Decarbonization of European industry: a cluster-oriented modelling framework

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Abstract

The decarbonization of industry is a timely and urgent matter to achieve net-zero. According to the International Energy Agency, in 2021, industry accounted for 38% of total global final energy use 2021, with an increase of 5 percentage points in 21 years. In this context, Industrial clusters contribute 15%-20% of global CO_2 emissions, highlighting their significance as prime targets for emission reduction initiatives. In its broadest definition, industrial clusters are groups of industries that belong to the same or different industrial sectors, are physically located in the same area, and share common infrastructures. Industrial districts are a subset of this category and can be defined as an agglomeration of industries characterized by a specific industrial specialization in a more Given their interactions with ports and onsite renewable generation, clusters can offer a novel perspective on the possible decarbonization pathways, uptake of low-carbon technologies, and use of low-carbon spread-out areas.

Although sophisticated mathematical models, such as Integrated Assessment Models (IAMs) and Energy System Optimization Models (ESOMs), can be employed to provide insights into energy planning, they still need to be capable of capturing the highly

heterogeneous and cluster-based nature of the industry sector.

This work bridges this literature gap. It will develop a novel modelling framework for the energy planning of European industrial clusters. The modelling approach uses open-source modelling and open-source databases. It integrates industrial stakeholders' insights to inform on the role of low-carbon fuels and vectors, onsite generation, and sector coupling aligned with the national decarbonization plan. The modelling framework stems from energy models for national energy planning. The novelty introduces a customizable approach to account for heterogeneity and the link with the geographical location typical of the sector. In fact, the model accounts for high technological granularity, energy demand disaggregation, finer sub-year resolution (time-slices), and cross-sector synergies. In this way, the modelling framework is an outstanding contribution to industrial modelling, advancing state-of-the-art compared to existing methodologies, which are merely based on macro-level analyses based on IAMs or ESOMs. The work proposed in this thesis will focus on Italy. The Italian industry sector has peculiar characteristics, such as the presence of industrial districts in different areas of the country and, at the same time, the proximity to the sea.

A GIS-based taxonomy for industry clusters will be developed in the first part of the thesis. The methodology, developed for Italy, can easily be extended to European countries, given the availability of open-source data. The proposed methodology allows cluster characterization related to graphical proximity and distinctive energy consumption and carbon dioxide features. In the second part of the thesis, two case studies will be presented to demonstrate the applicability of the modelling framework. These case studies were chosen to represent the most energy-intensive clusters.

The first case study is the industrial simulation of Taranto's cluster, Italy's only remaining primary steel plant and one of the largest steel plants in Europe and its port. The plant is a post-war production model without any environmental or health updates. Taranto is an emblematic example. Covering an area comparable in size to a residential center and adjacent to a vast urban area, it is causing vast environmental, health, and socio-economic impacts. The energy transition of the area could offer opportunities to maintain strategic steel production within national borders and avoid impacts on the job market: steel plants alone employ around 10,000 workers. The decarbonization strategy proposed includes the transformation of the plant from a traditional integrated route based on a blast furnace for iron production and basic oxygen furnace for steel production (BF-BOF) to a direct reduction plant coupled with electric arc furnaces (DR-EAF) fed by natural gas, blend with hydrogen or pure hydrogen. Decarbonization pathways that include carbon and capture technology and advanced production processes, such as the smelting reduction based on coal, are also assessed. Green hydrogen import options will be modelled, considering the South-H2 corridor through Tunisia and Algeria or new pipelines such as Poseidon from Egypt.

The second case study simulates the energy transition for the ceramics district of ceramics in the provinces of Modena-Reggio in Emilia-Romagna, a North Italy region. Here, biomethane and green hydrogen will be key to decarbonizing the high-temperature heat required in the firing system and the spray-drying process. Decarbonization in the industrial sector, particularly for efforts involving low-carbon fuels such as biomethane and hydrogen, faces notable challenges. Despite significant regional potential, the limited availability of biomethane presents a substantial barrier. Hidden costs, such as those associated with connecting to the distribution grid, and the current decree and incentives scheme for biomethane may need to be revised to exploit its potential fully. Additionally, many plants currently utilize biomethane to produce electricity, leading to competition between uses as long as separate incentivization schemes exist. This situation underscores the need to reevaluate policy frameworks to support biomethane's role in decarbonization.

Furthermore, the volatility in green hydrogen prices adds uncertainty to strategic planning and economic viability, requiring extensive investment in infrastructure and technology. Inflationary pressures have escalated the capital costs for electrolyzers, further complicating the transition towards green hydrogen production. There is also a critical need for comprehensive infrastructure planning for hydrogen's effective utilization, pointing to an inadequate focus on logistics and distribution networks crucial for a hydrogen economy. Such challenges necessitate a more cohesive and forward-thinking approach to decarbonization strategies. The feasibility of Carbon Capture and Storage (CCS) technologies in ceramics districts is particularly uncertain due to the diffuse nature of emissions and the geographical dispersion of industrial plants. This makes the development of CCS infrastructure challenging and positions it as a less probable option compared to other technologies. Addressing these multifaceted barriers, including optimizing biomethane use and overcoming logistical and economic challenges associated with hydrogen and CCS, is crucial for industries like the ceramics sector to effectively reduce their carbon footprint and move towards a sustainable, low-carbon future.