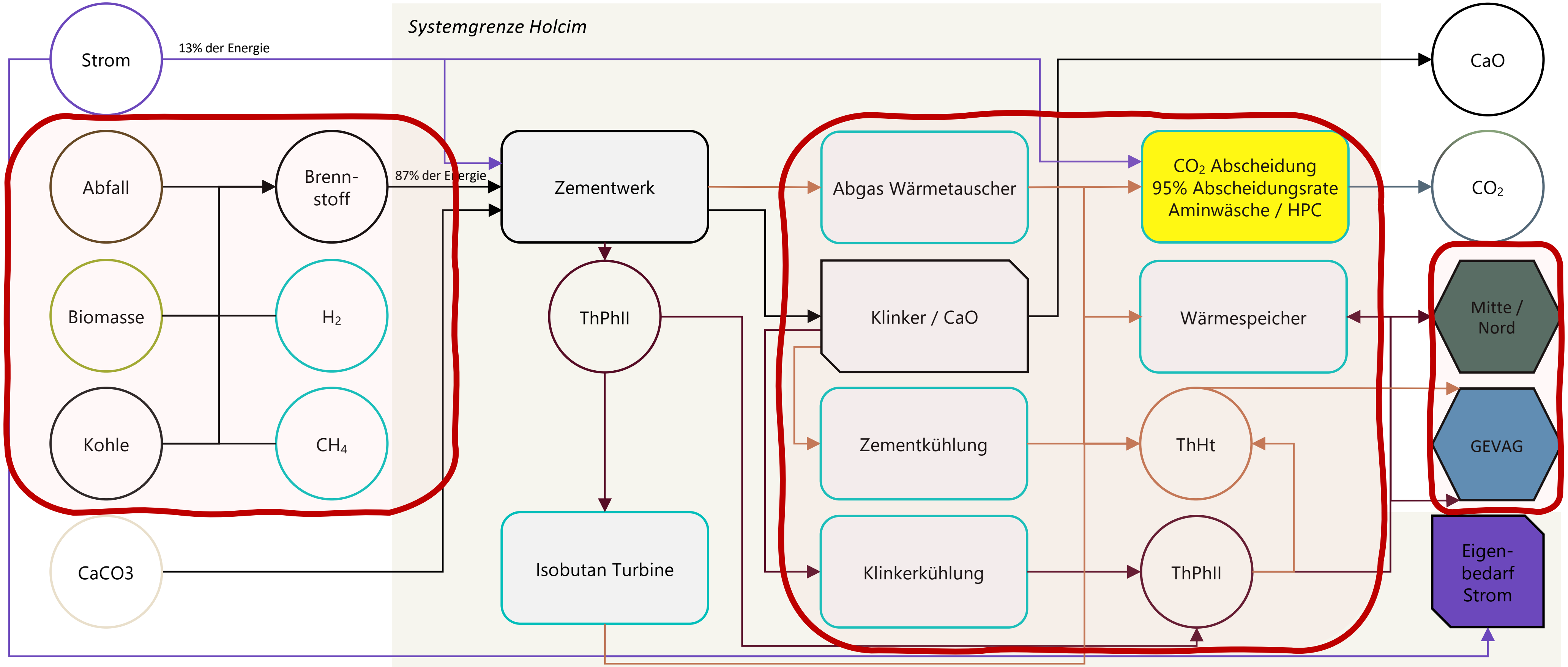
Mögliche Turbinenkonfigurationen GEVAG, 2050



Model of the cement plant Untervaz, «today»

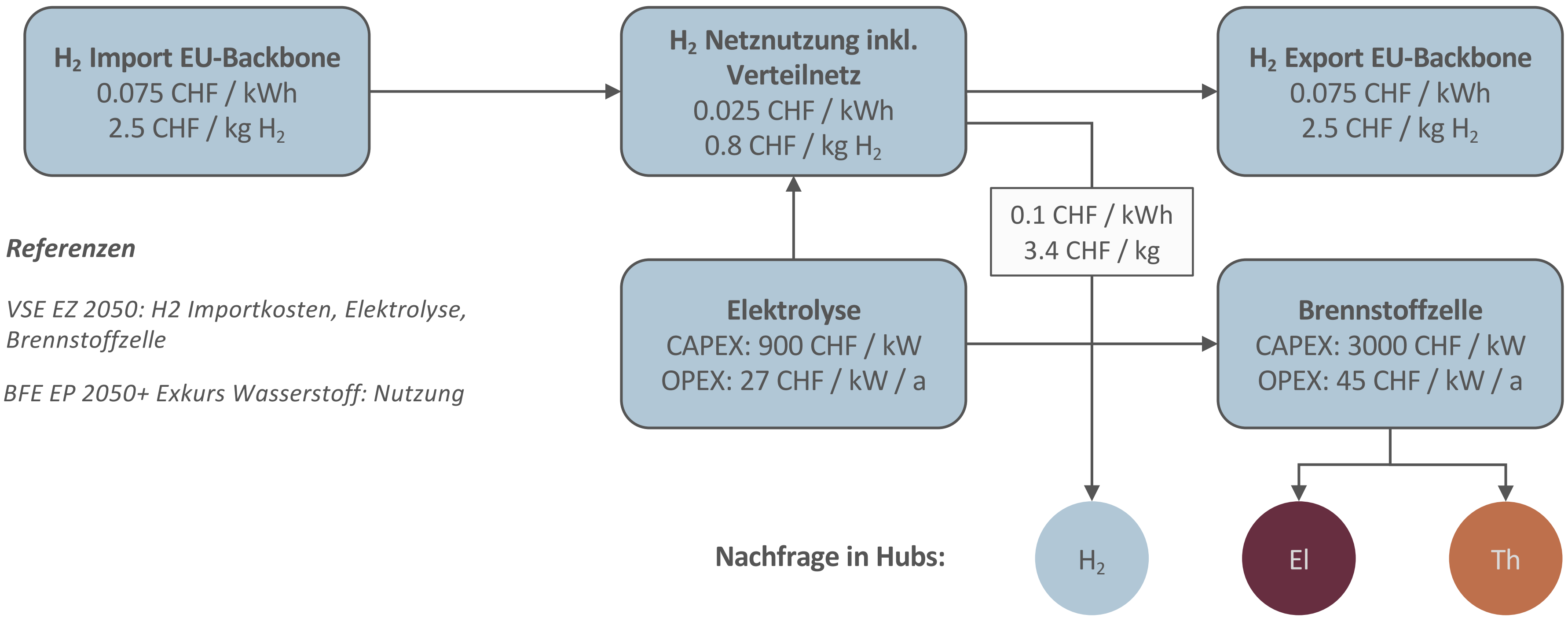


Model of the cement plant Untervaz, 2050



Szenariendefinition

Wasserstoff Import und Produktion 2050: Szenario 2050-pro: H_2 "Backbone" Anschluss

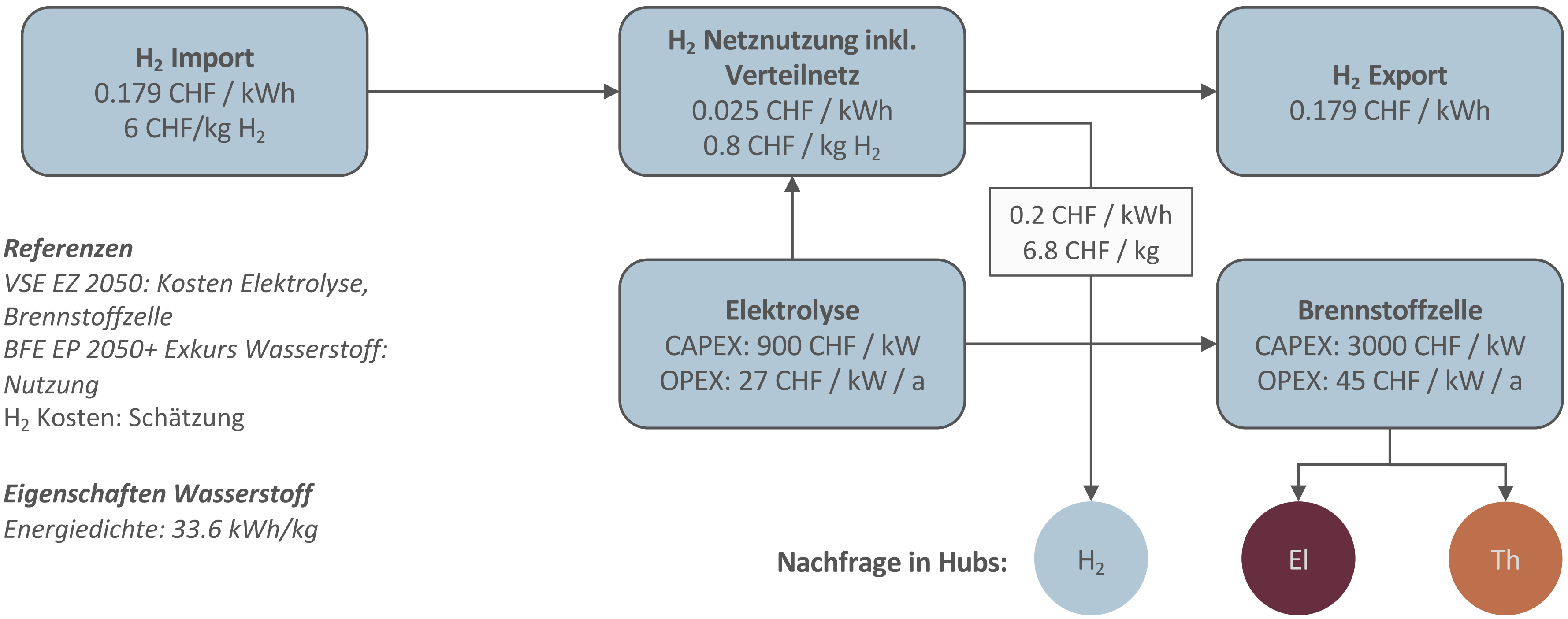


Referenzen

VSE EZ 2050: H2 Importkosten, Elektrolyse, Brennstoffzelle

BFE EP 2050+ Exkurs Wasserstoff: Nutzung

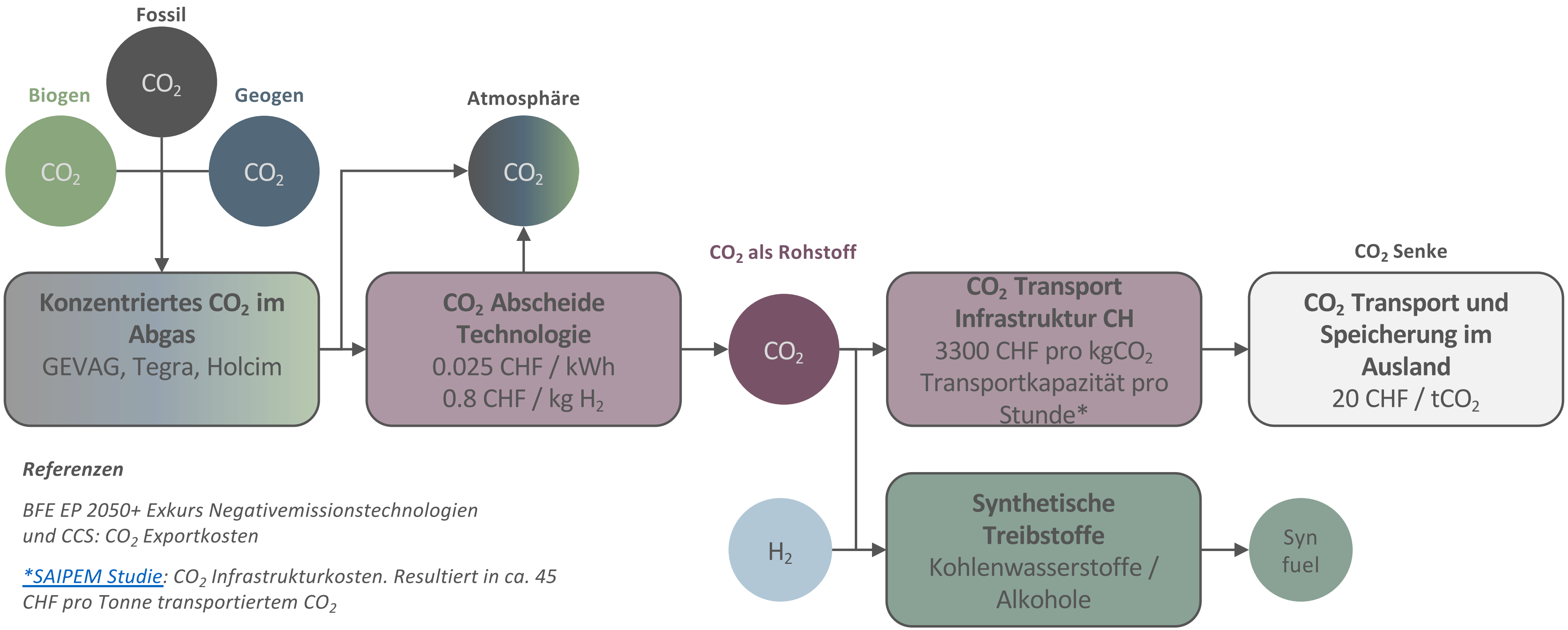
Wasserstoff Import / Produktion 2050
Szenario 2050-res: Kein H_2 "Backbone" Anschluss



Referenzen
VSE EZ 2050: Kosten Elektrolyse, Brennstoffzelle
BFE EP 2050+ Exkurs Wasserstoff: Nutzung
H_2 Kosten: Schätzung

Eigenschaften Wasserstoff
Energiedichte: 33.6 kWh/kg

CO_2 Abscheidung, Nutzung, Transport und Speicherung



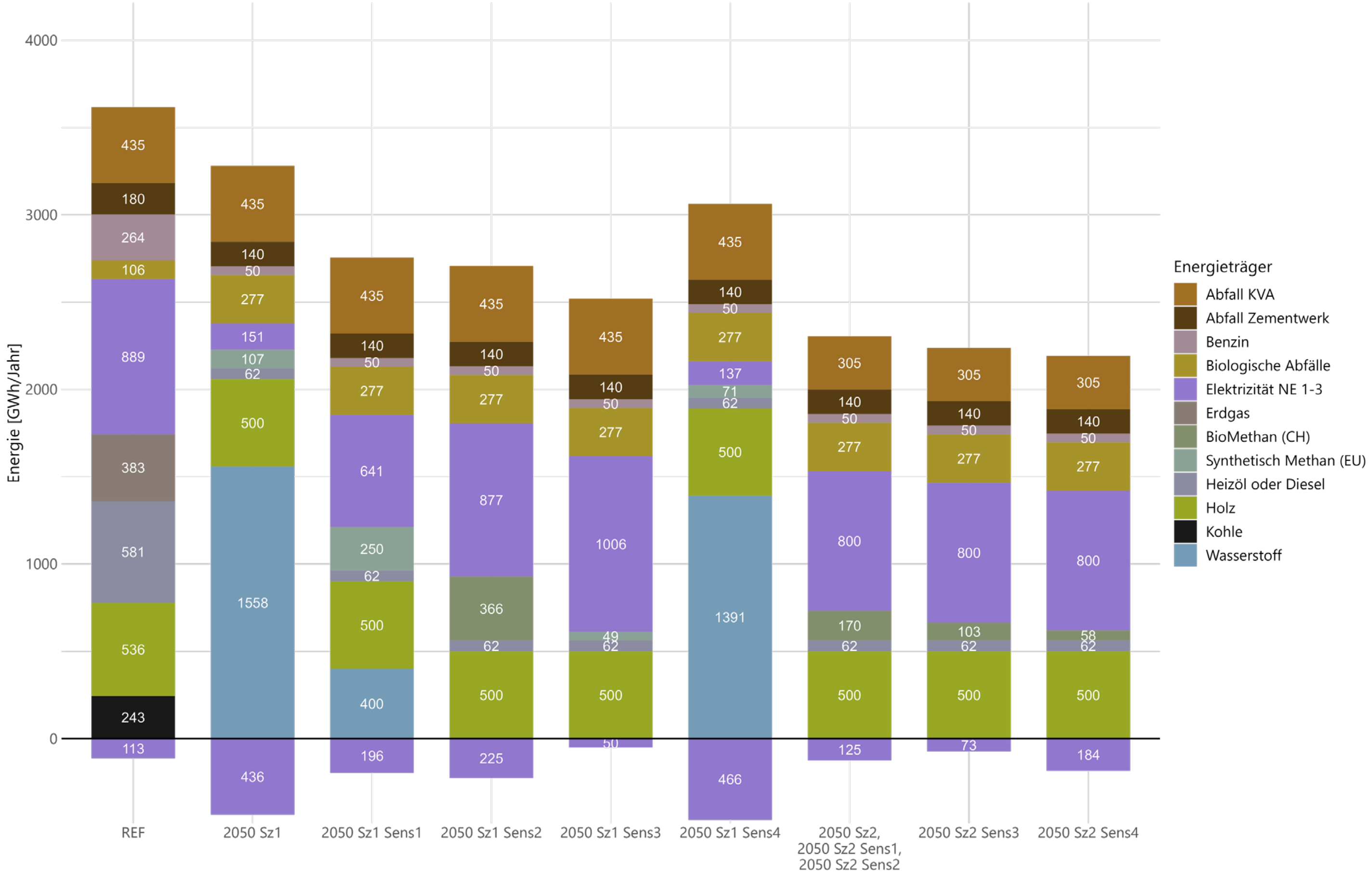
Referenzen

BFE EP 2050+ Exkurs Negativemissionstechnologien und CCS: CO_2 Exportkosten

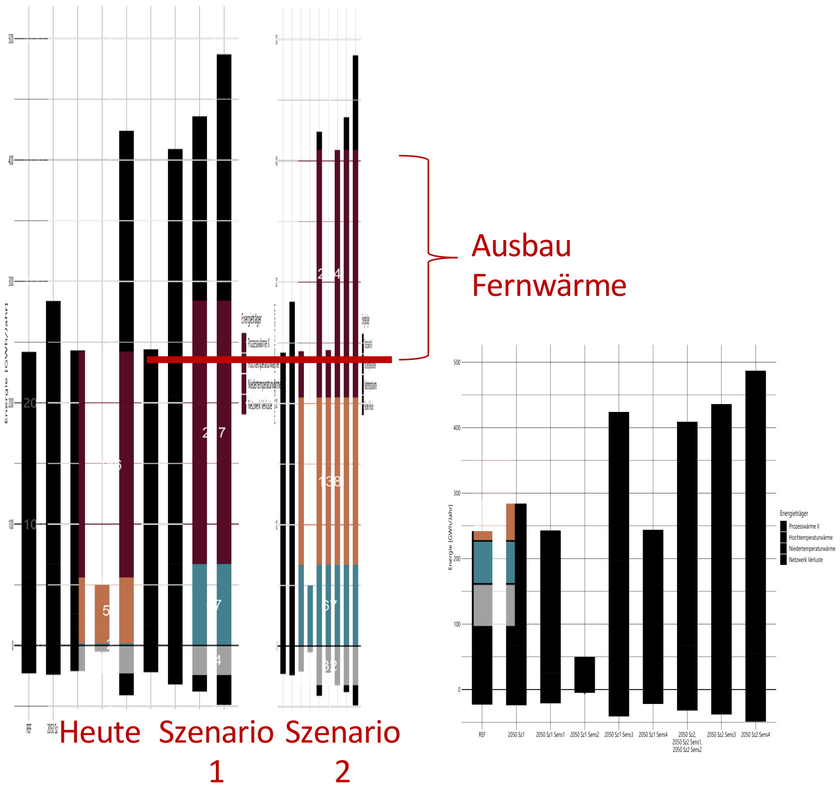
*[*SAIPEM Studie]: CO_2 Infrastrukturkosten. Resultiert in ca. 45 CHF pro Tonne transportiertem CO_2*

Die Synthese von Treibstoffen aus CO_2 und H_2, sowie ein H_2 / CO_2 Verteilnetz (inter-Hub) wird in der nächsten Phase des Projektes betrachtet.

Jährlicher Import & Export, Szenarienübersicht



Fernwärme kann weiterhin einen wichtigen Beitrag im Energiesystem leisten



- Wenn der Strombedarf nicht wesentlich steigen darf, übernimmt die Fernwärme verstärkt die Wärmeversorgung.
- Abwärmenutzung aus Industriehubs können Wärmebedarf für Fernwärme decken.

Szenario 1: Keine Restriktionen beim Stromnetzausbau sowie bei Importen von Wasserstoff und synthetischem Methan.

Szenario 2: Nur leichte Erhöhung der Importe von Wasserstoff und synthetischem Methan sowie moderater Ausbau der Stromnetzkapazität (+20%).

Motivation: Hydrogen in Rheintal Valley

- “Netto-Null Rheintal 2050” at EMPA:
  - Rheintal Valley in Graubünden
  - Aim net-zero CO_2 emissions by 2050
  - Development of a spatially resolved energy system model

- What is a Hydrogen Valley?
  - Regional integrated ecosystems encompassing the full hydrogen value chain
  - Facilitate green hydrogen scale-up by optimizing consumption
  - Enhance economic viability in targeted industrial clusters

ELSEVIER
International Journal of Hydrogen Energy
Volume 47, Issue 57, 5 July 2022, Pages 24121-24135

Techno-economic assessment of green hydrogen valley providing multiple end-users

Mario Petrollese, Giulia Concas, Francesco Lonis, Daniele Cocco

Source: Petrollese et al., International Journal of Hydrogen Energy 2022

Scenario: Hydrogen Valley

Baseline	**Scenario 1**	**Scenario 2**
Rheintal 2050	**Centralised Hydrogen**	**Hydrogen Valley**
Based on Netto-Null Rheintal 2050 project	+ Hub H2-SAF + H_2 Network	
No Hydrogen Imports allowed	Research	

- Hydrogen Valley Scenario:
  - Sensitivity analysis on SAF export price
  - Tipping point: SAF is being produced and exported

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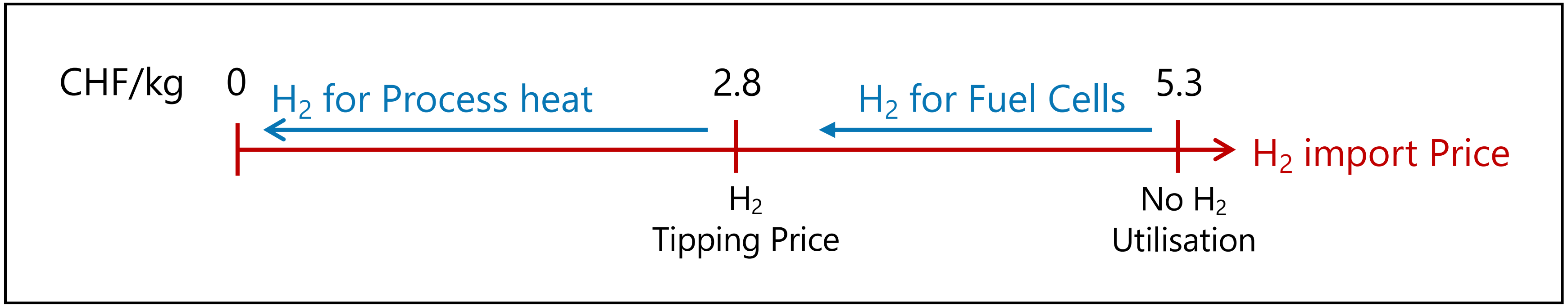
Results: Hydrogen Tipping point

Scenario 1

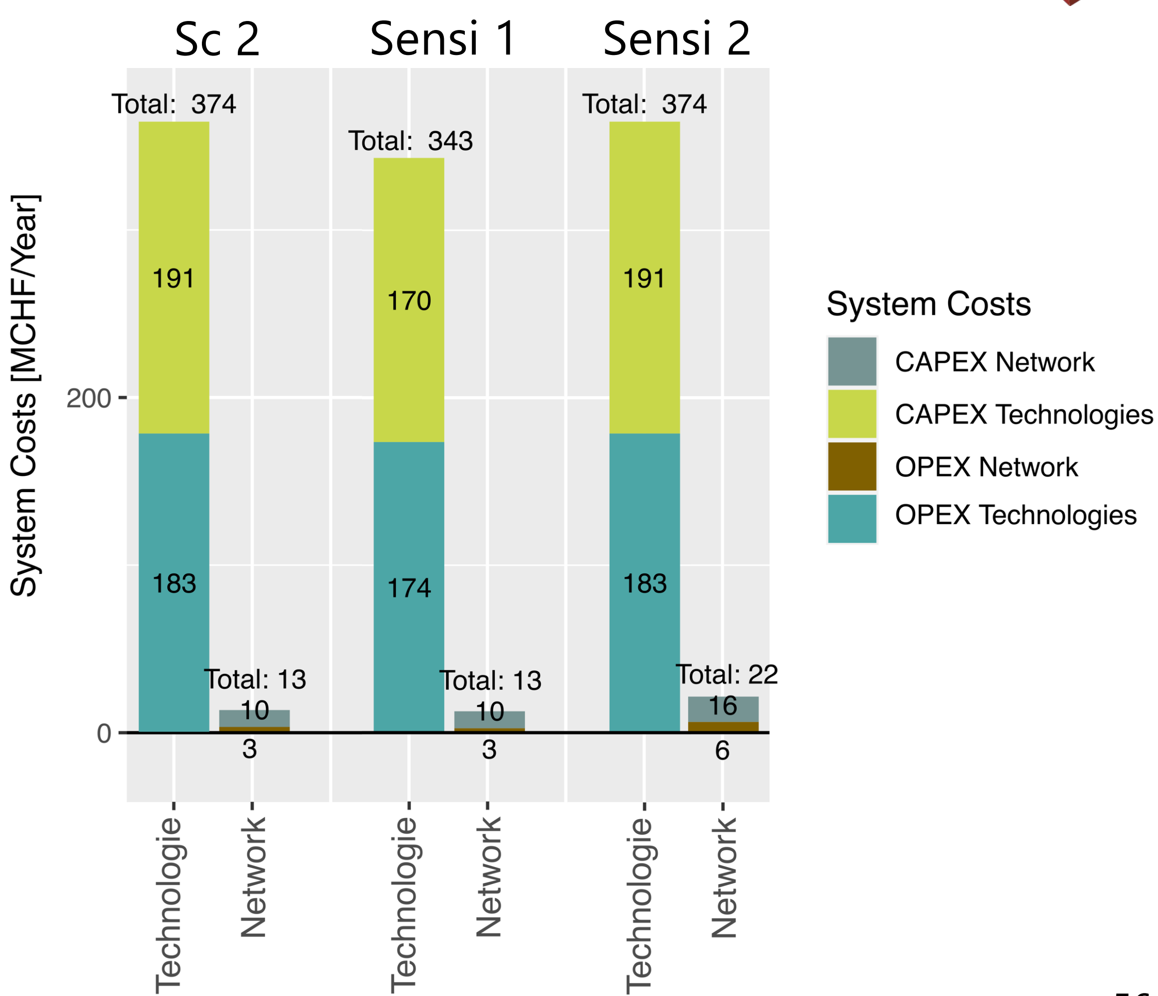


Sensitivity Analysis: CAPEX Impact

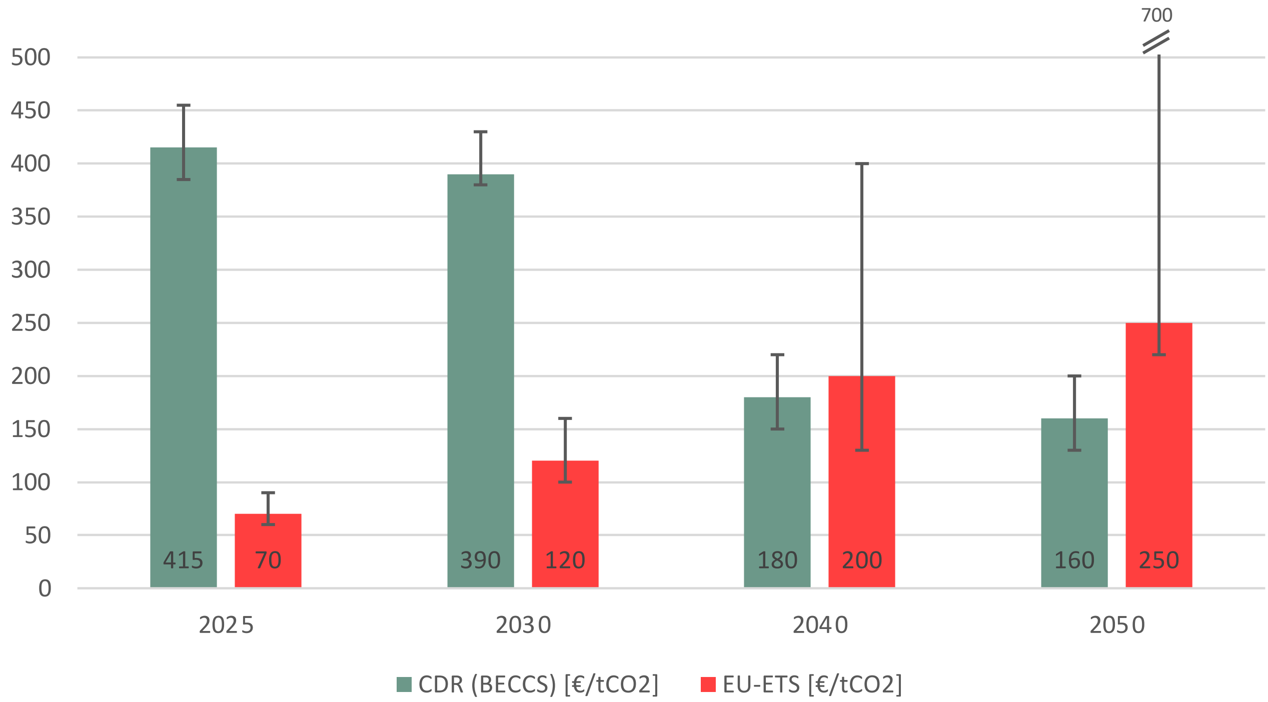
- Sensitivity 1: Fischer-Tropsch CAPEX:
  - 3000 CHF/kW to 600 CHF/kW
  - Reduction CAPEX by 21 MCHF and OPEX by 9 MCHF
  - 8% of total cost

- Sensitivity 2: Hydrogen pipelines CAPEX:
  - Repurposed vs new pipelines
  - 1000 CHF/kW to 2000 CHF/kW
  - Augmentation CAPEX by 6 MCHF and OPEX by 3 MCHF
  - 70% of network cost

- Robust results:
  - SAF production quantity unchanged by changing CAPEX
  - Sensitive only to H_2 import or SAF export price



Carbon Markets – a possible development



CDR: Carbon Dioxide Removal

- Voluntary market: DAC, BECCS, WtE (in CH) [1]

EU-ETS: European Emission-Trading-System [2]

- Mandatory market

References

[1] BAFU / VBSA Branchenvereinbarung

[2] FOEN, ETS

Graph: Plausible value range based on the expert knowledge of Jonas Lötscher, Airfix. Actual values will vary and are subject to high uncertainty.

Further plausibilization via EU-ETS, OPIS CDR Market Survey, IEA Bioenergy, ICAP, Bloomberg, Agora Energiewende, NGFS Climate Scenarios, Study «Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies", Study Carbon prices on the rise? Shedding light on the emerging second EU Emissions Trading System (EU ETS 2)

Glossary

BECCS: Bioenergy with Carbon Capture and Storage, DAC: Direct Air Capture, WtE: Waste to Energy