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Energy efficiency, demand side management and energy storage technologies – A critical analysis of possible paths of integration in the built environment

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ABSTRACT

The transition towards energy systems characterized by high share of weather dependent renewable energy sources poses the problem of balancing the mismatch between inflexible production and inelastic demand with appropriate solutions, which should be feasible from the techno-economic as well as from the environmental point of view. Temporal and spatial decoupling of supply and demand is an important element to be considered for the evolution of built environment, especially when creating sectorial level planning strategies and policies. Energy efficiency measures, on-site generation technologies, demand side management and storage systems are reshaping energy infrastructures and energy market, together with innovative business models. Optimal design and operational choices in buildings are systemic, but buildings are also nodes in infrastructural systems and model-based approaches are generally used to guide decision-making processes, at multiple scale. Built environment could represent a suitable intermediate scale of analysis in Multi-Level Perspective planning, collocated among infrastructures and users. Therefore, the spatial and temporal scalability of modelling techniques is analysed, together with the possibility of accommodating multiple stakeholders' perspectives in decision-making, thereby finding synergies across multiple sectors of energy demand. For this reason, the paper investigates first the cross-sectorial role of models in the energy sector, because the use of common principles and techniques could stimulate a rapid development of multi-disciplinary research, aimed at sustainable energy transitions. Further, relevant issues for the integration of energy storage in built environment are described, considering their relationship with energy efficiency measures, on-site generation and demand side management.

1. Introduction

The transition towards energy systems characterized by high share of renewable energy sources (RES) is necessary to reduce drastically carbon emission and avoid climate change related risks. Buildings have a great impact in terms of carbon emission at the EU [1], US and global scale [2] and the issue of resource efficiency for the building sector [3] is becoming increasingly relevant, highlighting the need for a systemic view and adequate policies, as well as adjustments in the energy market [4]. At EU level, for example, building accounts for approximately 40% of carbon emission, determined by their direct energy use [1,5], and for about half of the extracted materials, half of energy consumption, one third of water consumption, and one third of waste generated, if we consider the direct and indirect impact of the whole sector [6]. Additionally, at the global level, the rapid urbanization trend determines the need for a concentration of research and development efforts in the built environment area. From a practical stand-point, we have to prioritize actions, i.e. define policies able to cope effectively with the underlying problems, considering realistically technical, economic, social and environmental constraints.

Energy efficiency measures and, in particular, deep retrofit strategies for the existing building stock can constitute a great opportunity [7,8], considering also the convergence of economic [9] and technological paradigms, focusing on intelligent assets [10], and the emergence of innovative business models [11], which can contribute to reshape the energy market and to create new economic development. The transition from the present energy paradigm to a sustainable one is a great challenge that requires an open multi-disciplinary approach

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[12,13], based on the quadruple helix model of innovation [14,15], in which civil society organisations, industry, government and academia collaborate to share knowledge and data. In this sense, data models are essential to address analytically the problem of transitions [16–18] and a particular attention should be devoted to the role of open data and software [17] and optimization [18] formulations. Design, construction and operation practices in the building sector can profoundly benefit from the ongoing development in this area, using ontologies, semantic web technologies [19] and appropriate data formats [20]. High efficiency buildings are technically and economically feasible today [21] and Nearly Zero Energy Building (NZEB) paradigm [22], both for new and existing buildings, combines a radical energy demand reduction with on-site or nearby renewable energy supply. However, a high penetration of weather dependent RES poses the problem of balancing the mismatch between inflexible production and inelastic demand [23,24] and of being able to integrate it properly in the built environment [25] as well. On the infrastructural side, these technical issues can determine a consistent limit for the effective deployment of policies in this direction, as different countries at the EU level could reach in a few years limits in terms of RES penetration, if no adjustments will be done [26]. On the built environment side, the use of conventional electric energy storage technologies and systems are analysed with the scope of selecting profitable design configurations for customers [27].

As a matter of fact, this technology to achieve a complete self-sufficiency in buildings may be practically infeasible from the techno-economic (but also environmental) point of view, even in the case of a radical reduction of the cost of technologies, due to the necessity of long-term storage (to balance the seasonality of demands) when heating and cooling are supplied by electricity. These factors should be acknowledged when passing from building-level impacts to system wide impact on infrastructures [28]. Power-to-What (P2X) technologies, such as Power to Heat [29–31], Power to Hydrogen and Power to Gas [32–34] are opening new possibilities by combining the temporal and spatial decoupling of supply and demand with an interplay among different sectors in the energy system and among multiple energy carriers. Further, the present state of the art of research in decentralized energy systems is embodied in concepts such as Multi Energy Systems [35] and Energy Hubs [36,37], which can guarantee scalability and flexibility of application, from buildings to districts/neighbourhoods and cities. A relevant research effort has been devoted, in the last years, to the development of optimization models for energy hubs and multi-energy system [38], including simplification of electrical grid constraints [39,40], and thermal storage behaviour [41].

However, there could be further improvements with respect to modelling of temperature levels [42], selection of multi-objective optimal solutions [43], evaluation of stakeholders' perspectives and constraints [44], prediction of systems' operation [45], among others. Additionally, the applicability of calibrated data-driven models for energy management has been tested in extensively [46,47], showing a potential continuity with research dealing with building performance gap [48,49], considering also the incoming problem of embodied energy [50] and of long-term performance monitoring and data analysis [51].

For these reasons, this article introduces first relevant concepts such as Multi-Level Perspective planning [52] and analysis of complementarities [53] in sustainability transitions, to clarify the research background. After that, the article investigates the cross-sectorial role of models in the energy sector, because the use of common principles and techniques could stimulate a rapid development of multi-disciplinary research, aimed at sustainable energy transitions. Finally, the importance of demand side management and storage technologies is acknowledged, presenting relevant issues for their integration in the built environment. The goal of the article is indicating relevant elements to be considered for the evolution of research in built environment, insisting in particular on the scalability of techno-economic optimization and inverse modelling techniques, which can be further integrated and improved with respect to the current state of the art, following a continuous improvement strategy, empirically grounded.

2. Energy transitions planning

The topic of transition planning towards a low carbon and sustainable society is gaining increasingly importance. In fact, the transition from the present environmental, economic and societal paradigm to a sustainable one is a great challenge that requires a multi-disciplinary approach to innovation in which civil society organisations, industry, government and academia work together, in a quadruple helix model [14,15], to share knowledge and data among each other. In this framework, open data and software represent an enabling technology [17]. Further, experts in modelling and technology foresight cover a cross-disciplinary role for strategic decision-making, which encompasses clearly the implementation of cleaner energy systems, but which impacts, more in general, how we live, work and move in a profound way, determining potentially a structural change for its adoption [54]. Built environment is considered today one of the most important sectors for the implementation of circular economy models [9], which can guarantee long-term development perspectives to investors and, at the same time, can create multiple shared advantages [55]. Circular economy models for the building sector are routed in the following main features [9]:

1. sharing of assets and flexibility in the use of spaces;
2. efficient use by delivering utility virtually (tele-working, virtualization of services and processes, etc.);
3. optimal design and operation of buildings;
4. use of renewable energy sources;
5. modularity, flexibility, re-manufacturing of building components;
6. substitution of technologies with more efficient ones (energy efficient renovation).

In all these features we can identify synergies with the deployment of policies oriented towards energy efficiency and renewable energy use. For this reason, it is possible to envision a path of convergence between short-term economic objectives (i.e. job creation, economic growth, etc.) and long-term environmental objectives (i.e. decarbonisation, resource efficiency and sustainability) for the building sector. In general, improving energy efficiency in multiple sectors of economy requires appropriate legislation, successful market strategies and collaboration between private and public sectors. The increase of energy efficiency investments with respect to present state is crucial for the transition towards more competitive, secure and sustainable energy systems. More specifically for the building sector, energy renovation has a relevant role today [7]. However, the progressive refurbishment and substitution of inefficient building stock requires long-term planning. Planning should incorporate existing policy frameworks for growth, employment, energy and climate in order to create an effective energy renewal market that would increase employment and reduce energy demand in the building sector.

2.1. Multi-level perspective planning

Analysing and modelling at multiple levels the dynamics previously described requires the evolution of present tools and methodologies, including more adequate description of techno-economic and socio-economic aspects [12,16]. The evolution process will be driven by different types of stakeholders, including prosumers [11], which can act as investors on the energy market and can participate to relevant decision-making processes. It is worth noticing that the techno-economic side of the problem cannot be considered separately from the socio-economic side with respect to policy questions regarding stakeholders' behaviour and social acceptability of technical solutions.

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