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Smart Grids: Impacts and Challenges on Energy Sector

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Abstract:

Digitalisation, driven by the transformative impact of digital technologies, has an important role in the energy transition process. Advancements in these technologies are bringing about significant changes in how energy is generated, transmitted, and utilised. In particular, digital technologies enable modern smart grids to optimize energy management by integrating renewable energy sources more effectively. In this context, the paper explores the effects of smart grids on the energy transition, emphasising their benefits and the key incentives that promote investment. Additionally, it reviews current trends in smart grid development across European countries, with a specific focus on Italy. The objective is to provide a comprehensive overview of the investments required to implement both existing and new smart grid projects.

Keywords: energy sector, transition energy, digitalisation, ICT, smart grids.

JEL Classification: O13, O33, P28, P48, Q43, Q55, Q56.

Introduction

The challenges posed by climate change, coupled with the escalating global energy demand, have intensified concerns related to energy efficiency and the rising levels of carbon emissions. These issues underscore the urgent need for a transition toward cleaner energy sources. In response, the European Union has addressed these challenges through the implementation of a comprehensive set of directives, namely the "Clean Energy for All Europeans Package." This legislative framework aims to enhance energy efficiency and building performance, promote the adoption of renewable energy sources, and optimize the design of the European electricity market (European Commission, 2019).

The necessity to reinforce and modernize power grids has become increasingly urgent, particularly in light of the rising electricity consumption, which is projected to continue growing substantially in the coming years (IEA, 2024). This trend has generated a pressing need not only to meet the expanding energy demand but also to identify more efficient methods of addressing it. It is essential to maintain a heightened awareness of the environmental and societal impacts associated with energy activities. Accordingly, power projects should integrate sustainability practices, such as waste minimization, carbon emission reductions, cost efficiency, and enhanced operational efficiency, while also increasing the contribution of renewable energy sources. The overarching goals include expanding energy access, ensuring affordability, reliability, and adequacy of energy supplies, and mitigating environmental impacts across all levels (Kabeyi & Olanrewaju, 2022).

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In light of that, the transition to clean energy necessitates a comprehensive transformation of power systems, encompassing all stages from generation to distribution and end-use. Within this framework, smart grids emerge as a pivotal tool, representing a transformative evolution of conventional power systems. According to the International Energy Agency (IEA), a smart grid is defined as "an electricity network that utilises digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids coordinate the needs and capabilities of all generators, grid operators, end users, and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience, flexibility, and stability" (https://www.iea.org/energy-system/electricity/smart-grids).

In the context of the energy transition, smart grids offer multiple advantages: they reduce power losses and optimize the use of variable loads and power sources; enhance the reliability, security, and stability of the energy supply; alleviate the burden on generation facilities, thereby improving efficiency and minimizing waste; facilitate the integration of renewable energy sources, leading to a reduction in fossil fuel emissions; and enable the transition from consumers to "prosumers," encouraging reduced consumption and increased generation. Overall, smart grids reduce waste and pollution while improving system efficiency. As such, smart grid technologies are well-positioned to address the challenges associated with energy transformation and sustainability, supporting the shift from traditional to smart energy systems (Kabeyi & Olanrewaju, 2023).

Given the role of smart grid projects in shaping the energy transition process, examining their current state, the future developments and their effects on the energy sector ap-pear relevant. In light of that, this study explores the role of smart grids in the energy market by addressing the following questions: (1) How does an intelligent energy system enhance efficiency and sustainability in energy storage? (2) What are the economic implications of the digital trend in the energy sector?

To answer these questions, the study first provides a review of existing studies focusing on smart grids within the broader context of the energy transition and sustainability. Moreover, it offers an overview of the economic impacts of energy storage technology with a focus on Smart Energy systems. By identifying a large number of smart grid projects implemented at the EU and Italy countries levels, the paper explores incentives provided by the governments to speed up the investment process in them. The study contributes to the existing literature in several ways. First, it explores the specific impacts of smart grids on the sustainable energy transition, emphasizing how smart grid technologies enhance the efficiency, security, and sustainability of energy supply, distribution, and utilisation. Second, it investigates the economic implications of grid infrastructure projects to the integration of renewable energies.

The remainder of the paper is organized as follows. Section 1 provides an overview of existing studies focusing smart grids technologies. Section 2 discusses the main impacts and challenges entailed by smart grid systems. Section 3 presents the state of the art of smart grid in-vestments both at the European and Italy levels. The last Section presents the conclusions and policy implications.

1. Literature Review

Smart grids represent a significant evolution in traditional power systems, integrating advanced technologies to enhance the efficiency, reliability, and sustainability of electricity distribution. A growing body of literature highlights both the key technologies and benefits of smart grids, as well as the challenges and barriers that must be addressed to ensure their effectiveness. The primary topics covered in the literature include smart grid technologies and features, cybersecurity and privacy, costs and investments, regulatory frameworks, renewable energy integration and sustainability, and the social dimension including consumer perceptions.

Moreno Escobar et al. (2021) provide a thorough review of smart grids, offering a survey of key aspects, technologies, protocols, and case studies on current and future trends. They develop a taxonomy of existing smart grid (SG) algorithms, emphasizing the integration of communication infrastructure as a critical challenge. The current infrastructure is insufficient to meet the demands of smart grids, and the state of electrical energy and control in the production system is identified as a key area for future research. The paper also outlines the main benefits of adopting SG technologies, including improved network monitoring, reduced service interruptions and customer impact, timely and reliable fault management, real-time network reconfiguration, and the introduction of new services and electricity flow control. Similarly, Tuballa & Abundo (2016) review fundamental smart grid technologies, demonstrating how these innovations have shaped the modern electricity grid and continue to enhance the alignment of energy demand and supply. They trace the emergence and evolution of the smart grid concept, high-lighting the limitations of traditional grids and the necessity for "smarter" technologies.

The technologies discussed include smart meters, which enable two-way communication between meters and utilities; smart appliances that communicate with electrical grids and adjust energy use autonomously; advanced electricity storage and peak-shaving technologies; and time synchronization and intelligent control devices that optimize energy scheduling and track load demand fluctuations. These technologies underscore the importance of a robust communication infrastructure that can support two-way information sharing and real-time data analysis. Moreover, Zhang et al. (2017) provide an overview of smart grid development, discussing re-search results from various countries and summarizing achievements and challenges. The lack of funding and financial barriers, often due to unclear standards, are identified as significant challenges. Instead, Surender (2020) highlights the lack of awareness and adoption of standards among stakeholders as a major issue in smart grid development.

Another stand of literature focuses on one of the primary challenges facing smart grid networks: cybersecurity. Khoei et al. (2022) provide a wide classification of cyber-attacks targeting smart grids and evaluate various security solutions. The requirement for continuous, detailed information on user consumption patterns increases the vulnerability of smart grids to cyber-attacks, leading to privacy and security concerns. The authors classify techniques for detecting cyber-attacks and suggest countermeasures to ensure grid security. Musleh et al. (2019) review various cyber-physical attacks, focusing on false data injection at-tacks, while other studies explore customer privacy issues related to smart grids. The US National Institute of Standards and Technology has noted that the real-time data collection from customers, a significant advantage of smart grids, also presents major privacy challenges. Kua et al. (2023) provide a comprehensive review of privacy-preserving techniques for smart grids developed over the past decade.

Moreover, other studies discuss smart grids' contributions to climate and sustainability goals, including the International Smart Grid Action Network (ISGAN) report (Nordling et al. 2018). Specifically, it notes that smart grid technologies not only directly contribute to these goals but also indirectly aid in reducing carbon emissions, improving energy efficiency, and increasing the use of renewable energy sources (RES). Judge et al. (2021) provide a comprehensive review of the impact of smart grids, particularly on the clean energy transition and the integration of RES. They note that while smart grids can significantly reduce CO2 emissions, the integration of RES presents challenges due to their unpredictability and variability, which can affect grid stability. Strategies such as energy storage are important for ensuring the flexibility of smart grids, as discussed by Lamnatou et al. (2021). Their review also examines the role of smart grids in promoting Zero Energy Buildings (ZEBs) and sustainable practices in the building sector, which contribute to environmental benefits such as CO2 reduction, energy savings, and more efficient energy use.

De Oliveira-De Jesus & Henggeler Antunes (2018) explore the economic benefits of smart grid technologies, such as reducing capital and operational expenditures for electric utilities. Bigerna et al. (2016) conduct a comprehensive literature review of 148 articles on smart grids, examining the socioeconomic aspects, including private (direct) monetary costs and social (in-direct) costs like consumer privacy, regulation, cybersecurity, and perception. Their findings suggest that the literature often focuses on private costs while overlooking social costs, which may impede smart grid deployment. Rohde and Hielscher (2021) consider the social dimension of smart grids, emphasizing that energy supply systems are highly institutionalized, with entrenched regulations, norms, and cultural patterns. Implementing smart grids requires changes to existing institutions and regulatory frameworks, as well as adjustments to policies and market mechanisms. Other studies, including Ellabban & Abu-Rub (2016), examine consumer perception, identifying challenges like privacy concerns and safety issues that may hinder consumer engagement and the broader transformation of the energy system. Eventually, Vogt Gwerder et al. (2019) examine how market and regulatory factors influence stakeholder investments in European smart grid projects.

Overall, although many smart grid technologies are available, they are not yet widely deployed. To advance implementation, governments and investors require decision support to evaluate smart grid investments. Weak incentives may slow deployment, with existing regulations often hindering investments. In this regard, the ISGAN discussion paper on the social costs and benefits of smart grid technologies highlights high initial costs and investments as a major obstacle to implementation. Specifically, the report suggests that incentive-based and output-based regulatory mechanisms are more effective than cost-based or rate-of-return regulation in promoting smart grid investments.

2. Integrating Renewable Energy with Smart Grids

In the context of the energy transition and sustainable development, smart grids play an important and strategic role, enhancing the efficiency, safety, and sustainability of energy supply, distribution, and consumption, particularly through the integration of renewable energy sources. Smart grids enable real-time, bidirectional monitoring and control of electricity flows and facilitate the coordination among generators, consumers, and prosumers, allowing energy distribution in an efficient, sustainable, and economically viable manner. They address several challenges associated with traditional grids, such as energy supply reliability, outage management, and high carbon emissions. However, smart grids also face challenges, including high initial costs, interoperability issues, infrastructure risks, cybersecurity concerns, and regulatory and institutional requirements (Kabeyi & Olanrewaju, 2023).

The impact of smart grids on the energy system is driven by the adoption of innovative and intelligent technologies that enable real-time monitoring and control of power, integrated communication, and self-healing capabilities. Compared to traditional grids, smart grids support bidirectional communication and data flow, feature distributed and centralized power generation, utilise interconnected networks with advanced sensors, and incorporate automated monitoring, control, and digital operations. The smart grid architecture integrates various systems and technologies:

- Supervisory Control and Data Acquisition System (SCADA): Facilitates real-time data collection, analysis, and control of power flows.
- Energy Management System: Enables real-time monitoring, analysis, and optimization of power generation, transmission, and distribution.
- Wide Area Monitoring System: Provides a comprehensive view of grid performance to monitor stability and detect disturbances in real-time.
- Distribution Automation: Uses automated devices and systems for managing and control-ling the distribution network.
- Substation Automation: Monitors and controls electrical substations, reducing downtime caused by equipment failures, accidents, or natural events.
- Smart Metering System: Involves smart meters that support two-way communication and demand response programs.
- Blockchain Technology Infrastructure: Offers a secure, transparent, and decentralized method for recording and sharing data.

These technologies facilitate efficient and economical connections between various power plant technologies and generator sizes, encourage consumer participation in system optimization, and provide valuable data and power supply choices, ultimately reducing the environ-mental impact of the entire power system and ensuring a safe, reliable, and secure electricity supply. The primary benefits of smart grid systems include:

- Smart grids improve the utility and control of distribution system equipment, leading to greater power system stability and security (Conejo et al., 2010).
- Self-Healing Capabilities: These reduce maintenance costs through automatic reporting and tracking, which is more efficient and less costly than manual or physical inspections (Kabeyi & Olanrewaju., 2023).
- Smart grids transform traditional unidirectional grids into bidirectional systems, enabling two-way flows of information and power. This transition empowers consumers to become prosumers, with smart meters recording real-time energy data and communicating it to both consumers and suppliers. This enhances system reliability and stability by allowing active consumer participation, enabling accurate planning, and creating a more efficient and cost-effective energy system. Additionally, it provides revenue opportunities for consumers and encourages energy conservation and generation (Kabeyi & Olanrewaju, 2023).
- Smart grids optimize power generation costs and enhance consumer utility through real-time pricing technologies. Peak load shaving increases grid flexibility by shifting loads from peak to off-peak periods, reducing power losses, transmission oscillations, overloads, and blackouts by facilitating energy savings, automatic load management, and electricity rerouting.
- Smart grids integrate decentralized power generation using various local energy sources to meet regional electricity demand. The incorporation of renewable resources aligns with the goals of the energy transition by reducing fossil fuel emissions.

Smart grid systems address numerous challenges in power generation, transmission, distribution, and system control by providing the necessary capacity and infrastructure to enable efficient use of renewable energy and variable loads while ensuring stable and reliable power supply with minimal reliance on fossil fuels. The main impacts of smart grids include improved energy efficiency, reduced electricity waste, and the integration of renewable energy, leading to lower emissions.

Regarding energy efficiency, smart grids promote efficient energy use through innovative technologies. Fault and loss detection, along with self-healing capabilities, allow for rapid power restoration and prevent outages. Mechanisms like peak load shaving encourage more flexible and efficient energy use, avoiding unnecessary consumption. The bidirectional communication and power flow in smart grids enable customer engagement and interaction with the grid, while decentralized generation fosters the use of local and alternative energy sources, reducing transmission and distribution losses.

In terms of renewable energy, the integration of renewable sources into the grid is a critical pathway to sustainable development. Smart grid technologies enhance the integration of renewable energy, increasing the capacity of grid-connected clean energy sources like solar, wind, and photovoltaic systems (Zhuangli et al., 2014). Through these capabilities, smart grids pave the way for sustainable electricity generation and supply. They contribute to reducing carbon emissions by incorporating more renewable energy sources, such as wind, solar, and hydro-power, and by decreasing greenhouse gas emissions through more efficient resource use. Smart grids coordinate the needs of power plants, consumers, and other stakeholders to maximize efficiency, minimize costs, control environmental impacts, and ensure system reliability, stability, and resilience.

3. Challenges of Smart Energy Systems

Renewable energy systems require different solutions to integrate high shares of non-programmable generation. The several strategies, as well as the amount of renewable energy systems needed, are interdependent and should be analysed following a holistic vision. This concept is identified in literature with the Smart Energy Systems (SES, hereafter) approach, used to overcome the single-sector approach in favour of a holistic and integrated one. Indeed, the best strategies for improving a single sector can be identified only by considering the potential interconnections between different sectors (Pastore et al., 2022). An intelligent energy system as such should pursue not only the purpose of efficiency and safety but also sustainability. It is a primary value, which has environmental, economic, and social features. Reducing the impact on the environment is fundamental and the energy transition should aim at this objective: quickly decreasing climate-altering emissions, since a further increase in global temperature might cause harmful effects on the planet (Afgan, 2010).

In light of that, the energy transition should be aimed at an infrastructural change at the center of which smart grids there are.

Smart grids allow to balance the supply and demand of energy by reducing the electricity cost and improving the power grid's reliability. Moreover, these technologies are useful to optimize the use of energy during peak demand times and to predict changes in power demand. Then, based on this information the distribution of energy is adjusted to meet the needs of customers (Nazari & Musilek, 2023). Thus, the power grid has an important role to play by al-lowing a cleaner energy integration across the economy and by making the power supply reliable and secure even under worsened environmental conditions. Conolly et al. (2013) define the Smart Energy System as an energy system based on new technologies and infrastructures that create new forms of flexibility, especially in the conversion phase of the energy system. In other words, it is a combination of the different sectors (energy, thermal, and transport) that appears relevant to compensate for the lack of flexibility of renewable resources including wind and so-lar. Specifically, the authors highlight that the SES are built around three network infrastructures:

- Smart Electricity Grids: electrical infrastructures capable of intelligently integrating flexible electricity demands namely heat pumps and electric vehicles, to efficiently provide sustain-able, economical, and safe electricity supplies such as wind and solar energy;
- Intelligent thermal networks (Smart Thermal Grids): this is a network of pipes that connect the buildings of a neighbourhood, a town, or an entire city, to provide electricity and heating efficiently, for example through the construction of centralized systems;
- Smart Gas Grids which integrate electricity, heating, and transport, to efficiently provide sustainable, economical, and safe gas supply and storage.

Timely development of grid infrastructure is relevant to the EU recovery and the integration of renewable energies, including the respective potential for job and value development (Prettico et al., 2022). Many projects are funded by the Competitiveness and Innovation Framework Programs (CIP) namely the Information and Communication Technology Policy Support Pro-gramme (CIP-ICT-PSP) and the Competitiveness and Innovation Framework Programme – Intelligent Energy Europe program (CIP-IEE). These are two funding programs which ran from 2007 to 2013 with an overall budget of EUR 3 621 million. The former aims at wider uptake and best use of ICT and digital content by citizens, governments, and businesses, especially small and medium-sized enterprises (SMEs). The second one promotes efficiency and rational use of energy resources by incentivizing the use of renewable sources and providing incentives for the implementation of the latter in different sectors, including transport. Other programs namely FP7 and H2020 contribute to a strong increase (79%) in the Smart Grids projects, showing the growing importance of this field in the transition energy process towards a more secure, sustainable, and inclusive system. The total investments raised by over 80%, and EU funding by 145%. By including CIP-ICT-PSP and CIP-IEE in addition to FP7, H2020 a significant rise in the number of projects, total investments, and EU funding (25%, 59%, and 117% respectively) still appears evident. Table 2 shows the main project data, revealing an increase in activities in the smart grid area from 2007–2020 (Vasiljevska et al., 2021).

Table 1: Number of projects, total investment and EU funding for all programmes

Programmes	CIP-ICT-PSP	CIP-IEE	FP7	H2020
Total number of projects: 285	22	13	80	170
Total investment EUR 2.62 billion	EUR 94.71 million	EUR 17.91 million	EUR 798.25 million	EUR 1.71 billion
Total EU contribution EUR 1.96 billion	EUR 47.09 million	EUR 12.87 million	EUR 483.16 million	EUR 1.42 billion
Total number of R&D projects: 122	3	17	47	55
Total investment in R&D projects 460.41 million	EUR 2.41 million	EUR 29.84 million	EUR 245.7 million	EUR 182.46 million
EU contribution for R&D projects: EUR 365.96 million	EUR 1.68 million	EUR 20.77 million	EUR 166.05 million	EUR 177.46 million

Source: Our elaboration from Vasiljevska et al. (2021)

However, these programs are not uniformly distributed across Europe. Most of these are funded in EU15 countries, while the EU12 Member States still lag. In addition, Smart Grids are being deployed at a different pace, across Europe. In light of that, it might be more difficult to make trade and cooperation across national borders by getting in the way of the timely achievement of the EU energy policy goals. A useful way to bridge this gap in the future, is represented by the sharing and diffusion of knowledge and lessons learned in other countries (Giordano et al., 2011). Moreover, given the high costs of digital technologies, the involvement of financial institutions in providing support to investments in smart grid projects remains the unique key to economic recovery and energy transition.

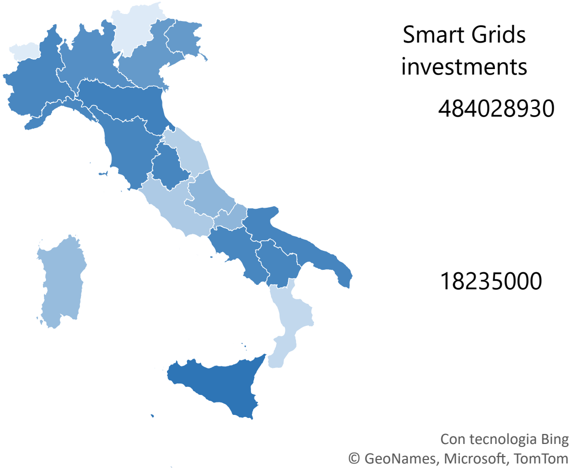
Smart Grids projects in Italy: the state of the art

The number of demonstration projects in comparison with R&D projects rose substantially in Europe from 2007 to 2020, thanks to the increasing maturity reached by many technologies and solutions and the growing focus on the demonstration of the enabling role of smart grids. The geographical distribution of involvement demonstrates significant differences across countries. Specifically, Spain, Germany, and Italy show the largest numbers of participation and the highest number of agreements with other countries (Vasiljevska et al., 2021). Specifically, Italy represents one of countries with the highest shares of collaborations with other countries.

To encourage the development of smart grids, the Italian National Recovery and Resilience Plan (NRRP) has allocated 3.6 billion euros for 22 projects aimed at adapting and strengthening electricity distribution networks. These investments aim to allow greater integration of renew-able energy and encourage the electrification of consumption. Thanks to these projects, the MASE (Ministry for the Environment and Energy Security) plans to increase the capacity of the distribution networks by over 9.8 GW and provide energy to approximately 8.5 million inhabitants (MASE, 2022). Specifically, the investment aims to improve the soundness, security, and resilience of the national energy system by following two design lines: the former, has a target to ensure at least 4.000 MW the amount of renewable energy sources through the implementation of smart grid interventions on 115 primary substations and the related underlying network; the second, pursues the goal to transform to the electrification of consumables at least 1.850.000 users and realize new areas where prosumers assume a new role of energy consumers-producers. Smart grid innovations (power grids composed of intelligent sensors that im-prove power distribution in real-time) will be used in many substations to favour the efficiency of the grid and the use of electrical mobility, warming generated by heat pumps, and, overall, to favour a better use of electrical energy.

The following figure shows the geographical distribution and approximative amounts of all 22 projects approved in Italy aimed at increasing the capacity of the grids. All projects associated with this measure are based on PNNR funding and other resources (Table in Appendix shows details).

Figure 1. Geographical distribution of smart grid investments in Italy under NRRP.



Source: Our creation from data available at https://www.opencup.gov.it/portale/web/opencup/homepage

Meanwhile, several projects have been launched in the field of smart grids in Italy. Note-worthy is the Puglia Active Network project (PAN project, hereafter) launched by E-distribuzione and co-founded by the European Commission under the NER 300 programme (EU commission, 2016). This €170 million investment aims to boost the electric distribution network in Apulia, a southern region of Italy, through the integration of more than 3 gigawatts (GW) of renewable energy into the smart grid. The project, lasting 9 + 1 years (2014-2024), is based on three main actions:

- strengthening of the electricity grid, for greater efficiency and safety;
- development on a regional scale of a charging infrastructure for electric vehicles integrated into the distribution network, to implement a new model of eco-sustainable zero-emission mobility;
- monitoring energy consumption with the Smart Info+ kit to develop greater awareness in the use of electricity (in homes and small commercial businesses).

Recently, Italian DSO E-Distribuzione launched the project EDGE (Energy from Distributed Resources for the Management of the E-Distribuzione Network) aims to test and establish the most suitable strategy for the procurement of local ancillary services and related remuneration in Italy.

The project already approved by the Regulatory Authority for Energy, Networks and the Environment (ARERA) requires a partnership between E-distribuzione and with flexibility platform provider Piclo to offer the country's first local flexibility marketplace. The focus is contributing on the efficient, reliable, and safe operation of the distribution network and the optimal planning of its development. The areas of interest for the pilot project were identified within the provinces of Cuneo, Benevento, Foggia and Venice. The tenders for the approval of flexibility services will indicate the portions of the network identified and the resources connected therein, eligible to offer the service (Flexibility Perimeter) (Jones, 2023). These services will be provided by different categories of users who, thanks to remuneration, will modulate their energy behaviour. In other words, they will vary the electrical power consumed or produced for a certain period concerning specific requests from the electricity system. In this way, users will contribute to improving the resilience of distribution infrastructures and resolving any network congestion. The main advantage of "flexibility services" lies in the fact that customers will have the possibility of having an economic return for their ability to modulate consumption and production. Furthermore, these services will contribute to the efficient management of the network, supporting production from renewable sources and new methods of production and consumption, such as Energy Communities.

Another important project in the field of smart grids is Actea, conducted by ENEA in collaboration with La Sapienza University of Rome. The goals of the project are the following: Performance optimization of aprotic liquid electrolytes based on organic solvents and low fluoride calcium salts (WP2); Synthesis of materials, chemical-physical characterization of electrode materials (WP3), and study of their redox properties (WP4); Creation of complete Ca-ion batteries, by coupling and balancing the three functional components of the batteries (WP5). The aim is to build different batteries and offer new, more sustainable, and economical solutions by exploiting other resources, Ca-ion accumulators for an alternative technology to Lithium to achieve an energy transition as much as possible.

Furthermore, Italy is involved in some European projects for the development of smart grids. For example, the Horizon Europe FLEXCHESS project, which aims to study the integration of sources of demand flexibility within electricity networks characterized by intermittent sources such as renewables, involves the Iren group for the experiments. Specifically, Iren will work on the Italian pilot project in the city of Turin to study the potential of a Virtual Energy Storage System (VESS) and investigate the opportunities for balancing the networks. Total cost of the project amount at € 2 879 681,25 with an EU contribution equal to € 2 317 385,63 of which € 41 184,37 and € 43 443,75 will finance Iren Spa and Iren Energia Spa, respectively (EU Commission, 2022). Another Horizon Europe project namely Datacellar, focuses on developing a plat-form (Data Space) that collects data from energy communities to support the creation, development, and management of Local Energy Communities (LECs) in the European Union. It is led by RINA Consulting Spa which will collaborate with an international consortium composed of companies and institutions from different European countries, based on funds of almost nine million euros. The main objectives are: to develop a data center managing continuously updated, tried, and reliable data; to carry out privacy and cybersecurity-by-design measures; and, to develop a highly engaged data-sharing ecosystem of data providers. Furthermore, the initiative within 5GSOLUTIONS, involves Iren in the testing of the 5G network (and its main characteristics of speed, limited latency, and high reliability) in the use cases of Demand Side Management of building and Smart Charging of electric vehicle fleets.

In the future, the need to install energy storage to balance the non-programmable renewable generation, the increase in electrical vehicle recharging infrastructures for electromobility, and the rising demand response/awareness of consumers will create new challenges for the innovation technologies of smart grids. These will require to become “smarter” by developing innovative operating procedures in this new framework of energy efficiency improvement. In that context, the regulation should promote innovation in the distribution system and provide financial incentives so that future grids will have systems able to satisfy the novel paradigm of power generation (Coppo et al., 2015).

Conclusion

The swift digital transformation within the energy sector, encompassing smart grids and the energy internet, is paving the way for increased resilience and flexibility in sustainable energy systems. The main goal of this technologically-driven dimension of the energy transition is the creation of Smart Energy Systems that are able to improve the efficiency of energy storage. Thus, a sustainable energy future requires a significant increase in renewable sources and, implicitly, the modernization of electricity networks from a Smart Grid perspective.

In light of that, assessing the impacts of smart grids on the energy sector appears relevant. Accordingly, the paper investigates the role of smart grids within the broader context of the energy transition and sustainability. Moreover, it provides an overview of smart grids projects approved at EU and Italy countries level to favour efficiency and sustainability in energy storage. The aim is to examine benefit and costs of intelligence energy systems.

Based on mathematical modelling, artificial intelligence techniques, and advanced programming, smart grid entails the following advantages: 1) it allows coordinated use of distributed resources; 2) it enables network integration of higher quota non-programmable generation with environmental benefits and greater creation of value for the entire energy supply chain; 3) it makes the producer-consumer relationship more flexible by opening up new supply mechanisms based on the active involvement of the user (consumer and prosumer) and encouraging the formation of energy communities both local and widespread (Valenti & Graditi, 2020).

Although these positive impacts of smart grids on energy transformation, there are also disadvantages to adopting these technologies. One of these is that smart grids are extremely expensive and time-consuming implying higher labour costs; however, at the same time, smart grid developments can entail a new energy market, thus creating many jobs. Moreover, another drawback of a smart grid system is represented by continuous data collection, which may entail a violation of privacy standards and may lead to security issues due to hacks or other malware attacks. Eventually, digital technologies require substantial investments.

In terms of policy message, the study underscores how smart grids, through their diverse systems and technologies, play a vital role in driving a sustainable energy transition both directly, by integrating renewable energy sources, and indirectly, by enhancing the grid's overall flexibility and efficiency. Consequently, smart grids facilitate the adoption of strategies aimed at achieving energy and environmental sustainability, as well as addressing climate change, making them an essential infrastructure for a sustainable energy future. As the global shift towards a more sustainable energy landscape continues, ongoing investment and advancement in smart grid technologies will be essential. By fully harnessing the potential of smart grids, we can create a cleaner, more secure, and more efficient energy future for future generations.

Credit Authorship Contribution Statement

Authors contributed equally to the research and development of this work. Both authors have reviewed and approved the final version of the manuscript for publication and agree to be accountable for all aspects of the work.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest related to this research.

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Useful websites

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Appendix A

The following table indicates the geographical distribution and detailed amounts of all 22 projects approved in Italy aimed at increasing the capacity of the grids. All projects associated with this measure are based on NRRP funding and other resources.

Table A: Smart grid investments in Italy under NRRP

Regions	Amounts
TRENTINO-ALTO ADIGE	150.000,00 €
PUGLIA	610.414,00 €
TRENTINO-ALTO ADIGE	1.668.447,00 €
ABRUZZO	2.255.015,00 €
EMILIA-ROMAGNA	2.610.506,00 €
MARCHE	3.690.313,00 €
TRENTINO-ALTO ADIGE	5.542.933,00 €
TOSCANA, UMBRIA	7.601.986,00 €
CAMPANIA	12.882.228,00 €
TRENTINO-ALTO ADIGE	13.247.723,00 €
SARDEGNA	13.347.845,00 €
EMILIA-ROMAGNA	16.067.126,00 €
EMILIA-ROMAGNA	16.985.416,00 €
VALLE D'AOSTA	18.235.000,00 €
MOLISE, ABRUZZO	19.013.938,00 €
LAZIO	21.838.558,00 €
SICILIA	22.049.593,00 €
CALABRIA	27.060.690,00 €
BASILICATA, PUGLIA	28.111.851,00 €
PIEMONTE, LIGURIA	29.704.271,00 €
LOMBARDIA	34.959.198,00 €
FRIULI-VENEZIA GIULIA, VENETO	38.388.548,00 €
CAMPANIA	38.686.135,00 €
SICILIA	49.479.949,00 €
TOSCANA, UMBRIA	62.195.605,00 €
EMILIA-ROMAGNA	68.411.222,00 €
VENETO, FRIULI-VENEZIA GIULIA	70.974.349,00 €
CALABRIA	91.332.609,00 €
MARCHE	125.942.310,00 €
LAZIO	126.032.915,00 €
LOMBARDIA	141.131.934,00 €
LIGURIA, PIEMONTE	145.221.675,00 €
SARDEGNA	192.091.370,00 €
LOMBARDIA	203.474.816,00 €
ABRUZZO, MOLISE	207.734.594,00 €
FRIULI-VENEZIA GIULIA, VENETO	229.774.963,00 €
PIEMONTE, LIGURIA	238.064.468,00 €
EMILIA-ROMAGNA	332.368.577,00 €
TOSCANA, UMBRIA	347.464.169,00 €
CAMPANIA	362.405.637,00 €
BASILICATA, PUGLIA	390.608.451,00 €
SICILIA	412.499.388,00 €