Abstract - Marina Micari

Climate change is one of the greatest challenges of our time. Decarbonizing the industrial sector is essential to counteract climate change and achieve net-zero emissions by 2050.

My research focuses on advanced separation processes for CO_2 capture and efficiency improvement, positioning them as key enablers of industrial decarbonization. Specifically, I aim to bridge the persistent gap between early-stage material development and real-world process design. While laboratory-scale material innovations are progressing rapidly, their impact on process performance and sustainability is rarely quantified, as we lack methods to project early-stage technologies to full-scale operation. This constitutes a ***critical barrier to sustainability enhancement***: materials cannot be fully optimized without knowledge of process-level performance, and processes cannot be sustainably enhanced without integrating the latest material innovations. By developing integrated uncertainty-aware modeling frameworks, my research enables the simultaneous optimization of materials and processes, accelerating the deployment of high-performance, clean separation technologies.

In the context of CO_2 capture, my previous works showed that advanced materials are essential to make membrane technology competitive with state-of-the-art absorption. I demonstrated that graphene membranes are economically attractive for carbon capture by introducing, for the first time, ***uncertainty-aware models*** for the design of multi-stage processes. This approach revealed also that graphene membranes enhance cost robustness against future scenario uncertainty, thanks to their high performances. Importantly, the integration of material innovation and process optimization makes membrane technology viable even for applications traditionally considered unsuitable for membranes because of the low CO_2 concentration.

Furthermore, my group has developed the ***first framework for multi-criteria assessment*** of membrane processes. This allows to compare alternative systems by identifying trade-offs between key objectives, i.e., energy requirement and process footprint as well as economic and environmental impact indicators. We applied the framework to the design of capture processes based on mixed matrix membranes, to identify optimal matrix-filler combinations tailored to specific applications. Our analysis showed that the environmental burdens associated to membrane synthesis and disposal, typically overlooked in the literature, contribute substantially to the total impacts and must therefore play a central role in material selection.

Beyond capture, membrane-based processes offer significant opportunities to improve energy efficiency of industrial processes. In air separation, I established quantitative performance ***guidelines for O_2/N_2 membrane separation*** through a rigorous techno-economic analysis, and I identified attractive properties ranges. These guidelines directly informed the development of advanced functionalized graphene membranes, allowing substantial energy and cost savings for natural gas combustion with oxygen-enriched air. In the context of ammonia production, we are currently working on the integration of membrane processes into the traditional Haber-Bosh process, with the aim to replace energy-intensive cryogenic condensation. Our techno-economic results indicate that ***membrane integration can cut up to 80% of the total energy*** requirement of the ammonia production process.

Overall, my talk will demonstrate the transformative potential of integrating material innovation and process optimization to accelerate industrial decarbonization via clean separation technologies.