Summary

Nowadays, energy transition is an extremely felt theme. Current energy systems, mainly based on fossil fuels, are clearly not sustainable and their transformation towards the achievement of carbon neutrality has started, aiming to reduce carbon emissions in all economic sectors. The boost of the European Union towards this objective has been reinforced by the publication of the European Green Deal, which aims to transform Europe into an efficient, fair and zero-carbon society by 2050. The advocated energy system changeover is often linked to a wider deployment of renewable energy sources, which in turn goes hand-in-hand with an expected higher electrification of final uses. These considerations are essential in the hereby PhD dissertation, which explores the role of electricity as a means for the energy transition, through diverse applicative studies, related to both demand- and supply-side perspectives. Furthermore, when dealing with energy transition phenomena, it is fundamental to keep in mind that energy systems are enclosed in intricate social, economic and political patterns and changes in their structure may have a strong impact also on society and economics. Purely techno-economic-based decisions do not represent the right approach for dealing with long-term transitions, neglecting various non-technical aspects, which conversely should play a not trivial role in the decision-making process. Long-term and low-carbon transitions need to be handled with a multi-disciplinary vision and to be supported by a strong policy framework, which in turn should be based on decision-making approaches able to integrate all the various facets of energy issues. Indeed, environmental concerns are pushing international and national governments to define policies to support the transformation of the current energy paradigm, identifying appropriate financial and market strategies to further boost and accelerate it.

These considerations represent the *fil rouge* of the research activities developed during the PhD, aiming to assess energy transition with a multi-disciplinary, multi-dimensional and multi-scale vision, with the scope of supporting and guiding the decision-making process at different scales and with diverse focuses, providing outcomes in the form of "usable knowledge". In the light of the above, the PhD research pathway attempts to respond to the current challenge set to science, which should effectively provide evidences in support of the decision-making process, easily understandable by policy makers. To accomplish this, a general multi-layered

methodological approach is defined, aiming to provide a scientific basis for assisting the decision-making process in different contexts. The methodological framework is adopted at different scales of analysis, varying the level of knowledge, the research objectives and the targeted audience. In particular, the methodological approach is tailored depending on the analysed context, aiming to pinpoint the technologies and actors that are most likely to be core protagonists of the energy transition phenomena under investigation, to define tools to properly value and promote them and to identify the instruments that can be exploited to provide "usable knowledge" to the interested stakeholders. Specific applications at micro, meso and macro scales are presented and discussed, aiming to address some of the current challenges of the energy systems and the role of electricity in their transition, ranging from the increasing electrification of end-uses (focusing on the building sector) to the need for stronger policy support for the planning of large-scale electricity infrastructure.

Starting from the **micro scale**, in line with the vision of low-carbon and zero-energy buildings, great focus is put on the provision of all-electric buildings, which asks for a deep understanding of the possible technologies for providing heating and cooling services. Two applications are presented, both highlighting the role that energy efficient and sustainable HVAC systems play in the transition of the building sector. Attention is mainly devoted to electric solutions (i.e. heat pumps), thanks to their high energy efficiency and low environmental impact, if coupled with renewable energy sources. Both applications aim to value electric technologies, thanks to the development of ad-hoc analytical tools (i.e. simple or aggregate KPIs) for either market-oriented or policy-oriented purposes. The first application focuses on the valorization of the polyvalent heat pump technology, a promising solution for the decarbonization of the heating and cooling sector and for responding to new energy needs in buildings, highlighting the need to use a multi-perspective approach in the assessment and comparison of alternative technological solutions. This conclusive consideration is central in the second application at micro scale, in which proper graphical and analytical tools are defined, aiming to disclose information on the financial and environmental performances of widespread technologies for heating purposes for the residential sector, assessing the environmental benefits (or risks) that their adoption in individual buildings would guarantee (or generate). The analysis is developed to forecast and assess the reciprocal competitiveness of the technologies under investigation on the medium- (2030) and long-term (2050), to support the future energy planning of the building sector, and to study its variation according to different policy strategies.

Moreover, the latter analysis is extended to the **meso scale**, moving the lens from an individual technological assessment to a national perspective, studying possible pathways towards the decarbonization and electrification of the Italian residential sector. The meso scale analysis presents a technological-oriented study, which allows to identify the medium- and long-term electrification potential of the Italian residential building stock (mainly focusing on thermal uses), as well as to estimate the contribution of an electrification pathway to the overall reduction of energy consumptions and emissions. Thanks to the definition and use of appropriate aggregate metrics to drive the technological shifts within the national building stock, the application allows to address the impacts that possible future policy measures could have on the electrification potential of the thermal uses of residential buildings.

Finally, moving from demand-side to supply-side evaluations, attention is devoted to power system considerations. Specifically, the analysis at **macro scale** focuses on the assessment of a preliminary configuration of global grid, in line with the Global Energy Interconnection vision, permitting to transfer clean energy from RES-rich areas (i.e. Equatorial and Arctic regions) to the major load centres and exploring the associated challenges of transmission expansion planning at global and European scales. Different scenarios of electricity generation and consumption trends are compared, on the basis of regional- and global-scale metrics. Moreover, aiming to introduce non-technical factors in the planning of large-scale transmission planning and focusing on Europe, a second application is developed to combine the use of traditional power system modelling exercises (i.e. Optimal Power Flow) with multi-dimensional evaluation tools belonging to the operational research field (i.e. SWOT, multi-criteria decision analysis), to explore the capability of such tools to synthesize the energy complexity of large-scale transmission expansion planning and, thus, to guide the decision-making process in this field.

The elaboration of the PhD research is the result of activities carried out during the last years and supported by the external *stimuli* coming from international and national collaborations with experts in the field. The research pathway has allowed to identify a possible methodological approach to assess energy transition phenomena at different scales and with diverse energy system focuses and objectives. The scalability and multi-dimensionality of the research framework represents its main novel aspects, as well as the attention devoted to target the main stakeholders having the power to influence the investigated transition processes and to study the potential effects of appropriately defined policy strategies on stakeholders' decisions and expectations and on energy systems evolutions.

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