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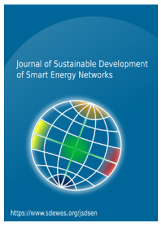

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Editorial

Smart Energy Networks: a pathway for the energy transition

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ABSTRACT

We are pleased to present the inaugural issue of the Journal of Sustainable Development of Smart Energy Networks, a platform dedicated to advancing research in energy systems powered by variable renewable energy sources. This highly interdisciplinary field is pivotal to the global transition toward a fully decarbonized energy paradigm. The development of smart energy networks requires the integration of diverse research disciplines, including energy engineering, control engineering, electrical engineering, environmental science, and social science. In this context, the Journal welcomes contributions that explore emerging technologies and their integration into innovative energy systems. A key challenge for future smart networks is the effective management of excess renewable energy production, which is essential for ensuring safe and robust system operation. Technologies such as Power-to-X (PtX), district heating and cooling systems, renewable energy communities, sector coupling, demand response strategies, the water-energy-food nexus, and advanced energy storage will play a central role in shaping these networks. Moreover, further efforts are needed to promote building energy efficiency, HVAC systems, renewable electrical and thermal technologies, hydrogen, fuel cells, and sustainable transportation systems. These technologies are critical to achieving decarbonization targets. The Journal also encourages contributions that examine circular economy principles and the social acceptability of smart energy networks, recognizing their importance in fostering sustainable and inclusive energy transitions. Through this Journal, we aim to cultivate a collaborative and forward-thinking research community dedicated to the sustainable development of next-generation energy networks.

KEYWORDS

Energy network, district heating and cooling, energy storage, renewables, buildings, energy efficiency.

INTRODUCTION

The global transition toward a fully decarbonized energy system is the key challenge for energy policymakers across most nations [1]. This urgent transition has been driven by the escalating impacts of climate change, primarily caused by anthropogenic greenhouse gas emissions. The persistent rise in Earth average temperature, coupled with increasingly frequent and severe climate-related events, underscores the necessity of moving away from the current fossil-fuel-dominated energy paradigm. The new model must be mandatory based on carbon neutrality, sustainability, and resilience [2, 3]. Achieving these goals requires a multifaceted approach, where the use renewable energy sources plays a pivotal role. Simultaneously, additional strategies must be also implemented to ensure a holistic and effective transition,

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including: energy efficiency, electrification of end-use sectors, and emission reduction technologies [4].

During the past few years, all the main players - academia, industry, and policymakers - have made substantial progress in developing innovative technologies and frameworks aimed at promoting sustainable development. These technologies include: smart grid systems, energy storage solutions, low-carbon transportation, and building retrofits. Despite these advancements, the rate of change remains insufficient, as recently shown by the International Renewable Energy Agency (IRENA) [5]. IRENA highlights several priority areas [6] that require accelerated action: expansion of renewable energy capacity; electrification of transport, heating, and industrial processes; development of high-efficiency technologies; use of heat pumps and district heating systems; development and scaling of hydrogen technologies [7].

Among these, the development of smart renewable energy networks stands out as a particularly underdeveloped yet potentially transformative solution [8]. This topic is widely investigated in the open literature, presenting a plurality of solutions to improve efficiency, stability and robustness of these novel energy networks. In particular, the integration of novel Artificial Intelligence (AI) techniques and the design of novel smart energy networks is one of the most popular topics. Alhasnawi et al. [9] recently presented a comprehensive review exploring the relationship between smart grids and smart cities, addressing applications, challenges, and future prospects. The urgent need to improve the efficiency of these grids is driven by the fact that around 75 % of worldwide energy consumption is due to the population living in cities. This paper emphasizes the role of AI, machine learning, IoT, and renewable integration in tackling the “energy trilemma” of sustainability, security, and affordability. The paper highlights gaps in research, such as cyber-physical security and AI-based energy management systems, and calls for integrated strategies to enhance resilience, optimize urban energy use, and ensure sustainable urban development. Modern AI techniques are also explored by Biswal et al. [6], analysing the impact of the use of machine learning and deep learning techniques for load forecasting in smart grids, compared to the conventional forecasting methods. This comparison shows that the new techniques come with a significant improvement in terms of assessment robustness also enhancing grid stability and achieving a more accurate load forecasting. This topic was also recently analyzed by Majidi et al.[10], presenting an extensive review of the available modeling tools, to be used in the analysis of smart energy networks, coupled with IoT and AI. It highlights the growing complexity of sector coupling, renewable variability, and distributed resources, emphasizing the need for adaptive, open-source, and multi-energy optimization frameworks. The study provides a comparative analysis, identifying strengths and limitations of tools for policy, planning, and operational decision-making in sustainable system transitions.

AI techniques demonstrated also extremely promising results in the management of the time shift between renewable power production (mainly wind and solar) and user demand. In particular, such techniques were successfully implemented by many researchers in the framework of demand response (DR) strategies, where users may significantly contribute to grid stability and peak shaving. Huang et al. [11] categorized DR into four types—Price-Based (PBDR), Incentive-Based (IBDR), Integrated (IDR), and Multi-Region (MRDR). This study also points out that DR often suffers for incomplete information, which maybe due to privacy constraints, communication failures, and data acquisition limitations. Here, some mitigation techniques - including regression methods, generative models (VAE, GAN), reinforcement learning (RL), and distributed algorithms (ADMM, MARL) – may be implemented to limit the effect of incomplete information. A similar study was presented by Akhila et al. [12], analysing the use DR in smart grids, focusing on its impact on cost optimization, pollution reduction, mobility integration, and grid resilience. The study also presents advanced optimization and machine learning techniques, and proposes a resilience-enhancing framework. Results show that DR can reduce peak loads by up to 59.9%, CO_2 emissions by 10.28%, and improve outage survivability metrics. DR is also widely used for the optimization of electric vehicles (EV) mobility [13], buildings loads [14], HVAC [15] and industrial loads [16]. All these studies underscore the transformative potential of DR in modern energy networks, emphasizing the crucial role of the novel digital technologies.

These novel digital technologies also showed huge potential in optimizing district heating and cooling (DHC) networks, used to deliver hot and chilled water to the users of a smart energy network. In this field, the most advanced technology is the 5th Generation DHC (5GDHC) which allows for bidirectional energy flows in the energy grids [17]. However, there is still an ongoing debate regarding the effective potential advantages of the 5GDHC vs the previous 4th generation DHC (4GDHC) [18], which is specifically designed for the integration with renewables and for maximizing the use of waste energy [19]. Zhou et al. [20] analyzed the use of machine learning techniques to optimize the operation of DHC networks, pointing out that advanced digital techniques are mainly used to optimize electrical systems, whereas their use for DHC is limited. They proposed a novel inter-city sharing energy system, using ML for energy planning and system optimization. Their approach showed important results in terms of demand prediction and energy dispatch. Nevertheless, some important challenges were identified in the availability of suitable energy storage systems and in the management of the energy congestion problem. A similar study was also conducted by Ahmed et al. [8] analyzing the use of ML for forecasting and optimizing purposes. This paper also outlines future research directions, including multi-agent systems, demand-side management, and resilient energy architectures for sustainable urban development. Lilliu et al. [21] present a systematic review of business and pricing models in DHC. This work identifies trends such as the dominance of heat pumps, hourly granularity, and mathematical optimization in model design. The paper highlights gaps in research, including the lack of models for district cooling, CHP systems, and non-European contexts. It calls for future work on machine learning-based models, peak shaving strategies, and multi-objective optimization to enhance flexibility, profitability, and environmental performance in DHC systems. In the framework of novel DHC networks, heat pumps (HP) are considered the most promising technology for providing space heating and cooling due to their ultra-high efficiency and to the possibility to be integrated with renewables and/or waste heat sources [22]. They can be powered by the electricity produced by renewables or even convert waste heat into cooling energy, for ultra-high conversion efficiency [23] and their effectiveness can be further increased by their integration with suitable thermal energy storage systems (TES) [24]. The use of HP is only one of the possible actions to be taken to reduce the building energy demand. The reduction of buildings energy consumption is one of the main goals of the future energy networks, also considering that buildings account for about 40 % of the overall energy consumption. Many actions can be implemented to this goal: improvement of buildings envelope [25–27], use of renewables [28], optimization of HVAC systems [29], use of optimized control systems, etc [30]. In this framework, in many EU Countries, the target to achieve net zero energy buildings [31] must be mandatorily achieved in case of new buildings or major refurbishment of existing buildings, whereas specific funding policies have been proposed for existing buildings [32, 33].

The topic of energy storage is probably the most challenging one in the framework of novel smart energy networks. These future energy systems will be featured by unpredictable renewable energy sources (mainly wind and solar) and by extremely variable user energy load demands. In addition, the novel smart energy networks will be featured by bidirectional energy flows where the conventional players (producers and consumers) are replaced by a novel one, the so called prosumers, who might both inject or withdraw energy to/from the grid, depending on the time dependent energy balance [34–36]. In this framework, the development of novel, efficient, robust and reliable energy storage systems is crucial to achieve a safe operation of the grid, operating under bidirectional energy flows. This is particularly critical in case of electrical networks, where power quality, voltage stability and frequency stabilization are crucial issues [37]. In particular, it is well known that the storage of electricity is much more complex and challenging than the thermal energy storage [38]. Thermal energy storage is commonly realized using sensible heat [39, 40], by varying the temperature of a fluid. However, to reduce the size of these storages [41], phase change materials (PCM) can be also used [42], whereas the use of reversible chemical processes is rare [43–45]. The most common electrical storage technology is based on the use of conventional electrochemical batteries [46]. Li-ion batteries offer the best performance in terms of energy density, response time and adaptability. Emerging technologies, such as vanadium redox flow batteries and sodium-sulfur batteries, are also available but they are far from a mature commercialization [47]. Electrochemical batteries are the reference technology for electrical storage for low-medium scale cases. However, their application for large scale (e.g. grid-scale) problems seems to be unfeasible. For grid-scale electrical storage several other technologies are under investigation. Gronman et al. [48] recently provided a comprehensive classification of these alternative technologies:

- Gravity based systems: during the charge phase, some weight is lifted to higher elevations, whereas during the discharge phase its potential gravitational energy is converted to electricity.
- Compression/expansion: during the charging phase a certain fluid (e.g. air or carbon dioxide) is compressed and stored in a vessel in gaseous or liquid form, whereas in the discharging phase the fluid is expanded to recover electricity [49].
- Power to power: during the charging phase the electricity is used to convert some fluid into a fuel (e.g. water is converted into hydrogen [50]via electrolysis[51]), in the discharging phase the fuel is used to produce electricity (e.g. by conventional engines or fuel cells) [51–56].
- Supercapacitors: devices featured by ultra fast response time, long life and small dimensions although presently unavailable for large capacities [57].
- Hydro-pumping: in charging mode water is pumped to a high-level basin, whereas in discharging mode it operates as a conventional hydro power plant [58–61].

Additional novel systems (flywheels [62, 63], thermochemical, magnetic) are presently under investigation but extremely far from a long-term demonstration [64].

As previously mentioned, the optimal management of the phase shift between renewable energy production and user demand represents a key challenge for the robust development of future smart renewable energy networks. This issue becomes significantly more complex when renewable energy production is fragmented across a multitude of small-scale systems [65]. In this context, several innovative regulatory and technical frameworks have recently emerged to encourage the use and sharing of renewable energy. The most prominent model is the renewable energy community, in which a group of prosumers can share their locally generated renewable energy [66]. This approach aims to minimize both the excess energy fed into the grid and the electricity drawn from it [67]. This result is crucial in the view of the ongoing expansion of the electrical system due to the increasing installation of renewable power plants. Using this approach, long-distance transmission can be significantly limited, facilitating the management of the transmission infrastructure[68]. This scheme is presently adopted by EU Countries as a result of a EU Renewable Energy Directive (CEP4), introducing the concept of Renewable Energy Community (REC). However, each national regulatory approach presents some specific features, showing also some severe gaps. According to Lopez et al. [69], the majority of EU energy communities are found in Germany. Denmark, Netherlands and UK also show a non-negligible number of REC (ranging from 400 to 700). For most of the remaining EU Countries, the number of running REC is very low (lower than 50). This relatively slow development of REC paradigm is due to the need to completely change the electricity system value chain structure and the corresponding business model. A number of technical and regulatory barriers need to be addressed to promote the development of REC paradigm. Simultaneously, social acceptability of novel REC is still an open issue, since the majority of the players involved (citizens, social entrepreneurs, public authorities, public utilities, etc) are not familiar with this scheme. In particular, citizen active participation (also including the development of a sense of community) has been identified as a key factor for the future success of REC [70]. Giannuzzo et al. [71] also pointed out that it is crucial to clearly identify the suitable Key Performance Indicators (KPI), to be used to evaluate the energy performance and the economic profitability of REC. In this study, authors clearly identified Energy, Economic, Environmental and Social KPI, also investigating their impact on the Sector Domain (stakeholders, policymakers, REC mem and REC). This multifaceted analysis allows one to capture the huge complexity of REC paradigm, also avoiding partial and restricted conclusions when considering only a specific aspect of REC. This point was also analyzed by Cavana et al. [72], presenting an extensive analysis of Italian REC. They found a lack of comparable data, with self-sufficiency ratios varying from 36 % to 84 %. They also emphasized that REC are driven only by economic aspects, whereas energy and environmental points of view are scarcely addressed, paying poor attention to possible energy saving measures or to the energy efficiency.

Another strategy that is commonly investigated to improve grid stability and resilience consists in the integration of electric vehicles (EV) storage capacity within the grid, in the framework of the so-called vehicle to grid (V2G) paradigm [57]. In particular, the excess renewable production is injected into the EV, up to their maximum allowed state of charge. Conversely, when renewable power production is lower than users demand, EV can discharge the stored electricity to the grid. This easy strategy may dramatically improve grid stability, allowing one to artificially increase the overall storage capacity. Many companies are presently investing in V2G technology. Abdolrasol et al. [73] analyzed more than 2000 patents from 2008 to 2025 in this field, also identifying real-world implementations (e.g., Ford, Nissan, Nuvve) to validate the commercial relevance of patented technologies. The paper underscores the importance of standardization, cybersecurity, and interdisciplinary collaboration for future V2G deployment. On the other hand, V2G has still to overcome severe barriers (grid overload, lack of standards, user behavior) to get a stable operation. To this scope, standardization is a crucial issue to obtain a safe and resilient operation [74]. Several studies also show that V2G may be significantly enhanced by the use of fuel cells [75] and AI technologies [76, 77].

Finally, it is also extremely important to point out that future energy networks must mandatorily consider the close relationship between energy and water, specially for remote communities like islands. It is commonly recognized that freshwater scarcity will become the most challenging issue during the next decades [78, 79]. Considering that the artificial production of freshwater requires huge amounts of energy, the integration of this process in energy networks is crucial for achieving a robust and resilient system. Several studies are available in the open literature, analyzing different aspects of the so called water-energy nexus (in some cases water-energy-food nexus or energy-food nexus), paying attention to the impacts on ecosystems, human health, and sustainability. Javan et al. [80] identified a loop (energy emissions, climate change, water scarcity) responsible for the water scarcity. Authors recommended integrated governance, AI-driven tools, and renewable energy adoption to address water issue. Unfortunately, a huge research effort must still be performed to quantify the water-energy-food nexus and to design the actions to optimize their integration. Li et al. [81] showed that the majority of the studies providing quantification of resource interactions in water-energy-food nexus dramatically suffers for data limitations, methodological misalignments, and geographic biases. Similar results are obtained by Bamgboye et al. [82]

AIM AND SCOPE

The Journal aims at establishing an open platform for the dissemination of research findings in the field of design of resilient and robust energy networks powered by variable renewable energy sources (wind, solar, etc). Novel paradigms, based on advanced and smart energy storage systems, demand-response strategies, and sector coupling, are crucial topics to be addressed. In this framework, the Journal is open to accept papers discussing the recent innovations regarding the technologies and strategies allowing one to improve grid balance. Here, Power-to-X (PtX) technologies play a relevant role in grid balancing, energy storage and the water-energy nexus. PtX technologies offer a pathway to convert excess renewable energy, which might otherwise be wasted, into storable and versatile forms such as hydrogen, synthetic fuels, heat, and water, thereby contributing to grid stability and increased system flexibility. Similarly, novel and advanced renewable technologies, suitable for their integration in the future energy networks, will be analysed and discussed to assess their future technical and economic feasibility. On the user side, the Journal is open to discuss all the technologies and strategies to reduce user energy consumption and to mitigate the phase shift between renewable production and user demand. Special attention will be paid to the user demands for space heating and cooling, analyzing in detail the possible technologies to be implemented to improve energy efficiency in buildings, such as: heat pumps, refurbishment of building envelope, the integration of electric heavy and light vehicles, etc.

The Journal welcomes papers dealing with topics related to renewable energy networks, including but not limited to:

- Dynamic simulations of energy systems
- Building dynamic simulation
- Energy efficiency in buildings
- HVAC systems
- 4th and 5th generation district heating and cooling networks
- Power-to-X Technologies and Applications
- Net-Zero Energy City
- Power-to-Water and Water-Energy nexus
- Vehicles to Grid
- Sector Coupling and Decarbonization
- Demand-Response Strategies
- Hydrogen and Fuel Cells
- Waste-to-Energy paradigm
- Sustainable Mobility: e-fuels, biofuels, and electric vehicles.
- Novel technologies for managing the excess of electric and thermal energy
- Innovative Renewable Energy Systems: Solar, wind, geothermal, biomass, hydropower, etc.
- Novel technologies for advanced electric and thermal energy storage
- Advanced control strategies for energy systems
- Renewable energy communities
- Biocircular economy approach

CONCLUSIONS

The development of resilient, robust, and efficient energy networks powered by variable renewable energy sources represents a key challenge in the transition toward a fully decarbonized energy scenario. A growing number of researchers are actively contributing to this field, developing innovative technologies aimed at enhancing the integration of renewable energy sources into existing energy infrastructures. Several promising innovations are already available, and many more are expected to emerge in the coming years. In this context, the Journal of Sustainable Development of Smart Energy Networks seeks to provide a dedicated platform for discussing recent advancements, analyzing cutting-edge technologies, and exploring their integration into novel energy systems. The Journal publishes high-quality research papers that present both numerical and experimental analyses of advanced technologies and systems. Authors are encouraged to address economic, social, and environmental dimensions, which are essential for enabling the widespread commercialization and adoption of these technologies. The Journal is supported by an outstanding editorial board composed of internationally recognized experts whose research and editorial expertise span the diverse disciplines involved in the development of smart and sustainable energy networks. A rigorous peer-review process will be ensured, and the Journal will follow an open-access publishing model to promote broad dissemination of research findings. Our goal is to attract high-quality contributions and establish the Journal as an internationally recognized platform for scholarly discussion in the field of renewable energy networks.

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