

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



N. Soares<sup>a,b,c,\*</sup>, A.G. Martins<sup>c,d,e</sup>, A.L. Carvalho<sup>f</sup>, C. Caldeira<sup>a,c</sup>, C. Du<sup>a,c</sup>, É. Castanheira<sup>a,c</sup>, E. Rodrigues<sup>a,c</sup>, G. Oliveira<sup>c,e</sup>, G.I. Pereira<sup>c,e,g</sup>, J. Bastos<sup>a,c</sup>, J.P. Ferreira<sup>c,h</sup>, L.A. Ribeiro<sup>e,i</sup>, N.C. Figueiredo<sup>c,e</sup>, N. Šahović<sup>c,e</sup>, P. Miguel<sup>c,e</sup>, R. Garcia<sup>a,c</sup>

<sup>a</sup> ADAI, LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

<sup>b</sup> ISE, Department of Civil Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

<sup>c</sup> Energy for Sustainability Initiative, University of Coimbra, Pólo II, Coimbra, Portugal

<sup>d</sup> Department of Electrical and Computer Engineering, University of Coimbra, Rua Sílvio Lima, Pólo II, 3030-290 Coimbra, Portugal

<sup>e</sup> INESC Coimbra, Rua Sílvio Lima, Pólo II, 3030-290 Coimbra, Portugal

<sup>f</sup> Federal Institute of Education, Science and Technology Sul-Rio-Grandense, Rua General Balbão, 81. Centro, Charqueadas, RS, Brazil

<sup>g</sup> MIT Portugal Program in Sustainable Energy Systems, Massachusetts Institute of Technology, 77 Massachusetts Avenue, E18-430, Cambridge, MA 02139, USA

<sup>h</sup> GOVCOPP, Faculty of Economics, University of Coimbra, Av. Dias da Silva, 165, 3004-512 Coimbra, Portugal

<sup>i</sup> Postgraduate Program in Architecture and Urbanism of the Polytechnic School at Faculdade Meridional (IMED), Passo Fundo, Brazil

### ARTICLE INFO

#### Keywords:

Electricity markets  
Electricity distribution  
Industrial ecology tools  
Urban planning  
Electric vehicle  
Bioenergy systems

### 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

\* Corresponding author at: ADAI, LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal.

E-mail address: [nelson.soares@dem.uc.pt](mailto:nelson.soares@dem.uc.pt) (N. Soares).

<https://doi.org/10.1016/j.rser.2018.07.023>

Received 7 November 2017; Received in revised form 19 June 2018; Accepted 13 July 2018

1364-0321/ © 2018 Elsevier Ltd. All rights reserved.

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 inter-related 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

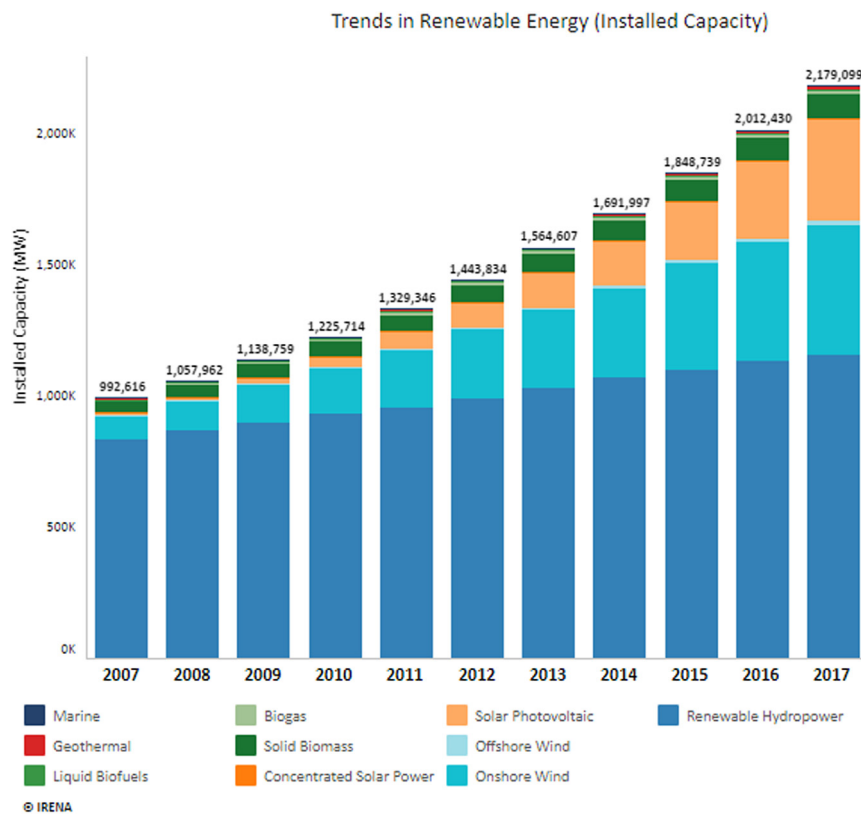


Fig. 1. Worldwide renewable energy installed capacity trends [1].

diffusion of distributed energy resources in the form of distributed solar photovoltaic or wind generation, electricity storage, electric vehicles (EVs) and charging infrastructure, as well as the increase of information and communication technologies that contribute to better monitoring and control capabilities [11–15], which make distribution networks smarter. Additionally, on the policy side, recent EU policies stimulate a shift toward cleaner energy sources and sustainable development [16–18]. These are further supported by the Energy Union [19], and the recent Clean Energy for All Europeans package [20], with specific proposals for redesigning the electricity sector [21–23].

The changes described in technology and policy can be observed as drivers for a transition to a smarter and more sustainable electricity sector. In the EU, this transition builds on the structural changes brought by market liberalization [10,24], through which electricity distribution was established as a regional natural monopoly, mandated to act as a neutral market facilitator separated from competitive activities in generation and retail. In this context, the roles and responsibilities of electricity distribution system operators (DSOs) have been significantly policy-driven, and their operations have been regulated by National Regulatory Authorities (NRAs) at the Member State level [25–27].

However, the observed changes represent possibilities for new tasks to be performed at the distribution level [28]. For instance, DSOs could become more active network managers by coordinating system flexibility made possible by the growth of distributed generation and smarter loads and enabled by the increasing levels of monitoring and control. Nonetheless, these possibilities lead to a series of challenges related to the extent to which DSOs should be involved in activities and services associated with a smarter and more sustainable electricity system, such as: promoting energy efficiency, DR and demand side management measures; deploying, owning, and managing EVs charging infrastructure; deploying, and owning smart meters; managing distributed generation; and handling growing amounts of data [29]. These areas have been recently presented as “grey areas” for DSOs in the

future [30–32]. This uncertainty is associated with: the need for DSOs to act as neutral market facilitators in a liberalised sector; the possibilities for some of these activities to be developed in a competitive market; and, the fact that DSOs have an operational scale and connected grid-users base that could position them as adequate providers for innovative smart grid services.

The regulated monopoly nature of electricity distribution further exacerbates the challenges associated with adaptation, given that DSOs must continue providing a reliable and affordable service, while going through the challenges of a changing sector. Considering these challenges through a network industry transformation lens calls for intertwined efforts to solve technological, institutional, and organisational issues underpinning electricity distribution adaptation [33,34]. This triad is also valuable for organising future research efforts to shed light into these challenges and how to best overcome them. Technological adaptation-oriented research has contributed with knowledge on the integration of electricity storage in distribution systems [35–39], integration of distributed generation sources from wind [40–42], solar [43–47], CHP [48–50], and micro-CHP [51–54], integration of EVs [55–58], integration of smart meters [59–64], implementation of DR [65–69], deployment of active distribution management systems [70–74], and advanced grid monitoring and control [75–77], as well as the use of artificial intelligence methods [78–80], and machine learning applications [81,82], and the role of blockchain in enabling local energy communities [83,84]. Institutional adaptation-oriented research has contributed with knowledge on the adaptation of the existing regulatory framework [85–90], with analyses of different regulatory approaches, such as incentive regulation [91–93], and innovative methods to stimulate electricity distribution adaptation to smart grids [94–96], which often include regulatory recommendations for NRAs [97,98]. In addition to a number of studies on the impact of regulatory frameworks on adaptation [99–103], the branches of research presented are but a sample of the ongoing progress aiming at a better understanding of the technological and institutional changes necessary

to the transition towards smarter and more sustainable electricity distribution.

In this context, the organisational adaptation aspects of electricity distribution have been explored to a limited extent, despite the evident importance of facilitating organisational change and business model innovation as part of the energy transition [104–107]. Contributions from business model adaptation-oriented research have focused mostly on the impacts of market liberalization [107–110], whilst fewer efforts are visible on understanding the ability of DSOs to adapt to a smarter and more sustainable electricity sector [106,111].

Exploring the business model dimension of electricity distribution becomes more relevant as the importance of the social sciences and humanities gains momentum within energy research [112,113], for which interest on individual behaviours and their potential can be observed as a growing field of study [114–116]. In this context, DSOs represent complex technological and policy-driven businesses, for which a better understanding of their ability to adapt towards smart grids and innovate existing business models can contribute insights to ongoing policy debates [117–119]. This knowledge can shape future policies and electricity market designs to consider business model innovation opportunities and constraints. These go beyond technical aspects (such as the extension of distribution networks, and electricity distributed), and regulatory aspects (such as incentive models, and regulatory approaches). Future research must consider the complex technical, and managerial capabilities; and resources whose characteristics and flexibility to adapt to a rapidly changing paradigm remain significantly understudied to this day. This will allow for an overarching understanding of the agility and adaptability of existing business models, to a far more decentralized, decarbonized, and digital electricity sector.

There is a need to develop a body of knowledge focused on the adaptability of electricity distribution utilities in a changing electricity sector. Possible approaches should focus on business model innovation and strategic capabilities, and how these are influenced by business characteristics (e.g.: ownership, connected consumers, unbundling type, technical characteristics, operational expenditures, capital expenditures, network length, electricity distributed, etc.) [120,121], as well as market factors (i.e. sector structure, sector liberalization, regulatory method, innovation policies, etc.) [122]. Additionally, it will be valuable to explore how market factors and business characteristics influence the role of DSOs on engaging in innovation activities, transition to more digital operations, and engagement in smart grids diffusion efforts. Furthermore, this knowledge can be transferable to other network infrastructure industries facing profound sustainability transitions, such as the changing water distribution, gas supply, and transportation sectors.

Only a more detailed understanding of the organisational dimension of electricity distribution will contribute with the insights needed for the debate on business model innovation and electricity market redesign [19,22,123,124]. This proposed research efforts combined with ongoing research on technological and institutional adaptation can facilitate the transition of electricity distribution to a configuration in which connected consumers reap the benefits of innovative technologies and cleaner energy sources, all part of a smarter and more sustainable electricity sector.

#### 4. The potential of city scale residential demand response in the electricity grid

The impact on the electricity distribution system of DR actions will result of changes in the electricity usage by end-use consumers in response to stimuli. DR is a designation used for programs that seek to take profit of price elasticity of demand to get short-term load reactions to price signals or to signals related to some kind of operational grid constraint. However, due to the dispersed and uncontrolled nature of the management of end-use appliances, estimating the energy and

power output of the aggregation of a high number of consumers enrolled in a DR program requires a specific approach which can take into account the random nature of load response.

The electricity grid is one of the most significant technological achievements of the 20th century and is considered by many the most complex system ever built. This remarkable infrastructure carries electricity to enable services now considered essential for living [125]. However, there is a need to continuously balance supply and demand throughout the day in real time. Over the years, utilities have made various cost-effective improvements to the generation and dispatch of electricity to maintain reasonably reliable and affordable service to evolving electricity demands. Today, utility companies must also address new societal and regulatory obligations – mitigating emissions of GHG in their energy generating facilities, combining the traditional energy generation processes with dispersed generation, renewable energies and energy efficiency measures/requirements. Renewable energy sources, energy efficiency related measures and grid operation programs, e.g. DR, must be integrated both into the network and in the market. The future of both the electricity grid and the market needs the coordinated actions of competing players – producers, suppliers, consumers, prosumers (consumers that also produce and/or sell and/or store energy) and energy service providers [126].

The management of electricity consumption is an important tool to balance demand and supply. Instead of strongly investing in new network infrastructures and installing more generators to operate during peak demand periods, with low load factors [127–129], it is possible to manage energy use in households, through the so called DR strategies [130]. In the smart grid context, new devices have been proposed to modernize electrical power systems, combining features of smart metering with Residential Energy Management Systems (REMS). According to Roe et al. [131], REMS are a combination of hardware and software that conducts monitoring, planning and control functions of energy uses within a dwelling. However, having such a resource requires an investment by the DSOs, the utility company and/or by the energy consumer.

Of the available renewable energy sources, the most likely to be used at a larger scale are solar and wind, both of which are non-dispatchable, irregular and difficult to forecast. According to Kempton and Tomic [132], while solar resources have a fairly and predictable daily cycle with photovoltaic peak power occurring at solar noon, wind power is more complex because it fluctuates, making it extremely more complex to predict. Using current tools to manage load and supply fluctuations, it is possible to deal with the variability of renewables at low levels of implementation. However, an increase in penetration of renewables of 10–30% of the power supply capacity requires additional resources to make the fluctuating supply match the also fluctuating load [132].

Another reason for the study of new tools to balance supply and demand is that transmission networks in Europe, due to new market mechanisms, are becoming a platform for increasing energy flows [133,134]. In addition to this burden, technological advances require more energy to supply new appliances. Thus, the gap between electricity supply and demand is increasing in many countries [135,136]. Conventional approaches to solve the referred problems are based on the expansion of the supply-side resources, even if only to serve as idle backup power. These are usually high-investment solutions which are expected to operate for a very small fraction of time. An alternative approach is then to manage the energy consumption, in order to compensate fluctuations, avoiding the need of new, most of the times stranded, supply capacity [127–129]. Recently, Celik et al. [137] stated that while the impact of DR at the household level is well studied, it still needs to be further investigated at a larger scale, e.g. neighbourhood level.

The possibility to use load control techniques or, more generically, to manage resources in households, exists because consumers do not need energy by itself. Instead, they need energy services, e.g., lighting,



hot water, cooling/heating, among others, which should be provided in the most efficient way. This idea is not new, and it was underlined more than 30 years ago by Schweppe et al. [138]. The possibility of having equipment managing household energy resources can provide significant changes that need to be studied. Former Demand Side Management (DSM), focused on improving the efficiency of electricity consumption in general, and DR programs focusing in Load Management (LM) were run and almost completely controlled by the load manager (utility company) while price response programs depended almost exclusively on the energy consumer [139]. The deployment of DR programs and the recent trend to use advanced smart meters require the assessment of their possible aggregated impact. For that purpose, the knowledge of the household consumption pattern (and its composition in terms of the individual end-uses) is fundamental.

DR is based upon the assumption that the several elements of the electric grid can communicate with each other their response to comply with the needs of the grid operation. Possible examples are: managing demand to deal with grid events, switching off appliances temporarily in order to cope with peak load situations, shifting loads in order to reduce losses and take more advantage of available renewable generation. If no doubts exist that DR can help optimize system operation, it is unclear whether it effectively reduces energy use from consumers, bringing energy savings and environmental benefits. Some DR activities may provide net energy savings while others do not. In an emergency situation, dimming lights in an installation during the required time will not mean they will consume more energy afterwards, but for other equipment (e.g. air conditioning) switching it off during a system event can lead to an increase in consumption after the event is over. A complete review and description of DR programs was performed by Albadi and El-Saadany [130]. Kostková et al. [140] provided an extensive review on load management methods, techniques and programs, theoretically described or practically used. Recently, Celik et al. [137] provided a review on residential load modelling in a single home and concepts of coordinating mechanisms for multiple homes.

Several simulations of load control have been presented by many researchers, using diverse techniques. However, as stated before, a deployment at a larger scale has been weakly addressed. The following works have addressed diverse methodologies and techniques to simulate REMS performance. Karnouskos and de Holanda [141] stated that if a REMS system can only be implemented with high technical and financial effort, only few devices can be controlled and the involvement of consumers with low power input is not profitable. The simulated infrastructure implemented an energy controller agent that continuously monitors the overall power generation and consumption with any deviation beyond a specific predefined limit result in a control action, thus balancing supply and demand. If the systems account higher consumption than generation, the energy controller agent tries to shed some devices or to start new generation resources. If instead, there is higher generation than consumption, the energy controller reconnects loads. The capacity to shift the demand of certain household appliances was quantified by Teng and Yamazaki [142] according to the cost of electricity from two electric power sources, the energy grid and renewable energy locally produced in the household. Commercial supply was considered, when in use, to represent a high cost option, while renewable energy was referred to as a low cost option. An open industry standard for system-level modelling called SystemC [143] was used to create a simulation framework to model a house equipped with several home appliances and a smart metering device. The proposed platform scheduled three working periods. The presented simulation reduced the household peak power consumption from 2.73 kW to 1.19 kW in a four hour period. A simulation tool regarding the optimization of the operation of household appliances using DSM strategies was presented by Gudi et al. [144]. The formulation problem was performed using particle swarm optimization, trying to automatically select which appliances will operate at each moment, adjusting energy usage and minimizing energy costs. The optimization results revealed a

reduction of 19–21% in electricity energy costs for the consumer. Molderink et al. [145] used three techniques to create control structures for the simulation environment of REMS. Artificial neural networks were used to predict a daily local production, using the consumption pattern, micro combined heat and power generation. A second technique consisted in performing a global programming approach in order to minimize the mismatch between what was consumed (demand) and what was produced (renewable energy). A final approach consisted in using a linear integer program to optimize the control of equipment in households. Local prediction using artificial neural networks performed well for 39 residences, for a single day simulation. The authors concluded that it is possible to make a forecasting for a group of houses based on predicted heat demand.

Real time pricing and DR stimulated by higher penetrations of renewable energy were studied by Roscoe and Ault [146]. This study had as its premise the use of real-time pricing of electricity, providing consumers to be flexible but to retain overall control. Two main objectives were set, the first one consisted in assessing the likely financial benefits of such tariffs for consumers and for the power network in general, the second goal consisted of predicting possible problems with implementing real-time pricing, by examining the difficulty in predicting demand and setting prices. A time-domain simulation with probabilistic appliance events was developed, taking into consideration the percentage of all households with electricity load types, the average electricity demand kWh/house/day (for all houses), the average electricity demand kWh/house/day (households without gas) and the average UK electricity demand for 25 million households. The events were scheduled using Poisson distributions and characterized by increments of a certain power value (e.g. 150 W) and a temporal duration (0.5 h) which are switched on at times of lower energy costs provided by the need to sell renewable energy in certain periods of the day (excess production) and in order to balance demand and supply. The simulation was influenced by a process of delaying working cycles of electrical appliances and by price elasticity. This simulation estimated an 8–11 GW potential peak demand reduction for the United Kingdom, strongly depending on the level of assumed elasticity. The authors also concluded that many customers will perceive real-time pricing tariffs as better value than the fixed-price tariffs. This is suggested because, on average, simulated consumers on real-time pricing tariffs manage to use more energy, although paying less. This may explain why electricity suppliers may be unwilling to offer such tariffs, since their profits may be reduced. Finally, the authors recommend further work on demand-forecasting and the price-setting strategies.

Roe et al. [131] developed a discrete event simulation to study DR action in a household. The methodology of this simulation was divided into two steps. The first one delays controllable appliances so they are not used during the DR service time. The second step manages a stationary battery in order to help reducing residential power demand during DR request time (load reconnection). Each daily power demand was simulated 50 times for each scenario. Differences between simulations consist in slightly modifying appliance start times and in the number of controllable appliance events, in order to model random consumer behaviour. The study considered the simulated results to compute the REMS simple payback period regarding the resulting energy savings. The conclusions of the study revealed that the simple payback period was in the order of one year for a REMS equipped household with no stationary battery. With a stationary battery, the simple payback period was extended to over 10 years. The simulation presented by Zeilinger [134] tries, according to the author, to be as flexible as possible in order to cope with DR options, defining the end-use behaviour to perform the simulation of appliances. Therefore, the study separated the household appliances in groups. This way of thinking led the author to present a working methodology in which each appliance has a control unit installed that independently determines the need to influence the power consumption due to the current energy supply situation. This can also be used to analyze the

demand flexibility of energy resources in households. Miguel et al. [147] presented a simulation for an hypothetical 20% deployment of a residential energy management system on the city of Coimbra, Portugal, based on the Energy Box concept [148]. The authors described a methodology that identifies the start of operating cycles of appliances and other loads on a given general load diagram, enabling the simulation of load shifting caused by the operation of residential energy management systems. The results show the release of almost 3% of the demand on periods of higher price, but also the occurrence of a pronounced peak during the night period, an occurrence which may need to be dealt with, and for which some solutions were proposed. The developed methodology used spot prices, as those referred to by Miguel et al. [149], by applying clustering algorithms to historical data, namely using a hierarchical method and a self-organising neural network, to obtain clusters of diagrams representing characteristic daily diagrams of electricity price.

Future results of appliance-focused testbed projects aiming at identifying the price elasticity related behaviour of electricity demand will hopefully lead to a deeper understanding of the impact that DR may have on optimizing the power system management and increasing the share of renewable energy. Such understanding may provide the basis to evaluate DR under different circumstances, crossing demand and generation capacity and their respective variations during the year. The original question that prompted some of these works consists in finding how an investment in an infrastructure can be justified without knowing what could be its outcome. REMS equipment is supposed to provide the network operator with a set of standard flexible loads. Currently, many of DR studies deal with delays to the operation of appliances. Other additional possibilities include interrupting the operation of appliances, considering more types of loads, e.g. appliances dealing with thermal energy or EVs, and considering local renewable generation. The possible introduction of new peak demand periods in the diagram implies the need to take into consideration management strategies. This is strongly related with the willingness and the time availability of consumers for the DR actions that are considered. One possible management hypothesis would be the introduction of a random delay when defining the re-start of the various end-use loads. Peak coincidence would thus be reduced and the resulting aggregated diagram would be smoother. A different possibility may imply the DSO to have some degree of control, imposing a queue in order to only enable the switching-on of controlled appliances at an established maximum rate.

## 5. Renewable energy cooperatives and other citizens' power initiatives towards a community based distributed energy generation

In the 20th century, power systems have mainly been built to accommodate central power plants, meaning large fossil fuel plants, nuclear plants and hydro power stations. The emergence of renewable energy technologies for distributed electricity generation and their increasing cost competitiveness with traditional means has slowly, since the 1980 s, initiated a disruption in electricity markets. More and more distributed energy resources are being introduced into the power system. End-users are becoming not only producers but also active participants in network balancing operations. Although there is no single definition, a broad consensus is that distributed energy generation systems are small-scale units that are connected to the distribution grid. They usually have one or several strong local dependencies. They are connected to the distribution network, not the very high voltage transmission grid. The energy source is available locally (e.g. wind, solar, biomass, biogas, geothermal, ocean energy, hydro), the producers consume the electricity for their own needs and/or they are relatively small actors in the electricity market (e.g. a municipality, a cooperative, a private investor, a land owner) [150]. Community renewable energy (CRE) initiatives are one example of such actors, emerging across

Europe in different forms, as a result of local traditions and possibilities at their disposal in accordance with the existing relevant landscapes (e.g. market structure, grid accessibility and rules, financial infrastructure, institutions and renewable energy policy measures, support networks [151]).

While the classical regime of energy provision usually involves highly centralized energy infrastructures with "end-of-wire captive consumers" [152], CRE initiatives, in most cases, constitute a substantially different socio-economic model of energy production, distribution and use. What distinguishes CRE initiatives from investor owned or government renewable energy projects is that, as enterprises, they belong to the Social Economy. This is a middle-path, or third sector, that lies between the private sector dominated by investor owned firms and the public sector dominated by state owned enterprises. Social Economy enterprises are characterized by association-based economic activities founded on a specific set of values. They are autonomous in management, and practice a democratic decision-making system, such as "one person – one vote" in the case of "traditional" cooperatives where, regardless of the number of shares, a cooperative member holds one vote in the general assembly. Their *modus operandi* is based on the principles of participation, empowerment, individual and collective responsibility and care for the community. Their aim is to provide a service to members and/or the community rather than solely generating profits and seeking financial returns, assigning primacy to persons and work over capital. Unsurprisingly, as such many CRE initiatives have sprung out of social-movements belonging to the "political left", harbouring anti-nuclear (such as Elektrizitätswerke Schönau in Germany) or self-sufficiency and local energy security sentiments (Sifnos Island Cooperative in Greece).

The success of CRE initiatives depend on the voluntary contributions, intrinsic motivations and collective action capacities of their members, including their skills, knowledge, leadership qualities, embodied sustainable development values and objectives, and enthusiasm for grassroots initiatives dedicated to protection of the environment [153]. The EU, in its Energy Union Package [19], encourages this niche in the energy transition effort through outlining a vision of an Energy Union with citizens at its core, where citizens take ownership of energy transition, benefit from new technologies, and participate actively in the market.

CRE initiatives established with the objective of developing and operating renewable electricity projects have attracted increased attention in sustainable energy transition literature over the past couple of years. Although there is no universally accepted consensus in literature, researchers infer varying degrees of community involvement in the CRE term [154]. One of the most commonly cited categorizations [155] is that community projects are considered as those with a high degree of direct involvement and decision-making influence of local people in the planning, installation and operation of a project, and/or where the benefits of a project are distributed through local job creation, contribution to local infrastructure regeneration, providing local education resources and sensitizing the local population to sustainable energy provision topics (in addition to the wider global contribution towards further renewable capacities accumulation). However, within this defined scope, CRE initiatives analyzed in literature still remain quite multifaceted, and a diversity of ownership models exists. Projects can be either completely owned by the community or developed in partnership with private or public sectors. Such ventures include many legal and financial models (local institutional landscape permitting) such as cooperatives, community charities, development trusts representing communities' interests, and shares owned by community based organizations [156].

Within the variety of institutional, legal and financial models utilized in setting up CRE initiatives, cooperatives constitute the organisational form that is the most common vehicle for citizens' active participation in electricity markets and influence exertion on local energy policies in continental Europe. They provide the institutional

framework to involve citizens with political, social and financial aspects of renewable energy deployment, thus “democratizing” the energy sector [157]. Renewable energy cooperatives carry with them underlying social values and ethical principles. Those principles are voluntary and open membership, democratic member control, economic participation by members, autonomy and independence, education, training and information, cooperation among cooperatives, and concern for the community [158].

From the technology perspective, and resulting from local biophysical conditions, solar PV and wind energy technologies have clearly been documented in the literature as the most extensively applied systems in renewable energy cooperatives [152]. Photovoltaics are particularly attractive because of their modularity, simplicity, high reliability, low maintenance requirements and short lead times. Those favourable characteristics can also be attributed to the case of on-shore wind energy, where the simplicity of the power generation process, the high reliability of the technology and the availability of service providers (in countries where many RE cooperatives are found today) facilitate its application. In addition, an increasing number of rural biomass farmers’ cooperatives are documented in Austria and the South Tyrol province of Northern Italy [159].

CRE literature aims to classify the drivers and barriers for citizens’ energy initiatives [159,160]. They can be identified within the boundaries set by systemic factors (as classified in ref. [161]) that define the electricity market and renewable energy landscape in the countries where they operate. Such factors include the market structure, namely division of activities, generation, transmission, distribution, and retail, and the level of competition within them, or degree of monopolistic concentration. Indeed, the majority of CRE initiatives in Europe are based in countries where liberalization has led to increased competition among retailers and unbundling of activities in the energy market. Namely, according to the European Federation of Groups and Cooperatives of Citizens for Renewable Energy (REScoop) [162], there are 2.397 CRE initiatives and renewable energy cooperatives in Europe (defined according to the REScoop as organizations operating “a business model where citizens jointly own and participate in RES and energy efficiency projects”). The overview of the REScoop membership structure reveals that the national counts of such enterprise is very disproportional. Almost 55% of member entities are based in Denmark, Germany and Sweden while Greece, Portugal and Spain altogether are represented by only 18 initiatives in the REScoop Federation. The number of such enterprises in Central and Eastern European (“new”) EU member states is negligible. Moreover, in countries where the liberalization of the energy market is a reality, CRE schemes are responsible for significant renewables’ capacities, most prominently in Germany where they constitute nearly 50% of installed RES capacities [163], and in Denmark where 70% of wind power plants are owned by cooperatives and farmers [164].

Further systemic factors are the complexity of administrative procedures for building permits, the transparency of grid connection processes and their costs, the access to renewable energy project financing (e.g. banks willingness to provide loans or the financial potential of citizens to purchase shares in projects), the public opinion and support for renewables, and the knowledge about potential benefits of CRE schemes. In the context of the latter, several studies suggest that small-scale community-based wind power projects receive strong levels of support from local people [165–167], and that local opposition towards wind energy projects, the so-called NIMBY (“not in my back yard attitude”), has been reduced through local participation, participatory decision-making processes, and (equal or fair) distribution of economic benefits [168–171].

The existence of a legal framework under which CRE initiatives (such as renewable energy cooperatives) may be established as legal persons, the rules of economic association that it prescribes, the actors that may join it (individuals, municipal institutions, etc.), and tax status that it carries, will determine whether such enterprises can be formed in

the specific local context, operate in accordance with their defined set of values, and secure the envisaged benefits for their members and local community. Finally, and most importantly, the stability of political and financial renewable energy support policy schemes is identified as paramount factor for the success of CRE projects, most prominently for the development of new initiatives. The 2014 reform of the German renewable energy act, for example, resulted in a significant decrease in the formation of renewable energy cooperatives in the country, dropping to 29 new cooperatives in 2014, as opposed to 194 newly registered in the country in 2011 [161].

Nevertheless, cooperatives have also been found to be resilient to crisis, thus making them sustainable in terms of longevity. Such resilience, resulting from the dedication, capabilities and values that drive their members has helped cooperatives adapt their business models to overcome sudden and adverse renewable energy policy support shifts [172]. The International Labor Organization [173] has underlined that renewable energy cooperatives – as enterprises with a triple bottom line: people, planet and profit – have great potential for contributing to development, and poverty and energy poverty alleviation. By making energy accessible and affordable they can improve productivity and living conditions. Moreover, they create jobs, including green jobs, particularly in rural areas.

## 6. Input-output multi-objective models to assess economic-energy-environment policies

The input-output (IO) methodology is an interesting and flexible tool for the theoretical or empirical investigation of a wide range of applications encompassing the analysis of more aggregated or disaggregated systems, depending on the objectives of the study [174]. Indeed, IO analysis has been applied for a wide set of specific problems, such as inflation, transportation requirements, environmental pollution, depletion of non-fuel mineral resources, impacts on the employment [175–178] at different micro and macro level of analysis (such as national economic planning [179–181]; regional planning [182]; analysis of a specific sector [182,183]; and study of enterprise's economy [184–186]). Some extensions and combination of IO models with other methods have been developed in order to extend their application to different topics and allowed modelling complex systems regarding economic and physical relations [187–189]. IO models have been modified for the explicit analysis of the energy sector (e.g. see [190–192]), whereas intrinsic features regarding economic activity, energy use and environment effects have led to extensions of IO models that combine both environment and energy modelling (e.g. see [193–198]) and to analyze energy-economy-environment (e3) interactions (e.g. see [199–201]). As referred to by Faucheux and Levarlet [202], the e3 models are well suited to address the complex interactions between the process of energy production and consumption, the economy and the environment. Examples of the extension of IO models are the Economic Input-Output Life-Cycle Assessment (EIO-LCA) method, IO Hybrid models and IO Multi-Objective Linear Programming (IO-MOLP) models.

The EIO-LCA method has been developed for the application of IO analysis to Life-Cycle Assessment (LCA) [203–206]. The LCA methodology assesses the environmental impacts associated with the life-cycle (LC) of the product under study and has an important role in public and private environmental management [207–209]. The advantages of the EIO-LCA models over the standard LCA's come from the capability of capturing all the intra-sector flows (both direct and indirect) without “double counting”, less resources and time requirements and inclusion of emissions caused by services and machinery ([205,210,211]). The main strength of EIO-LCA model compared to standard LCA's is to provide a more complete supply chain of economic activity needed to produce any commodity in the economy, therefore extending the boundaries of the analysis to the entire economy [204]. For that reason, as referred to by Jeswani et al. [212], this method can

be viewed as a macro-level LCA covering the "cradle to gate" portion of the LC that is potentially more useful to support high-level (e.g. national) policy decision-making rather than for decision-making on specific products or processes. On the other hand, some limitations of EIO-LCA (also derived from the assumptions of the basic IO model) can be identified: the model often assumes the same production technology for imported and domestic products; problems related with the homogeneity and linearity assumptions in which each sector produces a single commodity using a single technology; proportionality between environmental loads and economic flows for sectors with different characteristics; problems of aggregation; the use and the end-of-life stages are neglected; and problems regarding reliable and up-to-date data [204,205,213].

Nevertheless, production and consumption systems are best represented by a combination of bottom-up and top-down perspectives in a model that reveals the microstructure of the important parts of a product system and, at the same time, covers the entire economic system [205,214]. As a result, hybrid methods have been proposed to combine process-based LC inventories and environmentally extended IO (EE-IO) inventories in order to use the strengths of both [215]. The term "hybrid" herein represents not only the integration of IO and process based data, but also the combined use of both physical (process-based) and monetary (IO-based) data, which opens the possibility of combining environmental and economic aspects [212,216,217]. In the hybrid models the combination of physical and monetary units into the IO matrices is made, in which new rows and columns are included for energy sectors, substituting flows in monetary units by flows in physical units [218]. The use of the hybrid IO formulation helps eliminating the effect of price distortion on the results, *i.e.* specifying the energy transactions in physical units in this hybrid formulation allows that the energy conservation conditions can be expressed as a set of physical relationships independently of the prices of energy [196]. However, as stated by Majeau-Bettez et al. [214], the lack of quantitative assessments of the presumed advantages of hybrid approaches relatively to LCA and EE-IO models may partly explain their slow adoption. Therefore, LC databases should also incorporate hybrid perspectives, rather than a strictly process-based approach. The inclusion of economic aspects in LC databases will allow the progressive compilation of hybrid inventories.

IO analysis has influenced the early development of linear programming models as a result of the empirical programming needs [219,220]. Several studies in using linear programming models coupled with the IO framework for different purposes are identified [221–227], as well as introducing environmental and energy (and combinations of both) objectives [228–230]. However, IO-MOLP models can better capture the real world problems and have been applied to study the impacts of national and regional policies on the employment, water pollution, energy requirements, CO<sub>2</sub> emissions, foreign trade balance, *etc.* [231–234]. IO-MOLP models using hybrid frameworks and external expansions of the IO model have been used to assess energy-environment-economic-social objectives [218,235–237]. Some studies have developed MOLP models based on IO analysis incorporating explicitly the uncertainty treatment: Chang and Juang [238] and Chang [239] have applied a MOLP model with fuzzy coefficients in the objective function; Borges and Antunes [240] have developed a MOLP with fuzzy coefficients in the objective function and in the right hand side vector; Henriques and Antunes [241] have applied a MOLP model with interval coefficients in the objective function, the right hand side vector and also in technical coefficients. The IO-MOLP models are able to capture the complexity and conflicting nature of real world problems allowing obtaining insightful information that would not be possible to achieve with a separated application of both methodologies.

Future opportunities exist in developing new methodologies focused on the e3 analysis at a more disaggregated level, such as: (i) integrating inter-regional IO models with MOLP; (ii) integrating inter-regional IO models with hybrid units and MOLP; and (iii) incorporating uncertainty

analysis in inter-regional IO-MOLP models. The development of those methodologies will be useful for the e3 analysis of specific states or regions inside a national economy, whereas dealing with uncertainty sources in the scope of IO-MOLP models. Other additional possibility is coupling hybrid IO-MOLP framework encompassing economic (consumption, production, *etc.*), energy (production and consumption of renewable and non-renewable sources), environmental (especially GHG emissions) and social (especially employment levels) spheres with LCA estimates. The integration of LCA and hybrid IO-MOLP models will be useful for the analysis of specific energy commodities, allowing to incorporate different processes into the model and expanding the boundaries of the analysis to the entire economic system such that direct and indirect effects in an integrated- or country-basis analysis can be accounted for [242].

## 7. The potential of urban planning in reducing environmental and health impacts

The demands of a growing population and the increasing migration of population to urban areas, together with technology developments and lifestyle trends, have driven cities to rapid development and growth [243–245]. Today, more than half of the world's population lives in urban areas (73% of the population in Europe), and this share is expected to continue to increase [246]. While urban areas cover a relatively small fraction of terrestrial land (less than 3%) [247], they are responsible for more than 60% of the energy consumption worldwide [248,249]. Urban areas also embody the heaviest consumption of natural resources and production of pollution and waste: they are estimated to account for over 70% of the total GHG emissions associated with anthropogenic activities, which are recognized as the main driver of global warming [246,250]. A relevant reduction of the resource requirements and emissions associated with urban areas would be a major contribution at local and global scales [246,250–252].

In the last decades, the emerging concept of sustainable development has led to a generally wide interest on identifying an environmentally sustainable urban form (*i.e.* the spatial configuration and shape of a city), as it has been recognized to strongly affect environmental performance in the built environment [252–255]. Attention has been paid to the debate on the effects of two archetypal concepts: the compact and the disperse city. However, the complexity of the multi-dimensional linkages between urban form and environmental impacts associated with human activities makes it challenging to achieve consensual agreement, or universally applicable solutions [252,255]. While some urban planning and design principles are generally supported to improve environmental performance, such as compact, dense and mixed use developments, sustainable transportation systems and green infrastructure, there is an evident need for empirical frameworks to assess and to compare alternative approaches, strategies and policies, to inform planners, designers and decision-makers [252,254–256].

Buildings are one of the most significant contributors to resource use and environmental impacts in urban areas [257]. Most research has focused on individual buildings and its components or materials [114], and environmental assessments have addressed in-dwelling resource and energy requirements, and associated environmental impacts [258–261]. Several studies have explored the influence of urban form and design characteristics on the environmental performance of buildings [259,262,263], in particular comparing different building typologies, such as apartment buildings and single-family housing (e.g. [264,265]). However, buildings affect anthropogenic activities and demands well beyond in-dwelling requirements. As an example, location, design and density in the built environment influence mobility choices, including active travel [114,266–268]. The interplays between buildings and the urban scale should be addressed, in order to adequately assess and evaluate different planning strategies and policies. Coordinated planning, decisions and actions from many stakeholders across multiple jurisdictions are required to effectively improve urban



sustainability. The coordination of urban planning and transportation strategies can also offer additional benefits, including reduced traffic congestion and improved air quality. Research on low-energy buildings has explored the potential for architectural design and building systems to satisfy the users' energy needs, or even to generate more energy than they require [269]. For instance, district energy systems (e.g. heating, cooling and domestic hot water supply in a neighbourhood, a city centre, or a city) can play an important role in urban sustainability, as they can have lower environmental impacts, when compared with conventional systems [270]. Nowadays, the main challenge of district-energy systems is to replace fossil fuel based by renewable energy based systems (e.g. solar energy, biomass, geothermal, and seasonal heat storage). The use of alternative energy technologies (e.g. heat pumps and polygeneration [270]) is also challenging. Therefore, centralized energy systems face as future challenges the supply of district heating (or cooling) in a scenario of new low-energy buildings; the reduction of the network energy losses in the distribution grid; the integration of renewable energy sources; the reduction of energy waste; the encouragement of integrated and smart management of electricity, gas, fluids and thermal grids; and the assurance of suitable planning and cost structures to transform the energy systems into more sustainable systems [271].

Another crucial link between urban form and environmental performance is on the connection between land use and transportation impacts. Many empirical studies have provided insight on how the distribution of activities (e.g. residential, employment, education, leisure and shopping) and infrastructure (e.g. energy, transport) in urban areas might affect the relative performance of private transportation and transit systems and, consequently, users' mobility demand and choices [272–278]. In addition to the resource consumption and the regional and global environmental impacts, transportation plays a central role in urban sustainability due to its dominant contribution to local ambient air pollution and consequent health effects [279,280]. Urban form determines where transportation emissions occur (through infrastructure layout), the dispersion and resulting ambient concentration levels of pollutants (through the configuration of buildings and street canyons), and population exposure (through land use, density and the resulting population distribution). While denser mixed urban areas might contribute to less motorized transportation demand and promote active travel, they are often associated with higher exposure to traffic-related noise and air pollution [281]. Urban planning and sustainability policies need to consider local environmental and health impacts, identify critical areas of exposure and vulnerable populations that might be subject to higher exposures. Spatially-resolved approaches can be particularly valuable in this context, as they can identify improvement opportunities and priorities for policies to focus on the most affected areas [256].

The urban heat island, which has also been subject of research for decades [282], is particularly relevant as climate change contributes to an increasing occurrence of extreme climate events, which are intensified by heat island effects [283,284]. The rise of the urban air and surface temperatures is associated with different urban form features, such as the type of land-cover and density patterns, the use of low albedo materials, impermeable surface areas, etc. [285]. Urban climates can be evaluated using thermal remote sensing [286]. These techniques allow the identification and characterization of urban hot spots [287–289], supporting decision-making on strategies to prevent or decrease the potential effects of heat waves, which have been often associated with higher mortality and morbidity [290]. Some of the mitigation strategies include creating and increasing vegetation areas, reducing impervious surfaces [291,292]; designing buildings and urban pavements with high albedo and low absorptance materials; and improving urban form, including the geometry and orientation of buildings, in order to improve airflow, reduce heat effects and improve air quality [282].

Public outdoor lighting, which has increased up to 20% per year [293], also affects urban energy demand. Public lighting is needed for street and traffic lighting: it contributes to safety, potentially reducing accidents, injuries and crime rates, and increasing pedestrians comfort, thus motivating increased road and street use [294]. Outdoor public lighting can represent up to 3% of the electric energy consumption in a city [295]. Poor lamp design or maladjusted lighting may also result in "energy waste" and "light pollution" (e.g., higher energy consumption and sky glow) [293,296]. The development of innovative lighting technologies (e.g. solid-state lighting lamps [297–299]) and new strategies for the management of public lighting (e.g. dimming [300,301]) is a challenging area of research, towards a more sustainable urban environment. Photovoltaic panels with battery storage allow having powered renewable energy stand-alone lighting, thus reducing GHG emissions associated with artificial lighting [302]. However, this kind of approach does not work at all times and there is a trend for increasing research on alternative renewable energy solutions for stand-alone applications (e.g., fuel cells) [303]. At the policy level, several cities have been implementing public lighting energy efficient measures, such as substituting bulbs of public lamps for more energy efficient alternatives, with expected direct energy savings that can return the investment in less than 5 years [304]. However, in the past, energy efficiency policies have produced the "rebound" effect of stimulating the overall use of artificial lighting [293]. More efforts have to be carried out to foster sustainable public lighting policies.

Most studies and current practice have focused on specific sectors and urban components, such as buildings or transportation, isolating them from the urban context and its implications, and addressing one or two environmental indicators (mostly energy and GHG emissions) [258,259]. The literature includes few examples of holistic system approaches that provide an empirical understanding of how different urban form characteristics influence the global and local environmental impacts of cities; however, understanding and addressing these interplays between different components and the urban scale and addressing a wider set of environmental and health effects is crucial to identify and avoid unintended trade-offs in decision-making [251,256,258,259,305,306]. To better inform and support planners, designers, and decision-makers in general, comprehensive and robust assessments for environmental, air quality and health risk, are needed, which can identify improvement opportunities, as well as potential trade-offs, and evaluate and compare strategies and policies that can reduce environmental impacts associated with urban areas. Urban planners, architects, policy-makers and other stakeholders need objective frameworks, tools and data to support decision-making, in particular to address environmental and health impacts [307,308].

Industrial ecology tools have been used to assess the environmental performance of the built environment, including urban metabolism, material flow analysis and LCA (e.g. [243,309–312]). These tools have great potential in the assessment of urban systems because they can quantify resources used and potential environmental impacts associated with processes within and beyond the geographic limits of an urban area (e.g. raw materials extraction or energy production), with consistent metrics [313,314]. A comprehensive and function-centered character can be particularly useful in comparing alternative strategies or designs and in identifying improvement opportunities and trade-offs between a wide diversity of impact indicators [305]. These tools have been widely applied to buildings and building elements [260,261], and to whole cities or metropolitan areas [305]. There is an increasing trend to apply them to intermediate urban scales, such as neighbourhoods, addressing the interplays between different components of urban systems (e.g. urban density, mobility demand, shared equipment and infrastructure, etc.) [315,316]. Environmental impact assessment-based studies should be required and adequately performed in urban planning and architectural practice.

## 8. Influence of commuting in the urban economies and the environment

Transport policy is a central issue in urban governance with critical impacts in terms of energy consumption. The decision to become a commuter is to a large extent dependent on transportation costs borne by households (both in monetary and in time spending). When local, regional or federal governments decide to build a new highway or a bridge, or to finance public transportation or to develop transport networks, in fact, they are using taxes to favor those that will use such infrastructures more intensively. On the contrary, when the burden falls on the commuter (at least in the long term) commuting is discouraged. Indeed, the recent decrease in international oil price, which could lead to important and sustained deflation in fuel prices, may reduce the costs supported by those that commute by car and contribute to increase commuting attractiveness. Accordingly, the argument runs that national governments should maintain the prices at a significant level. This can be done through fiscal policy on "oil and its derivatives" or through the introduction of subsidies that are in turn applied to improve the quality of life of those living in the central business district (CBD) [317]. These measures can be complemented by, for example, the introduction of congestion tolls (already applied, with different specifications, in London, Singapore, Durham or Milan). Alternatively, parking policies could be applied to reduce traffic in the city centre [318,319] and give priority to benefit non-commuters living in the CBD, in occupying the limited number of parking places available there. Without doubt, while roads and highways are built to reduce congestion, it seems that these infrastructures also contribute to exacerbate commuting and to increase GHG emissions.

The growth of megacities has been intrinsically linked with increasing sprawling that compels millions of workers to commute. Commuting has often been "either neglected or typically seen as the market working just fine" [320]. In a more "traditional" economic view, if commuting is seen as the cost of time and distance, then commuting is only an option if it is compensated by either a rewarding job or by additional welfare gained from a pleasant living environment. However, as a mass phenomenon, commuting has benefits and costs well beyond those supported by each individual, which further shape the economies and the environment. Indeed, it is indisputable that the growth of commuting has made a critical contribution for stretching urban areas' boundaries and exacerbating energy consumption and GHG emissions.

Taking into account the complexity of this phenomenon, to measure commuting impacts, an application of an innovative commuting satellite account (CSA) embodied in a multi regional input-output (MRIO) framework was proposed by Ferreira [321]. This tool is capable of simultaneously integrating five critical elements of commuting: (i) commuting flows are represented in a specific geographic and economic context [322]; (ii) commuting influences the regional distribution of income [323]; (iii) commuting affects household consumption structures; (iv) commuting is intrinsically linked with the rental prices of housing and business premises [324]; and, (v) commuting is a major cause of energy consumption and CO<sub>2</sub> emissions [325]. These dimensions are widely acknowledged in the literature but the design of a modelling framework capable of incorporating all of them within the context of a specific region is still missing from regional and urban economic studies. So, to assess commuting opportunity costs, the CSA extension to the MRIO framework has already been applied to the Lisbon Metropolitan Area (LMA) and the results are illustrative of what could be the social increase in well-being if somehow policy measures and urban planning were applied efficiently and properly. Two hypothetical extreme scenarios were considered for this, both assuming that commuters change their status to non-commuters: one by considering the change of their place of residence to the municipality where they work; and the other one by assuming that the corresponding production activities are displaced to the suburbs [326]. According to

the results, in the case of a less sprawled city, important savings would emerge in terms of economic, social and environmental (opportunity) costs. In this scenario, where agglomeration forces are strengthened and density increases, the end of commuting flows and, consequently, a change in households' consumption structure, contributes to an expansion of the national economy. Therefore, for the LMA, the gross value added (GVA) loss in the suburbs (216 million Euros in the *Península de Setúbal* and 43 million Euros in the "Rest of the Country") is more than offset by an increase in Greater Lisbon GVA (921 million Euros). The difference between the benefits in Greater Lisbon and the losses in *Península de Setúbal* and the "Rest of the Country" indicates that the Portuguese GVA would increase by 0.5%. This is even more relevant as energy consumption and CO<sub>2</sub> emissions should simultaneously decrease (about 0.7% of the national emissions). This is exclusively due to the reduction in the consumption of "oil and its derivatives" (which decreases more than 150,000 toe), as the economy expansion would lead to an increase in the consumption of natural gas and coal (increasing approximately 33,000 and 17,000 toe, respectively).

On the other hand, if commuting vanishes due to the economic activity dispersion towards the suburbs, the economic consequences would be likely to be globally negative, despite the increase in the suburbs' economic production. Therefore, the *Península de Setúbal* and the "Rest of the Country" GVAs would increase by more than 4159 and 883 million Euros, respectively. However, the decline in Greater Lisbon would be much more significant leading to a 1.5% loss in national GVA. In terms of employment, the national decrease would be less significant (approximately 0.5%) as the economy would be more concentrated in less productive regions (and so, more workforce would be needed for the same amount of Output). Thus, for the LMA case study, the results indicate that the dispersion would imply a reduction in economic productivity that would overwhelm the benefits of ending commuting.

The comprehensive analysis of these first applications indicates dichotomous, yet complementary, conclusions: commuting, by itself, induces significant economic, social and environmental costs, although commuting, as one of the many elements associated with the agglomeration phenomenon, is undoubtedly linked to increasing productivity and economic growth. The "apparent neutrality" of commuting, promoted by some governmental and political institutions, has contributed to a situation where commuting prevails and will probably continue to be more and more relevant in the future [327]. A new perception of mass commuting must comprise the analysis of several consequences as: the negative economic burden in the society [328], the unsustainable use of land, other natural resources [274,329] combined with increase impacts in GHG emissions [330], the tremendous financial effort devoted to many times redundant road, train or other public transit infrastructures in metropolitan areas [331] or the social consequences of increasing dysfunctional communities and cities [332,333]. As cities become large and fuzzy, scientific studies must combine multi-disciplinary approaches and methods to study increasing complex urban issues [334]. Undoubtedly, in the case of commuting, only a new multi-dimensional perspective can have a decisive role in supporting policy designed to accomplish the 11st Sustainable Development Goal of the UN 2030 Agenda [335], which calls upon world leaders to make cities and all "human settlements inclusive, safe, resilient, and sustainable".

## 9. The importance of consumer preferences on the diffusion of electric vehicles

Road transportation has a negative impact on the environment through the release of harmful emissions and the high consumption of oil derivatives. Increasing the number of non-fuelled vehicles on light duty vehicle fleets, such EVs, has been pointed out as one of the solutions that may potentially decrease this environmental burden. This context led to the implementation of several measures worldwide in order to increase the circulation of EVs over fuelled vehicles. As a

result, nearly all automotive manufacturers have at least one EV model on their fleets. From the policy-makers side, several governments designed and implemented policy packages to encourage consumers to purchase EVs, with purchase subsidies [336–339], taxes exemption [340–344] or the allowance of drive in low occupancy lanes being the most commonly applied policies [339,341,345–347]. However, the market penetration of EVs depends on the DR. As consumer preferences are considered one of the most important factors that influence the decision of purchasing a product [348], a satisfactory match between vehicle characteristics and consumer preferences is crucial for gaining market acceptance of these products [349] and it is vital in the development of such new products and policies design [350]. Preference information for EVs is also particularly important to support companies in adjusting their new vehicles characteristics according to consumer evaluations and requirements for future vehicle adoption [351,352]. The extensive number of studies focused on consumer preference analysis for EVs underlines the importance of considering such information to effectively increase the market penetration of these vehicles. The analysis of the time horizon of those studies highlights the current relevance of understanding the consumer concerns on the diffusion of EVs with more than 60% of the 100 studies reviewed being developed from 2000 onwards.

In the literature, two main research lines are identified. One line comprises studies focused on the consumer preferences assessment for EVs, where two main trends and gaps were identified. The first trend regards the geographical scope of the studies. In the 80 s and 90 s, North American markets were the focus of most of the studies (e.g. [353–357]), a trend that shifted to European (e.g. [358–362]) and Asian markets since 2000 (e.g. [363–366]). There are, however, several countries that have strongly encouraged electric mobility, for instance by joining the EVs Initiative [367], that remain to be analyzed. Therefore, focusing the analysis on such countries is suggested for future studies, namely France, Portugal, Sweden, Italy and Spain. The second trend regards the methodology used to estimate the consumer preferences, with all the studies using Discrete Choice or Conjoint Analysis models as estimation procedures. The other line of research concerns the analysis of influential factors on consumer preferences for EVs. The main influential factors were gathered in three main groups: technology, consumer and context. Purchase cost, battery limitation and charging time were the main technology-related factors analyzed. Regarding the consumer-related factors, five characteristics are the most focused in the literature, namely age, gender, income, level of education and family size. The context-related factors commonly involve the analysis of the influence of the fuel price, the development of charging infrastructure, social exposure and government policies on EVs diffusion. In these studies, the influence of some factors is corroborated in all studies, such as the "positive" influence of fuel price increments (e.g. [337,345,368]) and the "positive" influence of the charging infrastructure on increasing the demand of EVs (e.g. [342,369–373]). However, the influence of other factors was not easily identified so far, namely the influence of consumer factors, such age and income, or the influence of some government policies, such as purchase and tax incentives. A trend identified in the second line of research is the overall assumption that consumer preferences are static, *i.e.* preferences do not change over time. However, several researchers, by analysing consumer preferences for EVs, verified that preferences were dynamic [374–377]. Dynamic preferences are considered preferences that are likely to change under different market conditions, *i.e.* consumer's concerns and valued characteristics change and evolve according to different contexts. As ignoring or underestimating the evolution of preferences may lead to inaccurate predictions of vehicle market shares [360,376] dynamic preferences should not be left out from diffusion analysis of new vehicle technologies [375].

## 10. Factors influencing the environmental impacts of electric vehicle adoption

EVs have the potential to drive the transport sector towards sustainability by reducing GHG emissions, fossil fuel dependence, and urban pollution. However, a large-scale adoption of EVs faces significant challenges and its environmental merits depend on a number of direct and indirect factors, which should be assessed considering a LC perspective [378–381]. The LCA methodology [382], which takes into account the impacts arising from vehicle manufacturing, use and end-of-life, as well as potential indirect effects in other systems, has been widely applied, uncovering environmental hotspots and trade-offs of EV adoption.

The electricity source used for charging has been pointed out as one of the most critical factors in the environmental assessment of EVs and in the comparison with conventional technologies [378,383–386]. Only if EVs are charged with low fossil-content electricity can their adoption lead to high GHG reductions [378,383,386–388]. However, the assessment of emissions from EVs charging is complex and can be performed using different perspectives [389]. On one hand, EVs electricity consumption can be regarded as part of the total load of the electricity system (attributational approach); therefore, average emission factors for electricity supply are employed. On the other hand, EVs can be considered a new load added on top of existing load (consequential approach) and marginal electricity supply and corresponding emissions should thus be used to assess the change induced in the electricity system due to EVs charging. Marginal effects can have a distinct and larger magnitude than the average behaviour of the electricity system, leading to very distinct results [390].

Irrespective of the approach taken, which depends on the research question leading the analysis, both temporal and geographical aspects underlying electricity generation should be considered. Because the electricity system varies significantly from country to country and even between regions, as regards energy sources, and technologies, driving the same EV in different geographical areas can result in very different environmental profiles [391–394]. Furthermore, the annual electricity mix can vary significantly from year to year, for instance, due to changes in electricity demand, technology portfolio, availability of renewables, and net imports [395]. Most importantly, it can vary significantly throughout the day resulting in different environmental impacts depending on the charging schedule [394,396]. The time of EV charging and its effects on environmental impacts is a current topic of research, but there is still controversy regarding the optimal charging schedule [394,396,397].

A large-scale adoption of EVs entails changes in electricity demand potentially affecting the electricity system operation and configuration in the long term. On one hand, a shift towards electricity in the transportation sector will place an additional stress upon the electricity generation system and distribution infrastructure [398,399]. On the other hand, EVs are also seen as a way of increasing renewable energy penetration, due to their potential demand response abilities [55,398,400]. Several studies have assessed the effects of EVs in the electricity system, regarding, for instance, the impact on energy and CO<sub>2</sub> emissions [401–403], and the integration of renewable energy sources [398,400]. However, few studies have addressed interactions between EVs and other potentially competing technologies in the grid, such as the interaction between large storage capacity (e.g., pumped hydro storage) and EV charging [404].

Factors influencing electricity consumption and therefore the environmental impacts of EVs include the driving profile, which should be assessed using real-world data [384,394,396], and air temperature, which has an important effect on vehicle efficiency due to heating, ventilation, and air conditioning use, as well as temperature-related

battery efficiency effects [405–407]. Regarding vehicle manufacturing, several authors have shown that vehicle and battery manufacturing impacts of EVs can be twice as those from conventional technologies (e.g., GHG emissions) [383,387,408] and a substantial body of literature has focused on the assessment of the environmental impacts of different battery chemistries for electric mobility using LCA [409–415]. Energy demand during battery manufacture is a source of uncertainty in LCA of batteries and can have higher influence in the results than battery chemistry [416]. Charge-discharge efficiency, cycle life and energy density are found to be equally relevant for the environmental impact of batteries [416]. Explicit consideration of these parameters, which are seldom considered in LCA studies, would increase robustness of results.

Resource depletion and toxicity impacts are major environmental concerns regarding battery manufacturing and disposal. Resource criticality issues, which arise from the use in batteries and electronic components of lithium and other scarce metals with limited global supply, have been pointed out as important factors to consider [417]. A large-scale adoption of EVs will potentially affect reserves of these minerals, and extensive and efficient recycling systems, which are currently poorly developed, will be needed [418]. Other authors have focused on the reuse of EV batteries for stationary storage as a way of minimizing LC impacts [419–421], but have not analyzed the effect of delaying scrapping in future resource availability. Toxicity impacts resulting from mining processes associated with the production of electric powertrain components are also an area of concern [383,387]. However, there is a lack of robust LC impact assessment methods for both toxicity and resource depletion, and these impact categories are usually disregarded in LCA studies of EVs, leading to an underestimation of important environmental burdens [383].

The impact reduction potential of EVs is also dependent on the environmental performance of the displaced technology [417]. EVs environmental benefits will depend on how they compare with increasingly more energy-efficient conventional vehicles, as the introduction of EVs in the fleet is gradual and its effects will not be seen in the short term [422]. Therefore, the assessment of the environmental impacts of EVs adoption should consider dynamic aspects regarding the shift of technologies over time, as well as advances in material processing, technology development and changes in electricity production [386,423]. Applying a dynamic fleet-based LC approach, as opposed to a single-vehicle LCA, can help capture these effects as well as the scale and timing of changes, so that indirect impacts on other systems (e.g., the electricity system) can be assessed [424]. Potential environmental rebound effects arising from the different cost of electric and conventional vehicles and the different operation conditions of these technologies (e.g., range, re-fuelling/re-charging convenience, which may divert some of the vehicle kilometres travelled to alternative transport modes) should also be taken into account in LCA studies to inform policy making towards environmentally sustainable EV systems [425].

## 11. Challenges of emerging biofuel technologies

Sustainability is presently an essential principle in environmental resources management [426,427]. Currently, it is increasingly clearer to society that the continued use of fossil fuels for energy purposes is unsustainable. Increasing difficulties and costs in exploration of oil global reserves, and the need to reduce GHG emissions associated with their use worldwide are undermining the usage of fossil fuels. In this context, biofuels are particularly important since they can be used in today means of transportation with little or no engine modifications. Additionally, it could present an important option for means of transportation that lack other fuel options, especially trucks, ships and aircrafts.

First generation biofuels derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of

pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests [428]. Therefore, other innovative technologies and sources of energy must be developed to replace fossil fuels. The overall sustainability of biofuels will depend on the development of viable, sustainable, advanced technologies that do not appear to be commercially viable yet. In this perspective, various feedstocks for producing advanced biofuels are generating substantial awareness in many countries for their advantages in relation to first generation biofuels. Several studies have been conducted on the technical feasibility of growing different types of organisms for biofuel production in the laboratory [429–432], which have proved the absence of many of the major drawbacks associated with current biofuels. However, although several companies are emerging in this developing area, the price of these biofuels still appears to be too high to be competitive when compared to currently used fuels, even renewable ones. Therefore, economic feasibility is believed to be currently the main hurdle to overcome for still immature biofuel technologies. On the other hand, the price of oil, their main competitor, increased in 2018 but it is considerably low (US\$ 67.88 per WTI crude oil barrel on May 27th, 2018) [433] in order to advanced biofuels to compete.

In order to boost the adoption and development of advanced biofuels, there is a strong need to influence both the speed and the direction of the innovation and technological change. With that in mind, policymakers are putting their efforts to support the development of emerging renewable biofuels, either through direct means such as government-sponsored research and development (R&D), or by enacting policies that support the production of renewable technologies [434]. Experts consent that public investment in R&D is the most important policy to be adopted by countries. They also emphasize the potential impact of advanced biofuels subsidies and petrol taxes. Mandates are also considered of great importance. These actions can serve as recommendations concerning public policies to be enacted through policy makers [434].

The question is not whether advanced biofuels are technically possible, but rather focuses on the issue of whether they can be produced in a sustainable (environmental, economic, and social) manner and at a scale sufficient to help contributing to the world's fuel demand. Advanced biofuels have, consequently, a strong potential in multiple domains, such as energy, food and agriculture, national supply security and sustainability. The task that remains is how to disentangle the puzzle of a sustainable production process. It will, thus, require innovative dimensions of political and institutional cooperation to achieve the solution to this complex challenge.

## 12. Sustainability of bioenergy systems

Bioenergy production involves a chain of activities, from the growing of feedstock to energy conversion and use, which encompasses several sustainability challenges. GHG emissions of bioenergy systems have been the focus of many research studies [435,436], and recently other relevant environmental impacts have been assessed, including those deriving from Land-Use Change (LUC) [437–439], and the impacts on biodiversity, water resources, water, air and soil quality [440–442]. In addition, it is of importance to consider social-economic impacts of bioenergy together with environmental impacts when assessing sustainability of bioenergy production [443].

Environmental impacts of bioenergy are different in the various phases of its chain, but also depend on the pathway namely on factors such as feedstock characteristics, production location, agricultural practices or the conversion efficiency of biomass. The growing demand for land for biomass production results in the conversion of land to agricultural use and/or improvement of productivity on existing farmland, thus causing direct and/or indirect LUC [444]. LUC is an important driver of increased GHG emissions and may lead to altered soil organic carbon [445–447] and changes in a host of ecosystem services [448]. In addition, LUC is regarded as one of the major drivers



of the ongoing loss of biodiversity [449]. Besides LUC, water impacts of biomass production have been receiving growing attention from researchers and are typically distinguished in terms of water availability, due to irrigation or divert water used to grow food crops, and water quality impacts [442]: nitrogen or phosphorous fertilizers and pesticides used in crops cultivation can enter in water and soil causing impacts such as eutrophication (algal growth), aquatic oxygen depletion, toxicity and loss of biodiversity. Although most renewable energy technologies have lower impacts than conventional ones, electricity generation from biomass can produce significant NO<sub>x</sub>, particulate matter (PM), and hazardous air pollutants, such as polycyclic aromatic hydrocarbons (PAHs) [450]. In addition, Malça *et al.* [451] showed that emissions of PM are significantly higher when biodiesel is used in pre-Euro heavy-duty vehicles (up to double the emissions of fossil diesel use), with direct implications on air quality and potential health problems.

Social-economic impacts of bioenergy identified in existing literature include both positive and negative impacts. Negative social-economic impacts of bioenergy found in previous studies are associated with food security, land tenure and labor rights. According to a World Bank study [452], bioenergy production will push up prices for food staples, causing 3% price rise of corn and other major grains, and 8% of sugar by 2020. Increasing food prices are expected to have larger negative impacts on people from developing countries, who spend a greater share of their income on food. A number of developing countries have observed increasing conversion rate of food-to-energy land use in order to meet the increasing demand of biomass from developed countries. Competition for land between food and energy may lead to conflicts of land tenure [453–455]. Field workers of bioenergy croplands in developing countries have been reported to suffer from poor working conditions from excessive working hours to lack of assurance of occupational health and safety [456]. Respiratory diseases of workers and local communities due to particulate matter emissions are among the negative social impacts of bioenergy production and use [457]. Positive social-economic impacts of bioenergy are related with its contributions on economic development and job creation. Bioenergy production can contribute to the income of agro-business and create job opportunities cost-effectively [458,459]. Investment cost of creating one job in bioenergy industry is estimated to be lower than in fossil fuel and other renewables [460].

As indicated by the impacts identified above, environmental and social-economic impacts of bioenergy need to be assessed from a supply chain perspective, considering various stakeholders. LC methodologies such as LCA [461], Life-Cycle Costing (LCC) [462], Social Life-Cycle Assessment (SLCA) [463] and Life-Cycle Sustainability Assessment (LCSA) [464] have the abilities to assess impacts associated with a supply chain. LCA aims at assessing the environmental impacts of a product (or service) throughout its LC, and its methodologies are well established with two international standards ISO 14040 and ISO 14044. LCA has been widely applied to assess environmental impacts of bioenergy systems [465]. LC approaches assessing social-economic impacts such as SLCA, LCC, and LCSA are relatively novel methods, and call for further methodological development and practices of case studies. However, bioenergy is among one of the most assessed topics in existing studies [466–468]. Although the depth and breadth of LC approaches have developed rapidly in the past decades, further research is needed to consolidate important controversies and close methodological gaps. In LCA, further development on impact assessment methods is crucial on the following issues [469]: (i) characterization of impacts on biodiversity, land use change and water footprint; (ii) integration of spatial and temporal perspectives on regional impact categories (e.g. acidification, eutrophication and toxicity); and (iii) characterization of field emission to soil and water considering site-specific soil conditions. Consensus should be reached on the applicability of various types of LCA methods (e.g. attributional vs. consequential), and how to account for uncertainties when interpreting LCA results [470]. SLCA, LCC and

LCSA all possess a short history of methodological developments, international standards and widely-accepted documentations still need to be established or updated.

To ensure sustainability of bioenergy systems and to maximize the benefits of using biomass as energy source while avoiding negative environmental and social-economic impacts, there is the need, in one hand, to increase the comprehensiveness and robustness of LC sustainability assessment tools by addressing the aforementioned limitations and integrating uncertainty analysis [470,471] and, on the other hand, to develop policies that promote the development of technologies to efficiently convert feedstocks such as forestry or agricultural wastes [472]; to investigate alternative feedstocks to increase feedstock diversification; to improve agricultural management practices [473]; and to develop regional plans for bioenergy production taking into account the type of feedstocks available in the regions. Moreover, due to the different criteria that need to be taken into account to support the development of sustainable bioenergy systems and policies there is a research need to provide tools that support the interpretation and communication of LC results considering trade-offs among the different dimensions of sustainability in a scientifically sound manner. A potential approach that has been gaining prominence is to use Multi-Criteria Decision Analysis (MCDA) [474] as it provides a structured decision support framework that can be used to integrate the LC data in the form of easily understandable rankings, performance scores, and classifications of the systems and policies under evaluation [472].

### 13. Energy for Sustainability (EfS) Initiative

Back in 2006 a group of professors at the University of Coimbra decided to create a multidisciplinary Initiative designated Energy for Sustainability (EfS). Its roots were the previous collaborations that had taken place in the context of joint supervision of PhD and MSc theses. These professors found out there was a great deal of common scientific interests among them and a significant potential to carry out new scientific projects and contracts with industry, as well as new postgraduate interdisciplinary educational programs. The implementation of a Master and a PhD programs followed shortly, in 2007, after approval by the University Senate, which included the formal recognition of the existence of the EfS Initiative. The number of professors involved grew progressively along the decade from the original 20 to 100, plus those post-doc researchers that, after obtaining the PhD degree, remained at the research units where they participate in project teams or lead those teams.

Its bottom-up origin and nature has opened the possibility of developing an autonomous and participative process of collective learning among the engaged faculty and researchers. It allowed a progressive definition of the grounds on which the Initiative sets out its ambitions to contribute to change. It is now clear that the three classical pillars of sustainability translate into university action, in education, in research, in facilities operation and management and in community involvement. "Do as you preach" is understood as a social obligation that should drive the definition of institutional commitment. However, the Initiative's bottom-up nature also prevents it from holding the levers that are only available to the institution's governing bodies. Classical organisational barriers [475] are most of the times in the way of accomplishing the objectives that could be attained through a consistent "do as you preach" attitude. Therefore, the Initiative has adopted the perspective of maximizing the results of its action, in view of the constraints it cannot control but does not give up trying to modify. This translates into doing all that it can through its own decisions and actions and exert the maximum influence possible on those who hold the levers. Sustainability is by definition a long term goal. So is the Initiative's praxis in advanced education, in research, in community oriented action, in support to facilities management.

The EfS Initiative is, by option, based on the research units where the professors and other researchers perform their activities. The

backgrounds are very diverse, covering all the classic engineering fields (civil, mechanical, electrical, chemical), computer science, psychology, architecture, economics, life sciences, sociology, law, physics, earth sciences, represented by 15 research units. For all purposes, the Initiative acts exactly on the same grounds as the University itself. The EfS Initiative is the University's frontend for the wide interdisciplinary area of energy for sustainability: it manages scientific research, post-graduate studies and industrial liaison through contacts with companies. A fourth stream of activity is also organised, towards the sustainable management of the University campuses. In 2012, in spite of the common place barriers, the University of Coimbra recognized the role the EfS Initiative had been playing as an actual institutional frontend. The Initiative was then officially considered a strategic institutional project directly depending from the University's Rector, with a statute published in the official journal. The bottom-up drawbacks did not diminish, though. The road ahead kept bumpy but also kept appealing.

Results so far confirm it. The general overview provided in this paper of some of the most relevant contemporary challenges regarding energy for sustainability, is the result of many accumulated years of research by young scientists integrated in multidisciplinary research teams. Either as students or afterwards, as graduated researchers, they are frequently stimulated by cross-boundary debates and exposed to diversified perspectives on known societal challenges or to not previously known challenges. All faculty and all new students are permanently encouraged to adopt a double supervision model, where two faculty members of different scientific backgrounds act as supervisors. Although this does not always happen, it happens very frequently, always having as background all the Initiative's activities where the virtues of multiple perspectives on problems are constantly emphasized.

Scientific research is always carried out at the research units, which are responsible for all the activity, as they own and administer the corresponding funding. The Initiative's management structure, however, is not based on an organic representation of the underlying research units, thus ensuring the distance needed to a cross-cut view of the existing potential and of the common interest of the University and the research units. Information is maintained available to the EfS community in general on the existing competences within the Initiative, specific information on calls for projects is selectively disseminated and the potentially interested researchers are encouraged and supported towards building proposals/applications based on multidisciplinary teams. Often, students apply and obtain scholarships within funded projects. This systematic practice has led to a big majority of multidisciplinary projects. It is frequent to find project teams where environmental researchers work together with social scientists and engineers, based on the assumption that no contemporary problem is prone to single-sided approaches, based either on technology, on market instruments or on behaviour. There are no overheads charged by the Initiative which, on the other hand, cares to facilitate the whole path towards ultimately signing a contract: identifying the funding opportunities, fostering the building up of multidisciplinary teams, help mobilising the University resources needed to support all the preparatory work, and actively participate in the dissemination of the research results. A similar approach is used regarding industrial connections.

A yearly meeting is organised with a set of partners comprising more than 30 companies, the energy regulator, and the Portuguese energy agency. In this meeting the partners get in touch with the current research, visit a research unit, contact the students working on their theses, mainly through a poster contest and exhibition, and meet with faculty and researchers to discuss the next year roadmap. On the other hand, bilateral meetings with companies are frequently organised, either at the company's premises or at the University, where topics of common interest are identified and possible cooperation paths are envisaged, either in the area of education and training or in any

interdisciplinary research stream that may reveal of usefulness to the company.

A commitment with sustainable management of a University campus requires a clear definition of policy, a roadmap for action and a specific structure with specialized human resources which can only be decided at the level of the University top management. The EfS Initiative intervenes within the scope of its autonomous decision capability inside the University, which lacks the power for deciding corporate action. In what concerns awareness raising, it promotes contests among students (best thesis awards, sustainability driven photo contests), besides organising very frequent public events with or without external invited guests, most of the times strongly connected either with ongoing research projects or with its educational programs – as, for example, the seasonal workshops centered on the development of PhD thesis projects. As regards to the involvement of faculty and students on physical action on campus buildings and facilities, activities are carried out through numerous projects where students are involved, mainly directed at the energy efficiency improvement in University buildings. This can involve energy audits, building up energy efficiency plans [476], modifying and upgrading building management systems [477], improving the efficiency of energy systems within buildings or the internal environmental quality, in cooperation with the University's facilities management service. Faculty members are called, eventually not so frequently as the existing potential would recommend, to provide advice on some intricate situations involving internal comfort, energy use, historical buildings, *etc.*, usually leading also to the involvement of students on related activities. However, the intervention of students on campus is mostly dependent on faculty action, responding to the stimulus that the EfS Initiative permanently exerts towards the definition of challenges to MSc and PhD students that may have influence on campus sustainability. Although without the power to act on fundamental levers, the Initiative persists on trying to exert influence on institutional policy. It has given, for example, a nuclear contribution to the present mid-term University plan, a proposal was specified to implement a campus sustainability management system [478]. The management structure of the Initiative provides the required instruments to keep these orientations up and running. Besides a top management board, four committees develop their action on four main fields: scientific research including relation with R&D units, sustainable campus, communication and management of the educational programs, including strongly personalized relations with students.

Educational activities include a Ph.D. programme on Sustainable Energy Systems, operating in cooperation with two other Universities, a MSc programme and a post-graduate diploma on Energy for Sustainability, all having begun in 2008/09, and a distance learning programme on Sustainability at Local Level, beginning in 2018/2019. The programs were conceived following a structured design approach described by Batterman *et al.* in ref. [479]. PhD students are encouraged to have two supervisors of different scientific backgrounds, in order to foster interdisciplinary work. The first PhDs graduated in 2013. Since then, 27 PhD graduated until March 2018. The first MScs graduated in 2010 and 70 graduated up to February 2018. Many of the young PhD researchers graduated within the Sustainable Energy Systems programme are spread throughout the world, in companies and research institutions. The ones that chose to remain at the University of Coimbra are presently a very important research working force, multidisciplinary as expected, who care to actively contribute to knowledge advancement. A specific framework existed for almost ten years for the PhD programme, consisting of an international cooperation agreement established by the Portuguese government with the Massachusetts Institute of Technology (MIT): the MIT-Portugal Program (MPP). It contributed to several attributes of the PhD programme. On one hand, many PhD students had the opportunity to stay at MIT for extended periods of time, from some months to a whole year, directly profiting from the direct contact with their local co-supervisors and from specific

conditions to their thesis development. On the other hand, frequent short visits of MIT faculty provided opportunities for wide exchange of ideas and insights, mostly directed at helping students to organise their ambitions towards robust structured research projects. The MPP provided also many contacts between faculty members of both sides, which in turn resulted in unveiling new terms of cooperation, directly benefiting PhD students guidance. This cooperation also allowed some methodological changes through the adaptation of certain aspects of the MIT student supervision praxis to the Portuguese faculty current methods.

The overall environment provided by the existence of the EfS Initiative, as a result of the initial commitment to interdisciplinary research of a group of very diverse faculty members, has been the background upon which new approaches to sustainability have been developed, based on a healthy, amiable and fertile relationship among research units, faculty, researchers and students. It has been creating a positive bias towards cooperation and global thinking.

#### 14. Conclusions

This paper presented and discussed several topics on energy systems towards a more sustainable and energy efficient future. The multidisciplinary framework of the covered issues reflects the character of both the EfS Initiative of the University of Coimbra and the Sustainable Energy Systems focus area of the MIT-Portugal Doctoral Program. On the other hand, the diversity of the subjects discussed in this paper emphasizes the importance of analysing different energy systems and their interrelations in a more holistic way. The next paragraphs outline the main conclusions of the paper, highlighting areas of research that should be further investigated in the near future.

- **Renewables and the sustainability of electricity markets** – A paradigm shift is faced in the electricity system. Pursuing a more sustainable electricity system is driving all stakeholders, imprinting the increasing need for reliable renewable technologies. Moreover, electricity system reforms in Europe are aiming for unified and competitive electricity markets. The increasing penetration of renewables and the pressure on GHG emissions are in everyone's mind. Stakeholders promote the discussion of the impacts of this shift and try to prepare for the change that is already happening. The need to research the different impacts of renewables on electricity markets, a vast field of study, was never so important.
- **Understanding utilities adaptability and business models innovation in a rapidly changing electricity sector** – The electricity sector transition towards a smarter and more sustainable setting brings challenges for DSOs and their role in a changing sector. These challenges encompass complex institutional, technological, and organisational issues, associated with their roles, activities, and responsibilities. In this context, while technological and institutional aspects have received significant attention, the organisational and business model innovation dimension have been explored to a lesser extent. However, a transition in technologies and policies that is not matched by a more detailed understanding of the organisational behaviour of DSOs can hinder innovation in the sector and halt the delivery of benefits to connected consumers and the economy. Given this, research efforts that explore the organisational characteristics of electricity distribution companies, as a source of insight on flexibility and adaptability of the electricity distribution industry, can be valuable for the design of new policies and business models for DSOs, and prove useful to other capital-intensive network industries.
- **The potential of city scale residential DR in the electricity grid** – DR remains an interesting research topic because it must consider the uncertainty associated to consumer and utility adoption, as well as, the randomness of loads use, the intermittency of renewables generation and energy storage. The introduction of demand

response programs may provide the possibility to benefit both the consumer and the network operator while also helping to integrate renewable energy generation. Such programs may include the management of a set of standard flexible loads to postpone its start or interrupting the operation of consumer authorized appliances. DR can also make use of EVs or other type of energy storage capacity to provide certain types of network services. The increased study of DR may certainly help to verify and justify possible investments in its enabling technologies.

- **Can community renewable energy thrive in Southern and Eastern Europe?** – CRE initiatives are relatively new stakeholders in energy systems and energy markets, and they are important actors in the energy transition in several countries in Europe. The literature has observed major differences in the regional diffusion of the CRE model, and has identified systemic factors, drivers and barriers for the development of such enterprises in countries where the CRE model is well established. Using these examples as a point of departure, it would be fruitful to conduct similar case studies to analyze the development of CRE in the South and East of Europe, where the sector is emerging at a much slower rate as compared to the north and west of the continent, and draw comparisons. Biophysical conditions in Southern and Eastern Europe for distributed energy systems are unquestionable, especially in the south of the continent with its abundance of solar radiation. Therefore, such analysis may indicate systemic factors (technical, institutional, cultural) intrinsic to those countries landscapes that are hindering similar results of CRE initiatives. To obtain the required data, it is necessary to undertake "desk and field" research, surveys and interviews with CRE initiative members in Southern and Eastern Europe. The results will help CRE initiatives to align their development strategies with the prevailing environments and stages of energy transitions in their local landscapes, and can provide guidance for policy makers. Such a multiple case-study would evaluate the transferability of existing CRE models to countries where citizens are not active in the field of renewables, or where their deployment is progressing at an unsatisfactory rate. It would also improve the understanding of "if" and "how" CRE initiatives can provide bottom-up contributions to those countries efforts for achieving short and long term renewable electricity generation targets (EU 2020, 2030, 2050).
- **IO-MOLP models combined with other methodologies to assess economic-energy-environment policies** – The IO-MOLP models are practical and useful as an analytical tool for empirical research supporting the policy making in a wide variety of problems. The possibility of extending and integrating the IO-MOLP model with other methodologies in order to assess the interactions between the economic activities, energy requirements and the environment is particularly appealing. In this sense, future developments of this methodology can be achieved by the integration of hybrid IO-MOLP model and LCA approaches. This methodology allows incorporating different processes into the model, expanding the boundaries of analysis and can be useful for the analysis of policies for a specific energy commodity. Other possible development is the integration of inter-regional IO models and MOLP models. These models will be useful for the analysis of e3 policies for specific regions/states, whereas coupling the treatment of uncertainty could provide more robust outcomes.
- **Urban planning agenda for reducing environmental and health impacts** – Urban form directly or indirectly influences most environmental impacts associated with urban areas, from local water and air quality, to GHG emissions and global climate change. Most research has focused on specific sectors and urban components, such as buildings or transportation, isolating them from the urban context and its implications, and addressing one or two environmental indicators (mostly energy and GHG emissions). However, it is important that urban components (such as buildings and

transportation systems) are addressed together, with a comprehensive approach centered on users, and considering a wide range of environmental and health impacts, in order to identify and avoid unintended trade-offs in decision-making. Industrial ecology tools can be applied in the development of such holistic approaches. The empirical understanding of the linkages between urban form and environmental performance is crucial to enable the potential of urban planning and design in reducing environmental impacts associated with anthropogenic activities, which is especially relevant due to its comprehensive and long lasting effects.

- **Policies to reduce commuting and its environmental impacts** – Future research concerning commuting impacts needs to be performed taking into account the local and regional specificities of each geographical space. This can help to uncover the most adequate policies to reduce commuting and its environmental impacts. The solution is not independent from the cultural, economic and social backgrounds of a given region. What is clear is that urban and regional planning matters and they should be made at the correct level of governance. Finally, land-use and transport policy can favor less sprawled regions and, consequently, less commuting with significant impacts in the energy consumed and in the GHG emissions.
- **Agenda for future research on EVs diffusion** – The analysis of consumer preferences for EVs is a very active research field in transportation studies. Therefore, the extensive literature on this subject allows identifying several research paths that can be addressed in future studies, such as: to analyze preferences using methodologies other than discrete choice or conjoint analysis, for instance through the Analytic Hierarchy Process or the Multiattribute Utility Theory methods; to address the influence of influential factors on consumer preferences for EVs that has been, so far, inconclusive in order to achieve robust conclusions regarding their influence on EVs diffusion; and to include dynamic preferences on EVs diffusion studies due to their revealed importance on more reliable vehicles forecasts. Future research should then continue to address the preference analysis about EVs as it will allow to efficiently achieve the market penetration targets defined for these vehicles in each considered market.
- **A system-wide approach linking the transportation and electricity systems towards environmentally sustainable EV systems** – The environmental impacts of a large scale adoption of EVs result not only from the intrinsic characteristics of the vehicles and its life cycle, but also from indirect factors arising from the interaction with the existing transportation and electricity systems. Therefore, research should focus, on one hand, on developing efficient recycling systems for batteries and maximizing its cycle life and charge-discharge efficiency, as well as in assessing and minimizing toxicity and resource depletion impacts from battery manufacturing and other electric powertrain components. On the other hand, further research is needed on the interactions between EVs charging and the electricity system, namely regarding the effects of EVs in power systems that also have utility-scale storage capacity. Environmental impacts of EV adoption are affected by both spatially and temporally heterogeneous factors (e.g., climate, electricity mix, driving profiles) so that detailed analysis is needed for any specific energy and transportation system while considering future technological improvements. Potential environmental rebound effects of EVs adoption should also be taken into account when informing policymaking on the net benefits of EVs over conventional transport.
- **Key challenges towards sustainable bioenergy systems** – The development and implementation of sustainable bioenergy systems is a very complex issue and involves a comprehensive assessment of their environmental and social-economic impacts from a supply chain perspective. Although LC approaches are promising tools to measure impacts in the required holistic manner, more research is necessary in the development of: (i) comprehensive methods for the characterization of local/regional environmental impacts (e.g.

impacts on biodiversity, land use change, water footprint); (ii) tools that improve the comprehensiveness and robustness of LC approaches by integrating uncertainty; (iii) decision-aiding tools towards novel engineering systems approaches to analyze and better communicate potential trade-offs among multiple objectives as for example the combination of MCDA and LC methods; and (iv) policies, technologies and economic support for the expansion of advanced biofuels that are economically, socially and environmentally sustainable.

The scope of energy systems research extends beyond energy technologies and infrastructures: it affects transportation and land use patterns (at urban, suburban, community levels), industrial development, agriculture and food provision, and several other environmental, social and organisational aspects. Facing the challenges in energy for sustainability research requires an understanding of the whole supply chain – from energy provision to end-use consumption – as well as the technical, economic, environmental and governance factors needed to manage and transition current energy systems towards sustainable energy systems. A multidisciplinary approach is key to accomplish such endeavour within increasingly complex and interrelated energy systems.

## Acknowledgment

This work has been framed under the EFS Initiative of the University of Coimbra and the Sustainable Energy Systems focus area of the MIT-Portugal Program. It was partially supported by the Portuguese Foundation for Science and Technology (FCT) under grants SFRH/BD/51639/2011, SFRH/BD/52309/2013, PD/BD/105841/2014, PD/BD/105991/2014 (awarded in the framework of the MIT Portugal Program funded through the POPH/FSE), SFRH/BPD/99668/2014 and SFRH/BPD/114869/2016 (funded through POCH/FSE). The work has also been funded by FEDER funds through the COMPETE 2020-POCI, and by FCT in the framework of the projects POCI-01-0145-FEDER-016750 | PTDC/EMS-ENE/6079/2014, PTDC/EMS-ENE/3238/2014 | POCI-01-0145-FEDER-016760 | LISBOA-01-0145-FEDER-016760, POCI-01-0145-FEDER-016764 | PTDC/AGR-FOR/1510/2014 and POCI-01-0145-FEDER-016765 | PTDC/AAG-MAA/6234/2014 | UID/MULTI/00308/2013. Additionally, this work has been partially supported by FCT under project grant SAICTPAC/0004/2015-POCI-01-0145-FEDER-016434. The authors have obtained authorization from the International Renewable Energy Agency (IRENA) to include Fig. 1 in this paper.

## References

- [1] International Renewable Energy Agency. Trends in renewable energy (installed capacity), <<http://resourceirena.irena.org/gateway/dashboard/?Topic=4&subTopic=16>> [Accessed 4 June 2018].
- [2] Figueiredo NC, da Silva PP. Explanatory variables on south-west spot electricity markets integration. In: Godinho P, Dias J, editors. *Assessment methodologies: energy, mobility and other real world application*. Coimbra: Coimbra University Press; 2015. p. 65–88.
- [3] Henriot A, Glachant J-M. Melting-pots and salad bowls: the current debate on electricity market design for integration of intermittent RES. *Util Pol* 2013;27:57–64.
- [4] da Silva PP, Figueiredo NC. *Renewables optimization in energy-only markets*. In: Bianco V, editor. *Analysis of energy systems*. Management, planning and policy. Taylor & Francis; 2016.
- [5] Figueiredo NC, da Silva PP, Cerqueira PA. Evaluating the market splitting determinants: evidence from the Iberian spot electricity prices. *Energy Pol* 2015;85:218–34.
- [6] Figueiredo NC, da Silva PP, Cerqueira PA. It is windy in Denmark: does market integration suffer? *Energy* 2016;115:1385–99.
- [7] Figueiredo NC, da Silva PP, Cerqueira P. Wind generation influence on market splitting: The Iberian spot electricity market. In: *Proceedings of the 12th international conference on the european energy market (EEM)*, 2015. p.1–5. ISBN: 978-1-4673-6692-2.
- [8] Newbery D. Missing money and missing markets: reliability, capacity auctions and interconnectors. *Energy Pol* 2016;94:401–10.
- [9] Boillot M. *Advanced smart grids for distribution system operators*. 1. John Wiley & Sons, Inc; 2014.
- [10] Pérez-Arriaga LJ. *Regulation of the power sector*. London: Springer-Verlag; 2013.



- [11] Aiello M, Pagani G. How energy distribution will change: an ICT perspective. In: Beaulieu A, de Wilde J, Scherpen J, editors. *Smart grids from a global perspective*. Springer; 2016. p. 11–26.
- [12] Gellings CW. The smart grid: enabling energy efficiency and demand response. Lilburg, GA, USA: The Fairmont Press; 2009.
- [13] Jansen D, Ostertag K, Walz R. Sustainability Innovations in the electricity sector. Physica-Verlag; 2012.
- [14] Pereira GI, da Silva PP. The smart grid and distributed generation nexus. In: de Castro N, Dantas G, editors. *Distributed generation: International experiences and comparative analyses*. André Figueiredo; 2017. p. 13–36.
- [15] de Castro N, Dantas G. Distributed generation: international experiences and comparative analyses. Rio de Janeiro, Brazil: André Figueiredo, Publit; 2017.
- [16] European Commission. Energy 2020. A strategy for competitive, sustainable and secure energy. Brussels; 2010.
- [17] European Commission. A policy framework for climate and energy in the period from 2020 to 2030. Brussels; 2014.
- [18] European Commission. Energy Roadmap 2050. Brussels; 2011.
- [19] European Commission. A framework strategy for a resilient energy union with a forward-looking climate change policy. Brussels; 2015.
- [20] European Commission. Clean energy for all Europeans. Brussels; 2016.
- [21] European Commission. Directive of the European parliament and of the council on common rules for the internal market in electricity; 2017.
- [22] European Commission. Regulation of the European parliament and of the council establishing a European union agency for the cooperation of energy regulators (recast); 2017.
- [23] European Commission. Regulation of the European parliament and of the council on the internal market for electricity; 2017.
- [24] Mallet P, Granström P-O, Hallberg P, Lorenz G, Mandatova P. Power to the people: european perspectives on the future of electric distribution. *IEEE Power Energy Mag* 2014;12(2):51–64.
- [25] European Union. Directive 96/92/EC of the European parliament and of the council of 19 December 1996 concerning common rules for the internal market in electricity; 1996.
- [26] European Union. Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC; 2003.
- [27] European Union. Directive of 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing directive 2003/54/EC [p. L 211/55 - L 211/93]. *Off J Eur Union* 2009; [p. L 211/55 - L 211/93].
- [28] Martinot E, Kristov L, Erickson JD. Distribution system planning and innovation for distributed energy futures. *Curr Sustain/Renew Energy Rep* 2015;2(2):47–54.
- [29] van den Oosterkamp P, Koutstaal P, van der Welle A, de Joode J, Lenstra J, van Hussen k, et al. The role of DSOs in a smart grid environment. Final report. DG ENER, Amsterdam: European Commission; 2014.
- [30] CEER. The future role of DSOs. A CEER public consultation paper. Brussels; 2014.
- [31] CEER. The future role of DSOs. A CEER conclusions paper; 2015.
- [32] Meeus L, Glachant J-M. Electricity network regulation in the EU – The challenges ahead for transmission and distribution. Edward Elgar Pub; 2018.
- [33] Markard J, Raven R, Truffer B. Sustainability transitions: an emerging field of research and its prospects. *Res Policy* 2012;41(6):955–67.
- [34] Praetorius B, Bauknecht D, Cames M, Fischer C, Pehnt M, Schumacher K, et al. Innovation for sustainable electricity systems. Exploring the dynamics of energy transitions. Physica-Verlag Heidelberg; 2009.
- [35] Purvis A, Papaioannou IT, Debarberis L. Application of battery-based storage systems in household-demand smoothening in electricity-distribution grids. *Energy Convers Manag* 2013;65:272–84.
- [36] Carr S, Premier GC, Guwy AJ, Dinsdale RM, Maddy J. Energy storage for active network management on electricity distribution networks with wind power. *IET Renew Power Gen* 2014;8(3):249–59.
- [37] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. *Appl Energy* 2015;137:545–53.
- [38] Suberu MY, Mustafa MW, Bashir N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renew Sustain Energy Rev* 2014;35:499–514.
- [39] Carpinelli G, Celli G, Mocci S, Mottola F, Pilo F, Proto D. Optimal integration of distributed energy storage devices in smart grids. *IEEE Trans Smart Grid* 2013;4(2):985–95.
- [40] Huber M, Dimkova D, Hamacher T. Integration of wind and solar power in Europe: assessment of flexibility requirements. *Energy* 2014;69:236–46.
- [41] Broer T, Fuller J, Tuffner F, Chassin D, Djilali N. Modeling framework and validation of a smart grid and demand response system for wind power integration. *Appl Energy* 2014;113:199–207.
- [42] Pinto RT, Bauer P, Rodrigues SF, Wiggelinkhuizen EJ, Pierik J, Ferreira B. A novel distributed direct-voltage control strategy for grid integration of offshore wind energy systems through MTDC network. *IEEE T Ind Electron* 2013;60(6):2429–41.
- [43] Diaz RR, Alarcon ALJ, Moreno RJ. Monitoring system for global solar radiation, temperature, current and power for a photovoltaic system interconnected with the electricity distribution network in Bogota. In: *Proceedings of the IEEE 56th international midwest symposium on circuits and systems (MWSCAS)*, 2013, p. 485–488.
- [44] Rathore KGS, Edupuganti AK, Srinivasan A. D. Optimal low switching frequency pulse width modulation of current-fed five-level inverter for solar integration. In: *Proceedings of the applied power electronics conference and exposition (APEC)*; IEEE; 2016. pp. 943–50.
- [45] Cheng L, Chang Y, Huang R. Mitigating voltage problem in distribution system with distributed solar generation using electric vehicles. *IEEE T Sustain Energy* 2015;6(4):1475–84.
- [46] Goop J, Odenberger M, Johnsson F. Distributed solar and wind power? Impact on distribution losses. *Energy* 2016;112:273–84.
- [47] Foster JM, Trevino G, Kuss M, Caramanis MC. Plug-in electric vehicle and voltage support for distributed solar: theory and application. *IEEE Syst J* 2013;7(4):881–8.
- [48] Zhang X, Karady GG, Ariaratnam ST. Optimal allocation of CHP-based distributed generation on urban energy distribution networks. *IEEE T Sustain Energy* 2014;5(1):246–53.
- [49] Franco A, Versace M. Optimum sizing and operational strategy of CHP plant for district heating based on the use of composite indicators. *Energy* 2017;124:258–71.
- [50] Ma X, Wang Y, Qin J. Generic model of a community-based microgrid integrating wind turbines, photovoltaics and CHP generations. *Appl Energy* 2013;112:1475–82.
- [51] Adam A, Fraga ES, Brett DJL. Options for residential building services design using fuel cell based micro-CHP and the potential for heat integration. *Appl Energy* 2015;138:685–94.
- [52] Sorace M, Gandiglio M, Santarelli M. Modeling and techno-economic analysis of the integration of a FC-based micro-CHP system for residential application with a heat pump. *Energy* 2017;120:262–75.
- [53] Ruzzenenti F, Bravi M, Tempesti D, Salvatici E, Manfrida G, Basosi R. Evaluation of the environmental sustainability of a micro CHP system fueled by low-temperature geothermal and solar energy. *Energy Convers Manag* 2014;78:611–6.
- [54] Navalho JEP, Pereira JMC, Pereira JCF. A methodology for thermal analysis of complex integrated systems: application to a micro-CHP plant. *Appl Therm Eng* 2017;112:1510–22.
- [55] Richardson DB. Electric vehicles and the electric grid: a review of modeling approaches, impacts, and renewable energy integration. *Renew Sustain Energy Rev* 2013;19:247–54.
- [56] Green RC, Wang L, Alam M. The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. *Renew Sustain Energy Rev* 2011;15(1):544–53.
- [57] Galus MD, Zima M, Andersson G. On integration of plug-in hybrid electric vehicles into existing power system structures. *Energy Pol* 2010;38(11):6736–45.
- [58] Zakariazadeh A, Jadid S, Siano P. Multi-objective scheduling of electric vehicles in smart distribution system. *Energy Convers Manag* 2014;79:43–53.
- [59] Schenato L, Barchi G, Macii D, Arghandeh R, Poolla K, Meier A. Bayesian linear state estimation using smart meters and PMUs measurements in distribution grids. In: *Proceedings of the international conference on smart grid communications*. (SmartGridComm). 2014, p. 572–577.
- [60] Dyson MEH, Borgeson SD, Tabone MD, Callaway DS. Using smart meter data to estimate demand response potential, with application to solar energy integration. *Energy Pol* 2014;73:607–19.
- [61] McHenry MP. Technical and governance considerations for advanced metering infrastructure/smart meters: technology, security, uncertainty, costs, benefits, and risks. *Energy Pol* 2013;59:834–42.
- [62] Barai GR, Krishnan S, Venkatesh B. Smart metering and functionalities of smart meters in smart grid – a review. In: *Proceedings of the IEEE electrical power and energy conference (EPEC)*, 2015, p. 138–145.
- [63] Pereira R, Figueiredo J, Melicio R, Mendes VMF, Martins J, Quadrado JC. Consumer energy management system with integration of smart meters. *Energy Rep* 2015;1:22–9.
- [64] Depuru SSSR, Wang L, Devabhaktuni V. Smart meters for power grid: challenges, issues, advantages and status. *Renew Sustain Energy Rev* 2011;15(6):2736–42.
- [65] Aghaei J, Alizadeh M-I. Demand response in smart electricity grids equipped with renewable energy sources: a review. *Renew Sustain Energy Rev* 2013;18:64–72.
- [66] Williams T, Wang D, Crawford C, Djilali N. Integrating renewable energy using a smart distribution system: potential of self-regulating demand response. *Renew Energy* 2013;52:46–56.
- [67] Mazidi M, Zakariazadeh A, Jadid S, Siano P. Integrated scheduling of renewable generation and demand response programs in a microgrid. *Energy Convers Manag* 2014;86:1118–27.
- [68] Maharjan S, Zhu Q, Zhang Y, Gjessing S, Basar T. Dependable demand response management in the smart grid: a stackelberg game approach. *IEEE Trans Smart Grid* 2013;4(1):120–32.
- [69] Deng R, Yang Z, Chow M-Y, Chen J. A Survey on demand response in smart grids: mathematical models and approaches. *IEEE T Ind Inform* 2015;11(3):570–82.
- [70] Kanchev H, Lu D, Colas F, Lazarov V, Francois B. Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications. *IEEE T Ind Electron* 2011;58(10):4583–92.
- [71] Safdarian A, Fotuhi-Firuzabad M, Lehtonen M. A distributed algorithm for managing residential demand response in smart grids. *IEEE T Ind Inform* 2014;10(4):2385–93.
- [72] Chukwu UC, Mahajan SM. Real-time management of power systems with V2G facility for smart-grid applications. *IEEE T Sustain Energy* 2014;5(2):558–66.
- [73] Hernandez L, Baladron C, Aguiar JM, Carro B, Sanchez-Esguevilas A, Lloret J, et al. A multi-agent system architecture for smart grid management and forecasting of energy demand in virtual power plants. *IEEE Commun Mag* 2013;51(1):106–13.
- [74] Wang Z, Chen B, Wang J, Begovic MM, Chen C. Coordinated energy management of networked microgrids in distribution systems. *IEEE Trans Smart Grid* 2015;6(1):45–53.
- [75] Laaksonen H. Advanced islanding detection functionality for future electricity distribution networks. *IEEE T Power Deliv* 2013;28(4):2056–64.
- [76] Fadel E, Gungor VC, Nassef L, Akkari N, Malik MGA, Almasri S, et al. A survey on

- wireless sensor networks for smart grid. *Comput Commun* 2015;71:22–33.
- [77] Giannakis GB, Kekatos V, Gatsis N, Kim S-J, Zhu H, Wollenberg BF. Monitoring and optimization for power grids: a signal processing perspective. *IEEE Signal Proc Mag* 2013;30(5):107–28.
- [78] Aziz AFA, Khalid SN, Mustafa MW, Shareef H, Aliyu G. Artificial intelligent meter development based on advanced metering infrastructure technology. *Renew Sustain Energy Rev* 2013;27:191–7.
- [79] Rigas ES, Ramchurn SD, Bassiliades N. Managing electric vehicles in the smart grid using artificial intelligence: a survey. *IEEE T Intell Transp* 2015;16(4):1619–35.
- [80] Raza MQ, Khosravi A. A review on artificial intelligence based load demand forecasting techniques for smart grid and buildings. *Renew Sustain Energy Rev* 2015;50:1352–72.
- [81] Chang W-H, Lin C-H, Mu S-P, Chen L-D, Tsai C-H, Chiu Y-C, et al. Generating routing-driven power distribution networks with machine-learning technique. *IEEE T Comput Aid D* 2017;36(8):1237–50.
- [82] Eskandarpour R, Khodaei A. Machine learning based power grid outage prediction in response to extreme events. *IEEE T Power Syst* 2016;32(4):3315–6.
- [83] Mengelkamp E, Notheisen B, Beer C, Dauer D, Weinhardt C. A blockchain-based smart grid: towards sustainable local energy markets. *Comput Sci Res Dev* 2018;33:207–14.
- [84] Mengelkamp E, Gärtner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets. A case study: the Brooklyn microgrid. *Appl Energy* 2018;210:870–80.
- [85] Ruester S, Schwenen S, Batlle C, Pérez-Arriaga I. From distribution networks to smart distribution systems: rethinking the regulation of European electricity DSOs. *Util Pol* 2014;31:229–37.
- [86] Schiavo LL, Delfanti M, Fumagalli E, Olivieri V. Changing the regulation for regulating the change: innovation-driven regulatory developments for smart grids, smart metering and e-mobility in Italy. *Energy Pol* 2013;57:506–17.
- [87] Connor PM, Baker PE, Xenias D, Balta-Ozkan N, Axon CJ, Cipcigan L. Policy and regulation for smart grids in the United Kingdom. *Renew Sustain Energy Rev* 2014;40:269–86.
- [88] Crispim J, Braz J, Castro R, Esteves J. Smart grids in the EU with smart regulation: experiences from the UK, Italy and Portugal. *Util Pol* 2014;31:85–93.
- [89] Fox-Penner P. Smart power anniversary edition – Climate change, the smart grid and the future of electric utilities. Washington, DC: Island Press; 2014.
- [90] de Joode J, Jansen JC, van der Welle AJ, Scheepers MJJ. Increasing penetration of renewable and distributed electricity generation and the need for different network regulation. *Energy Pol* 2009;37(8):2907–15.
- [91] Jamasb T, Pollitt M. Incentive regulation of electricity distribution networks: lessons of experience from Britain. *Energy Pol* 2007;35(12):6163–87.
- [92] Cambini C, Croce A, Fumagalli E. Output-based incentive regulation in electricity distribution: evidence from Italy. *Energy Econ* 2014;45:205–16.
- [93] Anaya KL, Pollitt MG. Integrating distributed generation: regulation and trends in three leading countries. *Energy Pol* 2015;85:475–86.
- [94] Marques V, Bento N, Costa PM. The ‘smart paradox’: stimulate the deployment of smart grids with effective regulatory instruments. *Energy* 2014;69:96–103.
- [95] Perez-Arriaga IJ, Jenkins JD, Batlle C. A regulatory framework for an evolving electricity sector: highlights of the MIT utility of the future study. *Econ Energy Environ Policy* 2017;6(1):71–92.
- [96] Agrell PJ, Bogetoft P, Mikkelsen M. Smart-grid investments, regulation and organization. *Energy Pol* 2013;52:656–66.
- [97] Shaw R, Attree M, Jackson T. Developing electricity distribution networks and their regulation to support sustainable energy. *Energy Pol* 2010;38(10):5927–37.
- [98] Niesten E. Network investments and the integration of distributed generation: regulatory recommendations for the Dutch electricity industry. *Energy Pol* 2010;38(8):4355–62.
- [99] Anuta OH, Taylor P, Jones D, McEntee T, Wade N. An international review of the implications of regulatory and electricity market structures on the emergence of grid scale electricity storage. *Renew Sustain Energy Rev* 2014;38:489–508.
- [100] Fini AS, Moghaddam MP, Sheikh-El-Eslami MK. An investigation on the impacts of regulatory support schemes on distributed energy resource expansion planning. *Renew Energy* 2013;53:339–49.
- [101] Shen B, Ghatikar G, Lei Z, Li J, Wikler G, Martin P. The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges. *Appl Energy* 2014;130:814–23.
- [102] Ropenus S, Jacobsen HK, Schröder ST. Network regulation and support schemes? How policy interactions affect the integration of distributed generation. *Renew Energy* 2011;36(7):1949–56.
- [103] Cossent R, Gómez T, Frías P. Towards a future with large penetration of distributed generation: is the current regulation of electricity distribution ready? Regulatory recommendations under a European perspective. *Energy Pol* 2009;37(3):1145–55.
- [104] Pereira GI, da Silva PP. Determinants of change in electricity distribution system operators – A review and survey. In: *Proceedings of the 13th International conference on the European energy market (EEM)*. 2016.
- [105] Markard J. Transformation of infrastructures: sector characteristics and implications for fundamental change. *J Infrastruct Syst* 2011;17(3):107–17.
- [106] Kiesling L. Implications of smart grid innovation for organizational models in electricity distribution – Handbook of smart grid development. Hoboken: Wiley; 2016.
- [107] Dubois U, Saplaçan R. Public service perspectives on reforms of electricity distribution and supply: a modular analysis. *Ann Publ Cooper Econ* 2010;81(2):313–56.
- [108] Persideanu V, Rascanu V. Changes in the electrical energy distribution branch. *Econ, Manag Financ Mark* 2011;6(1):555–63.
- [109] Tsoukas H, Papoulias DB. Managing third-order change: the case of the public power corporation in Greece. *Long Range Plan* 2005;38(1):79–95.
- [110] Trygg P, Toivonen J, Järventausta P. Changes of business models in electricity distribution. *Int Energy J* 2007;8(4):243–8.
- [111] Kossahl J, Kranz J, Nicky O, Kolbe L. A perception-based model for smart grid adoption of distribution system operators – An empirical analysis. In: *Proceedings of the AMCS*; 2012.
- [112] Sovacool BK. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Res Soc Sci* 2014;1:1–29.
- [113] Sovacool BK, Ryan SE, Stern PC, Janda K, Rochlin G, Spreng D, et al. Integrating social science in energy research. *Energy Res Soc Sci* 2015;6:95–9.
- [114] Soares N, Bastos J, Dias Pereira L, Soares A, Amaral AR, Asadi E, et al. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. *Renew Sustain Energy Rev* 2017;77:845–60.
- [115] Anda M, Temmen J. Smart metering for residential energy efficiency: the use of community based social marketing for behavioural change and smart grid introduction. *Renew Energy* 2014;67:119–27.
- [116] Verbong GPJ, Beemsterboer S, Sengers F. Smart grids or smart users? Involving users in developing a low carbon electricity economy. *Energy Pol* 2013;52:117–25.
- [117] Meeus L, Hadush S. The emerging regulatory practice for new businesses related to distribution grids. Florence School of Regulation, Robert Schuman Centre for Advanced Studies; 2016.
- [118] Pereira GI, da Silva PP, Soule D. Policy-adaptation for a smarter and more sustainable EU electricity distribution industry: a foresight analysis. *Environ Dev Sustain* 2018.
- [119] Pereira GI, da Silva PP, Soule D. Assessment of electricity distribution business model and market design alternatives: evidence for policy design. *Energy Environ* 2018.
- [120] Nisar A, Ruiz F, Palacios M. Organisational learning, strategic rigidity and technology adoption: implications for electric utilities and renewable energy firms. *Renew Sustain Energy Rev* 2013;22:438–45.
- [121] Helms T. Asset transformation and the challenges to servitize a utility business model. *Energy Pol* 2016;91:98–112.
- [122] Cambini C, Meletiou A, Bompard E, Masera M. Market and regulatory factors influencing smart-grid investment in. *Eur: Evid Pilot Proj Implic Reform Util Pol* 2016;40:36–47.
- [123] European Commission. Clean energy for all Europeans. Brussels; 2016.
- [124] European Commission. Directive of the European parliament and of the council on common rules for the internal market in electricity (recast); 2017.
- [125] Electric Power Research Institute. The green grid. Energy savings and carbon emissions reductions enabled by a smart grid; 2008.
- [126] IEA. Technology roadmap – smart grids. Paris, France; 2011.
- [127] Borenstein S, Jaske M, Rosenfeld A. Dynamic pricing, advanced metering, and demand response in electricity markets. eScholarship repository. Berkeley, California, USA: University of California; 2002.
- [128] Rassenti SJ, Smith VL, Wilson BJ. Controlling market power and price spikes in electricity networks: demand-side bidding. *P Natl Acad Sci USA* 2003;100(5):2998–3003.
- [129] Guo Y, Zeman A, Li R. Utility simulation tool for automated energy demand side management. Conference Material. In: *Proceedings of the First international workshop on agent technologies for energy systems, and 9th international conference on autonomous agents and multiagent systems (AAMAS 2010)*, Toronto, Canada, 2010, p. 37–44.
- [130] Albadi MH, El-Saadany EF. A summary of demand response in electricity markets. *Electr Pow Syst Res* 2008;78(11):1989–96.
- [131] Roe C, Meliopoulos S, Entrißen R, Chhaya S. Simulated demand response of a residential energy management system. *IEEE* 2011 Energy 2011:1–6.
- [132] Kempton W, Tomic J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. *J Power Sources* 2005;144(1):280–94.
- [133] Union for the co-ordination of transmission of electricity. Final report – System disturbance on 4 November 2006; 2006.
- [134] Zeilinger F. Simulation of the effect of demand side management to the power consumption of households. In: *Proceedings of the 3rd international youth conference on energetics*. 2011.
- [135] DOE. Report of the DOE power outage study team on electric reliability events of the Summer of 1999; 2000.
- [136] Roozbehani M, Dahleh MA, Mitter SK. Volatility of power grids under real-time pricing. *LIDS Rep* 2011:1–14.
- [137] Celik B, Roche R, Suryanarayanan S, Bouquain D, Miraoui A. Electric energy management in residential areas through coordination of multiple smart homes. *Renew Sustain Energy Rev* 2017;80:260–75.
- [138] Schweppe F, Tabors RD, Kirtley JL, Outhred HR, Pickel FH, Cox AJ. Homeostatic utility control. *IEEE Trans Power Appar Syst* 1980;99(3):1151–63.
- [139] Gellings CW. Then and now – The perspective of the man who coined the term ‘DSM’. *Energy Pol* 1996;24(4):285–8.
- [140] Kostková K, Omelina L, Kyčina P, Jamrich P. An introduction to load management. *Electr Pow Syst Res* 2013;95:184–91.
- [141] Karnouskos S, de Holanda TN. Simulation of a smart grid city with software agents. In: *Proceedings of the third UKSim european symposium on computer modeling and simulation EMS’09*, 25–27 Nov; 2009.
- [142] Teng R, Yamazaki T. Bit-Watt home system with hybrid power supply. *IEEE* 2010;5:59–63.
- [143] Park S, Kim H, Moon H, Heo J, Yoon S. Concurrent simulation platform for energy-

- aware smart metering systems. *IEEE Trans Consum Electron* 2010;56(3):1918–26.
- [144] Gudi N, Wang L, Devabhaktuni V, Depuru SSSR. Demand response simulation implementing heuristic optimization for home energy management. In: *Proceedings of the North American power symposium* 2010.
- [145] Molderink A, Bakker V, Bosman MGC, Hurink JL, Smit GJM. Management and control of domestic smart grid technology. *IEEE Trans Smart Grid* 2010;1(2):109–19.
- [146] Roscoe AJ, Ault G. Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response. *IET Renew Power Gen* 2010;4(4):369–82.
- [147] Miguel P, Neves L, Martins AG. Methodology to simulate the impact of a large deployment of a residential energy management system in the electricity grid. *Electr Pow Syst Res* 2014;116:399–407.
- [148] Livengood D, Larson R. The energy box: locally automated optimal control of residential electricity usage. *Serv Sci* 2009;1(1):1–16.
- [149] Miguel P, Gonçalves J, Neves L, Martins AG. Using clustering techniques to provide simulation scenarios for the smart grid. *Sustain Cities Soc* 2016;26:447–55.
- [150] European Parliament. *Decentralised energy systems*; 2010.
- [151] Geels FW. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res Policy* 2002;31(8–9):1257–74.
- [152] Schreuer A, Weismeier-Sammer D. Energy cooperatives and local ownership in the field of renewable energy technologies: A literature review. *RiCC – research report* 2010/4; 2010.
- [153] Oteman M, Wiering M, Helderma J-K. The institutional space of community initiatives for renewable energy: a comparative case study of the Netherlands, Germany and Denmark. *Energy Sustain Soc* 2014;4(11).
- [154] Seyfang G, Park JJ, Smith A. A thousand flowers blooming? An examination of community energy in the UK. *Energy Pol* 2013;61:977–89.
- [155] Walker G, Devine-Wright P. Community renewable energy: what should it mean? *Energy Pol* 2008;36(2):497–500.
- [156] Okkonen L, Lehtonen O. Socio-economic impacts of community wind power projects in Northern Scotland. *Renew Energy* 2016;85:826–33.
- [157] Yildiz Ö, Rommel J, Debor S, Holstenkamp L, Mey F, Müller JR, et al. Renewable energy cooperatives as gatekeepers or facilitators? Recent developments in Germany and a multidisciplinary research agenda. *Energy Res Soc Sci* 2015;6:59–73.
- [158] International Cooperative Alliance. Co-operative enterprises build a better world; 2017. <<http://ica.coop/>>.
- [159] Viardot E. The role of cooperatives in overcoming the barriers to adoption of renewable energy. *Energy Pol* 2013;63:756–64.
- [160] Müller J, Rommel J. Is there a future role for urban electricity cooperatives? The case of Greenpeace Energy. In: *Proceedings of the Biennial international workshop on "Advances in energy studies"*; 2010.
- [161] Mignon I, Rüdinger A. The impact of systemic factors on the deployment of co-operative projects within renewable electricity production – An international comparison. *Renew Sustain Energy Rev* 2016;65:478–88.
- [162] REScoop. European federation of renewable energy cooperatives, <<https://rescoop.eu/facts-figures-0>>; 2017.
- [163] Hall S, Foxon TJ, Bolton R. Financing the civic energy sector: how financial institutions affect ownership models in Germany and the United Kingdom. *Energy Res Soc Sci* 2016;12:5–15.
- [164] UNDP Croatia. Innovative financing and business models for RES. In: *Proceedings of the joint IRENA-ENC workshop on renewable energy. Energy community*; 2016.
- [165] Barry M, Chapman R. Distributed small-scale wind in New Zealand: advantages, barriers and policy support instruments. *Energy Pol* 2009;37(9):3358–69.
- [166] Rogers JC, Simmons EA, Convery I, Weatherall A. Public perceptions of opportunities for community-based renewable energy projects. *Energy Pol* 2008;36(11):4217–26.
- [167] Warren CR, McFadyen M. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy* 2010;27(2):204–13.
- [168] Breukers S, Wolsink M. Wind power implementation in changing institutional landscapes: an international comparison. *Energy Pol* 2007;35(5):2737–50.
- [169] Agterbosch S, Vermeulen W, Glasbergen P. Implementation of wind energy in the Netherlands: the importance of the social-institutional setting. *Energy Pol* 2004;32(18):2049–66.
- [170] Musall FD, Kuik O. Local acceptance of renewable energy – a case study from southeast Germany. *Energy Pol* 2011;39(6):3252–60.
- [171] Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: how can we account for the differences? *Renew Sustain Energy Rev* 2008;12(4):1129–47.
- [172] Kaphengst T, Velten EK. Energy transition and behavioural change in rural areas – the role of energy cooperatives. *Deutschland: Ecologic Institut*; 2014.
- [173] International Labour Office. Providing clean energy and energy access through cooperatives. Geneva: International Labour Office (ILO), Cooperatives Unit (ENT/COOP), Green Jobs Program; 2013.
- [174] Barata E. Solid waste policy in Portugal: an environmental input output approach. Keele, UK: Keele University, School of politics international relations and the environment; 2002.
- [175] Leontief W. National income, economic structure, and environmental externalities. in: *The measurement of economic and social performance*, NBER, 1973, p. 565–576.
- [176] Leontief WW, Hoffenberg M. The economic effects of disarmament; 1961.
- [177] Leontief W. The future of nonfuel minerals in the United States and world economy: input-output projections. Lexington, Mass., USA: Lexington Books; 1983. p. 1980–2030.
- [178] Leontief W, Duchin F. The future impact of automation on workers. New York, USA: Oxford University Press; 1986.
- [179] Ciaschini M. Input-Output Anal: Introd 1988.
- [180] Førsund FR. Chapter 8 Input-output models, national economic models, and the environment. *Handbook Nat Resource. Energy Econ* 1. 1985. p. 325–41.
- [181] Pearson PJG. Proactive energy-environment policy strategies: a role for input-output analysis? *Environ Plan A Econ Space* 1989;21(10):1329–48.
- [182] O'Connor R, Henry EW. Input-output analysis and its applications. London: Charles Griffin and Company; 1975.
- [183] Cruz LMG. A Portuguese energy-economy-environment input-output model: policy applications. Keele, UK: Keele University, School of politics international relations and the environment; 2002.
- [184] Albino V, Kühtz S. Enterprise input-output model for local sustainable development – the case of a tiles manufacturer in Italy. *Resour Conserv cl* 2004;41(3):165–76.
- [185] Matsumoto M, Fujimoto J. The development of an enterprise input output model and its application to industrial environmental management. *J Appl Input-Output Anal* 2008;1314:123–43.
- [186] Lenzen M, Lundie S. Constructing enterprise input-output tables – a case study of New Zealand dairy products. *J Econ Struct* 2012;1(6):1–15.
- [187] Hawdon D, Pearson P. Input-output simulations of energy, environment, economy interactions in the UK. *Energy Econ* 1995;17(1):73–86.
- [188] Cumberland JH. A regional interindustry model for analysis of development objectives. *Pap Reg Sci Assoc* 1966;17(1):65–94.
- [189] Munksgaard J, Pedersen KA. CO<sub>2</sub> accounts for open economies: producer or consumer responsibility? *Energy Pol* 2001;29(4):327–34.
- [190] Yuan C, Liu S, Xie N. The impact on chinese economic growth and energy consumption of the global financial crisis: an input – output analysis. *Energy* 2010;35(4):1805–12.
- [191] Tang X, Zhang B, Feng L, Snowden S, Höök M. Net oil exports embodied in China's international trade: an input-output analysis. *Energy* 2012;48:464–71.
- [192] Logar I, van den Bergh JCM. The impact of peak oil on tourism in Spain: an input-output analysis of price, demand and economy-wide effects. *Energy* 2013;54:155–66.
- [193] Gay PW, Proops JLR. Carbon-dioxide production by the UK economy: an input output assessment. *Appl Energy* 1993;44(2):113–30.
- [194] Jr Cruz JB, Tan RR, Culaba AB, Ballacillo J-A. A dynamic input-output model for nascent bioenergy supply chains. *Appl Energy* 2009;86:S86–94.
- [195] Zhang B, Qiao H, Chen ZM, Chen B. Growth in embodied energy transfers via China's domestic trade: evidence from multi-regional input-output analysis. *Appl Energy* 2016;184:1093–105.
- [196] Chung W-S, Tohno S, Shim YS. An estimation of energy and GHG emission intensity caused by energy consumption in Korea: an energy IO approach. *Appl Energy* 2009;86(10):1902–14.
- [197] Chung W-S, Tohno S, Choi K-H. Socio-technological impact analysis using an energy IO approach to GHG emissions issues in South Korea. *Appl Energy* 2011;88(11):3747–58.
- [198] Chen S, Chen B. Urban energy consumption: different insights from energy flow analysis, input-output analysis and ecological network analysis. *Appl Energy* 2015;138:99–107.
- [199] Lenzen M, Dey CJ. Economic, energy and greenhouse emissions impacts of some consumer choice, technology and government outlay options. *Energy Econ* 2002;24(4):377–403.
- [200] Nässén J, Holmberg J, Wadeskog A, Nyman M. Direct and indirect energy use and carbon emissions in the production phase of buildings: an input-output analysis. *Energy* 2007;32(9):1593–602.
- [201] Huang Y-H, Wu J-H. Analyzing the driving forces behind CO<sub>2</sub> emissions and reduction strategies for energy-intensive sectors in Taiwan, 1996–2006. *Energy* 2013;57:402–11.
- [202] Faucheux S, Levarlet F. Energy-economy-environment models. In: van den Bergh JCM, editor. *Handbook of environmental and resource economics*. Edward Elgar; 1999.
- [203] Moriguchi Y, Kondo Y, Shimizu H. Analysing the life cycle impacts of cars: the case of CO<sub>2</sub>. *Ind Environ* 1993;16(1–2):42–5.
- [204] Matthews HS, Small MJ. Extending the boundaries of life-cycle assessment through environmental economic input-output models. *J Ind Ecol* 2000;4(3):7–10.
- [205] Suh S. Functions, commodities and environmental impacts in an ecological-economic model. *Ecol Econ* 2004;48(4):451–67.
- [206] Suh S, Huppes G. Methods for life cycle inventory of a product. *J Clean Prod* 2005;13(7):687–97.
- [207] Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life cycle assessment. Part 1: framework, goal and scope definition, inventory analysis, and applications. *Environ Int* 2004;30(5):701–20.
- [208] Narayanaswamy V, Altham WJ, Berkel RV, McGregor M. A primer on environmental life cycle assessment (LCA) for Australian grains. Curtin University of Technology, Centre of Excellence in Cleaner Production; 2002.
- [209] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, et al. Life cycle assessment – an operational guide to the ISO standards – Part 3: scientific background. Leiden, the Netherlands: Centre for Environmental Studies (CML), Leiden University; 2001.
- [210] Flemmer C, Flemmer R. The relationship between environmental sustainability and input output analysis of the New Zealand dairy farming sector. In: *Proceedings of the ANZSEE conference reinventing sustainability: a climate for change*; 2007.
- [211] Suh S. Waste input-output analysis: concepts and application to industrial ecology by Shinichiro Nakamura and Yasushi Kondo. *J Ind Ecol* 2009;13(5):835–6.
- [212] Jeswani HK, Azapagic A, Scheepelmann P, Rithoff M. Options for broadening and deepening the LCA approaches. *J Clean Prod* 2010;18(2):120–7.



- [213] Hendrickson CT, Lave LB, Matthews HS. Environmental life cycle assessment of goods and services. An input-output approach. *Resources for the Future*; 2006.
- [214] Majeau-Bettez G, Strömman AH, Hertwich EG. Evaluation of process- and input-output based life cycle inventory data with regard to truncation and aggregation issues. *Environ Sci Technol* 2011;45(23):10170–7.
- [215] de Haes HAU, Heijungs R, Suh S, Huppes G. Three strategies to overcome the limitations of life-cycle assessment. *J Ind Ecol* 2004;8(3):19–32.
- [216] Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, et al. System boundary selection in life-cycle inventories using hybrid approaches. *Environ Sci Technol* 2004;38(3):657–64.
- [217] Lee C-H, Ma H-W. Improving the integrated hybrid LCA in the upstream scope 3 emissions inventory analysis. *Int J Life Cycle Assess* 2013;18(1):17–23.
- [218] de Carvalho AL, Antunes CH, Freire F, Henriques CO. A hybrid input-output multi-objective model to assess economic-energy-environment trade-offs in Brazil. *Energy* 2015;82:769–85.
- [219] Dantzig GB. *Linear programming and extensions*. Santa Monica: The Rand Corporation; 1963.
- [220] Albers DJ, Reid C. An interview with George B. Dantzig: the father of linear programming. *Coll Math J* 1986;17(4):292–314.
- [221] Clark PB, Taylor L. Dynamic input-output planning with optimal end conditions: the case of Chile. *Econ Plan* 1971;11(1–2):10–30.
- [222] Bergendorff HG, Clark PB, Taylor L. Welfare gains from optimization in dynamic planning models. *Econ Plan* 1973;13(1–2):75–90.
- [223] Dorfman R, Samuelson PA, Solow RM. *Linear programming and economic analysis*. J Bus 1959;32(1):85–6.
- [224] Ebfefung AA, Kostreva MM. The generalized Leontief input-output model and its application to the choice of new technology. *Ann Oper Res* 1993;44(2):161–72.
- [225] Zhu E, Kim M-K, Harris TR. Input-output analysis, linear programming and modified multipliers. In: *Proceedings of the southern agricultural economics association annual meeting*. Atlanta, Georgia, USA; 2009.
- [226] Jackson R, Murray A. Alternative input-output matrix updating formulations. *Econ Syst Res* 2004;16(2):135–48.
- [227] Strömman AH. A multi-objective assessment of input-output matrix updating methods. *Econ Syst Res* 2009;21(1):81–8.
- [228] Muller F. *Energy and environment in interregional input-output models*. USA: Kluwer Academic Publishers; 1979.
- [229] Moulik TK, Dholakia BH, Dholakia RH, Ramani KV, Shukla PR. Energy planning in India: the relevance of regional planning for natural policy. *Energy Pol* 1992;20(9):836–46.
- [230] Hristu-Varsakelis D, Karagianni S, Pempetzoglou M, Sfetsos A. Optimizing production with energy and GHG emission constraints in Greece: an input-output analysis. *Energy Pol* 2010;38(3):1566–77.
- [231] Cho C-J. The economic-energy-environmental policy problem: an application of the interactive multiobjective decision method for Chungbuk Province. *J Environ Manag* 1999;56(2):119–31.
- [232] Hsu G-JY, Chou F-Y. Integrated planning for mitigating CO<sub>2</sub> emissions in Taiwan: a multi-objective programming approach. *Energy Pol* 2000;28(8):519–23.
- [233] Kravtsov MK, Pashkevich AV. A multicriteria approach to optimization of the gross domestic product. *Autom Rem Contr* 2004;65(2):337–45.
- [234] Chen T-y. The impact of mitigating CO<sub>2</sub> emissions on Taiwan's economy. *Energy Econ* 2001;23(2):141–51.
- [235] Oliveira C, Antunes CH. A multi-objective multi-sectoral economy-energy-environment model: application to Portugal. *Energy* 2011;36(5):2856–66.
- [236] Oliveira C, Antunes CH. A multiple objective model to deal with economy-energy-environment interactions. *Eur J Oper Res* 2004;153(2):370–85.
- [237] de Carvalho AL, Antunes CH, Freire F, Henriques CO. A multi-objective interactive approach to assess economic-energy-environment trade-offs in Brazil. *Renew Sustain Energy Rev* 2016;54:1429–42.
- [238] Chang S, Juang M. Decision analysis on CO<sub>2</sub> reduction for industrial and energy sectors – an FMOLP approach. In: *Proceedings of the Conference on East asian environmental and resource economics and policy – institute of economics*. Taipei; 1998.
- [239] Chang S-L. Decision analysis of sustainable energy development and GHG mitigation in Taiwan - A fuzzy multiobjective programming approach. In: *Proceedings of the 28th Annual IAEE international conference*. Taipei, Taiwan.
- [240] Borges AR, Antunes CH. A fuzzy multiple objective decision support model for energy-economy planning. *Eur J Oper Res* 2003;145(2):304–16.
- [241] Henriques CO, Antunes CH. Interactions of economic growth, energy consumption and the environment in the context of the crisis – A study with uncertain data. *Energy* 2012;48(1):415–22.
- [242] de Carvalho AL, Antunes CH, Freire F. Economic-energy-environment analysis of prospective sugarcane bioethanol production in Brazil. *Appl Energy* 2016;181:514–26.
- [243] Kennedy C, Cuddihy J, Engel-Yan J. The changing metabolism of cities. *J Ind Ecol* 2007;11(2):43–59.
- [244] Stephan A, Crawford RH, de Myttenaere K. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. *Build Environ* 2013;68:35–49.
- [245] UN. World urbanization prospects. The 2011 revision; 2011.
- [246] UN. World urbanization prospects. The 2014 revision; 2015.
- [247] Omer AM. Energy, environment and sustainable development. *Renew Sustain Energy Rev* 2008;12(9):2265–300.
- [248] UN. World cities report 2016; 2016.
- [249] Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havránek M, et al. Greenhouse gas emissions from global cities. *Environ Sci Technol* 2009;43(19):7297–302.
- [250] UN. World urbanization prospects. The 2007 revision; 2007.
- [251] Breheny M. The contradictions of the compact city. In: *Sustainable Development and Urban Form*; 1992.
- [252] Jenks M, Burton E, Williams K. The compact city: a sustainable urban form? London: E & FN Spon; 1996.
- [253] Doughty MRC, Hammond GP. Sustainability and the built environment at and beyond the city scale. *Build Environ* 2004;39(10):1223–33.
- [254] Jabareen YR. Sustainable urban forms: their typologies, models, and concepts. *J Plan Educ Res* 2006;26(1):38–52.
- [255] Williams K. Urban form and infrastructure: a morphological review. Technical Report. Government Office for Science; 2014.
- [256] Bastos J. Linking the urban form to environmental and health impacts with a life-cycle approach. Coimbra, Portugal: University of Coimbra; 2017.
- [257] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. *Renew Sustain Energy Rev* 2014;29:394–416.
- [258] Rickwood P, Glazebrook G, Searle G. Urban structure and energy – a review. *Urban Pol Res* 2008;26(1):57–81.
- [259] Anderson JE, Wulffhorst G, Lang W. Energy analysis of the built environment – a review and outlook. *Renew Sustain Energy Rev* 2015;44:149–58.
- [260] Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: a review of recent developments based on LCA. *Cons Build Mater* 2009;23(1):28–39.
- [261] Sharma A, Saxena A, Sethi M, Shree V, Varun. Life cycle assessment of buildings: a review. *Renew Sustain Energy Rev* 2011;15(1):871–5.
- [262] Okeil A. A holistic approach to energy efficient building forms. *Energy Build* 2010;42(9):1437–44.
- [263] Ewing R, Rong F. The impact of urban form on US residential energy use. *Hous Policy Debate* 2008;19(1):1–30.
- [264] Stephan A, Crawford RH, de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. *Appl Energy* 2013;112:23–34.
- [265] Bastos J, Batterman SA, Freire F. Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon. *Energy Build* 2014;69:344–53.
- [266] Maat K, Timmermans HJP. Influence of the residential and work environment on car use in dual-earner households. *Transp Res A-Pol* 2009;43(7):654–64.
- [267] Newton P, Meyer D. The determinants of urban resource consumption. *Environ Behav* 2010;44(1):107–35.
- [268] Cao X(J). Examining the impacts of neighborhood design and residential self-selection on active travel: a methodological assessment. *Urban Geogr* 2015;36(2):236–55.
- [269] Lund H, Möller B, Mathiesen BV, Dyrrelund A. The role of district heating in future renewable energy systems. *Energy* 2010;35(3):1381–90.
- [270] Rezaie B, Rosen MA. District heating and cooling: review of technology and potential enhancements. *Appl Energy* 2012;93:2–10.
- [271] Lunda H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th generation district heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. *Energy* 2014;68:1–11.
- [272] Kenworthy JR, Laube FB. Automobile dependence in cities: an international comparison of urban transport and land use patterns with implications for sustainability. *Environ Impact Assess Rev* 1996;16(4–6):279–308.
- [273] Handy S. Methodologies for exploring the link between urban form and travel behavior. *Transp Res D-Tr E* 1996;1(2):151–65.
- [274] Badoe DA, Miller EJ. Transportation – land use interaction: empirical findings in North America and their implications for modeling. *Transp Res Part D* 2000;5(4):235–63.
- [275] Stead D, Marshall S. The relationships between urban form and travel patterns. An international review and evaluation. *Eur J Transp Infrastruct Res* 2001;1(2):113–41.
- [276] Woodcock J, Banister D, Edwards P, Prentice AM, Roberts I. Energy and transport. *Lancet* 2007;370(9592):1078–88.
- [277] Mitchell G, Hargreaves A, Namdeo A, Echenique M. Land use, transport, and carbon futures: the impact of spatial form strategies in three UK urban regions. *Environ Plan A* 2011;43(9):2143–63.
- [278] Dulal HB, Brodnig G, Onorioso CG. Climate change mitigation in the transport sector through urban planning: a review. *Habitat Int* 2011;35(3):494–500.
- [279] Karagulian F, Belis CA, Dora CFC, Prüss-Ustün AM, Bonjour S, Adair-Rohani H, et al. Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. *Atmos Environ* 2015;120:475–83.
- [280] Nieuwenhuijsen MJ, Khreis H. Car free cities: pathway to healthy urban living. *Environ Int* 2016;94:251–62.
- [281] Naess P. Urban form, sustainability and Health: the case of Greater Oslo. *Eur Plan Stud* 2014;22(7):1524–43.
- [282] Gago EJ, Roldan J, Pacheco-Torres R, Ordóñez J. The city and urban heat islands: a review of strategies to mitigate adverse effects. *Renew Sustain Energy Rev* 2013;25:749–58.
- [283] Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature* 2005;438:310–7.
- [284] Laaidi K, Zeghnoun A, Dousset B, Bretin P, Vandentorren S, Giraudet E, et al. The impact of heat islands on mortality in Paris during the August 2003 heatwave. *Environ Health Perspect* 2012;120(2):254–9.
- [285] Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, et al. Global change and the ecology of cities. *Science* 2008;319(5864):756–60.
- [286] Voogt JA, Oke TR. Thermal remote sensing of urban climates. *Remote Sens Environ* 2003;86(3):370–84.
- [287] Stathopoulou M, Cartalis C. Daytime urban heat islands from Landsat ETM+ and Corine land cover data: an application to major cities in Greece. *Sol Energy* 2007;81(3):358–68.



- [288] Aniello C, Morgan K, Busbey A, Newland L. Mapping micro-urban heat islands using LANDSAT TM and a GIS. *Comput Geosci* 1995;21(8):965–9.
- [289] Rosenzweig C, Solecki WD, Parshall L, Chopping M, Pope G, Goldberg R. Characterizing the urban heat island in current and future climates in New Jersey. *Glob Environ Change B Environ Hazards* 2005;6(1):51–62.
- [290] Zhao L, Lee X, Smith RB, Oleson K. Strong contributions of local background climate to urban heat islands. *Nature* 2014;511:216–9.
- [291] Dimoudi A, Nikolopoulou M. Vegetation in the urban environment: microclimatic analysis and benefits. *Energy Build* 2003;35(1):69–76.
- [292] Onishi A, Cao X, Ito T, Shi F, Imura H. Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban For Urban Green* 2010;9(4):323–32.
- [293] Hötker F, Moss T, Griefahn B, Kloas W, Voigt CC, Henckel D, Hänel A, et al. The dark side of light: a transdisciplinary research agenda for light pollution policy. *Ecol Soc* 2010;15(4):13.
- [294] Painter K. The influence of street lighting improvements on crime, fear and pedestrian street use, after dark. *Landsc Urban Plan* 1996;35(2–3):193–201.
- [295] Kostic M, Djokic L. Recommendations for energy efficient and visually acceptable street lighting. *Energy* 2009;34(10):1565–72.
- [296] Narisada K, Schreude D. Light pollution handbook. Netherlands: Springer; 2004.
- [297] Li F, Chen D, Song X, Chen Y. LEDs: a promising energy-saving light source for road lighting. In: *Proceedings of the power and energy engineering conference, 2009. APPEEC 2009. Asia-Pacific*; 2009.
- [298] Long X, Liao R, Zhou J. Development of street lighting system-based novel high-brightness LED modules. *IET Optoelectron* 2009;3(1):40–6.
- [299] Lee XH, Moreno I, Sun C-C. High-performance LED street lighting using microlens arrays. *Opt Express* 2013;21(9):10612–21.
- [300] Müllner R, Riemer A. An energy efficient pedestrian aware smart street lighting system. In: *J Perv Comput Commun* 2011;7(2):147–61.
- [301] Leccese F. Remote-control system of high efficiency and intelligent street lighting using a ZigBee network of devices and sensors. *IEEE T Power Deliv* 2013;28(1):21–8.
- [302] Costa MAD, Costa G, dos Santos AS, Schuch L, Pinheiro JR. A high efficiency autonomous street lighting system based on solar energy and LEDs. In: *Proceedings of the 2009 Brazilian Power Electronics Conference, IEEE; 2009*.
- [303] Lagorse J, Paire D, Miraoui A. Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery. *Renew Energy* 2009;34(3):683–91.
- [304] Radulovic D, Skok S, Kirincic V. Energy efficiency public lighting management in the cities. *Energy* 2011;36(4):1908–15.
- [305] Heinonen J, Junnila S. Implications of urban structure on carbon consumption in metropolitan areas. *Environ Res Lett* 2011;6:014018.
- [306] Bauer C, Hofer J, Althaus H-J, Del Duce A, Simons A. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. *Appl Energy* 2015;157:871–83.
- [307] National Research Council. Pathways to urban sustainability: research and development on urban systems: summary of a Workshop. Washington, DC: The National Academies Press; 2010.
- [308] Ramaswami A, Russel AG, Culligan PJ, Sharma KR, Kumar E. Meta-principles for developing smart, sustainable, and healthy cities. *Science* 2016;352(6288):940–3.
- [309] Barles S. Urban metabolism of Paris and its region. *J Ind Ecol* 2009;13(6):898–913.
- [310] Kennedy C, Pincetl S, Bunje P. The study of urban metabolism and its applications to urban planning and design. *Environ Pollut* 2011;159(8–9):1965–73.
- [311] Chester M, Nahlik MJ, Fraser AM, Kimball MA, Garikapati VM. Integrating life-cycle environmental and economic assessment with transportation and land use planning. *Environ Sci Technol* 2013;47(21):12020–8.
- [312] Bastos J, Batterman SA, Freire F. Significance of mobility in the life-cycle assessment of buildings. *Build Res Inf* 2016;44(4).
- [313] Weisz H, Steinberger JK. Reducing energy and material flows in cities. *Curr Opin Environ Sustain* 2010;2(3):185–92.
- [314] Pincetl S, Bunje P. Potential targets and benefits for sustainable communities research, development, and demonstration funded by the PIER Program; 2009.
- [315] Codoban N, Kennedy CA. Metabolism of neighborhoods. *J Urban Plan D-ASCE* 2008;134(1):21–31.
- [316] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Build Environ* 2015;93(2):165–78.
- [317] Cruz L, Barata E, Ferreira J-P, Freire F. Greening transportation and parking at University of Coimbra. *Int J Sustain High Educ* 2017;18(1):23–38.
- [318] Verhoef E, Nijkamp P, Rietveld P. Second-best regulation of road transport externalities. *J Transp Econ Policy* 1995;29(2):147–67.
- [319] Barata E, Cruz L, Ferreira J-P. Parking at the UC campus: problems and solutions. *Cities* 2011;28(5):406–13.
- [320] Ewing R. Is Los Angeles-style sprawl desirable? *J Am Plan Assoc* 1997;63(1):107–26.
- [321] Ferreira J. How commuting shapes the urban economies and the environment: a commuting satellite account applied to the Lisbon Metropolitan Area [Ph.D. thesis]. Coimbra, Portugal: University of Coimbra; 2016.
- [322] Haddad EA, Hewings GJD, Porsse AA, Van Leeuwen ES, Vieira RS. The underground economy: tracking the higher-order economic impacts of the São Paulo subway system. *Transp Res Part A* 2015;73:18–30.
- [323] Hewings GJD, Okuyama Y, Sonis M. Economic interdependence within the Chicago metropolitan area: a Miyazawa analysis. *J Reg Sci* 2001;41(2):195–217.
- [324] Malpezzi S. Housing prices, externalities, and regulation in US metropolitan areas. *J Hous Res* 1996;7(2):209–41.
- [325] Muñoz I, Galindo A. Urban form and the ecological footprint of commuting. The case of Barcelona. *Ecol Econ* 2005;55(4):499–514.
- [326] Ferreira J-P, Ramos P, Cruz L, Barata E. The opportunity costs of commuting: the value of a commuting satellite account framework with an example from Lisbon Metropolitan Area. *Econ Syst Res* 2018;30(1):105–19.
- [327] Ferreira J-P, Ramos P, Cruz L, Barata E. Modeling commuting patterns in a multi-regional input-output framework: impacts of an ‘urban re-centralization’ scenario. *J Geogr Syst* 2017;19(4):301–17.
- [328] Ciscel DH. The economics of urban sprawl: inefficiency as a core feature of metropolitan growth. *J Econ Issues* 2001;35(2):405–13.
- [329] Cervero R. Mixed land-uses and commuting: evidence from the American housing survey. *Transp Res A* 1996;30(5):361–77.
- [330] Golob TF, Hensher DA. Greenhouse gas emissions and Australian commuters’ attitudes and behavior concerning abatement policies and personal involvement. *Transp Res -D* 1998;3(1):1–18.
- [331] Ewing R, Pendall R, Chen D. Measuring sprawl and its transportation impacts. *Transp Res Res* 2003;1831:175–83.
- [332] Kahneman D, Krueger AB. Developments in the measurement of subjective well-being. *J Econ Perspect* 2006;20(1):3–24.
- [333] Stutzer A, Frey BS. Stress that doesn’t pay: the commuting paradox. *Scand J Econ* 2008;110(2):339–66.
- [334] Jim CY, Lo AY, Byrne JA. Charting the green and climate-adaptive city. *Landsc Urban Plan* 2015;138:51–3.
- [335] UN. Transforming our world: the 2030 Agenda for Sustainable Development; 2015.
- [336] Ewing G, Sarigöllü E. Assessing consumer preferences for clean-fuel vehicles: a discrete choice experiment. *J Public Policy Mark* 2000;19(1):106–18.
- [337] Hidruc MK, Parsons GR, Kempton W, Gardner MP. Willingness to pay for electric vehicles and their attributes. *Resour Energy Econ* 2011;33(3):686–705.
- [338] Hevelston JP, Liu Y, Feit EM, Fuchs E, Klampf E, Michalek JJ. Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China. *Transp Res A Pol* 2015;73:96–112.
- [339] Diamond D. The impact of government incentives for hybrid-electric vehicles: evidence from US states. *Energy Pol* 2009;37(3):972–83.
- [340] Bhat CR, Sen S, Eluru N. The impact of demographics, built environment attributes, vehicle characteristics, and gasoline prices on household vehicle holdings and use. *Transp Res Part B: Methodol* 2009;43(1):1–18.
- [341] Borthwick S. Persuading Scottish drivers to buy low emission cars? The potential role of green taxation measures. In: *Proceedings of the 8th annual Scottish transport applications and research conference in transport research institute, Edinburgh Napier university*; 2012.
- [342] Sierczula W, Bakker S, Maat K, van Wee B. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. *Energy Pol* 2014;68:183–94.
- [343] Whitehead J, Franklin JP, Washington S. The impact of a congestion pricing exemption on the demand for new energy efficient vehicles in Stockholm. *Transp Res A Pol* 2014;70:24–40.
- [344] Mabit SL, Fosgerau M. Demand for alternative-fuel vehicles when registration taxes are high. *Transp Res D-Tr E* 2011;16(3):225–31.
- [345] Gallagher KS, Muehlegger EJ. Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology. *J Environ Econ Manag* 2011;61(1):1–15.
- [346] Riggieri A. The impact of hybrid electric vehicles on demand and the determinants of hybrid-vehicle adoption [Ph.D. thesis]. Atlanta, GA, EUA: School of Public Policy, Georgia Institute of Technology, Georgia Institute of Technology; 2011.
- [347] Potoglou D, Kanaroglou PS. Household demand and willingness to pay for clean vehicles. *Transp Res D-Tr E* 2007;12(4):264–74.
- [348] Novemsky N, Dhar R, Schwarz N, Simonson I. Preference fluency in choice. *J Mark Res* 2007;44(3):347–56.
- [349] Gärling A, Thøgersen J. Marketing of electric vehicles. *Bus Strategy Environ* 2001;10(1):53–65.
- [350] Steiner M, Helm R, Szelig A. Preference measurement and unacceptable attribute levels. University of Regensburg Working Papers in Business, Economics and Management Information Systems; 2011.
- [351] Zhang T, Gensler S, Garcia R. A study of the diffusion of alternative fuel vehicles: an agent-based modeling approach. *J Product Innov Manag* 2011;28(2):152–68.
- [352] Kurani KS, Turrentine T, Sperling D. Testing electric vehicle demand in hybrid households using a reflexive survey. *Transp Res D-Tr E* 1996;1(2):131–50.
- [353] Beggs S, Cardell S, Hausman J. Assessing the potential demand for electric cars. *J Econ* 1981;17(1):1–19.
- [354] Bunch DS, Bradley M, Golob TF, Kitamura R, Occhiuzzo GP. Demand for clean-fuel vehicles in California: a discrete-choice stated preference pilot project. *Transp Res A Pol* 1993;27(3):237–53.
- [355] Segal R. Forecasting the market for electric vehicles in California using conjoint analysis. *Energy J* 1995;16(3):89–111.
- [356] Brownstone D, Bunch DS, Golob TF, Ren W. A transactions choice model for forecasting demand for alternative-fuel vehicles. *Res Transp Econ* 1996;4:87–129.
- [357] Chéron E, Zins M. Electric vehicle purchasing intentions: the concern over battery charge duration. *Transp Res A Pol* 1997;31(3):235–43.
- [358] Eggers F, Eggers F. Where have all the flowers gone? Forecasting green trends in the automobile industry with a choice-based conjoint adoption model. *Technol Forecast Soc* 2011;78(1):51–62.
- [359] Ziegler A. Individual characteristics and stated preferences for alternative energy sources and propulsion technologies in vehicles: a discrete choice analysis for Germany. *Transp Res A Pol* 2012;46(8):1372–85.
- [360] Axsen J, Orlebar C, Skippon S. Social influence and consumer preference formation for pro-environmental technology: the case of a U.K. workplace electric-

- vehicle study. *Ecol Econ* 2013;95:96–107.
- [361] Jensen AF, Cherchi E, Mabit SL. On the stability of preferences and attitudes before and after experiencing an electric vehicle. *Transp Res D-Tr E* 2013;25:24–32.
- [362] Hackbarth A, Madlener R. Willingness-to-pay for alternative fuel vehicle characteristics: a stated choice study for Germany. *Transp Res A-Pol* 2016;85:89–111.
- [363] Nissan. The Future of Electric vehicles in South East Asia. Position paper. Frost & Sullivan.
- [364] Kudoh Y, Motose R. Changes of Japanese consumer preference for electric vehicles. *World Electr Veh J* 2010;4:880–9.
- [365] Shin J, Bhat CR, You D, Garikapati VM, Pendyala RM. Consumer preferences and willingness to pay for advanced vehicle technology options and fuel types. *Transp Res C-Emerg* 2015;60:511–24.
- [366] Ko W, Hahn T-K. Analysis of consumer preferences for electric vehicles. *IEEE Trans Smart Grid* 2013;4(1):437–42.
- [367] Electric vehicles initiative (EVI). Clean Energy Ministerial; 2016.
- [368] Zhang Y, Yu Y, Zou B. Analyzing public awareness and acceptance of alternative fuel vehicles in China: the case of EV. *Energy Pol* 2011;39(11):7015–24.
- [369] Daziano R, Chiew E. Electric vehicles rising from the dead: data needs for forecasting consumer response toward sustainable energy sources in personal transportation. *Energy Pol* 2012;51:876–94.
- [370] Struben J, Stermann JD. Transition challenges for alternative fuel vehicle and transportation systems. *Environ Plan B* 2008;35(6):1070–97.
- [371] Egbue O, Long S. Barriers to widespread adoption of electric vehicles: an analysis of consumer attitudes and perceptions. *Energy Pol* 2012;48:717–29.
- [372] Lieven T. Policy measures to promote electric mobility – A global perspective. *Transp Res A-Pol* 2015;82:78–93.
- [373] Zhang Y, Qian Z(S, Sprei F, Li B. The impact of car specifications, prices and incentives for battery electric vehicles in Norway: choices of heterogeneous consumers. *Transp Res C-Emerg* 2016;69:386–401.
- [374] Mau P, Eyzaguirre J, Jaccard M, Collins-Dodd C, Tiedemann K. The ‘neighbor effect’: simulating dynamics in consumer preferences for new vehicle technologies. *Ecol Econ* 2008;68(1–2):504–16.
- [375] Axsen J, Mountain DC, Jaccard M. Combining stated and revealed choice research to simulate the neighbor effect: the case of hybrid-electric vehicles. *Resour Energy Econ* 2009;31(3):221–38.
- [376] Meeran S, Jahanbin S, Goodwin P, Neto JQF. When do changes in consumer preferences make forecasts from choice-based conjoint models unreliable? *Eur J Oper Res* 2017;258(2):512–24.
- [377] Maness M, Cirillo C. Measuring future vehicle preferences: stated preference survey approach with dynamic attributes and multiyear time frame. *Transp Res Rec* 2012;2285:100–9.
- [378] Hawkins TR, Gausen OM, Strømman AH. Environmental impacts of hybrid and electric vehicles – a review. *Int J Life Cycle Assess* 2012;17(8):997–1014.
- [379] MacPherson ND, Keoleian GA, Kelly JC. Fuel economy and greenhouse gas emissions labeling for plug-in hybrid vehicles from a life cycle perspective. *J Ind Ecol* 2012;16(5):761–73.
- [380] Nordelöf A, Tillman A-M, Messagie M, Mierlo J. Less or different environmental impact? In: Sanden B, Wallgren P, editors. *Systems perspectives in electric mobility*. Göteborg: Chalmers University of Technology; 2014. p. 60–75.
- [381] Batista T, Freire F, Silva CM. Vehicle environmental rating methodologies: overview and application to light-duty vehicles. *Renew Sustain Energy Rev* 2015;45:192–206.
- [382] Guinée JB. Handbook on life cycle assessment. Operational guide to the ISO standards. Netherlands: Springer; 2002.
- [383] Nordelöf A, Messagie M, Tillman A-M, Söderman ML, Van Mierlo J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles – what can we learn from life cycle assessment? *Int J Life Cycle Assess* 2014;19(11):1866–90.
- [384] Noshadran A, Cheah L, Roth R, Freire F, Dias L, Gregory J. Stochastic comparative assessment of life-cycle greenhouse gas emissions from conventional and electric vehicles. *Int J Life Cycle Assess* 2015;20(6):854–64.
- [385] Girardi P, Gargiulo A, Brambilla PC. A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. *Int J Life Cycle Assess* 2015;20(8):1127–42.
- [386] Garcia R, Gregory J, Freire F. Dynamic fleet-based life-cycle greenhouse gas assessment of the introduction of electric vehicles in the Portuguese light-duty fleet. *Int J Life Cycle Assess* 2015;20(9):1287–99.
- [387] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. *J Ind Ecol* 2013;17(1):53–64.
- [388] Samaras C, Meisterling K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. *Environ Sci Technol* 2008;42(9):3170–6.
- [389] Yang C. A framework for allocating greenhouse gas emissions from electricity generation to plug-in electric vehicle charging. *Energy Pol* 2013;60:722–32.
- [390] Garcia R, Freire F. Marginal life-cycle greenhouse gas emissions of electricity generation in Portugal and implications for electric vehicles. *Resources* 2016;5(4):41.
- [391] Doucette RT, McCulloch MD. Modeling the CO<sub>2</sub> emissions from battery electric vehicles given the power generation mixes of different countries. *Energy Pol* 2011;39(2):803–11.
- [392] Tamayao M-AM, Michalek JJ, Hendrickson C, Azevedo IML. Regional variability and uncertainty of electric vehicle life cycle CO<sub>2</sub> emissions across the United States. *Environ Sci Technol* 2015;49(14):8844–55.
- [393] Wu Y, Yang Z, Lin B, Liu H, Wang R, Zhou B, et al. Energy consumption and CO<sub>2</sub> emission impacts of vehicle electrification in three developed regions of China. *Energy Pol* 2012;48:537–50.
- [394] Faria R, Marques P, Moura P, Freire F, Delgado J, de Almeida AT. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renew Sustain Energy Rev* 2013;24:271–87.
- [395] Soimakallio S, Kiviluoma J, Saikku L. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – a methodological review. *Energy* 2011;36(12):6705–13.
- [396] Rangaraju S, De Vroey L, Messagie M, Mertens J, Van Mierlo J. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: a Belgian case study. *Appl Energy* 2015;148:496–505.
- [397] Hoehne CG, Chester MV. Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions. *Energy* 2016;115:646–57.
- [398] Hedegaard K, Ravn H, Juul N, Meibom P. Effects of electric vehicles on power systems in Northern Europe. *Energy* 2012;48(1):356–68.
- [399] Tarroja B, Eichman JD, Zhang L, Brown TM, Samuelsen S. The effectiveness of plug-in hybrid electric vehicles and renewable power in support of holistic environmental goals: part 1 – evaluation of aggregate energy and greenhouse gas performance. *J Power Sources* 2014;257:461–70.
- [400] Dallinger D, Gerda S, Wietschel M. Integration of intermittent renewable power supply using grid-connected vehicles – a 2030 case study for California and Germany. *Appl Energy* 2013;104:666–82.
- [401] Camus C, Farias T, Esteves J. Potential impacts assessment of plug-in electric vehicles on the Portuguese energy market. *Energy Pol* 2011;39(10):5883–97.
- [402] McCarthy R, Yang C. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: impacts on vehicle greenhouse gas emissions. *J Power Sources* 2010;195(7):2099–109.
- [403] Pina A, Baptista P, Silva C, Ferrão P. Energy reduction potential from the shift to electric vehicles: the Flores island case study. *Energy Pol* 2014;67:37–47.
- [404] Garcia R, Freire F, Clift R. Effects on greenhouse gas emissions of introducing electric vehicles into an electricity system with large storage capacity. *J Ind Ecol* 2018;22(2):288–99.
- [405] Yuksel T, Tamayao M-AM, Hendrickson C, Azevedo IML, Michalek JJ. Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States. *Environ Res Lett* 2016;11(4):1–13.
- [406] Yuksel T, Michalek JJ. Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States. *Environ Sci Technol* 2015;49(6):3974–80.
- [407] Archsmith J, Kendall A, Rapson D. From cradle to junkyard: assessing the life cycle greenhouse gas benefits of electric vehicles. *Res Transp Econ* 2015;52:72–90.
- [408] Correia GN, Batista TP, Marques SS, Silva CM. How car material life-cycle emissions are considered in environmental rating methodologies? Suggestion of expedite models and discussion. *Renew Sustain Energy Rev* 2014;38:20–35.
- [409] Li B, Gao X, Li J, Yuan C. Life cycle environmental impact of high-capacity lithium ion battery with silicon nanowires anode for electric vehicles. *Environ Sci Technol* 2014;48(5):3047–55.
- [410] Peters J, Buchholz D, Passerini S, Weil M. Life cycle assessment of sodium-ion batteries. *Energy Environ Sci* 2016;9:1744–51.
- [411] Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, et al. Contribution of lithium-ion batteries to the environmental impact of electric vehicles. *Environ Sci Technol* 2010;44(17):6550–6.
- [412] Majeau-Bettez G, Hawkins TR, Strømman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ Sci Technol* 2011;45(10):4548–54.
- [413] Ellingsen LA-W, Majeau-Bettez G, Singh B, Srivastava AK, Valøen LO, Strømman AH. Life cycle assessment of a lithium-ion battery vehicle pack. *J Ind Ecol* 2014;18(1):113–24.
- [414] Zackrisson M, Avellán L, Orlenius J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *J Clean Prod* 2010;18(15):1519–29.
- [415] Marques P, Garcia R, Kulay L, Freire F. Life-cycle assessment of electric vehicle batteries – LiMn2O<sub>4</sub> versus LiFePO<sub>4</sub>. in: *Energy for Sustainability 2015 – designing for People and the Planet*; 2015.
- [416] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renew Sustain Energy Rev* 2017;67:491–506.
- [417] Miller SA, Keoleian GA. Framework for analyzing transformative technologies in life cycle assessment. *Environ Sci Technol* 2015;49(5):3067–75.
- [418] Söderman ML, Kushnir D, Sandén B. Will metal scarcity limit the use of electric vehicles? In: Sandén B, Wallgren P, editors. *Systems perspectives in electric mobility*. Göteborg: Chalmers University of Technology; 2014. p. 76–89.
- [419] Faria R, Marques P, Garcia R, Moura P, Freire F, Delgado J, et al. Primary and secondary use of electric mobility batteries from a life cycle perspective. *J Power Sources* 2014;262:169–77.
- [420] Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int J Life Cycle Assess* 2017;22(1):111–24.
- [421] Richa K, Babbitt CW, Nenadic NG, Gaustad G. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int J Life Cycle Assess* 2017;22(1):66–81.
- [422] Frischknecht R, Flury K. Life cycle assessment of electric mobility: answers and challenges-Zurich [April 6, 2011]. *Int J Life Cycle Assess* 2011;16(7):691–5.
- [423] Garcia R, Freire F. A review of fleet-based life-cycle approaches focusing on energy and environmental impacts of vehicles. *Renew Sustain Energy Rev* 2017;79:935–45.
- [424] Garcia R. Dynamic fleet-based life-cycle assessment: addressing environmental consequences of the introduction of electric vehicles in Portugal [Ph.D. thesis].

- Coimbra, Portugal: University of Coimbra; 2016.
- [425] Vivanco DF, Freire-González J, Kemp R, van der Voet E. The remarkable environmental rebound effect of electric cars: a microeconomic approach. *Environ Sci Technol* 2014;48(20):12063–72.
- [426] United Nations. Report of the world commission on environment and development: our common future; 1987.
- [427] Daly HE. Ecological economics and sustainable development, selected essays of Herman Daly. Edward Elgar Publishing; 2007.
- [428] Smolker R, Tokar B, Petermann A, Hernandez E, Thomas J. The real cost of agrofuels: impacts on food, forests, peoples and the climate; 2008.
- [429] Chisti Y. Biodiesel from microalgae. *Biotechnol Adv* 2007;25(3):294–306.
- [430] Brennan L, Owende P. Biofuels from microalgae – A review of technologies for production, processing, and extractions of biofuels and co-products. *Renew Sustain Energy Rev* 2010;14(2):557–77.
- [431] Sheehan J, Dunahay T, Benemann J, Roessler P. A look back at the U.S. Department of Energy's Aquatic Species program: biodiesel from algae. Golden, Colorado, USA: National Renewable Energy Laboratory; 1998.
- [432] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Golden, Colorado (USA): National Renewable Energy Laboratory; 2002.
- [433] <http://www.oil-price.net/> [Accessed July 2017].
- [434] Ribeiro LA, da Silva PP, Ribeiro L, Dotti FL. Modelling the impacts of policies on advanced biofuel feedstocks diffusion. *J Clean Prod* 2017;142:2471–9.
- [435] Malça J, Freire F. Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): assessing the implications of allocation. *Energy* 2006;31(15):3362–80.
- [436] Raymer AKP. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass-Bioenergy* 2006;30(7):605–17.
- [437] Castanheira EG, Freire F. Environmental life cycle assessment of biodiesel produced with palm oil from Colombia. *Int J Life Cycle Assess* 2017;22(4):587–600.
- [438] Tonini D, Hamelin L, Astrup TF. Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. *GCB Bioenergy* 2016;8(4):690–706.
- [439] Castanheira EG, Grisoli R, Coelho S, da Silva GA, Freire F. Life-cycle assessment of soybean-based biodiesel in Europe: comparing grain, oil and biodiesel import from Brazil. *J Clean Prod* 2015;102:188–201.
- [440] Correa DF, Beyer HL, Possingham HP, Thomas-Hall SR, Schenk PM. Biodiversity impacts of bioenergy production: microalgae vs. first generation biofuels. *Renew Sustain Energy Rev* 2017;74:1131–46.
- [441] Mathioudakis V, Gerbens-Leenes PW, Van der Meer TH, Hoekstra AY. The water footprint of second-generation bioenergy: a comparison of biomass feedstocks and conversion techniques. *J Clean Prod* 2017;148:571–82.
- [442] Caldeira C, Quinteiro P, Castanheira EG, Boulay A-M, Dias AC, Arroja L, et al. Water footprint profile of virgin and waste cooking oils: assessing freshwater degradation and comparing the WSI and the AWARE methods to address scarcity impacts. In: Proceedings of the SETAC Europe 22nd LCA case study symposium, September 20–22 Montpellier, France; 2016.
- [443] Elghali L, Clift R, Sinclair P, Panoutsou C, Bauen A. Developing a sustainability framework for the assessment of bioenergy systems. *Energy Pol* 2007;35(12):6075–83.
- [444] Dauber J, Bolte A. Bioenergy: challenge or support for the conservation of biodiversity? *GCB Bioenergy* 2014;6(3):180–2.
- [445] Castanheira EG, Acevedo H, Freire F. Greenhouse gas intensity of palm oil produced in Colombia addressing alternative land use change and fertilization scenarios. *Appl Energy* 2014;114:958–67.
- [446] Castanheira EG, Freire F. Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems. *J Clean Prod* 2013;54:49–60.
- [447] Brandão M, i Canals LM, Clift R. Soil organic carbon changes in the cultivation of energy crops: implications for GHG balances and soil quality for use in LCA. *Biomass Bioenergy* 2011;35(6):2323–36.
- [448] Harris ZM, Spake R, Taylor G. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. *Biomass Bioenergy* 2015;82:27–39.
- [449] Sala OE, et al. Biodiversity across Scenarios [In: Ecosystem services and Human well-being: Scenarios]. *Millenn Ecosyst Assess* 2005:375–408.
- [450] National Academy of Engineering and National Research Council. The power of renewables: opportunities and challenges for China and the United States. Washington, DC: The National Academies; 2010.
- [451] Malça J, Marques P, Serrano L, Castanheira E, Garcia R, Freire F. Comparative well-to-wheels assessment of biodiesel and fossil diesel for heavy duty transport in Latin America. In: Proceedings of the CEM2016 – Mechanical Engineering Conference; 2016.
- [452] World Bank. How global biofuel expansion could affect the economy, environment and food supply; 2011.
- [453] Schoneveld G, German L, Nutakor E. Towards sustainable biofuel development: Assessing the local impacts of large-scale foreign land acquisitions in Ghana; 2010.
- [454] German L, Schoneveld G. Social sustainability of EU-approved voluntary schemes for biofuels. Implications for rural livelihoods. Bogor, Indonesia: Center for international forestry research; 2011.
- [455] Obidzinski K, Andriani R, Komarudi H, Andrianto A. Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecol Soc* 2012;17(1):25.
- [456] Luz VG, Filho HRC, da Silva AJN, de Laat EF, de Gouveia Vilela RA, da Silva FOC, et al. Migrant labor and wear-out in manual sugarcane harvesting in São Paulo, Brazil. *Ciência Saúde Coletiva* 2012;17(10):2831–40.
- [457] Du C, Kulay L, Cavalett O, Dias L, Freire F. Life cycle assessment addressing health effects of particulate matter of mechanical versus manual sugarcane harvesting in Brazil. *Int J Life Cycle Assess* 2018;23(4):787–99.
- [458] Duarte CG, Gaudreau K, Gibson RB, Malheiros TF. Sustainability assessment of sugarcane-ethanol production in Brazil: a case study of a sugarcane mill in São Paulo state. *Ecol Indic* 2013;30:119–29.
- [459] Machado PG, Walter A, Picoli MC, João CG. Potential impacts on local quality of life due to sugarcane expansion: a case study based on panel data analysis. *Environ Dev Sustain* 2017;19(5):2069–92.
- [460] Domac J. Bioenergy and job generation. *Unasylva* 2002;53(211):18–9.
- [461] Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life cycle assessment: past, present, and future. *Environ Sci Technol* 2011;45(1):90–6.
- [462] Swarr TE, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent AC, et al. Environmental life-cycle costing: a code of practice. *Int J Life Cycle Assess* 2011;16(5):389–91.
- [463] UNEP Setac Life Cycle Initiative. Guidelines for social life cycle assessment of products. United Nations Environment Programme (UNEP); 2009.
- [464] UNEP. Towards a life cycle sustainability assessment: making informed choices on products. United Nations Environment Programme (UNEP); 2011.
- [465] McManus MC, Taylor CM. The changing nature of life cycle assessment. *Biomass Bioenergy* 2015;82:13–26.
- [466] Manik Y, Leahy J, Halog A. Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. *Int J Life Cycle Assess* 2013;18(7):1386–92.
- [467] Macombe C, Leskinen P, Feschet P, Antikainen P. Social life cycle assessment of biodiesel production at three levels: a literature review and development needs. *J Clean Prod* 2013;52:205–16.
- [468] Ren J, Manzano A, Mazzi A, Zuliani F, Scipioni A. Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making. *Int J Life Cycle Assess* 2015;20(6):842–53.
- [469] Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. *J Clean Prod* 2017;140:399–409.
- [470] Malça J, Freire F. Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues. *Renew Sustain Energy Rev* 2011;15(1):338–51.
- [471] Caldeira C, Queirós J, Noshadravan A, Freire F. Incorporating uncertainty in the Life cycle assessment of biodiesel from waste cooking oil addressing different collection systems. *Resour Conserv Recycl* 2016;112:83–92.
- [472] Reale F, Cinelli M, Sala S. Towards a research agenda for the use of LCA in the impact assessment of policies. *Int J Life Cycle Assess* 2017;22(9):1477–81.
- [473] Kluts I, Wicke B, Leemans R, Faaij A. Sustainability constraints in determining European bioenergy potential: a review of existing studies and steps forward. *Renew Sustain Energy Rev* 2017;69:719–34.
- [474] Tsoukiás A. On the concept of decision aiding process: an operational perspective. *Ann Oper Res* 2007;154(1):3–27.
- [475] Filho WL, Wu Y-CJ, Brandli LL, Avila LV, Azeiteiro UM, Caeiro S, et al. Identifying and overcoming obstacles to the implementation of sustainable development at universities. *J Integr Environ Sci* 2017;14(1):93–108.
- [476] Soares N, Pereira LD, Ferreira J, Conceição P, da Silva PP. Energy efficiency of higher education buildings: a case study. *Int J Sustain High Educ* 2015;16(5):669–91.
- [477] Bernardo H, Martins A, Gaspar A. The role of building automation and commissioning in energy efficiency of existing buildings: A research approach based on energy management and control systems enhancement. In: Proceedings of the 11th REHVA World Congress and 8th international conference on indoor air quality, ventilation and energy conservation in buildings, CLIMA 2013.
- [478] Votteler MK, Martins AG. A sustainable development management system for the University of Coimbra. In: Leal Filho W, Azeiteiro UM, Caeiro S, Alves F, editors. Integrating sustainability thinking in science and engineering curricula. Innovative approaches, methods and tools. Springer International Publishing; 2015. p. 361–73.
- [479] Batterman SA, Martins AG, Antunes CH, Freire F, Gameiro da Silva M. Development and application of competencies for graduate programs in energy and sustainability. *J Prof Iss Eng Ed Pr* 2011;137(4):198–207.