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Industrial decarbonization within the framework of energy systems modeling

Executive summary of the Master's Project of Vibhu Baibhav

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Addressing the urgent need to limit the global average temperature rise by reducing greenhouse gas (GHG) levels in the Earth's atmosphere is critical to combating climate change. The energy sector is responsible for about 75% of global GHG emissions, with industries consuming 40% of global energy and contributing 30% of total emissions. Therefore, decarbonizing industries is crucial to reducing overall emissions. This master's thesis focuses on the decarbonization of energy-intensive European industries—specifically steel, cement, glass, chemicals, and fertilizers—with the goal of achieving carbon neutrality by 2050.

The heavy reliance on fossil fuels in industrial processes is a major contributor to emissions. To mitigate this, alternative methods such as electrification, carbon capture, biomass usage, green hydrogen, and other technologies, are being explored. However, it is essential for industries to remain economically viable and globally competitive in an increasingly interconnected world. This study addresses this challenge by integrating various decarbonization options into a comprehensive energy system optimization model. The model is designed to identify sustainable production routes that balance both economic and environmental objectives.

A key contribution of this study is its holistic approach to decarbonization, which extends beyond industry-specific or site-specific solutions. It emphasizes the importance of considering the limited availability of green energy when developing decarbonization strategies. This comprehensive perspective is crucial to ensuring that sectors like transportation and buildings do not face clean energy shortages, which could inadvertently shift emissions to other areas.

The techno-economic model characterizing the European energy system in 2050 aims to efficiently meet the End-use demand by optimizing the configuration of resource consumption and technology installation. The demand encompasses four sectors: Households (Residential buildings), Services (Commercial buildings), Transportation, and Industry. To address fluctuations in demand and renewable energy production, a monthly averaged time series is utilized, balancing temporal resolution with computational efficiency. The model incorporates emissions through a life cycle assessment (LCA) approach, considering not only the operation of technologies but also their construction and the extraction of resources. For each industry, production routes are identified based on the decarbonization options in the literature, taking into account the energy demand, effectiveness, efficiency, and investment requirements. The existing production routes are also included in the model as a reference case, providing a basis for comparing the transition to alternative decarbonization pathways.

Following this numerical approach, several case studies were conducted to analyze the European energy system in 2050. Scenarios were explored for both energy-dependent and energy-independent Europe, with a focus on optimizing for minimum total cost and achieving carbon neutrality. The results indicate that if natural gas imports continue, integrating carbon capture at industrial sites will be an effective strategy. However, achieving energy independence in Europe is possible through a combination of electrification and the utilization of available biomass resources.

Electrification proves to be particularly effective in industries where fossil fuels are primarily used as high-temperature heat sources, such as steel and glass production. In contrast, the chemicals and fertilizers sectors, which use fossil fuels as feedstock, will require a shift to biomass-based production routes. The analysis also highlights the limitations of continued reliance on fossil fuel imports: while this approach results in only a modest 7% reduction in system costs, it necessitates a significant 57% increase in carbon sequestration efforts to meet net-zero targets.

Additional scenarios, such as the phase-out of nuclear power plants by 2050, were also analyzed to assess their impact on the energy system. Furthermore, the study examines the economic benefits of integrating industrial waste heat into district energy systems, taking into account the varying temperature levels across different production routes. The findings suggest that annual savings of 5.7 billion Euros are achievable by leveraging this symbiosis in a carbon-neutral Europe.

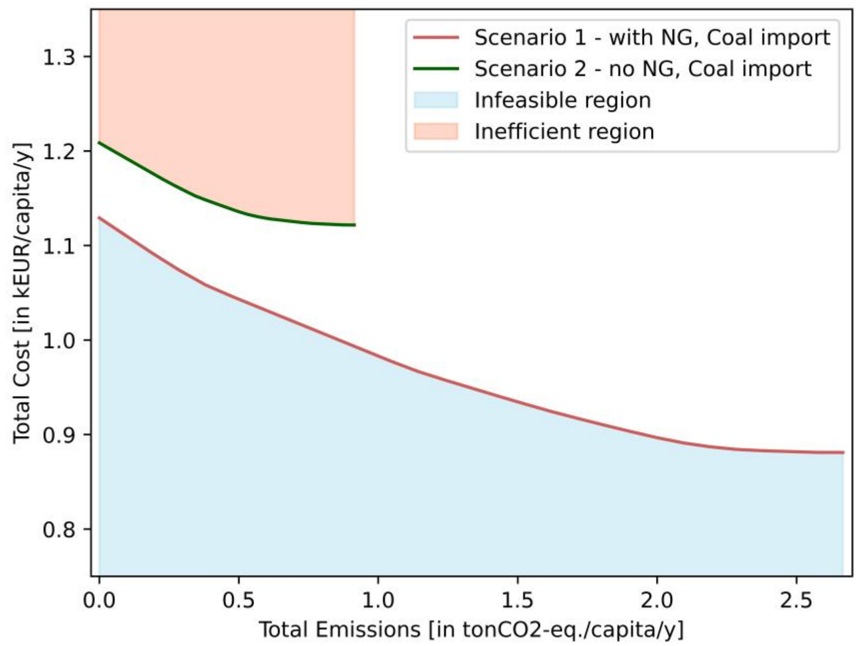

Figure 1: Pareto Front for the multi-objective optimization of the European energy system with industries. Scenario 1 shows the case when industries continue to rely on fossil imports in 2050, whereas Scenario 2 represents energy-independent Europe. For the net-zero emissions, Scenario 1 leads to 7% less cost but requires carbon to be captured on industrial sites, resulting in more sequestration efforts.

Overall, this project offers valuable insights into designing energy systems that support the transition to net-zero emissions. By providing practical solutions for industrial decarbonization, it aims to assist in decision-making and contribute to sustainable development.