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Assessing the societal impact of smart grids: Outcomes of a collaborative research project

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A B S T R A C T

Assessing the societal contributions of research is not simple, especially for research projects that produce outputs with low technology readiness level. This paper analyses the potential societal impacts of research resulting in technologies with low maturity, but with the potential to be further developed in the long-term. It uses the case of the ESGRIDS (Enhancing Smart Grids for Sustainability) collaborative research project and its outputs aimed at enhancing smart grids for sustainability. Data was collected from the four participant research teams through two sequential questionnaires about technologies' state of development and expected long-term societal effects. Among the main results, we underscore the influence of individual perceptions and organisational contexts over the process of eliciting future developments. The analysis of technologies' status, barriers for market uptake, and potential future developments was translated into a technology roadmap, which outlined the time-dimension for technology maturity evolution and implementation impacts. The technologies developed within the ESGRIDS project can contribute to support consumers' energy decision-making and to encourage them to have a more active role in the electricity market. Those technologies can also create job opportunities associated with the development of new products and services, and contribute to mitigating climate change by promoting the use of renewable energies thus reducing carbon dioxide emissions, in addition to contributing to energy cost reduction by optimizing the use of supply and demand resources. Future research avenues point towards a methodology that can be used for assessing the potential impacts of research projects with low technology readiness outputs.

1. Introduction

Global spending on research and development (R&D) reached record levels in 2020, around 2 trillion dollars or 2.5% of the world GDP [1]. High expenditures have been justified by the positive impact that research brings to society [2]. However, measuring the impacts of science, technology and innovation is challenging [3]. This has motivated researchers and research programs to determine how scientific research offers palpable benefits to society, turning the foci from an internal research community to a much broader and heterogeneous group of stakeholders [2]. As a well-known example of these efforts, one can cite the Research Excellence Framework (REF), a system developed for assessing the quality of research in the United Kingdom (UK) [4]. As reviewed by Smit and Hessels [5], other societal impact assessment methods exist, including the Payback Framework [6], the Science and Technology Human Capital, the Public Value Mapping, Monetization methods, SIAMPI/ERiC model [6], the Flows of Knowledge Framework [7], Contribution Mapping [8], ASIRPA [9], and the Evaluative Inquiry. These authors evaluated the interaction mechanisms employed by methods through which societal value can be created, namely, linear, cyclical, and co-created models. They also underscored the importance of having discussions about knowledge production processes in an individual-case base when selecting appropriate assessment methods.

Sivertsen and Meijer [10] also mentioned the Research Contribution Framework [9] and the IMPACT-EV [9] methods. Nonetheless, since the societal impact is often a criterion in the *ex-ante* evaluation process for funding entities, the authors stated that all mentioned frameworks focus on the end side of research performance: the interaction with society

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[10]. They argued that, besides evaluating the impacts of research, organizations should be also able to evaluate their own ability to continuously interact and learn from new research [10]. This aspect was also supported by Fecher and Hebin [11] when collecting evidence from academic researchers. These authors concluded that, even though most researchers were generally in favour of impact evaluation, few believed their institutions prioritized societal impact and reached relevant stakeholders in society [11]. In addition to these frameworks, the potential use of big data and analytics [12], interdisciplinary reports [13], and ways to deal with the dilemmas of research impact assessment [14] has been also discussed in the literature. However, regardless of approaches and problematics, societal impact measurement remains relevant for national evaluation programmes and key for attracting public funding and support for basic research [15].

The relevance of addressing the societal impacts of interdisciplinary research projects has become even more pronounced with the energy transition and the pursuit of the Sustainable Development Goals (SDGs) [16]. Energy access and climate change concerns represented by SD7 and SDG13, respectively, have prompted investment research towards more sustainable and reliable energy systems. Among technologies to achieve this end, the development of Smart Grids (SG) has been deemed essential to help Renewable Energy Sources (RES) reach their full potential and contribute to energy security and resiliency issues that will be exacerbated by climate change [17]. In addition, those technologies can create new opportunities within energy-related value-added services [18]. Focusing on the electricity grids, SG contribute to a new paradigm of power grids with decentralized generation, distributed control and more active involvement of consumers/prosumers [19]. SG are expected to encourage and facilitate the effective transformation of electrical power grids to respond to increasing electricity demands, reliability and sustainability concerns [20,21]. Apart from country-specific electricity generation mixes, many fossil-fuel-dependent countries and regions are expected to benefit from SG and RES integration as pilot projects have been developed globally [17]. SGs can also play a key role in supporting consumers' participation in the electricity market [22]. This is particularly relevant given the principles established by the recent European Union's (EU) electricity market directives (EU Directive 2019/944) calling for the need to ensure that final customers are entitled to act as active customers and can participate in the electricity market [23]. For this purpose, the integration of communication technologies into the electrical power grids can lead to more reliable and efficient management of inclusive electricity markets [24].

Nonetheless, even though a lot of research is undergoing for the development of SG and wide benefits are expected, further developments are still required for improving and implementing the concept [20] due to many technical, regulatory, economic, and societal barriers. The transition to SG infrastructures will demand deep changes in the traditional electric power grid and require new technologies, new market structures, new services, and new social processes [25]. Meadowcroft et al. [26], for instance, evaluated the socio-political changes resulting from SG deployment in Canada and the United States (US) and critically pointed to the existing gap between envisioned benefits and practical deployments of smart meters. Privacy and justice issues as a result of SG have also been raised [27]. If, on the one hand, SG can facilitate distributed electricity generation and transparent billing, on the other hand, it is arguable whether they contribute to a more accessible, equitable, and democratic energy system [27]. Regarding demand side management, Goulden et al. [28] underscored the influence that consumer engagement and information levels may have in different configurations of SG.

In this context, regulation, new business models, demand response (DR) programmes, and affirmative action policies are essential for encouraging the deployment of next-generation power grid architectures [29], as it is the assessment of societal impacts of SG. Still, Bigerna et al. [30], when comprehensively reviewing the theoretical and applied literature on the topic, concluded that half of papers considered SG technical features only. The other half did consider socio-economic aspects, such as RES deployment, social perception, system and electricity costs, cyber security, regulatory features, and privacy issues [30]. Therefore, even though SG have the potential to make a significant and comprehensive contribution to energy and environment sustainability [31], research is still needed to make sure that technologies are developed in the most useful and publicly desirable manner [32].

Within the scope of publicly funded research projects in the field of the energy transition, the potential of SG, and the growing concern of societal impacts of research, the present work aimed to evaluate the potential societal impacts of SG technologies with low Technology Readiness Level (TRL) resulting from research projects and how to identify their expected contributions. For this purpose, the Research and Development (R&D) project ESGRIDS for the development of SG technologies was assessed. This assessment was done through the application of two questionnaires that prompted: first, the selection of most relevant technologies developed by the research teams according to the TRL; second, the ranking of social, environmental, economic, and technical performance indicators; and third, the identification of barriers and potential societal contributions of the technologies developed. This information was then framed within a Technology Roadmap aimed at a time-based representation of ESGRIDS technologies' development towards a higher TRL, which can be used to better realize the potential societal impacts of those technologies Accordingly, the remainder of the paper is organised as follows. Section 2 describes the ESGRIDS project. Section 3 covers the development of research impacts and the use of performance indicators to assess them, as well as the use of TRL. Section 4 summarises the methods for questionnaire application and analysis, while Section 5 presents the results. Section 6 discusses the results and frame them into a Technology Roadmap. Finally, Section 7 concludes the paper with main findings, limitations, and implications for further research.

2. The ESGRIDS project

This paper addresses the case of the collaborative research project ESGRIDS - Enhancing Smart Grids for Sustainability (http://www.esgrids.eu/), a publicly funded Portuguese R&D project that took place from January 2017 to December 2020. The project ESGRIDS was aimed at developing novel solutions and technologies for the future challenges of the smart electrical power grids within three main aspects, the distribution grid, the market, and the energy end-user. Its consortium comprised four academic institutions, namely, INESC TEC (coordinator, University of Porto), INESC Coimbra (University of Coimbra and Polytechnic Institute of Leiria), C-MAST (University of Beira Interior), and ALGORITMI Research Centre/LASI (University of Minho). Further description of research teams is presented in Table 1. These teams gathered annually in workshops where developments were shared and discussed among participants. Within the project scope, models, computational applications, and laboratory prototypes were developed in the topics of DR, optimization of power grid operations under uncertainty and instability, and new business models involving retailers and Distribution System Operators (DSOs).

3. Theoretical background

3.1. Societal impacts of research

Even though the concepts of 'outcome' and 'impact' are used interchangeably, there are important differences between them. Outcomes can be understood as a middle step toward a long-term impact [33], whereas an impact relates to the end achievements of a research project and implies certain judgment about what is relevant for society and stakeholders [33]. Particularly, the European Commission (EC) [34] distinguishes *outputs* as related to direct products from the actions;

Table 1
ESGRIDS research teams.

Research team	Role in the ESGRIDS project	Further information
INESC TEC - University of Porto (Coordinator)	Development of advanced concepts and smart algorithms for supporting distribution grid operation, efficient energy end-use, and new market models.	http://www.inesctec.pt/
INESC Coimbra - University of Coimbra and Polytechnic Institute of Leiria	Design and development of innovative models, algorithms and computational implementations for efficient energy use, and a reliable and sustainable power system.	http://www.inescc.pt/
C-MAST - University of Beira Interior	Development of market simulation models to study the influence of new business models and market players in the market-clearing process and rules.	https://www.ubi.pt/entidade/C-MAST
ALGORITMI Research Centre/LASI - University of Minho	Development of power electronics prototypes for power quality improvement and EV battery charging under distributed energy resources deployment, and modelling and simulation.	https://algoritmi.uminho.pt/

results as related to benefits for direct beneficiaries from their participation; and *impacts* as wider effects of the action. Alternatively, the most widely used definitions [35] are those of the Organization for Economic Co-operation and Development (OECD) [36], in which: *outputs* are products, capital goods and services resulting from a development intervention; *outcomes* are likely or achieved short-term and medium-term effects; *impacts* are positive and negative, long-term effects produced by a development intervention, directly or indirectly, intended or unintended; and *results* is a term that may be used to refer to all three items.

For the EU Horizon 2020 (H2020) programme, an *ex-ante* research mission-oriented programme, impacts were categorized into three main categories: 'scientific', 'innovation/economic', and 'societal' [34]. Scientific impacts refer to the project's contribution toward excellence in science, the emergence of new technologies or fields of science, and the establishment of knowledge networks. Innovation/economic impacts comprise advancements in industrial innovation capabilities, technological development, and diffusion of innovation. Lastly, societal impacts would positively impact the quality of life, health, environmental protection, social inclusion, social acceptance of science and innovative solutions, and support policymaking aligned with citizen needs [34].

Particularly, societal impacts can be harder to evaluate than scientific impacts. While there are comprehensive approaches to evaluate economic impacts through monetary outcomes [3] and scientific impacts through bibliometric analysis and citations, these approaches do not appraise the contributions of research projects to society [15]. Furthermore, determining causal relationships between research and its societal impact is not a simple process. The variety of existing societal assessment frameworks and different approaches employed by them [5] show there is no clear consensus on best practices to be followed [37]. While the evaluation process requires time after the end of the research project [38], it becomes harder to attribute to a single research project a certain impact on society [39]. This has been referred to the "attribution problem" [40], i.e., the difficulty of determining what is the specific contribution of an intervention to outcomes against all other possible factors that could have influenced them. The task of determining future impacts becomes even more challenging when researchers are asked to do so for technologies in early stages of development, i.e., low TRL (Section 3.3).

Nevertheless, the concern over the needs of society is one of the pillars of responsible research and innovation (RRI) [41] and one of the H2020 priorities, as it promoted investment in research and innovation to benefit of citizens [42]. For that purpose, H2020 has a methodology of impact evaluation using a time-sensitive impact pathway including short, medium, and long-term impacts, containing both qualitative and quantitative information [43]. Likewise, literature on logic models can provide insights concerning different time-horizons and sustainability spheres [44]. Progress towards impacts was set to be monitored through indicators including headline indicators, such as share of GDP invested in research, and key performance indicators (KPIs) defined according to the programme objectives. The use of indicator-based approaches can facilitate the assessment of societal impacts, in particular for mid-term and long-term evaluations [42], but it should be recognized that, in face of the project diversity, methods and indicators need to be adapted to the unique context on a case-by-case basis [39].

3.2. Performance indicators

According to the EC [42], impact indicators represent what the successful outcome should be in terms of impacts on the overall economy and society beyond those directly affected by the intervention. The EC also specified a list of KPIs to be considered for assessing the impact of H2020 programme [42]. From a research perspective, indicators should also provide a solid and coherent basis for the monitoring and evaluation system. Indicator-based approaches identify variables that measure the achievement of impacts thus providing evidence that research was either sufficient or not in generating impact [39]. For the case of SG developments, Pramangioulis et al. [45] underlined the importance of KPIs for the evaluation process of technologies, as they indicate the research degree of success and its potential development. Likewise, Kourkoumpas et al. [46] argued that indicators are a pre-requisite for the environmental and energy assessment of RES systems integrated with energy storage systems (ESS). The authors recognized that a wide range of specific indicators assessing the energy and environmental performance of RES-ESS exist and proposed a limited number of best fitting and easily adaptable list of KPIs. These KPIs included, for example, "Share of RES" and "CO_2 avoided emissions". In Gouveia et al. [47], a set of KPIs is proposed to evaluate the benefits of the research project InovCity for four main criteria related to energy efficiency (e.g. "Peak to non-peak transfer", "Fraud detection rate"), operations efficiency (e.g. "O&M cost reduction", "Meter reading and orders cost reduction"), quality of service (e.g. "Quality of supply", "Customer satisfaction") and emerging technologies (e.g. "EV integration", "Increase in micro generation integration").

In Li et al. [48], a quantitative approach was proposed to weight and select KPIs for district and building energy performance analysis. Among the selected KPIs, there were "Accuracy of energy supply and demand prediction", "Renewable energy share", "Storage system efficiency", "Consumers' participation", "Energy loss reduction" and "Peak demand reduction". Also, the Eurostat [49] presented a compilation of indicators on energy, transport and environment derived from national data for the 28 EU Member States, including, for example, "Energy imports" and "Energy use". Pramangioulis et al. [45] presented a list of 45 KPIs that can be used to assess the performance of SG related technologies and their impact on society. Moreover, the Smart Grids Task Force [50] proposed a set of KPIs categorized in six policy criteria related to sustainability, grid capacity, grid connectivity and access, security and quality of supply, efficiency and service quality and cross border electricity markets.

The examples above, although far from being exhaustive, aimed to show the diversity of indicators that may be considered in energy-related projects and the need to follow a case-by-case approach when selecting KPIs. Table 2 summarises a short list of social, economic, environmental, and technical KPIs obtained from the reviewed literature and considered suitable to evaluate SG technologies. KPIs related to the quality of the (specialized or non-specialized) employment were not

Table 2
Social, environmental, technical, and economic KPIs for SG technologies assessment.

References	KPI	Definition
Social indicators		
[47]	Customers' satisfaction	Increase in consumers satisfaction with their energy supplier
[48]	Consumers' participation	Increase in consumers participation in demand response management programmes
[47]	Fraud detection	Improvement of fraud detection in the electric sector
[42]	Employment rate	Increase in the employment rate
Environmental indicators		
[46]	Reductions of GHG emissions	Reduction of GHG emissions (e.g., by energy savings and renewables use)
[47]	Energy efficiency	Improvement of the energy efficiency of electric appliances
[51]	Fossil fuel use	Reduction of the use of fossil fuels
Economic indicators		
[45]	Energy imports	Reduction of energy imports.
[49]	Energy cost	Reduction of energy cost (e.g., by reducing or shifting the energy use)
Technical indicators		
[48]	Energy losses	Reduction of energy losses in the distribution system
[51]	Peak-load	Curtailment of the peak power by load-shift or load-shedding
[46]	Share RES	Increase in the share of renewable energy in the generation of electricity
[49]	Energy use	Energy consumption reduction in different sectors (e.g., residential and industrial sector)
[47]	Electric vehicles integration	Increase of the number of electric vehicles in circulation over time
[47]	Distributed generation integration	Increase in electricity production in small and decentralized scale
[47]	Quality of energy supply	Improvement in quality of service for the consumers
[51]	Demand response (DR) uptake	Increased acceptance of DR programmes by the consumers and/or market operators
[48]	Accuracy of supply and demand prediction	Increase accuracy of the systems (reduction of the demand and/or supply forecast error)
[51]	Energy storage development	Development and increase in the use of storage technology

addressed for the sake of simplicity.

3.3. Technology readiness level

The TRL scale was developed at the National Aeronautics and Space Administration (NASA) in the 1970s with the purpose to evaluate technology maturity in a standard manner [52]. Since then, it has been applied to a wide range of projects in industries such as energy, transportation, and electronics [52], being used to assess a technology from when it is simply a research finding (low TRL) until fully integrated into a system (high TRL). The scale has 9 levels of technology readiness as summarised in Table 3 and it has also been included in the assessment of H2020 research outputs [53]. Considering that many research projects in the energy transition field are directed to the development of new technologies, the TRL scale comes handy not only to assess technical performance but also to indicate at which stage (i.e., when) broader societal impacts can be expected. Nevertheless, the lower the maturity of a certain technology, the harder the task of identifying potential societal impacts, i.e., linking research outputs to impacts. Yet, the latter is key for attracting public funding [15].

The TRL has been also used to assess SG technologies. Liu et al. [54], for instance, build their own technology maturity assessment method inspired by the TRL scale. Their framework, however, relied on three aspects: social and environmental impacts, economic value, and technical performance, being the latter the most detailed one. They applied their framework to evaluate the case of an EV charging and discharging technology implemented in a city from 2012 to 2014. Kirkham and Marinovici [55] also proposed a TRL scale applied to SG technologies, the Smart Grid Level (SGL). The authors did not consider technologies with SGL or TRL below 5, as they focused on a utility's view over SG technology maturity, and technologies with low TRL would not be ready for deployment yet. Focused on the discussion over low TRL SG technologies, Loureiro et al. [56] opened a discussion over works related to peer-to-peer trading (P2P), multi-agent systems, and blockchain technology. Crosbie et al. [57] focused on demand response technology readiness levels (DRTRLs) to encourage participation in DR energy management solutions. Lastly, Flore et al. [58] used a 10-step procedure to develop migration paths for SGs, including the development of RE integration, load, and Information Communication Technologies (ICTs). One of the mentioned steps comprised the evaluation of development maturity, which was considered to build SG roadmaps.

Table 3
TRL scale and definitions [53].

TRL	Definition
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

3.4. Technology roadmaps

Roadmaps can take various forms, being the most common a time-based chart comprised of three major layers [59]. Specific technology programs or developments (lower layer) are linked to future products and services (middle layer), and then to market or business opportunities (upper layer). A technology roadmap is used as a tool for technology integration, business operation, as well as strategic planning, providing a visual tool that allows identifying the potential challenges, opportunities, and risks, which may affect the chosen strategy. As Moehrle et al. [60] stated, a technology roadmap can take a range of graphical forms to suit the situation in terms of purpose, available information, resources, and desired use.

Although roadmaps can be useful to represent a collective vision of technological futures and anticipate some outcomes, they can hardly predict them [61]. Nonetheless, several studies have demonstrated the potential advantages of technology roadmapping, such as providing guidelines for policymakers, establishing goals and targets, assessing promising technology alternatives, identifying marks, barriers, and improving communication and coordination for technology development [62,63]. Examples of applications in the field of the energy transition include a technology roadmap to deal with GHG emissions from livestock in Germany [64], transformation of cities into smart sustainable ones [63], smart city developments [65], and SG transitions [58]. Even though roadmaps are frequently associated with a particular technology, product, or market, we use this time-based framework to better realize the full technology potential to contribute towards societal impacts (Section 6.3). In this proposed technology-time based approach, ESGRIDS research outputs addressing low TRL technologies (lower layer) will be linked to the future commercial stage through identification of potential barriers for the products or services (middle layer) and to the anticipated impacts (upper layer).

4. Materials and methods

The information used to analyse the societal impacts and draw ESGRIDS technologies roadmap was elicited through two different questionnaires (presented in Appendices A and B) applied to academic researchers participating in the project. Questionnaires were constructed based on two prior meetings realized with researchers from the ALGORITMI team. The first meeting aimed to get familiarized with one of the technologies developed by the team, the EV battery charging system. The second meeting performed with some researchers of the research team aimed to clarify the purpose of the research and the pertinence of the questions to be asked in the questionnaires.

Both questionnaires were sent to the main researchers responsible for coordinating the four research teams (INESC TEC, INESC Coimbra, C-MAST, and ALGORITMI). The authors made themselves available to answer any doubts researchers might have about the questions and assist them with the application supporting the questionnaires. The research team coordinators were asked to discuss the questions within their research teams and provide answers to the questionnaires within two weeks. The way in which the research teams gathered information to answer both questionnaires was not methodologically defined and was let open to the research teams choosing the technique that suited them best.

The first questionnaire (Appendix A) was sent to the ESGRIDS consortium partners in May 2019 and gathered information about the technologies/outputs developed in the scope of the project (Table A1). The questionnaire also prompted the four participant research teams to select the two most relevant technologies/outputs and indicate their target users, expected benefits, novelty, and expected TRL at the end of the ESGRIDS project (Table A2). A guideline for TRL score was also included in the questionnaire (Annex A.1) and was used to aid the selection of most relevant technologies (i.e., higher TRL).

After receiving and analysing the results of the first questionnaire, a second questionnaire was prepared and sent to researchers in June 2019 with responses being gathered in July 2019. This second questionnaire was composed by two sections and aimed to assess the expected contribution of the two most relevant technologies selected in the first questionnaire. In the first section, social, environmental, economic, and technical KPIs listed in Table 2 were presented (Table B1). The academic researchers were then asked about the importance of each KPI for the technologies deemed most relevant in the first step. This was measured using a 5-level Likert scale ("Not important at all"; "Not necessarily important"; "Important sometimes"; "Important"; "Extremely important") [66]. In the analysis of these results, for each technology, the relevance index (S_k) was calculated as the average value within each of the four KPI pillar (k) (i.e., social, environmental, economic, and technical) and the Global Relevance Index (GRI), as presented in equations below (Eqs. (1) and (2)).

$$S_k = \sum_{i=1}^{n} \frac{x_i}{n} \tag{1}$$

$$GRI = \sum_{k=1}^{4} S_k \tag{2}$$

where n represents the number of KPIs and x_i the value attributed to KPI_i in the Likert scale (i.e., one to five) within one KPI pillar. GRI is the sum of S across social, environmental, economic, and technical pillars (k). S was used to obtain a measure of the overall relevance of each pillar within each technology.

The second part of the questionnaire comprised nine open questions to obtain more detailed information about the perceived contributions of the technologies to society and barriers for their diffusion (Table B2). The contribution-related questions were based on H2020 societal objectives [67] linked to the following energy issues: (i) secure, clean and efficient energy: (ii) smart, green and integrated transport; (iii) climate action, environment, resource efficiency, and raw materials. The evaluation of open questions took place through content analysis processes.

5. Results

5.1. Technology inventory

Table 4 shows the results of the first questionnaire application containing the technologies considered as the most relevant by each research team, expected benefits, target users, novelty, and TRL at the end of ESGRIDs project.

5.2. KPIs relevance

As a result of the second questionnaire application, it was possible to assess the perception of relevance (S) of each research team concerning social, environmental, economic, and technical KPIs (Table 2) and technologies GRI as illustrated in Fig. 1.

Accordingly, Fig. 2 shows the average value obtained for all KPIs across the eight technologies considered. The average value of importance for each pillar was: economic 3.8, environmental 3.7, technical 3.2, and social 2.7.

5.3. Barriers and expected contributions

The answers to the open questions contained in the second part of the second questionnaire (Appendix B) were then analysed. Barriers and expected contributions of each technology/output were grouped under equivalent concepts as displayed in Table 5.

6. Discussion

6.1. Relevance of societal performance indicators

As it can be seen in Fig. 2, economic KPIs were seen as the most relevant, followed by environmental, technical, and societal. The indicator "renewable energy" was repeatedly highlighted suggesting the perceived importance of the technologies developed to support a large-scale integration of renewable energy sources in the energy generation mix. Technical indicators related to "energy losses", "accuracy of the system", "demand response uptake", "peak-load", were also frequently mentioned. On the other hand, societal KPIs had the smallest relevance across all technologies being the indicator "consumers' participation" the highest among societal KPIs (Fig. 2). As such, we may infer that ESGRIDS researchers expect to contribute towards one of the main barriers for DR development, namely the difficulty to engage consumers [57]. In addition to increasing customer satisfaction and consumer participation, the contribution to employment levels was also mentioned for a few technologies, such as the EV battery charging system, but with lower importance assigned.

The lower relevance attributed to societal impacts (Fig. 1) can be explained by some factors. First, the project nature and objectives of finding new methodologies and technological solutions capable of facing the future technical challenges of the electrical power systems. Second, the techno-economic perspective of participant research teams given the engineering background of most researchers [11]. Lastly, due to the low TRL of technologies (Table 4), primary concerns tend to be related to their economic feasibility and contributions towards cost-reduction aspects given the need to reach field trial and meet the stakeholders' expectations [55]. Moreover, the technologies that attributed higher scores for societal KPIs (S = 3.75) were related to: DR in the distribution level, which targeted market and network operators; EV battery charging system, which targeted automotive manufacturers; and UPQC-RES-ESS related to RES and ESS expected to be used by companies with specific power quality requirements. Conversely, all societal KPIs for the RES forecasting technology designed to provide

Table 4
Status of ESGRIDS technologies.

Technology	Description	Type	Benefits	Target users	Novelty	TRL	Refs.
DR in the transmission level	New model for scheduling of DR in both day-ahead market and real-time market proposed	Model	Cost-efficient operation of the transmission network	Market and network operators	New wholesale market schemes to implement DR	3	[68]
DR in the distribution level	New model for trading DR among customers and aggregators in a competitive way	Model	Cost-efficient operation of the distribution network	Market and network operators	New retail market schemes. to implement DR	4	[69]
RES forecasting	Forecasting model that combines geographically distributed measurements from power plants and ensures data privacy from multiple owners	Model	Improved accuracy in renewable energy forecasting	Renewable energy producer, system operators, prosumers, energy traders	Data-privacy and distributed learning	4	[70]
Distributed Optimal Power Flow	Distributed multi-period formulation for the three-phase unbalanced Optimal Power Flow problem	Model	Maximized integration of distributed energy resources; local management of technical constraints in a distribution grid with low communication requirements	System operators, local energy communities	Distributed optimization; multi-period optimization	3	[71]
Semivectorial bi-level programming approach for defining pricing schemes	Semivectorial bi-level programming approach to model the interaction between the electricity retailer and consumers, assisting the retailer in defining time-differentiated pricing schemes	Model	Higher profits for retailers	Electricity retailers	Algorithms used to solve the bi-level problem	4	[72]
Raspberry Pi	Raspberry Pi (low cost) microcomputer solving mixed-integer linear programming (MILP) models and running meta-heuristic algorithms to control loads	Prototype	Energy service provision cost reductions without jeopardizing comfort	Homeowners	Implementation of a metaheuristics-based energy management system on a low-cost Raspberry Pi microcomputer	5	[73]
EV battery charging system	Electric vehicle (EV) battery charging system with different operation modes	Prototype	Bidirectional operation with the power grid	Automotive manufacturers	Operation with innovative modes as: (1) Home-to-vehicle (H2V); (2) Vehicle-to- home (V2H); (3) Vehicle-for-grid (V4G)	4	[74–76]
UPQC-RES-ESS (Unified Conditioner Interfacing a Renewable Energy Source and an Energy Storage System	Unified Power Quality Conditioner interfacing RES and ESS	Prototype	Improvement of the power quality of the power grid and, simultaneously, production and storage of energy	Companies with specific requirements of power quality	Development of a new topology of power electronic converter and its algorithms, interfacing RES, energy storage and, simultaneously compensating power quality problems of voltage and current	4	[77–79]

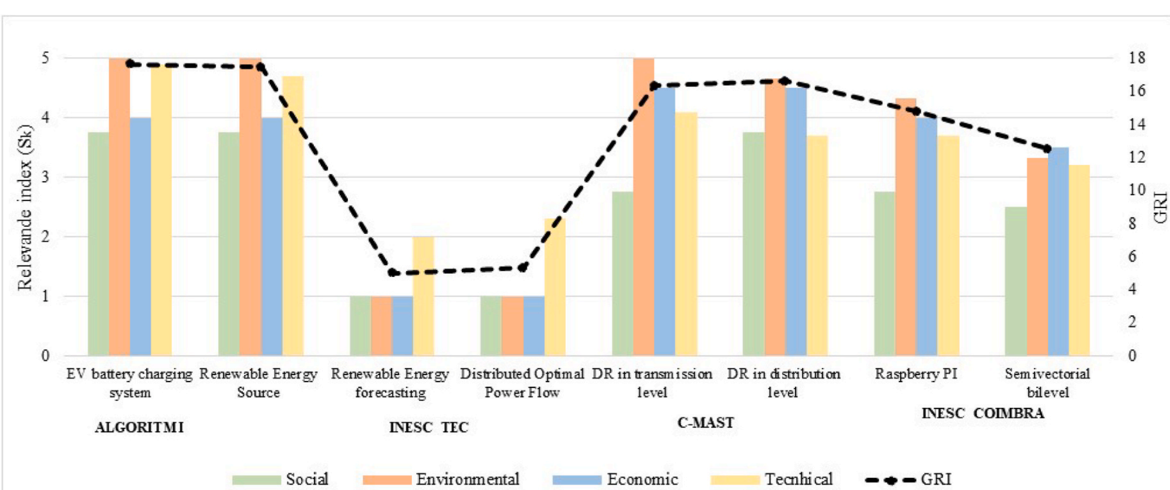

Fig. 1. Social, environmental, economic, and technical Relevance (S) of selected KPIs and Global Relevance Index (GRI) per technology and research team.

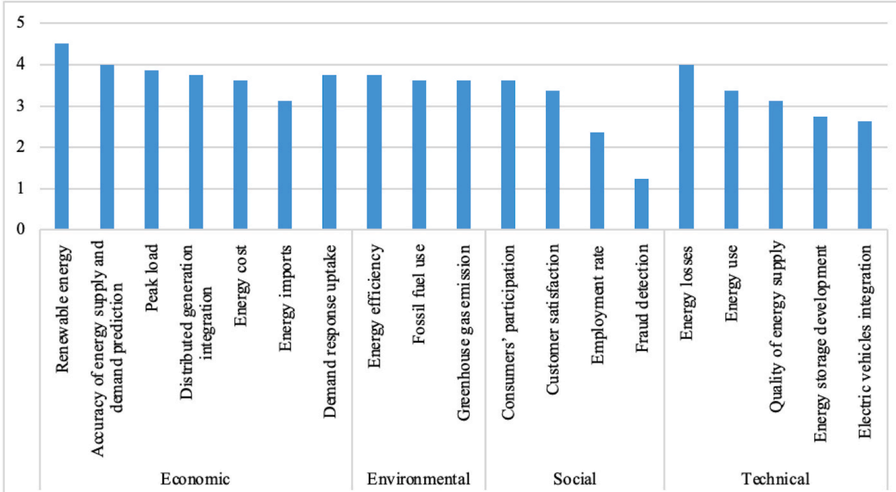

Fig. 2. Average value of KPIs for the eight most relevant ESGRIDS technologies.

accurate data for RE generation and the "Distributed Optimal Power Flow" model targeting distributed energy integration and management at local energy communities had scores 1 in the Likert-scale (i.e., "Not important at all"). Both technologies were developed by INESC TEC. Therefore, besides obvious differences across technologies and their target users that can explain dissimilar societal KPIs relevance, this gap in attributed relevance can be also explained by different perceptions of societal impacts by the research teams. As Fecher and Heber [11] discussed, researchers' societal goals differ between their disciplines and the types of organization that they work at. Therefore, these results highlight the influence of not only academic researchers' individual perceptions but also organizational cultures and values [11], as well as underscore the need for a standardized approach to elicit potential societal impacts of SG technologies with low TRL.

6.2. ESGRIDS expected contributions

When explicitly asked about barriers for the market uptake of technologies, researchers highlighted economic, regulatory, technical, and social barriers (Table 5), among which: high costs of storage systems, reduced battery autonomy and lifetime, lack of adequate infrastructure and business models, specificity of different distribution areas, lack of industry and market regulation standards, privacy issues, time-requirements for technology use, and consumers' unwillingness to participate. Particularly, end-users' perception and unwillingness to participate were identified as obstacles to develop the technology for DR in the distribution and transmission level, Raspberry Pi, and semi-vectorial bi-level programming approach for defining pricing schemes. Even though technical barriers are key, normative and governance aspects should not be overlooked as they remain great obstacles for the implementation of alternative pathways and associated technologies [80].

The social acceptance of SG technologies and demand-side measures has been already mentioned in the literature as key aspects to consider when evaluating their inclusion in power systems [18,81]. However, Kim et al. [82] also referred to the uncertainties in public-related issues with respect to energy and to the challenges of considering public perception into plans and policies. Although privacy-related issues related to data use have been already linked to SG [12,27], they are commonly absent from analysis presented in research papers [30], being less evaluated than cyber security, a topic that researchers did not mention as a barrier. Additionally, the time required for concluding a complete charging process through the EV battery charging system developed can be a balancing factor for technological uptake. As Öhrlund et al. [83] observed, consumers are more likely to engage in new behaviours when required changes do not cause any inconvenience, i.e., limit users' time flexibility. Summed to social barriers, the deployment of these pricing schemes and DR technology requires market changes and infrastructure investments [21], as noted by researchers in Table 5.

Regarding contributions, time-based electricity pricing for DR programmes would contribute to reducing GHG emissions and fossil fuels, whereas programming approaches to pricing schemes would reduce energy use and increase energy efficiency by influencing an hourly profile of electricity use. These aspects are in accordance with the literature since these pricing schemes are expected to promote electricity consumption in off-peak times, encourage investment in RES [84], and play an import role on cost and emissions reduction [85] and fossil fuel requirements [86]. Other ESGRIDS technologies are expected to technically contribute mainly to RES generation, power systems quality and efficiency, energy efficiency, and peak-load shaving profile. In societal terms, Raspberry Pi would reduce electricity prices and the Distributed Optimal Power Flow model would improve the grid performance, whereas DR in the distribution level could increase customer satisfaction by lowering the electricity bill with jeopardizing comfort. These aspects have been also referred to in the literature on SG potential benefits (e.g., customer satisfaction [18,45], quality [17], electricity prices [17,27,87]). Nevertheless, SGs are not always linked to positive impacts on electricity prices as shown by Milchram et al. [27]. In the UK, for instance, energy suppliers pass the cost of SG investments to customers by raising energy prices [27].

Increased customer participation was mentioned for the technologies: DR in transmission level, Distributed Optimal Power Flow, Semi-vectorial bi-level programming, Raspberry Pi, EV Battery Charging System, and UPQC-RES-ESS. Actually, promoting the active participation of end-users in market and grid operations is one of the main objectives of SG-related projects [22,28,45]. Also, employment is a key aspect of fair and people-centred transitions [88,89], which has been referred to as a potential contribution of six out of the eight ESGRIDS technologies. Nevertheless, most of the mentioned job opportunities would be for skilled labour, which is a critical aspect for unemployment rates resulting from the energy transition [89].

These considerations about researchers' perceived barriers for ESGRIDS technologies market uptake and their expected contributions show a lack of uniformity and, once again, the role individual perceptions and organizational contexts play when assessing future societal aspects [11]. Diverging perspectives presented in the literature concerning the societal benefits of SG technologies can be also seen because

Table 5
Barriers and expected contribution of ESGRIDS technologies.

Technologies/Outputs	Barriers	Expected contributions
DR in the transmission level **DR in the distribution level**-	- Lack of compatibility of the structure with the market regulation. - Low interest of end-users to participate in DR programmes.	-Creation of new structure to operate smart grids. - Decrease of electricity price through peak load shaving and reduced congestion of transmission lines. - Creation of jobs through the development of a DR aggregator that requires skilled professionals. -Reduction of pollution by reducing thermal power plants use. -Improvement of DR, usually much cheaper than using thermal power plants, also considering environmental externalities. -Improvement of RES usage and better dealing with uncertainty and therefore significantly reducing emissions. -Increase of the feasibility of scheduling RES production. -Improvement of customer participation in the electricity market.
RES forecasting	-Lack of a new business model for renewable energy forecasting. -Lack of policies for data sharing.	-Improvement of accuracy of RES forecasting, with a positive impact in predictive management. -Decrease of the financial risk associated with this technology and the levelised cost of energy (LCOE) of solar and wind power technologies. -Creation of opportunities for technology exploitation by a start-up company in data science (skilled jobs). -Increasing RES use in the power system and reducing emissions.
Distributed Optimal Power Flow	-Inadequate infrastructure in terms of ICT and computational resources at secondary substation level. -Lack of mechanisms for trading flexibility at the distribution grid level.	-Improvement of flexibility from distributed energy resources when combined with smart meters and a distribution transformer controller. -Increase of RES integration and emissions reduction. -Improvement on DSO ability to plan and activate demand-side flexibility, thus fostering consumer participation.
Semivectorial bi-level programming approach for defining pricing schemes	-Unwillingness of consumers to share electricity consumption data. -Lack of adequate regulatory framework.	-Improvement of retailers' potential to increase their profits and end-users to lower their energy costs; -Reduction of imported fossil fuels fired and promote the efficient use of other energy resources by inducing off-peak consumption, thus lowering emissions; -Increase the share of RES by better accommodating supply and demand through price signals; -Improvement on the information of the benefits of DR programs and motivating retailers and end-users to participate;
Raspberry Pi	-End-user's unwillingness to accept more complex electricity pricing schemes and the automated control of key appliances. -Lack of industry standards for appliance communications and controls.	-Demonstration of an automated home energy management system's feasibility using low-cost off-the-shelf components and customized software. -Promotion of energy efficiency, energy cost reduction and energy imports. -Increase the penetration of RES by optimizing the integrated use of energy resources. -Creation of jobs around new business opportunities. -Promotion of end-users to effective participation in electricity markets.
EV battery charging system	-Reduced EV autonomy because of battery limitations. -Time required to conclude a complete charging process.	- Improvement of power quality for the grid side and energy efficiency. - Promotion of economic growth through new opportunities for companies in the energy and automotive sector. -Creation of jobs in the EV-related, power electronics, and ICT industries. -Reduction of emissions, especially when batteries are charged with electricity from RES. -Contribution to grid flexibility, RES integration, and consumers' participation in the electricity market.
UPQC-RES-ESS	-High costs and reduced lifetime of batteries.	-More efficient energy management as local storage can increase RE generation and decrease losses in energy transmission and distribution networks. -Promotion of an active participation of consumers in energy markets. -Increase of job opportunities (skilled labour) for installation and maintenance of the UPQC-RES-ESS. In case of local manufacturing, local employment and economic growth can be promoted. -Lower emissions at energy generation, but manufacturing and materials recycling can also produce emissions.

of the low TRL of many technologies in the field and the associated uncertainty. Furthermore, time remains a critical aspect when assessing research impacts [38]. In terms of attribution [40], the joint development of numerous technologies, changes in governance, consumers' roles, infrastructure, and regulations associated with the energy transition will make the process of measuring the impacts of single projects even more challenging.

6.3. Technologies roadmap

This section presents a time-based technology roadmap to frame technologies with low TRL and summarises barriers and potential contributions identified by participant researchers. The technology roadmap designed was based on eight new technologies developed in the ESGRIDS project. Fig. 3 displays the proposed roadmap as a time-based chart divided into three main time segments: on-going, after, and long-term. The long-term impacts reflect the expected contributions of the project. These impacts will depend on the effective dissemination/commercialization of the technologies developed, which still require overcoming techno-economic barriers and the creation of a suitable regulatory framework to allow SG technologies to become effective [90]. Therefore, given the low TRL, the proposed roadmap is focused on the on-going layer. As these technologies will reach higher maturity levels and policy frameworks evolve, the linkage between technology development, products and market layers will become more evident and will provide further insight to update and improve the roadmap and better assess the impact of SG technologies development on society.

7. Conclusion

This research evaluated the publicly funded R&D project ESGRIDS and the potential societal impact of its outputs. The team members were asked to select what they considered to be their two most relevant outputs based on the TRL and elicit their main barriers and contributions to society. Among the main findings, this research has highlighted the challenges of identifying societal impacts of technologies with low TRL. First, in comparison to economic, environmental, and technical KPIs, societal performance indicators had the lowest relevance for the eight technologies evaluated. This can be a result of their low technological maturity and the need to overcome technical barriers before field trial and actual implementation. It was also recognized that researchers' individual perception and organisational context played a significant role in ranking performance indicators and identifying technologies contributions. This highlights the need for a standardised methodology to infer expected contributions of low-TRL technologies that goes beyond internal perceptions and stakeholders' expectations. This becomes even more relevant for the case of ex-ante assessment of R&D projects and their pursuit of funding.

For the technology roadmap, the designed pathway summarises the ESGRIDS project results and potential impacts based on the researchers' perspectives. However, it does not attempt to be a definitive picture and should be seen as a departing point that must be improved and further detailed for each one of the technologies. ESGRIDS technologies can contribute to SG developments, but several aspects should not be overlooked to ensure its effective transition to the commercial phase. These aspects include the need for additional developments in related technologies, assets or models (e.g., battery development, new weather forecasting models or additional grid switching devices), possible changes on the market organization and regulation (e.g., communication standards, data management policies and national and European electricity market regulation), and the involvement of consumers to ensure social acceptance of the technologies (e.g., assessment of consumers' willingness to participate, their needs, concerns and motivating factors).

Among the main limitations of this research, we underscore the lack of a unified methodology to elicit researchers' answers to the questionnaire, including the realization of prior meetings with all four research teams. Nevertheless, this supported the need for a standard approach to elicit potential contributions of SG technologies with low TRL that can consider the different backgrounds of research teams. The selection of one single set of indicators for all technologies, which could have been tailored to the technologies purpose, can be also seen as a limitation, Nevertheless, the selected KPIs referred to the most commonly discussed topics in the literature and were representative of

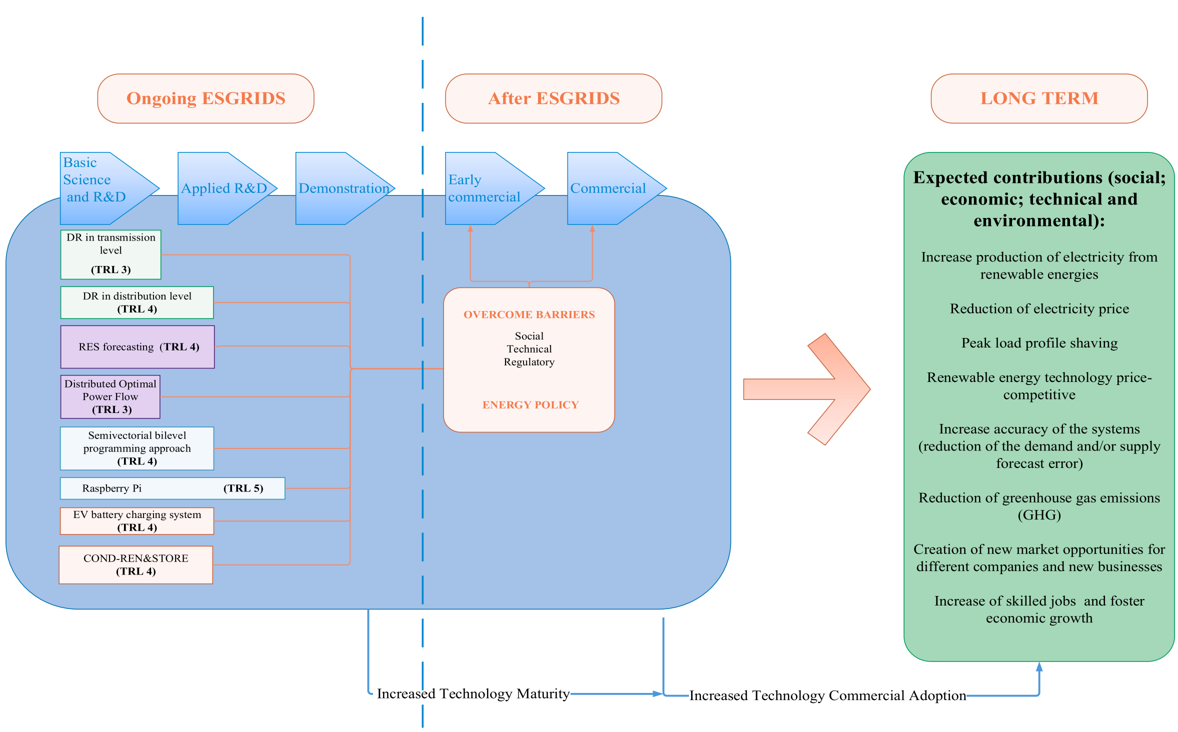

Fig. 3. ESGRIDS technologies roadmap.

SG technologies main aspects.

Therefore, the authors recognise future research opportunities related to the development of a robust method not only to assess real societal impacts of research considering differences between research fields [10][2] but also forecast them in the scope of R&D projects developing low TRL SG technologies. We also suggest the inclusion of the actors that are expected to be affected by technologies uptake in the process. Moreover, given the low TRL of ESGRIDS technology, their monitoring over time can provide insights as ways to manage innovation and achieve commercial stages. As for the technology roadmap, it can be used to help dealing with the challenging task of forecasting impacts of technologies with low TRL and give a time-based perspective over technologies development and deployment. The roadmap can be further detailed and improved once higher TRLs are achieved, and participative methods are used to gather information about barriers and future impacts.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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Appendix A. Questionnaire 1

Table A.1
Please indicate the name of the Technology / Output developed by your research team on project ESGRIDS, the classification (mark with X the most suitable one) and provide a brief description. Copy this table and fill it for each of the technologies/outputs which were developed on project ESGRIDS.

Technology/Output	Classification			
Name	Prototype	Models	Patents	Computational applications
Please make a brief description of the technology/output (not exceeding 250 words):				

Table A.2
Please select the two most relevant technologies/outputs and indicate which are the expected contributions for the technologies/outputs indicated in Table A.1

Technology/Output name:			
Target user of the technology	**Benefits of the technology**	**Novelty of the technology**	**Expected TRL at the end of ESGRIDS** (see Annex A.1)
Technology/Output name:			
Target user of the technology	**Benefits of the technology**	**Novelty of the technology**	**Expected TRL at the end of ESGRIDS** (see Annex A.1)

Note: If the technologies are already described in scientific articles please indicate the references.

Annex A.1

HORIZON 2020 – WORK PROGRAMME 2014-2015
Technology readiness levels (TRL)
Where a topic description refers to a **TRL**, the following definitions apply, unless otherwise specified:

- **TRL 1** – basic principles observed
- **TRL 2** – technology concept formulated
- **TRL 3** – experimental proof of concept
- **TRL 4** – technology validated in lab
- **TRL 5** – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 6** – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 7** – system prototype demonstration in operational environment
- **TRL 8** – system complete and qualified
- **TRL 9** – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Appendix B. Questionnaire 2

Table B.1
Please indicate the selected technologies for further analysis.

Technologies	Classification	Expected TRL at the end of ESGRIDs
1)		
2)		

Part I – Closed questions

Table B.2
- Please indicate your agreement on the importance of each indicator for the assessment of technology/ output indicated in Table B1. Mark with X the most suitable score.

Keys Performance Indicators (KPI)	1	2	3	4	5	The definition of Key Performance Indictors (KPIs)
Social indicators						
Customer satisfaction	☐	☐	☐	☐	☐	Increase of the consumer satisfaction with their energy supplier
Consumers' participation	☐	☐	☐	☐	☐	Increase of consumers participation in demand-side management programs
Fraud detection	☐	☐	☐	☐	☐	Improvement of fraud detection on the electric sector
Employment rate	☐	☐	☐	☐	☐	Increase of the employment rate
Environmental indicators						
Greenhouse gas emission	☐	☐	☐	☐	☐	Reduction of CO_2 emissions (e.g by energy savings and renewables use)
Energy efficiency	☐	☐	☐	☐	☐	Improvement of the energy efficiency of an electric appliance
Fossil fuel use	☐	☐	☐	☐	☐	Reduction of the use of fossil fuels
Economic indicators						
Energy imports	☐	☐	☐	☐	☐	Reduction of energy imports from outside Europe
Energy cost	☐	☐	☐	☐	☐	Reduction of energy cost (e.g. by reducing or shifting the energy use)
Technical factors						
Energy losses	☐	☐	☐	☐	☐	Reduction of energy losses in the distribution system
Peak load	☐	☐	☐	☐	☐	Curtailment of the peak by load-shift or load-shedding
Renewable energy	☐	☐	☐	☐	☐	Increase of the share of renewable energy in the generation of electricity
Energy use	☐	☐	☐	☐	☐	Reduction of energy use in different sectors (e.g. residential and industrial sector)
Electric vehicles integration	☐	☐	☐	☐	☐	Increase the number of electric vehicles in circulation over time
Distributed generation integration	☐	☐	☐	☐	☐	Increase the production of energy in a small and decentralized scale
Quality of energy supply	☐	☐	☐	☐	☐	Improvement in quality of service for the consumers
Demand response (DR) uptake	☐	☐	☐	☐	☐	Increased acceptance of DR programs by the consumers and/or market operators
Accuracy of energy supply and demand prediction	☐	☐	☐	☐	☐	Increase accuracy of the systems (reduction of the demand and/or supply forecast error)
Energy storage development	☐	☐	☐	☐	☐	Development and increase on the use of storage technology

Note: The agreement is measured by a 5-level Likert scale with 1 "Not important at all"; 2 "Not necessarily important"; 3 "Important sometimes"; 4 "Important"; 5 "Extremely important".

Part II – Open questions

1) Can you anticipate barriers for the market uptake of the model/technology (ex: technical; social; regulation; legal etc.)?
2) What is the contribution of this model/technology for fostering the smart grid technologies?
3) How will this model/technology contribute to boosting economic growth at the local, regional and national level?
4) Does the deployment of this model/technology have a beneficial impact on the growth and creation of new jobs? Please justify.
5) What will be the environmental benefits from the deployment of this model/technology?
6) Does this model/technology encourage the use of low cost and low carbon technologies? Please justify.
7) How can the deployment of this model/technology contribute to increasing renewables share in the electricity market?
8) Does this model/technology contribute to the active involvement of the consumers in the electricity market? (ex: demand response programs and electric mobility)
9) How can this model/technology contribute to support energy policy decision making?

References

[1] Data for the Sustainable Development Goals, Unesco Inst. Stat., 2021. http://uis.unesco.org/. (Accessed 6 October 2022). accessed.

[2] S. Hill, Assessing (For) impact: future assessment of the societal impact of research, Palgrave Commun 2 (2016) 1–7, https://doi.org/10.1057/palcomms.2016.73.

[3] L. de Almeida, D. Augusto de Jesus Pacheco, C.S. ten Caten, C.F. Jung, A methodology for identifying results and impacts in technological innovation projects, Technol. Soc. 66 (2021), 101574, https://doi.org/10.1016/j.techsoc.2021.101574.

[4] Research Excellence Framework, Excellence Framework 2014: the Results, 2014, pp. 1–66.

[5] J.P. Smit, L.K. Hessels, The production of scientific and societal value in research evaluation: a review of societal impact assessment methods, Res. Eval. 30 (2021) 323–335, https://doi.org/10.1093/reseval/rvab002.

[6] J. Spaapen, L. van Drooge, T. Propp, B. van der Meulen, T. Shinn, A. Marcovich, P. van den Besselaar, E. Castro-Martinez, B. D'Ippolito, A. Prins, J. Molas-Gallart, P. Tang, D. Pearson, T. Sveinsdottir, K. Morrison, K. Barker, D. Cox, S. De Jong, SIAMPI Final Report: Social Impact Assessment Methods for Research and Funding Instruments through the Study of Productive Interactions between Science and Society, 2011, p. 1. –36, http://www.siampi.eu/Content/SIAMPI_Final report.pdf.

[7] L. Meagher, C. Lyall, The invisible made visible: using impact evaluations to illuminate and inform the role of knowledge intermediaries, Evid. Policy. 9 (2013) 409–418, https://doi.org/10.1332/174426422X16419160905358.

[8] K. M.O., S. A.J., Contribution mapping: a method for mapping the contribution of research to enhance its impact, Health Res. Pol. Syst. 10 (2012) 1–16. http://www.health-policy-systems.com/content/10/1/21%5Cnhttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed10&NEWS=N&AN=2012495258.

[9] R. Flecha, M. Soler-Gallart, T. Sordé, Europe must fund social sciences, Nature 528 (2015), https://doi.org/10.1038/528193d, 193–193.

[10] G. Sivertsen, I. Meijer, Normal versus extraordinary societal impact: how to understand, evaluate, and improve research activities in their relations to society? Res. Eval. 29 (2020) 66–70, https://doi.org/10.1093/RESEVAL/RVZ032.

[11] B. Fecher, M. Hebing, How do researchers approach societal impact? PLoS One 16 (2021) 1–20, https://doi.org/10.1371/journal.pone.0254006.
[12] A. Gupta, A. Deokar, L. Iyer, R. Sharda, D. Schrader, Big data & analytics for societal impact: recent research and trends, Inf. Syst. Front 20 (2018) 185–194, https://doi.org/10.1007/s10796-018-9846-7.
[13] L. Bornmann, W. Marx, How should the societal impact of research be generated and measured? A proposal for a simple and practicable approach to allow interdisciplinary comparisons, Scientometrics 98 (2014) 211–219, https://doi.org/10.1007/s11192-013-1020-x.
[14] J.P. Lauronen, The dilemmas and uncertainties in assessing the societal impact of research, Sci. Publ. Pol. 47 (2020) 207–218, https://doi.org/10.1093/scipol/scz059.
[15] L. Bornmann, Measuring the societal impact of research. Research is less and less assessed on scientific impact alone-we should aim to quantify the increasingly important contributions of science to society, EMBO Rep. 13 (2012) 673–676, https://doi.org/10.1038/embor.2012.99.
[16] United Nations, Transforming Our World: the 2030, Agenda for Sustainable Development, New York, 2015.
[17] M.A. Ponce-Jara, E. Ruiz, R. Gil, E. Sancristóbal, C. Pérez-Molina, M. Castro, Smart Grid: assessment of the past and present in developed and developing countries, Energy Strategy Rev. 18 (2017) 38–52, https://doi.org/10.1016/j.esr.2017.09.011.
[18] M. Masera, E.F. Bompard, F. Profumo, N. Hadjsaid, Smart (electricity) grids for smart cities: assessing roles and societal impacts, Proc. IEEE 106 (2018) 613–625, https://doi.org/10.1109/JPROC.2018.2812212.
[19] M.S. Hossain, N.A. Madlool, N.A. Rahim, J. Selvaraj, A.K. Pandey, A.F. Khan, Role of smart grid in renewable energy: an overview, Renew. Sustain. Energy Rev. 60 (2016) 1168–1184, https://doi.org/10.1016/j.rser.2015.09.098.
[20] O. Majeed Butt, M. Zulqarnain, T. Majeed Butt, Recent advancement in smart grid technology: Future prospects in the electrical power network, Ain Shams Eng. J. 12 687–695. https://doi.org/10.1016/j.asej.2020.05.004.
[21] G. Dileep, A survey on smart grid technologies and applications, Renew. Energy 146 (2020) 2589–2625, https://doi.org/10.1016/j.renene.2019.08.092.
[22] F. Gangale, A. Mengolini, I. Onyeji, Consumer engagement: an insight from smart grid projects in Europe, Energy Pol. 60 (2013) 621–628, https://doi.org/10.1016/j.enpol.2013.05.031.
[23] European Parliament, Directive 2019/944 on Common Rules for the Internal Market for Electricity, Off. J. Eur. Union, 2019, p. 18.
[24] J. Gao, Y. Xiao, J. Liu, W. Liang, C.L.P. Chen, A survey of communication/networking in Smart Grids, Future Generat. Comput. Syst. 28 (2012) 391–404, https://doi.org/10.1016/j.future.2011.04.014.
[25] A. Mengolini, J. Vasiljevska, The Social Dimension of Smart Grids: Consumer, community, society, 2013.
[26] J. Meadowcroft, J.C. Stephens, E.J. Wilson, I.H. Rowlands, Social dimensions of smart grid: regional analysis in Canada and the United States. Introduction to special issue of Renewable and Sustainable Energy Reviews, Renew. Sustain. Energy Rev. 82 (2018) 1909–1912, https://doi.org/10.1016/j.rser.2017.06.106.
[27] C. Milchram, R. Hillerbrand, G. van de Kaa, N. Doorn, R. Künneke, Energy justice and smart grid systems: evidence from The Netherlands and the United Kingdom, Appl. Energy 229 (2018) 1244–1259, https://doi.org/10.1016/j.apenergy.2018.08.053.
[28] M. Goulden, B. Bedwell, S. Rennick-Egglestone, T. Rodden, A. Spence, Smart grids, smart users? the role of the user in demand side management, Energy Res. Social Sci. 2 (2014) 21–29, https://doi.org/10.1016/j.erss.2014.04.008.
[29] N. Shaukat, S.M. Ali, C.A. Mehmood, B. Khan, M. Jawad, U. Farid, Z. Ullah, S. M. Anwar, M. Majid, A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid, Renew. Sustain. Energy Rev. 81 (2018) 1453–1475, https://doi.org/10.1016/j.rser.2017.05.208.
[30] S. Bigerna, C.A. Bollino, S. Micheli, Socio-economic acceptability for smart grid development - a comprehensive review, J. Clean. Prod. 131 (2016) 399–409, https://doi.org/10.1016/j.jclepro.2016.05.010.
[31] Z. Hu, C. Li, Y. Cao, B. Fang, L. He, M. Zhang, How smart grid contributes to energy sustainability, Energy Proc. 61 (2014) 858–861, https://doi.org/10.1016/j.egypro.2014.11.982.
[32] A. Spence, C. Demski, C. Butler, K. Parkhill, N. Pidgeon, Public perceptions of demand-side management and a smarter energy future, Nat. Clim. Change 5 (2015) 550–554, https://doi.org/10.1038/nclimate2610.
[33] K. Harland, H. O'Connor, Broadening the Scope of Impact, 2015.
[34] European Commission, Interim Evaluation of Horizon 2020, 2017. Brussels.
[35] B. Belcher, M. Palenberg, Outcomes and impacts of development interventions, Am. J. Eval. 39 (2018) 478–495, https://doi.org/10.1177/1098214018765698.
[36] OECD-DAC, Glossary of Key Terms in Evaluation and Results-Based Management Proposed Harmonized Terminology, OECD, Paris, Paris, 2002.
[37] J.L. Ozanne, B. Davis, J.B. Murray, S. Grier, A. Benmecheddal, H. Downey, A. E. Ekpo, M. Garnier, J. Hietanen, M. Le Gall-Ely, A. Seregina, K.D. Thomas, E. Veer, Assessing the societal impact of research: the relational engagement approach, J. Publ. Pol. Market. 36 (2017) 1–14, https://doi.org/10.1509/jppm.14.121.
[38] A.I. Walter, S. Helgenberger, A. Wiek, R.W. Scholz, Measuring societal effects of transdisciplinary research projects: design and application of an evaluation method, Eval. Progr. Plann. 30 (2007) 325–338, https://doi.org/10.1016/j.evalprogplan.2007.08.002.
[39] M.S. Reed, M. Ferré, J. Martin-Ortega, R. Blanche, R. Lawford-Rolfe, M. Dallimer, J. Holden, Evaluating impact from research: a methodological framework, Res. Pol. 50 (2021), 104147, https://doi.org/10.1016/j.respol.2020.104147.
[40] L. Pal, G. Auld, A. Mallett, Beyond Policy Analysis: Public Issue Management in Turbulent Times, sixth ed., 2020.
[41] R. Carbajo, L.F. Cabeza, Renewable energy research and technologies through responsible research and innovation looking glass: reflexions, theoretical approaches and contemporary discourses, Appl. Energy 211 (2018) 792–808, https://doi.org/10.1016/j.apenergy.2017.11.088.
[42] European Commission, Horizon 2020 Indicators, 2015, https://doi.org/10.2777/71098. Brussels.
[43] European Commission, A New Horizon for Europe, 2018. Brussels.
[44] F. Ribeiro, P. Ferreira, M. Araújo, Sustainability assessment of electricity production using a logic models approach, Renew. Sustain. Energy Rev. 28 (2013) 215–223, https://doi.org/10.1016/j.rser.2013.07.034.
[45] D. Pramangioulis, K. Atsonios, N. Nikolopoulos, D. Rakopoulos, P. Grammelis, E. Kakaras, A methodology for determination and definition of key performance indicators for smart grids development in island energy systems, Energies 12 (2019) 242, https://doi.org/10.3390/en12020242.
[46] D.S. Kourkoumpas, G. Benekos, N. Nikolopoulos, S. Karellas, P. Grammelis, E. Kakaras, A review of key environmental and energy performance indicators for the case of renewable energy systems when integrated with storage solutions, Appl. Energy 231 (2018) 380–398, https://doi.org/10.1016/j.apenergy.2018.09.043.
[47] C. Gouveia, D. Rua, F.J. Soares, C. Moreira, P.G. Matos, J.A.P. Lopes, Development and implementation of Portuguese smart distribution system, Electr. Power Syst. Res. 120 (2015) 150–162, https://doi.org/10.1016/j.epsr.2014.06.004.
[48] Y. Li, J. O`Donnell, R. García-Castro, S. Vega-Sánchez, Identifying stakeholders and key performance indicators for district and building energy performance analysis, Energy Build. 155 (2017) 1–15, https://doi.org/10.1016/j.enbuild.2017.09.003.
[49] Eurostat, Energy, Transport and Environment Indicators, 2014, https://doi.org/10.2785/56625. Brussels.
[50] S.G.T. Force, Definition of an Assessment Framework for Projects of Common Interest in the Field of Smart Grids, 2012. Brussels.
[51] S3C, Guideline: KPIs for Energy Consumption Effects, (n.d.) vols. 1–9.
[52] A.L. Olechowski, S.D. Eppinger, N. Joglekar, K. Tomaschek, Technology readiness levels: shortcomings and improvement opportunities, Syst. Eng. 23 (2020) 395–408, https://doi.org/10.1002/sys.21533.
[53] European Commission, Technology Readiness Levels (TRL), Horiz. 2020 – Work Program. 2014-2015 Gen. Annex. Extr. From Part 19 - Comm, Decis. C., 2014. http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.
[54] L. Liu, H. Huang, W. Qi, Q. Zhao, X. Li, H. Jia, Y. Zeng, Y. Liu, Comprehensive evaluation of smart grid technology based on TRLs, in: 5th Int. Conf. Electr. Util. Deregul. Restruct. Power Technol., 2015, pp. 363–368.
[55] H. Kirkham, C. Marinovici, Technology readiness and the smart grid, 2013 IEEE PES Innov, Smart Grid Technol. Conf. ISGT (2013) 1–6, https://doi.org/10.1109/ISGT.2013.6497804.
[56] T. Loureiro, J. Espeche, M. Vinyals, U. Stecchi, D. Tzovaras, D. Ioannidis, D. Geysen, Distributed Schemes, Innovative Solutions for Smart Grids: P2P, Multi-Agent Systems & Blockchain, 2019, p. 5, https://doi.org/10.3390/proceedings2019020005.
[57] T. Crosbie, J. Broderick, M. Short, R. Charlesworth, M. Dawood, Demand response technology readiness levels for energy management in blocks of buildings, Buildings 8 (2018) 1–11, https://doi.org/10.3390/buildings8020013.
[58] A. Flore, J. Marx Gómez, Development and comparison of migration paths for smart grids using two case studies, Heliyon 6 (2020), https://doi.org/10.1016/j.heliyon.2020.e04913.
[59] D. Phaal, Robert, Clare Farrukh, Technology Roadmapping Probert, Linking Technology Resources to Business Objectives, University of Cambridge, 2001, https://doi.org/10.1215/ddnov.039030337.
[60] M.G. Moehrle, R. Isenmann, R. Phaal, Technology Roadmapping for Strategy and Innovation: Charting the Route to Success, Springer Berlin Heidelberg, 2013, https://doi.org/10.1007/978-3-642-33923-3.
[61] R.W. Rycroft, Time and technological innovation: implications for public policy, Technol. Soc. 28 (2006) 281–301, https://doi.org/10.1016/j.techsoc.2006.06.001.
[62] M. Amer, T.U. Daim, Application of technology roadmaps for renewable energy sector, Technol. Forecast. Soc. Change 77 (2010) 1355–1370, https://doi.org/10.1016/j.techfore.2010.05.002.
[63] M. Ibrahim, A. El-Zaart, C. Adams, Smart sustainable cities roadmap: readiness for transformation towards urban sustainability, Sustain. Cities Soc. 37 (2018) 530–540, https://doi.org/10.1016/j.scs.2017.10.008.
[64] C.R. Haddad, M. Uriona Maldonado, A functions approach to improve sectoral technology roadmaps, Technol. Forecast. Soc. Change 115 (2017) 251–260, https://doi.org/10.1016/j.techfore.2016.08.006.
[65] J.H. Lee, R. Phaal, S.H. Lee, An integrated service-device-technology roadmap for smart city development, Technol. Forecast. Soc. Change 80 (2013) 286–306, https://doi.org/10.1016/j.techfore.2012.09.020.
[66] S.-R. Toor, S.O. Ogunlana, Beyond the 'iron triangle': stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects, Int. J. Proj. Manag. 28 (2010) 228–236, https://doi.org/10.1016/j.ijproman.2009.05.005.
[67] European Union, Regulation (EU) No 1291/2013 establishing horizon 2020 - the framework programme for research and innovation (2014-2020) and repealing decision No 1982/2006/EC, off, Off. J. Eur. Union L 347 (2013) 104–173.
[68] S. Talari, M. Shafie-khah, F. Wang, J. Aghaei, J.P.S. Catalao, Optimal scheduling of demand response in pre-emptive markets based on stochastic bilevel programming method, IEEE Trans. Ind. Electron. 66 (2019) 1453–1464, https://doi.org/10.1109/TIE.2017.2786288.

[69] N. Hajibandeh, M. Shafie-khah, S. Talari, S. Dehghan, N. Amjady, S.J.P.S. Mariano, J.P.S. Catalao, Demand response-based operation model in electricity markets with high wind power penetration, IEEE Trans. Sustain. Energy 10 (2019) 918–930, https://doi.org/10.1109/TSTE.2018.2854868.

[70] R. Pinto, R.J. Bessa, J. Sumaili, M.A. Matos, Distributed multi-period three-phase optimal power flow using temporal neighbors, Electr. Power Syst. Res. 182 (2020), 106228, https://doi.org/10.1016/j.epsr.2020.106228.

[71] C. Goncalves, R.J. Bessa, P. Pinson, Privacy-preserving distributed learning for renewable energy forecasting, IEEE Trans. Sustain. Energy 12 (2021) 1777–1787, https://doi.org/10.1109/TSTE.2021.3065117.

[72] M.J. Alves, C.H. Antunes, A semivectorial bilevel programming approach to optimize electricity dynamic time-of-use retail pricing, Comput, Oper. Res. 92 (2018) 130–144, https://doi.org/10.1016/j.cor.2017.12.014.

[73] I. Gonçalves, Á. Gomes, C. Henggeler Antunes, Optimizing the management of smart home energy resources under different power cost scenarios, Appl. Energy 242 (2019) 351–363, https://doi.org/10.1016/j.apenergy.2019.03.108.

[74] V. Monteiro, J. Afonso, J. Ferreira, J. Afonso, Vehicle electrification: new challenges and opportunities for smart grids, Energies 12 (2018) 118, https://doi.org/10.3390/en12010118.

[75] V. Monteiro, J.C. Ferreira, A.A. Nogueiras Melendez, C. Couto, J.L. Afonso, Experimental validation of a novel architecture based on a dual-stage converter for off-board fast battery chargers of electric vehicles, IEEE Trans. Veh. Technol. 67 (2018) 1000–1011, https://doi.org/10.1109/TVT.2017.2755545.

[76] R. Leite, J. Afonso, V. Monteiro, A novel multilevel bidirectional topology for on-board EV battery chargers in smart grids, Energies 11 (2018), https://doi.org/10.3390/en11123453, 3453.

[77] A. Rodrigues, C. Oliveira, T.J.C. Sousa, L. Machado, J.L. Afonso, V. Monteiro, Unified three-port topology integrating a renewable and an energy storage system with the grid-interface operating as active power filter, in: IEEE 14th Int. Conf. Compat. Power Electron. Power Eng., IEEE, 2020, pp. 502–507, https://doi.org/10.1109/CPE-POWERENG48600.2020.9161670, 2020.

[78] V. Monteiro, T.J.C. Sousa, C. Couto, M.J. Seplveda, J.C.A. Fernandes, J.L. Afonso, A novel single-phase bidirectional nine-level converter employing four quadrant switches, in: Int. Conf. Smart Energy Syst. Technol., IEEE, 2018, pp. 1–6, https://doi.org/10.1109/SEST.2018.8495740.

[79] V. Monteiro, T. Sousa, J. Pinto, J.L. Afonso, A novel front-end multilevel converter for renewable energy systems in smart grids, in: ECOS 2018 - Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst., n.d.

[80] J. Lilliestam, S. Hanger, Shades of green: centralisation, decentralisation and controversy among European renewable electricity visions, Energy Res. Social Sci. 17 (2016) 20–29, https://doi.org/10.1016/j.erss.2016.03.011.

[81] C. Milchram, G. van de Kaa, N. Doorn, R. Künneke, Moral values as factors for social acceptance of smart grid technologies, Sustain. Times 10 (2018), https://doi.org/10.3390/su10082703.

[82] J. Kim, D. Jeong, D. Choi, E. Park, Exploring public perceptions of renewable energy: evidence from a word network model in social network services, Energy Strategy Rev. 32 (2020), 100552, https://doi.org/10.1016/j.esr.2020.100552.

[83] I. Öhrlund, Å. Linné, C. Bartusch, Convenience before coins: household responses to dual dynamic price signals and energy feedback in Sweden, Energy Res. Social Sci. 52 (2019) 236–246, https://doi.org/10.1016/j.erss.2019.02.008.

[84] E. Sarker, M. Seyedmahmoudian, E. Jamei, B. Horan, A. Stojcevski, Optimal management of home loads with renewable energy integration and demand response strategy, Energy 210 (2020), 118602, https://doi.org/10.1016/j.energy.2020.118602.

[85] M. McPherson, B. Stoll, Demand response for variable renewable energy integration: a proposed approach and its impacts, Energy 197 (2020), 117205, https://doi.org/10.1016/j.energy.2020.117205.

[86] J. Anjo, D. Neves, C. Silva, A. Shivakumar, M. Howells, Modeling the long-term impact of demand response in energy planning: the Portuguese electric system case study, Energy 165 (2018) 456–468, https://doi.org/10.1016/j.energy.2018.09.091.

[87] Q. Sun, X. Ge, L. Liu, X. Xu, Y. Zhang, R. Niu, Y. Zeng, Review of Smart Grid comprehensive assessment systems, Energy Proc. 12 (2011) 219–229, https://doi.org/10.1016/j.egypro.2011.10.031.

[88] P. García-García, Ó. Carpintero, L. Buendía, Just energy transitions to low carbon economies: a review of the concept and its effects on labour and income, Energy Res. Social Sci. 70 (2020), 101664, https://doi.org/10.1016/j.erss.2020.101664.

[89] IEA, World Energy Outlook 2021, 2021. www.iea.org/weo.

[90] M. Vallés, J. Reneses, R. Cossent, P. Frías, Regulatory and market barriers to the realization of demand response in electricity distribution networks: a European perspective, Electr. Power Syst. Res. 140 (2016) 689–698, https://doi.org/10.1016/j.epsr.2016.04.026.