IEAGHG 8th Post Combustion Capture Conference

16th to 18th September 2025 Marseille, France

Net-Zero through CCS: Energy system integration in a Swiss valley

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Abstract

Closely aligning with Switzerland's long-term climate policy, the canton of Graubünden aims to achieve net-zero CO_2 emissions by 2050. This study investigates cost-optimal transition pathways for an industry-residential cluster in the Rheintal valley of Graubünden. Due to the presence of waste incineration and cement industry, the per capita CO_2 emissions in the valley are around 11t per annum (2024), which is nearly three times as high as the Swiss average.

A sector-coupled, mixed-integer linear optimization (MILP) model is employed to evaluate the most cost-effective solution while complying with the emission targets of reaching net-zero targets. By explicitly incorporating the carbon cycle, the framework enables a comprehensive evaluation of both energy infrastructure and carbon capture and storage (CCS) solutions. This study aims to answer two research questions: 1) How can we efficiently and effectively design more complex sector-coupled energy systems on a regional scale? and 2) What are the roles and impacts of CCS and district heating networks (DHN) in achieving net-zero targets for an industry-residential cluster?

The valley is divided into seven energy balance hubs—three urban-residential hubs (West, Mitte, Nord) covering Domat/Ems, Chur, and Landquart, along with their surrounding municipalities and medium-sized industries, and four large industrial hubs, including amunicipal solid waste (MSW) incineration plant "Gevag", a cement plant "Holcim", a wood-fired combined heat and power (CHP) plant "Tegra", and a chemical plant "Ems". Since certain processes in hard-to-abate industries, such as cement production and waste incineration, are inherently carbon-intensive, meaning that fuel switching alone cannot fully eliminate emissions. To address these unavoidable process emissions, integrating post-combustion CO_2 capture (PCCC) technologies is crucial. Amine scrubbing and Hot-Potassium Carbonate (HPC) processes were identified as possible industry capture technologies for 2050.

A reference energy system model for 2024, reflecting the current regional energy landscape, is developed and validated in close collaboration with local industries, energy providers, and governmental authorities. Building on this calibrated reference, two contrasting baseline scenarios were defined for the future: 2050-pro, assuming full integration with the European hydrogen backbone, enabling cost-effective hydrogen trade and grid expansion, and 2050-res, where the hydrogen backbone bypasses Switzerland, doubling hydrogen import costs and imposing stricter grid and resource constraints. These scenarios are followed by a sensitivity analysis to assess the robustness of the findings and their implications for long-term system planning.

The Rheintal energy system reveals two major challenges today: 1) high carbon emissions per capita and 2) a significant amount of excess heat. Industrial processes generate substantial residual heat, only partially utilized via district heating networks, while the rest is released into the surroundings. The current energy system in Rheintal emitted approximately 840 kt CO_2 per year from fossil and geogenic sources. Additionally, 324 kt CO_2 of biogenic origin was released, primarily from the Tegra wood-fired CHP and the Gevag MSW incinerator. These biogenic emissions do not count as climate-impacting emissions but are considered climate-neutral

in the carbon cycle. **Figure 1** qualitatively illustrates the thermal demands in the urban-residential hubs alongside the excess heat from the four large industrial players and the CO_2 emissions in the valley. Reducing emissions requires both district heating expansion and CCS. In addition to district heating, excess heat from the industries can be utilized to power CO_2 capture systems co-located at industrial sites, allowing for large-scale point-source carbon mitigation.

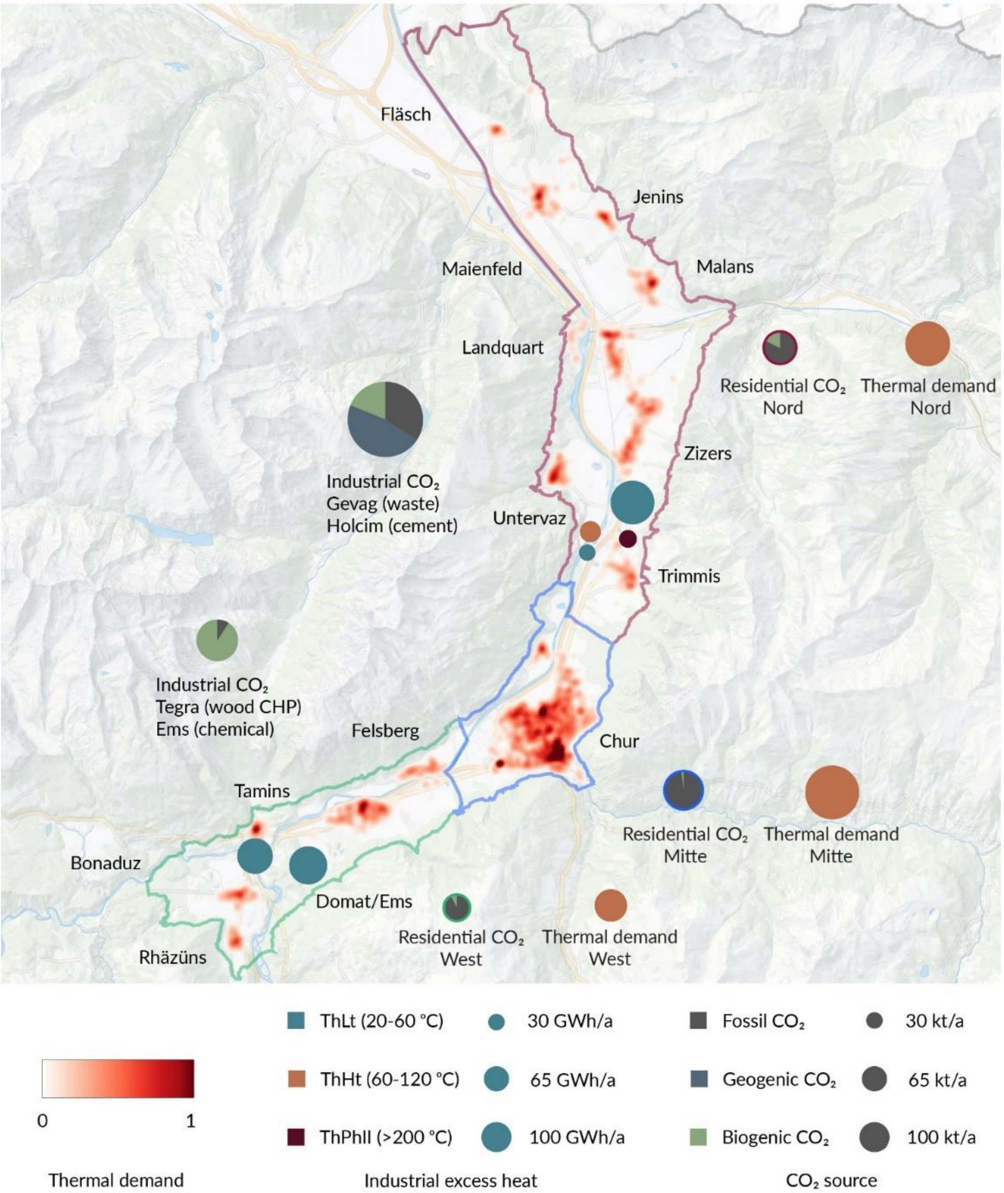

Figure 1: *Spatial distribution (qualitative) of thermal energy demand in the urban-residential hubs alongside the excess heat from the four large industrial players and the CO_2 emissions in the valley*

In the 2050 scenarios (**Figure 2**), DHN utilization was influenced by hydrogen price and availability, as well as electricity costs and supply. The 2050-pro scenario showed limited expansion of the district heating networks when there was cheap availability of renewable gases like hydrogen and synthetic methane. Whereas the 2050-res scenario maximizes high-temperature excess heat use and recovers substantial low-temperature heat, optimizing resource use within the system. The expanded DHN infrastructure supports local heat supply, relieves the pressure on electricity grid, and provides high-temperature heat for amine-based CO_2 capture.

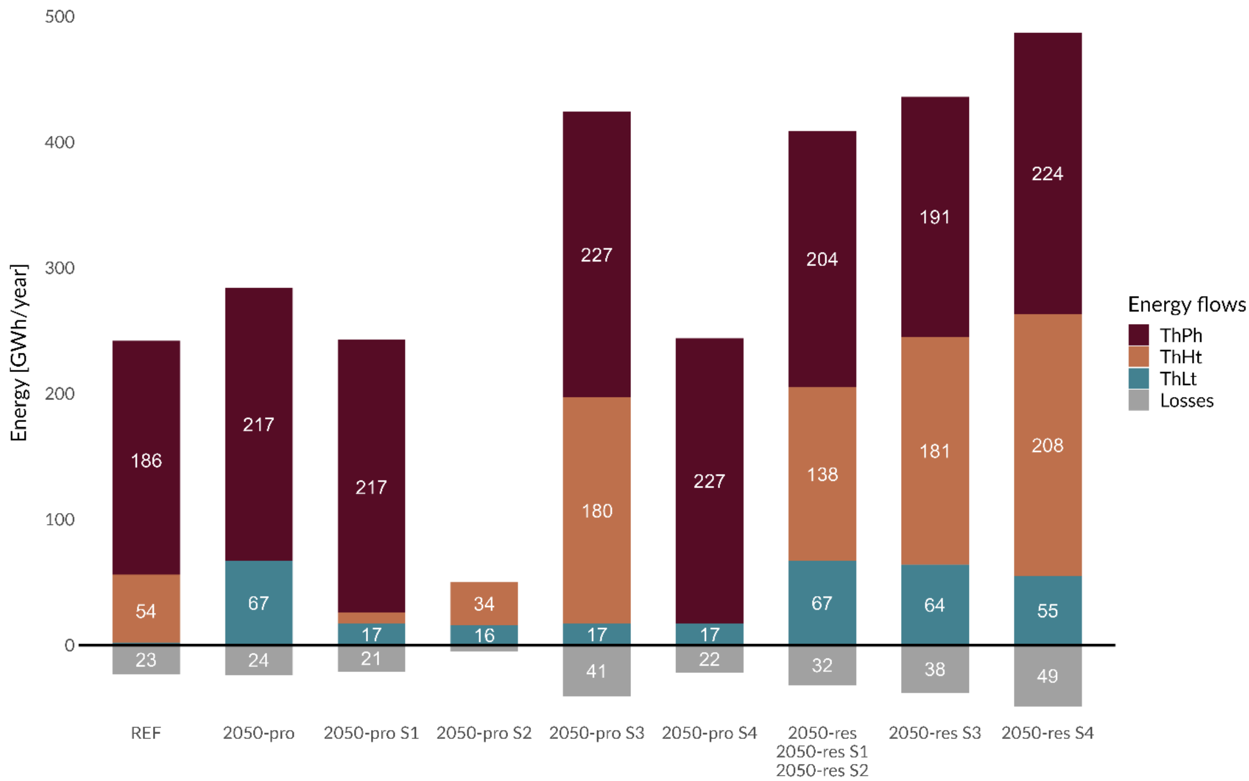

Figure 2: *Comparative analysis of energy flows across different temperature levels and scenarios in Rheintal's district heating networks. Here, ThPh – Process heat, ThHt – high temperature heat, ThLt – low temperature heat.*

In the 2050-pro scenario, unrestricted electricity imports favor Hot Potassium Carbonate (HPC) for CO_2 capture, while in 2050-res, electricity constraints make amine scrubbing the dominant choice due to its lower power demand. This shift in technology choice increases the use of high-temperature heat to replace electricity for CO_2 capture across all 2050-res cases. While the 2050-res exactly meets the net-zero emissions target (**Figure 3**), 2050-pro captures additional biogenic emissions, creating a negative carbon balance and economic benefits from CO_2 capture revenues.

The valley's dependence on energy imports decreases in 2050, while there is an increase in exports in most cases. Cleaner renewable fuels, such as hydrogen, synthetic or bio-methane, and biological waste, completely replace the heavy fossil-based sources like coal, natural gas, and heating oil in the future. In 2050-pro, cheap hydrogen substitutes grid electricity via fuel cells, but when imports are restricted, synthetic methane and electricity fill the gap. In 2050-res, the portfolio of energy imports remained more robust and consistent. Higher hydrogen costs limit its role, leading to greater reliance on electricity, which consistently reaches the electricity grid import limits.

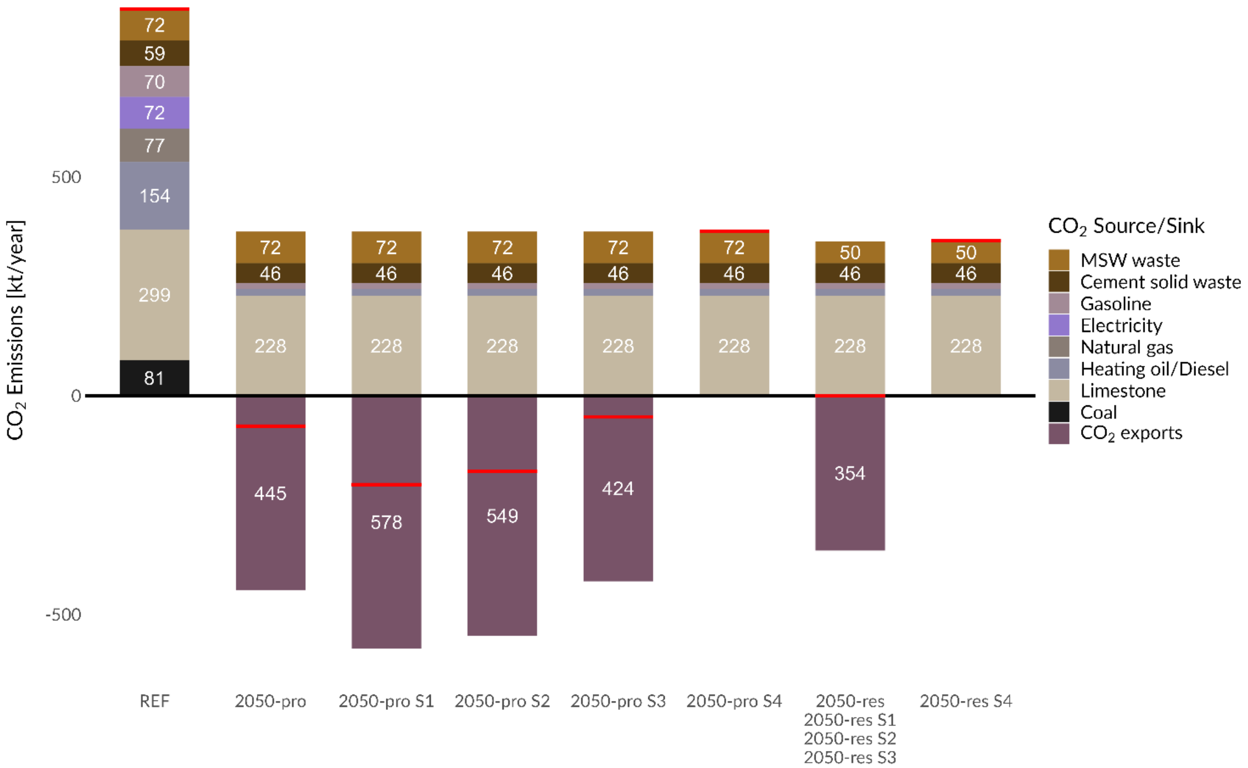

Figure 3: *Fossil and geogenic CO_2 sources and sinks across the different scenarios in Rheintal. The red line shows the net CO_2 emissions for the respective scenarios.*

The results consistently show that reaching net-zero emissions by mid-century in the Rheintal relies on three key strategies: (1) extensive electrification of buildings and mobility; (2) utilization of waste heat from industry using DHN; and (3) deployment of CCS to capture residual emissions, predominantly from cement production and waste incineration. Despite substantial up-front investments, the model suggests that total annual system costs could decrease relative to current levels, driven primarily by efficiency gains, increased use of local resources, and reduced reliance on fossil fuel imports. The analysis highlights the inherent synergy between industries and households in shaping a resilient future energy landscape and promotes coordinated decision-making among regional stakeholders to achieve climate targets.

Keywords: Net-Zero; CCS; energy systems integration; sector-coupling; techno-economic optimization