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Designing Smart Energy Systems in an Industry 4.0 Paradigm towards Sustainable Environment

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Abstract: Among the Sustainable Development Goals, 'Green Issues' have attracted significant research on sustainability transitions and regional diversification. The introduction of green environmental technologies within the frame of the Fourth Industrial Revolution is crucial for the diversification of local, sustainable activities to protect the environment against negative climate changes. The present paper provides evidence of the positive correlation among green activities if, and only if, green culture and capabilities are robust and exist. Close international coordination is needed. We point out that smart energy-designed systems are a real revolution in the post-industrial society dominated by the service sectors. Therefore, promoting 'intelligent' meters is a robust policy action in world energy-based economies. We investigate the policy effects for smart meter rollout in European countries by testing this green policy tool on different economic literature strands. A theoretical model is introduced, showing that a sustainable and efficient policy instrument will reinforce and develop local green culture. The spatial unit of investigation is the EU-28, and it verifies the effectiveness of smart meters as a valid post-industrial design tool toward more sustainable environmental policies.

Keywords: smart meters; Industry 4.0; environmental ecosystems; sustainability goals; Europe

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1. Introduction

Over the last few decades, the energy sector has undergone major promising changes, following the Fourth Industrial Revolution, the so-called Industry 4.0 (I4.0), which introduced new technologies and designed new production models. The present historical transformations in the world energy scenario are manifold: the costs of renewable energies that are clearly decreasing, the shale revolution that has rapidly transformed the US energy economy in less than a decade, a strong increase in gas consumption worldwide, a further digitalization of energy generation and consumption, and a rising necessity to fight climate changes. The transition to net carbon neutrality and the COVID-19 crisis continue to be the main current priorities and challenges of our time across the world. In this sense, recent European recovery programs have been designed to align public policies with climate objectives, orienting investment towards sectors and technologies that can accelerate the transition and improve resilience to future shocks from climate change.

Based on these "stylized facts", infrastructures are becoming increasingly intelligent at different levels, as in the now-widespread case of smart cities. Being smarter usually refers to the infrastructures for normal operation and use: we expect them to be more adaptive, smarter, better performing, and up-to-date. Digitizing processes using technology is the only way to survive in the future; another option is to risk becoming obsolete, and leaving the markets. Smartness is to simultaneously obtain all the advantages associated with economies of scale and scope. The goal is to achieve customized but high-volume production capable of sustaining a continuous flow of goods and services characterized by a series of differentiated products that, nonetheless, meet individual customer needs. New competitors are entering the global market every day from countries previously excluded from or on the fringes of the most industrialized economies, most notably China.

I4.0 has profoundly changed how companies are organized compared to previous 'revolutions', such that the production of goods and services now relies on the integration of plants with digital technologies [1]. Continuous and rapid progress in information and communication technologies (ICT) has given rise not to a single revolutionary enabling technology but to a bundle of them that, thanks to the Internet, are coming together in a systemic way into new production paradigms to which innovations of a very different nature are connected, depending on the sector concerned [2].

The I4.0 trend presents a technology-push innovation attitude [3], and it also implies a radical innovation in business models. Given its socio-economic sustainability aspect, long-term economic growth, and natural and social capital protection, must proceed in the same direction. Several studies [4,5] underline the importance of some digital tools (cloud computing, big data, Internet of Things) for servitization, while others [6,7] focus on digitalization as a mechanism for integrating servitization with all the dimensions of a company (the so-called value servitization pathway).

Starting from these studies, we stress that a link between I4.0 and intelligent systems exists in Smart Grid Industry 4.0 (SGI4.0), where technologies and digital innovation enable the efficiency and stability of the traditional network. The whole lifecycle is involved, since all data information is tracked in the network design. With the introduction of machine learning, a smart grid (SG) could interact directly with the whole cyber-system (i.e., optimization of energy consumption, pricing in real-time): an intelligent grid improves the efficiency of an electricity system, thus qualifying the industry and favoring a sustainable environment.

The relationship between I4.0 and sustainability could increase competitiveness and efficiency but, to the best of our knowledge, only a few studies have investigated these linkages [8,9]. The driving forces behind the whole phenomenon are the pivotal values on which companies must ground their innovation strategy. It is based on the integration of 'cyber-physical systems' (CPS) in production processes. CPS stands for the integration of 'physical' systems and 'intelligent machines' (cyber) that communicate with each other via the Internet. The essence of the concept is to connect the digital world with the physical one [10]. In other words, digital information, once collected, aggregated and analyzed, can integrate with the non-virtual world and contribute to the improvement of material, physical objects.

This is the case of the Internet of Things (IoT), whose role will be increasingly important in our daily lives. This technology makes objects in the physical world connected to each other via the Internet and, therefore, usable in a smart way. It includes the set of technological components and devices, which can be embedded in physical objects, and machines that provide the interface between the physical and digital worlds. They enable them to communicate with other objects through the Internet, exchange information, change behavior based on the inputs received, store instructions and, thus, learn from the digital interaction.

In the IoT, massive numbers of distributed devices (sensors, actuators, meters, etc.) are connected to collect data about objects in 'critical' infrastructures, including cities and government, industrial production, energy, transport, healthcare, and public safety infrastructures, among others, supporting many smart-world systems [11]. Examples of such systems are smart manufacturing, smart cities, SG (crucial in our case), smart transport, smart homes, and smart health systems, to name a few. For example, digital technologies allow the intelligent power grid to be built and controlled in real-time; thanks to IoT technology, data can be shared across the network and transferred to a remote location with a real improvement in performance for the end consumer. In other words, 'digitalization has already started to transform the ways energy is generated, transferred, and distributed to consumers' [12], page 977. It shapes production paradigms and business models, and takes into account consumer needs as well social and environmental ecosystems.

Based on these results, we are aware that research activity on sustainability transitions and regional diversification remains one of the main green issues in our digital era, with a large variety of topics, geographical applications, related theories and methods. Thus, only *ad hoc* policy measures will enhance regional abilities in supporting the acceleration of the ongoing green transition. Furthermore, the growing interest in renewable energy responds to the increasing global energy and gas demand over time, especially in emerging market economies, producing potential negative environmental impacts, particularly in the long term, on nature and climate changes. Therefore, the introduction of green environmental digital technologies is crucial for the diversification of local, sustainable activities to protect the environment and improve people's welfare.

Consistent arguments may exist explaining why green activities positively affect and attract each other only if a specific region has a deep green culture and embedded digital capabilities. Previous studies showed a U-shaped relationship among entry regions for sustainable technologies and 'relatedness' to green knowledge [13,14]. Even green activities usually exhibit a U-shaped growth curve; despite being newly independent, they are highly correlated to existing productive activities, presenting, for this reason, the same shape that characterized new economic activities at an intermediate stage of development. Moreover, the diversification of sustainable activities depends on intelligent, green environmental technologies.

In this perspective, promoting SG technologies, such as smart meters (SMs), becomes a robust policy action in world energy-based economies; SMs well represent the potential of digital infrastructure to capture the environmental capacity of a region to apply green technologies for a better future since they measure consumption with a higher temporal granularity than previous meters.

The present paper provides evidence of the positive correlation among green activities if, and only if, green culture and capabilities are robust and exist. We investigate whether the introduction and adoption of new green technologies present different development either at a meso-regional level (Europe) or at a micro-level (single country). The cognitive proximity and complementarity between the new sustainable technologies that regions can potentially develop are powerful to determine regional policies; if the new green technologies are based on cognitively close local knowledge, it is more likely that this green technology will emerge and endure in a specific region. We attempt to reconcile, through the analysis on the adoption of a green instrument (SM), different strands of literature in order to build a new theoretical model.

The paper proceeds as follows. Section 2 presents a critical review of the literature and suggests a theoretical model that emphasizes both the opportunity of finding suitable green-policy instruments and the necessity of driving people towards a more massive local green culture and usage. Section 3 shows the recent experience of smart energy designing depicting SG and SM. Section 4 offers an overview of the penetration of energy SMs in Europe using the benchmarking smart metering deployment, and Section 5 suggests concluding remarks and policy implications.

2. Literature Review and a Suggested Model of Green Culture

Among the Sustainable Development Goals (SDGs) for a better and more viable future, 'Green Issues' have attracted a significant research activity, mainly on sustainability transitions and regional diversification. Recently, the mutual relationships among the 17 SDGs have been investigated from a different perspective ranging from social sustainability to innovation and competitiveness. In particular, climate change and related policies are among the most critical challenges of our time, such that the design of environmental policies negatively affects the economy. The 2019 UN SDG themes range from ending world poverty to urgent action to fight climate change and its impacts by 2030 [15], Tables 1 and 3. The consequence is that in the short-medium term, there might be a trade-off between fighting climate change and ensuring a stable business cycle. Climate change remains a classic example of a negative externality: carbon emissions are a social cost that affects the market of origin and other markets; that is, they are global in nature and difficult to manage not only for markets but, also, for national governments [16].

In environmental innovations, instead, economic policies are related to the double-positive externality that characterizes sustainable improvements through knowledge spillovers and adaptation to the green technological changes [17]. In the regional diversification literature, the growing interest in green activities has a high level of past and place dependence: new and green activities arise more easily in technological sectors and industries closely related to those already operating [14–18]. Research in this field shows that the regional green diversification is strongly based on these driving forces, providing new and further insights, since the transition literature usually understates the addictive processes of past dependence and tends to neglect the role of regional capabilities [19].

The Sustainable Transition Literature (STL) focuses on policy initiatives at a regional and local level, revealing how urban and regional policies matter for sustainability transitions, often being ahead of national and supranational policies. The presence and nature of environmental policies differ widely among regions and within countries, but little attention is still paid to the effect of regional abilities (and correlation) on green culture and related results on economic activities [20]. Moreover, the transition literature states that new environmental technologies are disruptive. They are exposed to fundamental uncertainty (and to a high risk of failure) as they face many obstacles on both the supply and the demand sides, and unrelated diversification might be more common in sustainable transition processes. As a result, unrelated diversification might be more common in sustainable transition processes. Yet, this average country behavior does not represent every diversification path: a correlated diversification is a rule, whereas unrelated diversification is only an exception [14].

The Diversification Literature (DL) appraises the role of regional capabilities, essentially referring to quantitative terms, while the other one, using a geographic approach that emphasizes human-environment relationships in individual country cases, stresses the importance of policies in transformation processes. The synthesis of the two theoretical approaches, that have attempted to explain large-scale and long-term socio-technical changes, shows that new green technologies are radical innovations and refers to the need for transformative changes by doing things differently, enabling the greening of economies. A transformative change is a change that becomes sweeping, enabling towards sustainability, with a specific role for everyone, whether one is an individual, an organization, or a policymaker. It often starts small, but it is strategic. It includes individual decisions to help start or build new social rules and the legal changes that unlock all kinds of other changes [21]. Therefore, innovation for sustainable development needs both radical innovations that increase the environmental and social performance of goods and services production, without consumer benefit biases, and incremental innovations in the existing production and consumption systems due to path dependencies bringing temporal lock-in and *inertia*.

By default, environmental policy influences the development of new green specializations in some regions but not in others. A rationale is in the single policy implemented by each region and in their specific local capacities to transform national aids and local incentives into higher sustainable investments in new green activities; regional political support for environmental policies might enhance countries' abilities to develop new regional and local activities. A strong environmental sustainability campaign helps to reconcile the effectiveness of policy action at a geographical level. Thus, the introduction of peculiar, new techno-green instruments (SMs), if well sustained, could be the way to fulfill economic actions at the meso- (Europe) and micro (region)-policy level.

In order to investigate regional and European capacities in this respect, we use SMs' penetration as a tool of analysis and policy action. The public intervention provides incentives to facilitate green transitions by overcoming the initial lack of performance and cost competitiveness of new environmental technologies and mitigating barriers to their development and adoption. Green innovations require the implementation of several policy measures related to the peculiar (hybrid) nature of green knowledge that brings uncertainty and radical changes in social attitudes.

For this purpose, we use a benchmark study, offering an overview of the present situation at the meso- and micro-policy levels. It is important to underline that the benchmark we use [22] remains at present the only source of statistical information at the meso level since the topic, in this respect, is quite new and unexplored so far.

Moreover, technological innovation is a powerful mechanism for the transition towards more sustainable societies as it corrects market failures through government intervention [23]. Green growth policies seek to increase returns on investments in green innovation by reducing disparities between private returns from economic activity and benefits for society. Sustainable policy measures tend to develop payoffs that enhance natural resources through policies of green innovation or supporting specific technologies; they 'strengthen entrepreneurship and local firm absorptive capacity, support new knowledge creation and commercialization, and diffusion and adaptation of existing knowledge to new local contexts' [24] p. 72.

Intelligent energy feedback would be an effective driver of energy-related behavior change; in the SMs' case, it is necessary in an emerging technological system for which implementation requires solutions related to the engineering of the grid as well as policies and regulations from governments and agencies [25]. In the last decades, green technologies applied to the energy industry have experienced smart technological development [26]. However, green growth strategies are not able to solve, per se, structural constraints on economic growth and job creation, as market distortions and an unattractive business environment require a very efficient solution before their implementation. The opportunity for a new and smart specialization policy framework involves every single nation designing a new local policy within their regional framework to identify new sustainable green opportunities on a global scale.

Several studies theorized regarding the concept of e-inclusion and e-exclusion and linked the digitalization phenomenon to a more multidimensional process [27]. To understand the impact of technological disruption in today's economy, a future technological analysis (FTA) [28], enabling a better understanding of complex situations and defining effective policy responses, might be a good support for decision-makers in anticipating and coping with transformations. It integrates the two strands of literature mentioned above, where DL is founded on the existence of a twofold linkage between temporal and geographical dimensions so that new digital activities perform a positive correlation with the local technological sectors, and STL points out the total absence of such a disruptive dependence. Modelling the innovation path, FTA underlines the time-limit importance of bringing together both technical and commercial knowledge on potential new products and processes in the early stages of development. To coordinate them, FTA has been used, as it is a theoretical analysis for identifying and planning the most suitable long-term decision policy in order to absorb all the socio-cultural aspects involved in the green transformation. It is a valuable management and policy tool reinforcing classical strategy, planning, and decision-making approaches in post-industrial society (Figure 1).

Regional policies on green technologies influence the creation of new sustainable opportunities, but they do not work by default everywhere, and are subject to constraints. Therefore, countries that have just adopted green projects at the local level will easily succeed in introducing new green meso-actions (relatedness with existing green policy) only if their green activity is routine (green diversification). On the other hand, barriers emerge when the local green policy is not fairly supported; countries consider the regional policy disruptive (complexity).

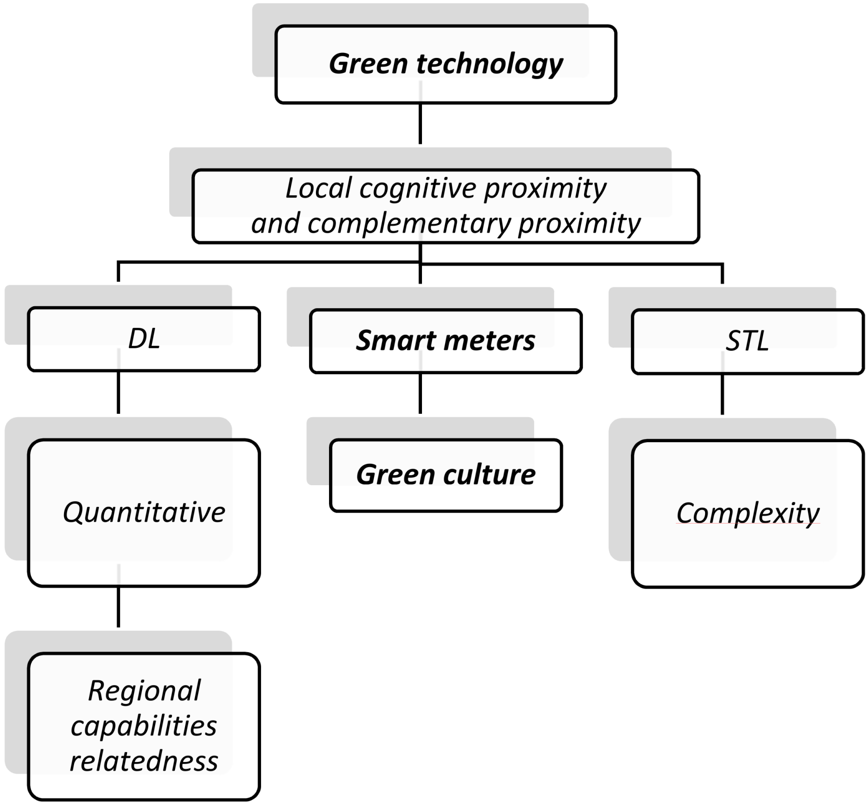

Figure 1. A sustainable model.

Introducing a green policy takes technological, commercial, organizational, and social uncertainty [28]. The last is strictly related to the socio-cultural aspects. Thus, while the other kinds of uncertainty could be investigated using quantitative analysis [29], the social uncertainty, due to its intangible characteristic, might be investigated by analyzing unwritten rules, social factors, and cultural behaviors [30]. In other words, it is useful to act on people's way of thinking sustainably and spreading and supporting green cultural skills so that a sustainable action becomes the rule and not the exception.

Both cognitive legitimacy, which takes place through the creation of specific green knowledge, and socio-political legitimacy, which involves institutions, stakeholders, people, and entrepreneurs, could fill the gap of uncertainty. In a green economy, the socio-cultural features heavily depend on local habits due to a multidimensional vision of well-being, recalling concepts such as equity, inclusive development, and sustainability. The common thread generates a collective cultural transition. The social value system is crucial in the behavioral tendency of the individual and the organization. It emerges from institutions' behaviors and choices, families, and individuals, such as 'codes', whether tangible or intangible, on which society relies.

Nevertheless, the question is if these positions might converge to a common vision, although they do not clearly mention, nor investigate, from an economic point of view, the presence, everywhere, of local cognitive proximity and complementarities. These two features simultaneously affect the regional policy.

The cognitive and institutional proximity determine the co-localized abilities of a place (green cultural skills). The local element helps to define the involved area, so it is possible to use only the specific local capabilities. The higher the cognitive and institutional proximity level, the higher the probability of introducing and sustaining a new successful green policy. Moreover, if a region has a high level of institutional and cognitive capabilities, the geographical proximity acts favoring a reaction in the immediate areas. Thus, introducing a green tool facility (i.e., SMs) in a place, through these proximity levels, could activate all the complementarities among people and places [31].

SMs are the most suitable technological instrument in the design process; they are disruptive and with a green diversification capability. This is also a good regional policy measure to determine sustainable changes at a local institutional level. The introduction and adoption of micro-grids such as SMs should substantially reduce the power consumption in the energy sector, driving energy saving, although incentivizing savings through social comparison and competition has not always been successful [32]. It allows the 'boomerang effect' to operate; when families realize they are using less energy than their average class, they start consuming more [33]. Several problems coming from financial obstacles in rural areas and a low capacity to change deeply entrenched social practices have also emerged. Most likely, several 'black holes' related to the different socio-cultural values of the population and to changes in routines remain in radical innovations due to a lack of credibility. Thus, only strengthening real public culture will allow all citizens to trust green policies fully.

Accurate identification of the obstacles to green technology adoption and potential barriers to the strategic process's implementation would increase the number of successful green policies. However, the cost and convenience advantage remains the core value message in advertising and social media, dimming green solutions and sustainable utility. Furthermore, green technologies' adoption requires high entry costs, facing social resistance because of the opposition of the typical consumer behavior to change habits due to social influence.

Thus, it is necessary to develop a specific proactive culture to facilitate the introduction of these new technologies. To reach the energy balance at the minimum cost (i.e., an efficient smart-grid system), an optimal IoT-based energy management framework must attract people. First, it is essential to create an increase on the demand side, and then create a related tool to meet the demand expectations. This is similar, in some respects, to what happened with mass customization, where flexibility and personalization of custom-made products with low unit costs were associated with mass production.

3. Designing a Smart Energy System: Smart Grids and Smart Meters

The relationship between revolutionary enabling technology (ICT) and economic sustainability is still of remarkable interest. In the post-pandemic scenario, nations aim to create a sustainable value based on social, economic, and environmental factors. Digitalization can assist in building the 'sustainable society' of the future. This sustainable perspective can be reached using digital innovation. In fact, digitalization, being part of a multidimensional process, involves many sectors and, among the others, the highly topical environmental contest like the energy contest; it has already started to transform the ways energy is generated, transferred, and distributed to consumers [34].

Since smart technologies can contribute to reach equity access to services and increase well-being, they could generate the best power efficiency by implementing renewable energy (transition to renewable generation technologies such as wind, solar, and geothermal energy) that modifies how energy is produced, transformed, and distributed to reduce CO_2 emissions. A recent application of smart technology to the energy sector is the SGs [35], as part of the EC's Digital Single Market Strategy, which permits measuring consumption in real-time and implementing the related services, substantially reducing the power consumption mainly in low-income regions. Through the IoT-based grid control, a cloud-based server may allow for energy network regulation while avoiding fluctuation in the daily supply of power, offering efficient energy management.

Indeed, connecting an SG to bus burs allows for the storage and the transmission of information in a digital form, substantially reducing the power consumption, especially in rural areas. Several elements of the digitalization process are involved in this mechanism because a cloud server can work and regulate an electricity network with a constant supply of power only if there is an IoT connection. An SG also represents the technological substrate that supports the formation of new contractual opportunities and the development of products and services able to conduct the consumer towards more informed and efficient energy use.

Creating an SG means designing an intelligent network through which an efficient and high-performance advanced measurement infrastructure is generated. Its logical, functional design is based on the presence of two information chains. The first exists for enhancing bidirectional data between the meters and the central system. SMs, through this chain, also improve remote management functions, so that suppliers can program some range of prices, vary the power used, change the degree of confidentiality on the display (with regard to sensitive information), and modify the contractual parties (i.e., switching). The second chain generates a one-way communication channel from the meter to the consumer without any other data transition.

An SG uses different digital tools that permit the demand to be targeted since it allows the peak to be managed with valley clipping. In other words, it would be possible to charge more than the peak demand period offset by lowering charges in off-peak moments. Moreover, an SG is an intelligent energy network that permits multiple devices' digital connection or bidirectional data circulation [36].

There are geographic and zone networks in a single intelligent grid, domestic net, and SM: the advanced metering infrastructure works if all peripheral networks act simultaneously. The foundation of an intelligent grid is a communication and control structure that is built in a particular way: if, in one of the substations, changes appear in the generation, transmission, or distribution of energy, the structure would detect them. Undoubtedly, the most important sustainable mechanism is the transmission, and SGs, substations, and control centers guarantee its efficiency. Moreover, within the network, there are synchronized phasors (based on frequency, current, and voltage angle) that direct the flow of power and quantity from one node to another and use several levels and multi-hop networks. Algorithms and software connect energy management systems and SGs for data elaborations [37]. In a word, infrastructures represent the link between consumers and the network [38].

The core of an SG is an SM; its introduction and adoption allow the creation of a centralized and automated measurement system. SMs are an emerging green technological system that limits the high degree of *inertia* and inefficiency of the old power grids. They also offer consumers a saving opportunity if they schedule their consumption at certain times of the day, reducing grid losses and operational costs. In terms of environmental design, and in line with the 'four orders of design' model [39], SMs are a digital infrastructure that makes known what was previously unknown, tangible what was previously intangible, and flexible what was previously inflexible [40,41].

An SM is part of a complex system that allows the best technological measurement to maximize performances, achieve energy efficiency, and have tangible benefits for consumers. A smart metering is an integrated wireless technological structure that is part of a central intelligent system and presents (i) a mechanism suitable to collect information and activate users' remote-control processes; (ii) the introduction and adoption of a digital technology, and (iii) a digital communication network for data transfer. These technological structures permit data to be shared in real time (high frequency) and allow several measurement systems to share the same communication infrastructure.

The adoption of SMs also allows the exploitation of economies of scale with low consumer involvement. They enable substantial improvements to industry services and processes and guide consumers towards a more informed and efficient use of electricity and gas [42]. Intelligent meters are controlled by a regulated monopoly with the limit that distributors have the responsibility of the measurement when they lose their primary interface role with consumers. If the monopolist has a data management service, it will give SMs availability to the other competing organizations.

The result is a low level of technological competition due to service standardization, even if these organizations operate in a context of liberalization of accessibility meters. The efficiency of SMs is closely related to the innovations they incorporate, but if only a part of this technology fails (for example, a relay), then a gap between the level of the old technology and the new, innovative one occurs.

Thus, the application of I4.0 tools can support a sustainable energy system. The real limit of this type of smart tool remains the consumers' green culture. New technologies often face barriers because of traditional rules and values, finding resistance from social groups that slow their application. Some relevant factors for the implementation of a successful policy initiative are the level of its related perception and acceptance, the perceived attitude toward technology (technology acceptance model) [43,44], the importance of trusting the agency that provides the service (government trust model) [45,46], and the characteristics of product and process (innovation diffusion model) [47].

The sustainability goal is to convert unsustainable economic activities into a viable, healthy environmental and a more inclusive economy. Sustainable culture and green training keep enforcing one another. The success of the previous one needs to be disseminated through *ad hoc* policy measures to enhance the local abilities in sustaining the acceleration of the ongoing green transition. Using sustainable energy resources leads to a reduction of the adverse effects caused by pollution and to an increase of the competitive advantages associated with proactive environmental activities [48]. The social resistance to adopt smart meters, a very interesting point that might require a single further investigation that goes beyond the economic aspects, involves different features (psychological, socio-economic, demographic, behavioral and legislative elements).

Several studies [49] show that, by enhancing knowledge and information diffusion, the I4.0 paradigm and related technologies are essential tools for generating income and 'new' employment in the long run, positively affecting environmental sustainability. Moreover, the simultaneous radical change in the economic strategies and the social roots of society pushed I4.0 to reshape the production and market models so far adopted, thanks to the flexibility in connecting machinery, plants, products, workers and consumers worldwide via the web.

According to one of the most used and questioned sustainability representations, the Venn diagram, the complex dynamic inter-relations among economic, environmental, and social aspects is described by three interconnected circles, where the resulting overlap is the sustainability area [50]. It is possible to consider this mechanism as distinct paths: each pillar refers to a different sustainability channel (environmental, social, and economic) and denotes that all factors are in harmony, i.e., an ideal status where economic growth with robust environmental protection and a strong green civic sense are simultaneously reached.

4. Some Results of Energy Smart Metering in the European Union

Current European policies adopt a market-driven approach for a valid SM deployment, but a deep green culture diffusion is still missing to reach a fully sustainable goal. Policymakers can influence green diversification through political support at a regional level, moderating and reinforcing the importance of countries' capabilities [51]. Several studies highlight that the chance of developing new eco-technologies in a specific area strongly depends on the past and present activities enforced in the existing local green actions [52,53].

Nevertheless, regions differ in their ability to diversify and adapt to technological change and to develop new green activities for their different distribution of specializations. In fact, regions' capacities play a crucial role in the local diversification process, whereby new economic activities tend to develop more easily in industrial or technological sectors closely related to those already existing in a specific area [54]. Therefore, the first step for supporting green actions is to identify the determinants that favor green diversification and drive inter-regional differences. Moreover, green technologies tend to exhibit higher complexity levels than non-green ones [55]. New green technologies stand out from innovations involving non-green knowledge often embedded in a core sector of the economy, showing a positive correlation between different political and economic interests [56–58]. Green technologies rely on ecosystems theory for the development of decision-making methods at the micro-level, promoting sustainable development and greater corporate environmental responsibility.

European countries support SMs in the introduction of renewable energy, a non–conventional energy source constantly replaced by nature. It is harnessed from the sun, directly and indirectly, or other natural features of the environment and provides advantageous environmental sustainability towards a more desirable nature–climate equilibrium. Renewables will simultaneously bring considerable benefits from a consumer, an environmental, and an economic perspective. Promoting renewables appears to be one of the most efficient and effective solutions for the future, and is very attractive in world energy-based economies [59].

However, also in Europe, these measures found at present some social resistance; the lower the social resistance in the adoption of digital infrastructures, capturing the environmental capacity of a region to apply green technologies for a better future, the greater the potential comparative advantage of it over others. Smart metering is a suitable tool to overcome social resistance because it relates to managing users' private information and data. Therefore, building up a 'sustainable consumer' culture is essential. Energy SMs are linked to a SG that, thanks to innovative technologies, permits a radical change of information among operators [60]. Their diffusion is strictly connected with a smart metering information system platform [61] that presumes a strong motivation (such as saving energy) for its use by intelligent consumers.

In order to verify the effectiveness of SM as a valid tool of sustainability, we investigate their effects in the EU countries' spatial unit, using the benchmarking smart metering deployment database [22]. The basic idea is that the introduction and adoption of new green technologies present different developments, either at a meso-regional level (Europe) or at a micro-level (single country). The cognitive proximity and complementarity between the new sustainable technologies that regions can potentially develop are powerful factors to determine regional policies; if the new green technologies can be based on cognitively close local knowledge, it is more likely that this green technology will emerge and endure in a specific region.

The European Union fixed a set of clear long-term objectives to guide environmental, sustainable and renewable policy with the support of dedicated research programs, legislation, and funding, while also determining several environmental priorities. Work is ongoing on many fronts in order to create new business and employment opportunities that stimulate further green investments. Each regional government still has national legislative responsibility for environmental protection issues; therefore, local policies on green technology could be used as a comparative indicator for environmental protection.

SMs are part of these European green actions. They are electronic devices that collect data on household and firms' electricity and gas consumption in real time and offer consumers the opportunity to monitor their energy consumption locally and remotely. The idea is that through feedback, it is possible to gain consumption information in real time and change behavioral attitudes. SMs reduce operational costs associated with meter reading, network monitoring, and maintenance, improving billing accuracy and management, and enabling other important smart grid functions (time-variant pricing and distributed renewable generation). Conversely, smart metering social acceptance is slowed by fears about privacy violations, rising electric and gas bills, and loss of control over energy use [62].

In Europe, SMs' penetration distinguishes electricity and gas supply. The last decade saw people becoming familiar with this tool in the electricity sector to achieve new European energy targets; conversely, the situation is very different for gas meters. Their slow implementation is due to the cross-cutting nature that requires the involvement of different stakeholders (the collaboration of national regulators, energy companies, technology providers, and consumers) [63]. Thus, SMs' effectiveness is strongly influenced by policy coordination and implementation.

In 2020, the European Union registered a high SM (electricity and gas) penetration rate. Since 2001, their diffusion in Europe increased, and Italy performed a large-scale rollout.

At the end of 2017, 9 member states made up more than 50% of SMs' household adoptions, and the penetration rate is expected to reach 58–71% by 2023 [64].

4.1. Electricity

Since the Electricity Directive 2009b (2009/72/EC), EU countries have been forced to introduce SMs, pushed by climate change and the necessity to implement research on renewable energies. The smart metering rollout program is part of the Third Energy Package, a legislative package for an internal gas and electricity market in the European Union to open renewable structures within the area further. It was enforced on 3 September 2009. Among other features, it includes ownership unbundling (separation of companies' generation and sale operations from their transmission networks) and requires each member to schedule verification of the real diffusion of this technological instrument. From a legislative perspective, all countries that have complied with the Directive by introducing SMs are obliged to *ad hoc* legislative directions.

The main drivers of SM implementation are consumer demand for timely and accurate electric billing, low population density, and the high cost of manual meter reading. SMs measure energy consumption and bidirectionally communicate it with billing information, real-time price, and power grid status [36,65]. Therefore, the bi-directional communication interoperability is the most crucial difference that distinguishes SMs from the conventional system.

However, even if the positive impact of SMs on energy efficiency is widely recognized, their diffusion is still lagging (Figure 2). The accessibility of different technologies has made information on production and consumption available, positively contributing to saving energy supply and decreasing distribution costs, with evident improvements in efficiency and reliability.

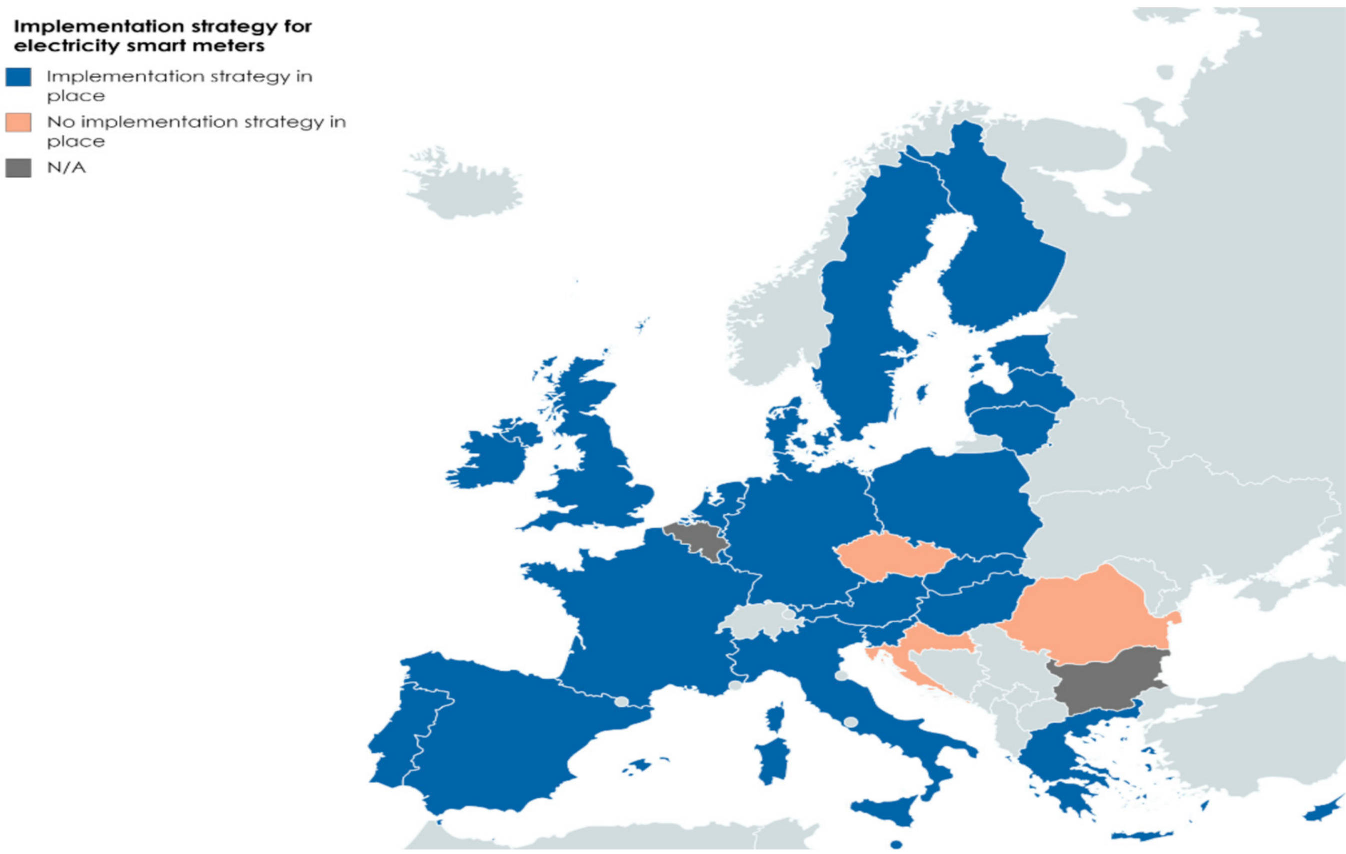

Figure 2. EU members with an implementation strategy in place for electricity meters (legal provisions) (2019). Source: [22], page 39.

For the future power grid, as the number of energy meters increases, an efficient maintenance technique able to query data from devices is essential. It is possible to construct and control the intelligent power grid in real-time through digital technologies. IoT technology shares data across the network to improve performance, transferring them to a remote location. In other words, digital technologies are shaping the paradigms of production and business models, taking into account the needs of consumers and social and environmental ecosystems.

Among the most relevant motivations that support the introduction of SMs in Europe, more than 20 countries answered to adopt this new technology for 'digitalizing distribution grid and optimizing network operations', while at the second level, there are 'enabling dynamic tariffs for households and SMEs' (Figure 3; the same country can choose more options). These two purposes align with the global digitalized process and the transition mechanisms of I4.0. Moreover, beginning in 2017, Europe has pushed for the adoption of SMs, also due to the big campaign for supporting renewable energies.

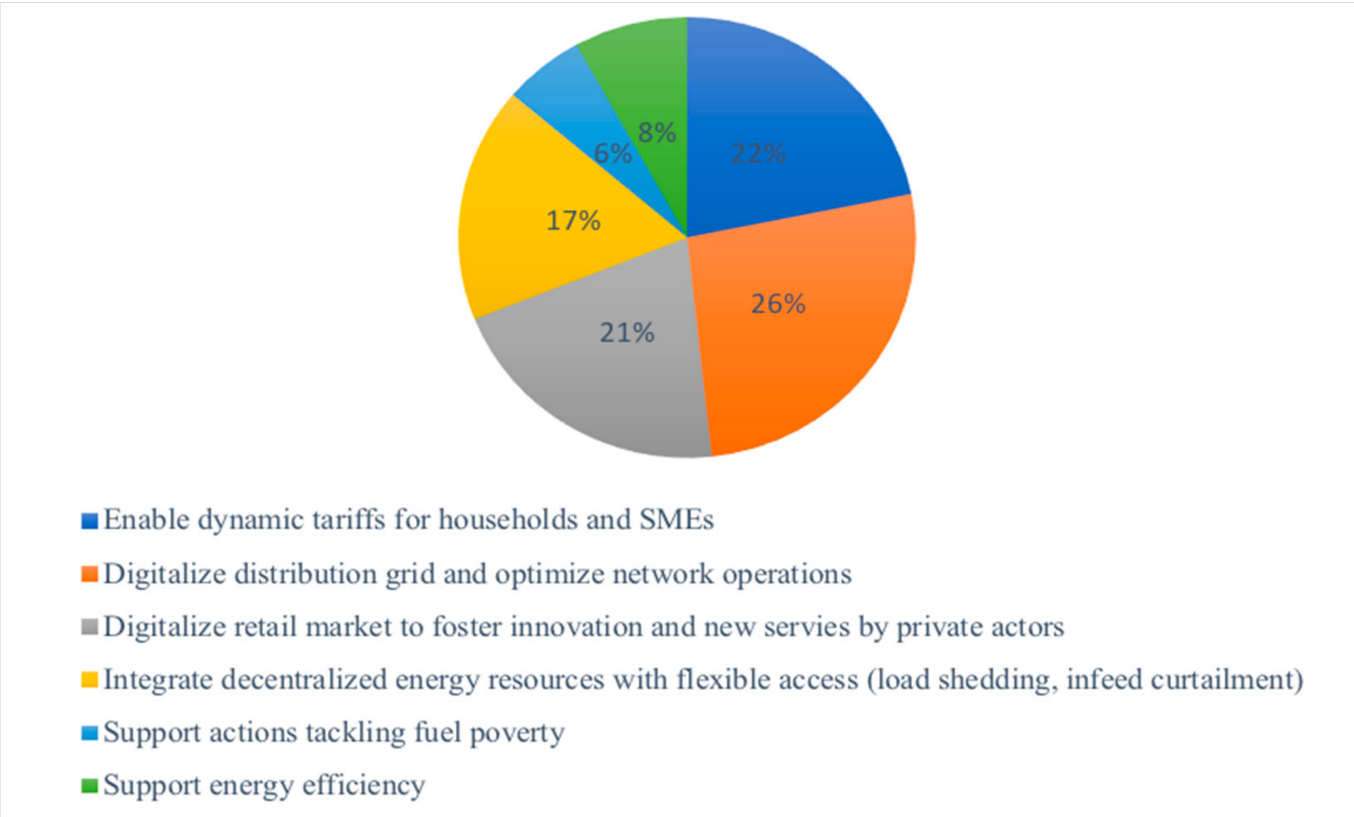

Figure 3. EU members' motivations in 2019 for introducing electricity smart meters (in percentage). Source: own elaboration on [22] database.

At the beginning of the conventional–digital replacement, most European countries showed a total absence of or very low SM penetration rates (Figure 4), including the United Kingdom, France, Germany, and the Netherlands. Only recently, Sweden, Italy, and Finland have achieved a market share of over 90%, ranking among the highest penetration rates.

Sweden was among the first European countries that implemented and introduced large–scale SM reform, aiming to increase consumer awareness with more accurate electric bills to favor responsible energy consumption by households and firms. Denmark, Germany, and Finland believe SMs are a useful technology for reducing carbon emissions and benefiting from significant changes in electricity consumption and production. Denmark, in particular, aims to have 100% of total energy consumption covered by renewable sources by 2050. Among the others, 22 countries have introduced electrical SMs, mainly beginning in 2017, but Belgium, Bulgaria, Cyprus, the Czech Republic, Greece, and Ireland currently don't.

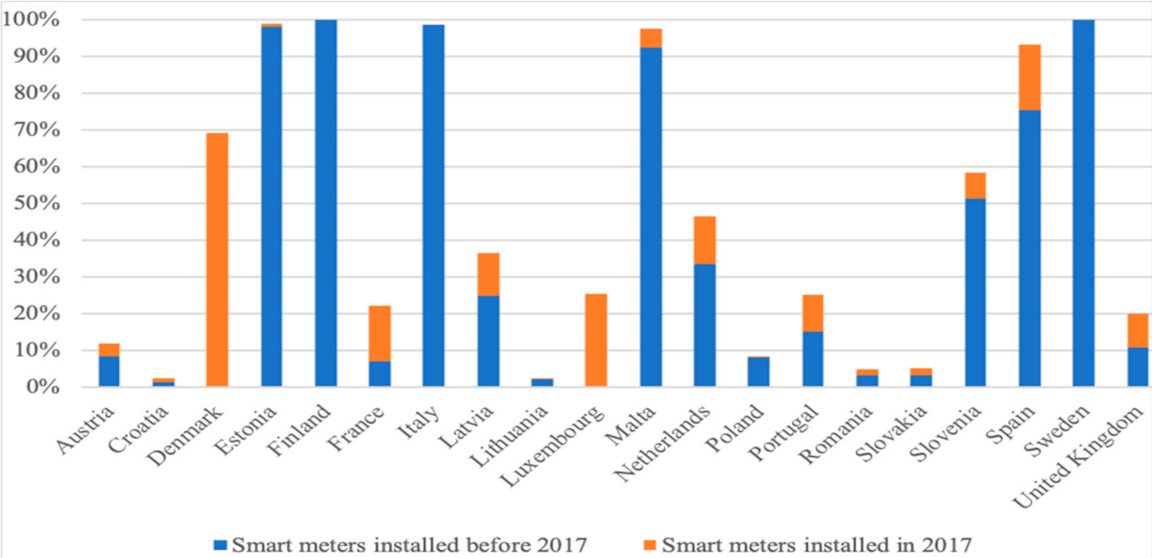

Figure 4. Total penetration of electricity meters in selected European countries (before and in 2017). Source: own elaboration on [22] database.

Figures 5 and 6 show the SM installation rate for small-medium enterprises (SMEs) and households before and in 2017. In this year, the medium-sized firms exhibited an increase in SM installation. This was also supported by the introduction of a specific legal provision in each country. France, Malta, Slovenia, United Kingdom have the best position, while Italy is still absent. Conversely, the installation of electricity meters in the household sector performed better (Figure 6). However, Germany showed an initial and relevant time lag in applying this tool because SM installation was considered too expensive according to a nationwide cost-benefit analysis. After 2017, the scenario changed; the process of meter implementation accelerated under the pressure of Europe.

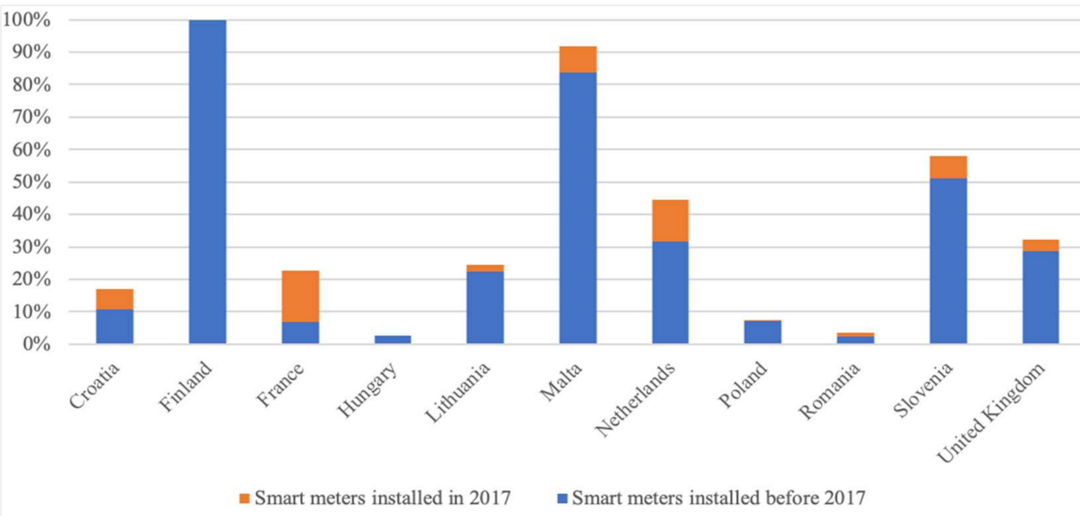

Figure 5. The state of SME electricity meters in selected European countries (before and in 2017). Source: own elaboration on [22] database.

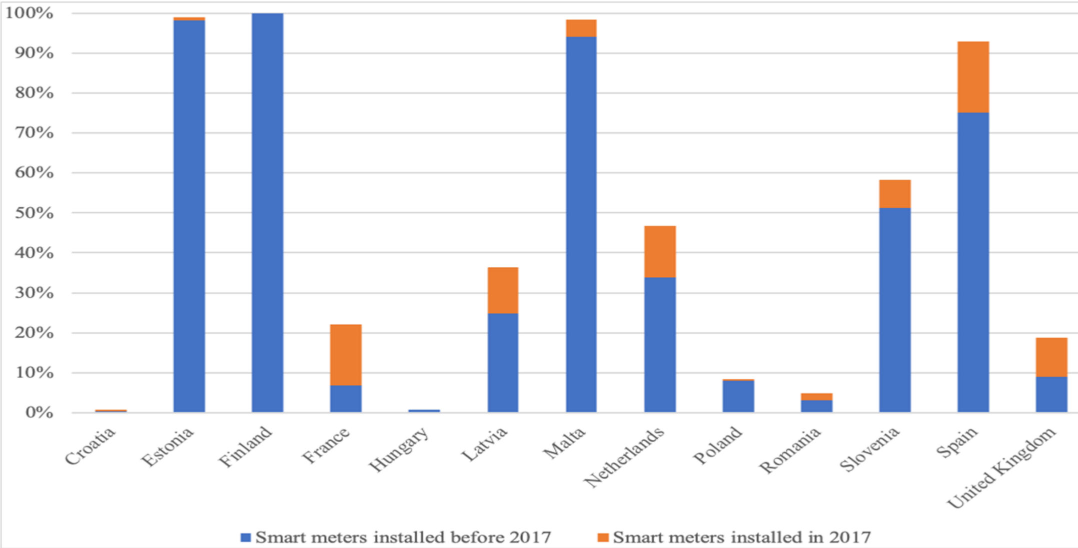

Figure 6. The state of household electricity meters in selected European countries (before and in 2017). Source: own elaboration on [22] database.

A recent report estimates France as the largest market by volume in 2020, with more than 6 million units of electricity meters shipped during the year, followed by Italy, which is currently in the midst of its second rollout, with over 5 million units deployed, and the United Kingdom, the Netherlands and Portugal [66].

4.2. Natural Gas

The EU's enlargement has suggested a new energy gas policy, mainly considering that several member states are largely dependent on Russian gas imports, with 155 billion cubic meters of natural gas in 2021, accounting for around 45% of EU gas imports and close to 40% of EU countries' total gas consumption. Progress towards Europe's net-zero ambitions will bring down its use and imports of gas over time. The EU members could reduce their dependence by more than one-third within a year through a combination of measures that would be consistent with the European Green Deal and support energy security and affordability, paving the way for further emission reductions in the years to come.

It is a real EU agenda priority to introduce a self-sustaining gas policy; only by ramping up energy efficiency measures in homes and businesses, the dependence on Russian gas can be reduced. Many European countries tried to duplicate the same legal framework adopted for electricity meters. Some of them, with the implementation of the Third Energy Package, have managed to introduce specific measures and their own SMs. Directives 2009/72–73/EC and related regulations on electricity and gas attempt to push SMs to actively participate to produce and use renewable energy, aiming at a sustainable, competitive, and secure energy supply. A cost-benefit analysis at the European level [22], based only on pilot projects, categorized member states into four groups (1st group, with a cost-benefit analysis: Austria, Italy, the Czech Republic, Denmark, Finland, Germany, Lithuania, the Netherlands, Romania, Slovakia, Slovenia, Spain, and Sweden; 2nd group, without any pilot projects: Estonia, Greece, Bulgaria, Croatia, Hungary, Poland and Portugal; 3rd group, without a natural gas network: Malta and Cyprus 4th group, with two gas analyses: France, Belgium, Latvia, Ireland, Luxembourg and the United Kingdom).

Specific gas laws favoring SM penetration are present in several states (Figure 7). For example, Belgium has been dealing with gas law since 2004, Hungary since 2008, Ireland and Italy since 2014, the latter when, transposing the Energy Efficiency Directive 2012/27/EU into national law, the Regulatory Authority for Energy, Networks and the Environment received specific functions as regards district heating and cooling, and set an SM rollout National Plan for Energy.

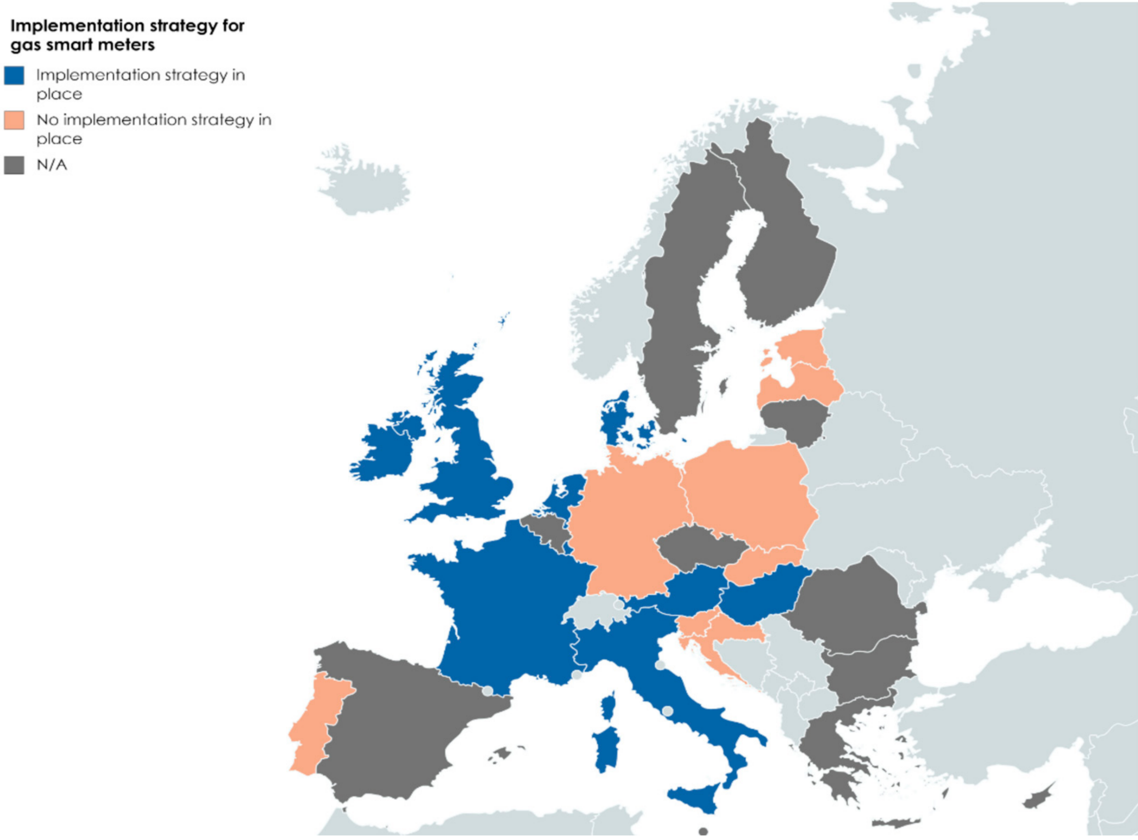

Figure 7. EU members with an implementation strategy in place for gas meters (legal provisions). Source: [22], page 75.

Although the smart meters' adoption is now growing fast in the European gas distribution market, in the beginning, gas exhibited more limits than electricity, since not all European countries have a natural gas network, and the associated costs and investments are higher than in the electricity sector. In fact, for gas meter installation, a high investment in the digital and technological infrastructure, on which meters are based, is compulsory, and essential maintenance costs and network management are to be considered. Only France, Hungary, the Netherlands, and the United Kingdom installed intelligent gas meters both for SMEs and for households (Figure 8).

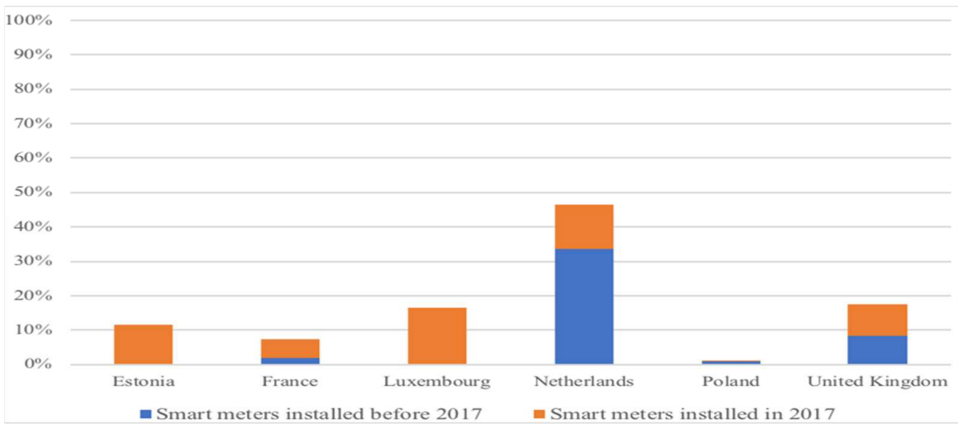

Figure 8. Total gas meter penetration in selected European countries (before and in 2017). Source: own elaboration on [22] database.

The Hungarian case is very peculiar since the transmission system operator has interconnection points with Slovakia, Ukraine, Romania, and Croatia, a unidirectional inlet point from Austria, and a unidirectional exit point to Serbia, serving a large part of Central Europe via a natural gas pipeline. In 2017, Hungarian SMEs registered the highest number of installed meters (3,500,000), following the Natural Gas Act XL of 2008 that enabled gas meters. The United Kingdom is the first country for household gas meter deployment (22.594.329), as a positive outcome of the parallel legislative legal provision for electricity and gas. A recent report evaluated the increase in EU gas meters' penetration rate in 2020 to be around 33%, with total annual shipments of 6.5 million units and a stable demand until the conclusion of several nationwide rollouts [66].

Italy, the United Kingdom, France, and the Netherlands are the main countries that registered the highest number of gas meter installations. Italy remains the largest market in 2020, with yearly shipments of 2.4 million units, while France performed 2.0 million units. After multiple delays, the UK market is expected to gradually ramp up smart gas meter installations to reach over 3 million units by 2025. In addition, some countries use the same wireless interface of intelligent electricity meters for reading gas data. Moreover, a hydrogen strategy for a climate-neutral Europe is capturing a rapidly growing attention instead of gas; it does not emit CO_2 and almost no air pollution when used. Although at the beginnings, hydrogen reached peaks of interest, it did not bloom. Today, the rapid decline of renewable energy costs, technological developments and the necessity to reduce drastically greenhouse emissions, are giving a second opportunity.

5. Conclusions

In the post-COVID-19 crisis world, a green recovery calls for long-term commitments and policies involving advanced and emerging economies. The goal is to re-work investment strategies and fiscal action towards a new, more sustainable paradigm. In short, boosting a green recovery, green culture and sustainable infrastructures become priorities. Current situations show, even more intensely, the greater speed and depth of the changes needed to fight climate change, the impacts of which are still unevenly distributed around the world. Climate change will significantly affect built environments, energy demand, and design.

The recent Glasgow Climate Conference (COP 26 negotiations) reaffirmed the emergent need to limit global warming, end fossil fuel financing, and achieve zero emissions by 2050. The eco-transition can no longer be postponed, although, in practice, it remains a "dead letter" in many respects. However, to fully understand the dynamics underway and the future of the energy market and its structures, to ensure that the world's energy supply is not under threat, it is essential to consider the recent advancement of China, as an energy leader, and the growing importance of many African and Asian states as key players in the sector.

Recent turbulence in international energy markets has determined, not only in Italy, a significant increase in the prices of electricity and, in general, of energy raw materials. In October 2021, due to the high volatility of these sectors, gas prices rose by 400% compared to April, also pushing up electricity prices (+200%). The new scenario might have uncertain effects on the decarbonization and energy transition process. For example, to avoid the risk of recent blackouts and keep the price of energy constant as much as possible, Italy is willing to finance new gas-fired power plants that will be in operation for the next 30 years. This is a fundamental paradox where, to get out of fossil fuels, the environmental policy strategy would still be "to resort" to fossil fuels, such as gas. This is quite far away from the COP 26 goals of reaching a green and inclusive economic recovery and supporting low-carbon development models worldwide.

Environmental quality remains central to our health, economy, and well-being. However, it faces several serious challenges, not least those of climate change, unsustainable consumption and production, and various forms of pollution. According to the European Third Energy Package, the introduction of intelligent energy design in smart metering systems is one of the core elements in current European policies targeting the environmental sustainability and the competitiveness of gas and electricity markets. The research activities' effect on sustainability transitions and regional diversification in the digital era is also due to the high-speed digitization and standardization of some services.

The vision for a green economy still asks for high goals. Opposing climate change requires, primarily, close international coordination and a strong and consistent political determination. National governments are the only institutions that can provide incentives for 'green' investments, enforce carbon taxes and fix regulations regarding the maximum amount of emissions allowed. The global goal largely depends on governments' willingness to embrace and implement the tools of a green economy fully. Traditional indicators of economic growth (GDP) dismiss externalities connected to the use of natural resources (among which are pollution and the loss of ecosystems), and the pricing of natural capital [67]. Therefore, it is necessary to find a mechanism to support green technological activities in a self-sustaining dynamic.

The economic policy debate has identified several areas within the I4.0 paradigm where designing intelligent energy systems is expected to yield relevant benefits. SMs lead to energy saving and accomplish efficiency both for the network operators, who want to digitally compete, and for the final users [68]. However, the design, implementation, and maintenance of the SM system still show dilemmas, mainly related to the high initial investment required. In a regulated market, it is presumed that there are no incentives to take risks. The situation is different in a liberalized market where risks are calculated and weighed. The adoption of common national and international policies, laws, and standards within a close international coordination framework would reach this goal.

At present, the time is not ready yet; a cost-benefit comparison, while positive at the country level, thanks to the ever-increasing focus of individuals and firms on a green sustainable culture, is not still possible at a meso-level. Smart grids for energy are quite recent. Unfortunately, the main limitations of the suggested analysis concern the lack of detailed statistical information. Nevertheless, they could be useful to test the proposed theoretical model driving governmental institutions towards a shared managerial sustainable vision. Among the observed European countries, households and firms still show immaturity and lack knowledge about the energy market structure and its operability. Thus, policymakers might support SMs through regulation and by educating people, instilling new green cultural skills through hourly rates, complete information on supplier change, and strong legislation on privacy and data protection, thus favoring social acceptance.

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