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# The challenging paradigm of interrelated energy systems towards a more sustainable future

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ABSTRACT

This paper brings together several contemporary topics in energy systems aiming to provide a literature review based reflection on how several interrelated energy systems can contribute together to a more sustainable world. Some directions are discussed, such as the improvement of the energy efficiency and environmental performance of systems, the development of new technologies, the increase of the use of renewable energy sources, the promotion of holistic and multidisciplinary studies, and the implementation of new management rules and "eco-friendly and sustainable" oriented policies at different scales. The interrelations of the diverse energy systems are also discussed in order to address their main social, economic and environmental impacts. The subjects covered include the assessment of the electricity market and its main players (demand, supply, distribution), the evaluation of urban systems (buildings, transportation, commuting), the analysis of the implementation of renewable energy cooperatives, the discussion of the diffusion of the electric vehicle and the importance of new bioenergy systems. This paper also presents relevant research carried out in the framework of the Energy for Sustainability (EfS) Initiative of the University of Coimbra, linking the reviewed areas to the multidisciplinary approach adopted by the EfS Initiative. To conclude, several research topics that should be addressed in the near future are proposed.

## 1. Introduction

This article discusses current topics on energy systems research towards a more sustainable future and analyses the major social, economic and environmental impacts of these interrelated energy systems. A comprehensive literature review on the covered topics (each with its own challenges) is undertaken, providing a wide and structured view on subjects and problems of high contemporary relevance and pointing out research gaps and areas of research that should be addressed in the near future. A great emphasis is placed on understanding whole energy

*Abbreviations:* CBD, Central business district; CRE, Community renewable energy; CSA, Commuting satellite account; DR, Demand response; DSM, Demand side management; DSOs, Distribution system operators; EE-IO, Inventories and environmentally extended input-output; EfS, Energy for sustainability; EIO-LCA, Economic input-output life-cycle assessment; EU, European Union; EVs, Electric vehicles; GHG, Greenhouse gas; GVA, Gross value added; IO, Input-output; IO-MOLP, Input-output multi-objective linear programming; LC, Life cycle; LCA, Life-cycle assessment; LCC, Life-cycle costing; LCSA, Life-cycle sustainability assessment; LMA, Lisbon metropolitan area; LUC, Land-use change; MCDA, Multi-criteria decision analysis; MRIO, Multi regional input-output; NRAs, National regulatory authorities; PV, Photovoltaic; REMS, Residential energy management systems; SLCA, Social life-cycle assessment

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systems from a multidisciplinary perspective, reflecting the approach taken within the Energy for Sustainability (EfS) Initiative at the University of Coimbra. The intrinsic fertility of the co-operative multidisciplinary environment created by the EfS Initiative, namely through its PhD programme on Sustainable Energy Systems, resulted in a diversity of competences which are showcased in this article.

This review begins by addressing how the emergence of renewable energy sources can increase the sustainability of electricity markets, with emphasis on the EU context (Section 2). Section three evaluates how electricity distribution adaptation can contribute to a smarter and more sustainable future. In the next section, the potential of city scale residential demand response in the electricity grid is discussed. Section five reviews the role of renewable energy cooperatives and other citizens' power initiatives towards a community based distributed energy generation pointing out the complexity of energy management within these communities. In section six, input-output multi-objective models to assess economic-energy-environment policies are reviewed. Section seven addresses the role of urban planning in reducing environmental and health impacts, recognizing the link between the urban form and all its components and the environmental performance of cities. Section eight addresses the need to quantify the wider economic impacts of commuting in order to uncover suitable policies to reduce commuting and its environmental impacts. In section nine, the importance of consumer preferences on the diffusion of electric vehicles (EVs) is discussed. In the next section, several factors that influence the environmental impacts of EVs adoption are reviewed, focusing on the need to assess the whole life cycle of these systems and the interactions between transport and electricity systems. Section eleven explores biofuel technologies setting out the negative aspects of the first generation of biofuels and the commercial challenges associated with developing the next generation of these fuels. Section twelve reviews the sustainability of bioenergy systems, showing the complexities of quantifying the wider environmental and socio-economic impacts from a supply chain perspective and the need for decision-aiding tools to support the implementation of advanced biofuel that are sustainable. At last, section thirteen sets out the vision of the EfS Initiative, which is inherent to this review article, showing how the organization of the Initiative enables the kind of multidisciplinary research needed to address these interrelated energy systems to be undertaken more effectively. In the conclusion section, recommendations for future research are pointed out in order to set out a research agenda for developing whole energy system approaches designed to deliver a sustainable future for all.

## 2. Renewables and the sustainability of electricity markets

Many electricity reforms in Europe have been implemented since 1990. In pursuit of economic efficiency and greater competition, a single energy market is gradually being implemented in Europe, largely dependent on the development of adequate interconnections and cross-border transfer rules. The implementation of cross-border implicit auctioning mechanisms (market splitting/coupling) was paramount in the convergence of electricity spot market prices, contributing for the European integration of electricity markets. The emergence of substantial amounts of intermittent renewable generation, in particular from wind and solar, resulting from strong financial support mechanisms, reduces dependency on imported fossil fuels and allows GHG emissions mitigation. This was seen mainly in Europe, but it was also observed in Australia and the USA, with the worldwide wind based generation and the solar based power generation having the highest growths during the last decade (Fig. 1). In fact, as shown in Fig. 1, the actual global installed solar photovoltaic capacity makes a significant contribution to renewable energy sources, growing at faster rates than wind capacity in the last years. Simultaneously, electricity markets and related liberalization are also observed in some other regions of the world. Nevertheless, with targets of renewable consumption share set to 45% for 2030 by the EU, the increasing deployment of renewables in some European electricity markets creates demanding challenges to the electricity sector and some concerns are raised about security of supply and efficient system balancing.

It is demonstrated that the effect of renewables on spot electricity markets, given their almost null marginal costs, is to decrease wholesale electricity prices [2]. In the so called "merit order effect", low marginal cost renewables displace, for each spot market period, the aggregated supply bid curve to the right, reducing dramatically the residual load assigned to technologies with higher marginal costs. Therefore, spot electricity prices decrease and the market fails to provide correct signals to sustain adequate generation capacity, configuring the "missing money problem". Nevertheless, this does not mean that the decrease in spot electricity prices originates a reduction of electricity price to the end consumer, as the costs associated to incentives given to renewable electricity producers are transferred to consumer tariffs and may not be completely offset by the spot electricity price decrease. This is currently the cause for a big political debate. Arguments about industrial competitiveness are exchanged, as the electricity costs and renewable incentives burden can cause, in extreme, companies to leave Europe.

Renewables integration into the electricity market requires market adjustments to overcome the identified failures. The "melting-pot" and "salad-bowl" concepts express two alternative routes for policy makers [3]. However, flexibility of the electricity system is fundamental to obtain an efficient electricity market. This flexibility can be obtained through a number of strategies, of which, regional market integration and demand response (DR) seem to be unanimously considered throughout the literature [4]. Electricity market integration is one of the fundamental requirements for the introduction of renewables into the electricity system, contributing to adequate levels of security of supply, whilst providing operational optimization of the generating infrastructure. However, it was demonstrated that the large renewable generation capacity deployment observed has a major influence on electricity price divergence among spot electricity markets [5–7]. The integration of renewables into the electricity spot markets can also benefit from the deployment of effective energy storage facilities, the possibility of wind power production curtailment and the expansion of transmission systems. Furthermore, to achieve renewables optimization and growth, aiming to reach the desired EU target of 27% and keeping market integration out of peril, cross-border interconnection capacity recommendation should be increased beyond the currently discussed target of 15% [7]. Moreover, the internal development of dispatchable reserve capacity for balancing and grid security purposes can be avoided through the development of an adequate cross-border interconnection capacity [8]. Therefore, EU policies should focus not only on the development of renewable energy, but also on aspects that allow their full integration in the energy mix: support energy storage research and development (R&D), and a robust transmission system (including cross-border interconnections).

Policy makers and regulators aim to harmonise the electricity sector; however, the dynamics involved are difficult to predict and new challenges arise in designing adequate measures to provide information to electricity system stakeholders, to guide investment priorities, establish risks and provide guidance in policy design and regulatory framework. The development of eco-friendly and sustainable measures should recognise that the environment and its diminishing resources represent a genuine threat to long-term prosperity.

## 3. Electricity distribution adaptation to a smarter and more sustainable future

Electricity distribution networks are a central component in the electricity value chain, traditionally designed to allow electricity flows from higher-voltages upstream coming from fossil generation, toward low-voltage downstream distributed loads [9,10]. However, this traditional role is evolving partly due to new technology and policy dynamics. On the technology side it is important to consider the growing