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Smart Metering Roll-Out in Europe: Where Do We Stand? Cost Benefit Analyses in the Clean Energy Package and Research Trends in the Green Deal

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Abstract: 2020 was a key year for several targets in European energy and climate policy, including the requirement for European countries to deploy smart metering for at least 80% of electricity consumers. This target was set to ease the transition towards a consumer-centered and digitalized energy system. In fact, there are numerous applications that are facilitated or are directly linked to smart meters. Among others: demand response programs that enable consumers to be active in the energy market, and remote grid monitoring by the Distribution System Operator. In this paper, we analyze the initial provisions of the Third Energy Package and those of the Clean Energy Package, with particular focus on the recently approved directive on common rules for the internal market for electricity and the newly introduced smart meters specifications. We present the highlights of the national cost–benefit analyses for smart metering roll-out, focusing on the decisions made by the Member States with respect to a potential smart meter roll-out, that was targeted to be completed by 2020 and present the current situation of smart metering roll-out. We also present and categorize some of the R&I smart grid projects realized over recent years, focusing on the ones that deal with smart metering integration in order to depict the smart metering applications and technologies tested on the ground. Therefore, this paper portrays a full picture with respect to smart meters in Europe today and gives insights for monitoring smart metering roll-outs taking into account the current trends in smart metering applications.

Keywords: cost–benefit analysis; smart metering; smart grid

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1. Introduction

During past years, smart metering roll-outs have taken place in many European countries, with smart meters replacing regular meters, thus contributing to the so-called grid transition. Smart meters are useful not only for automatic readings by the energy provider, but also for empowering the consumer in order to be aware of their own consumption. In addition, smart meters can be the means of communication between the consumer and the energy provider, thus enabling the shifting of electricity consumption after having received price incentives or on the other hand providing electricity generated at home, e.g., through Renewable Energy Sources—RES—to the market. Smart meters also have an important function in facilitating an efficient retail market functioning, allowing end-users to change providers, and thus achieving fair competition among energy retailers.

Through smart meters, consumers become aware of their consumption and/or generation, thus, they can handle their electricity consumption in a more efficient way. Smart meters are the enablers of demand response programs, allowing consumers to respond to incentives and cutting down on critical loads during peak hours. On the other hand, smart meters are an instrument for distribution system operators in order to supervise the network and receive automatic consumption and/or generation readings.

As it is clear from the above, smart meters roll-out can play an important role in the digitalization of the traditional grid and can facilitate market-oriented goals. There have been several policies in Europe aiming at smart metering roll-outs. The first-of-his-kind legislative provisions dealing with smart meters were part of the so-called "Third Energy Package", in force for all countries in Europe, which was approved by the Council and the European Parliament in 2009 (Annex I.2 to the Electricity Directive (2009/72/EC)). These provisions had to make sure that by the year 2020, a minimum of 80% of the consumers would have been served by smart meters. In order to safeguard specific situations, such roll-outs can be restrictive to a positive outcome of a cost–benefit analysis (CBA), assessing the costs and benefits from a long-term perspective. The Joint Research Centre of the European Commission (JRC) has been in charge of assessing the validity of the cost–benefit analyses carried out by the European Countries back in 2014, with results pointing in the vast majority of cases to a positive case for smart metering roll-out [1] and for a projected rate of 72% of total smart metering points by the year 2020.

A new legislation, the "Clean Energy for all Europeans" (https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans, accessed on: 12 January 2022) was approved in June 2019, shaping the smart metering roll-out in the coming years for those countries which had not completed the roll-out yet. This Clean Energy Package, is intended to contribute to Europe's "green" ambitions. Indeed, one out of six political guidelines for the current European Commission is the EU Green Deal, indicating climate neutrality by 2050. Smart meters are a fundamental component of the grid since they empower consumers to be active members of this energy transition by monitoring and controlling their consumption. In addition, smart meters are a crucial actor for the whole grid, since they are basic instruments for achieving promising programs, such as demand response, and they enable the digitalization of the energy grid. Thus, smart meters can be considered as a key factor for the successful achievement of the twin digital and green transitions.

It is therefore a consequential scientific question to analyze whether the target set has been reached and in which countries, and how this new legislation is expected to impact the status of roll-out as crystallized in the CBA roll-out plans presented by national governments to the European Commission back in 2014.

Bringing the analysis of smart metering reality forward, it is also interesting to examine the maturity of technologies that are linked to smart meter applications and especially the extent to which new services depend on smart meters. Indeed, smart meters have a key role in energy communities and system integration projects. This can be revealed by examining the smart grid projects realized over past years, especially after 2014, when the first benchmarking of the CBA analyses took place. Therefore, in this paper, we also study the smart grid projects that have been initiated in Europe after 2014 and derive conclusions regarding the maturity of smart metering applications.

The structure of the paper is shown in the following: Section 2 shows the highlights of the cost–benefit analyses performed by the Member States regarding their smart meter roll-out and their actual implementation. Section 3 describes the Clean Energy Package, while Section 4 tries to lay down the principles of a future evaluation of the impact on the Package on smart metering roll-out. Section 5 presents the R&I smart grid projects realized in Europe with a focus on smart meters integration. Section 6 presents future work to be undertaken, while Section 7 concludes the paper.

2. Highlights of the CBA Benchmarking

The results of the cost–benefit analyses that took place in the various Member States are illustrated in this Section. We take into account various sources for this scope. As a first step, we give an overview of what has been decided back in 2014 with respect to smart meter national roll-outs, a work carried out by the JRC. Afterwards, we present follow-up monitoring that took place through recent years by our team in the JRC, mainly through the Distribution System Operators Observatory [2,3]. The two versions of the Distribution System Operators Observatory are considered in this analysis, carried out in 2018 and 2020, respectively. In the first, we extract information about the wide-scale roll-out plan of the different countries, as well as information about wide-scale roll-out following CBA, as this is estimated by JRC.

We also consider the work performed in [4], which has been a follow-up of the initial benchmarking work carried out in 2014 and where updates with respect to Member States CBAs are presented. In [5], an update of the roll-out situation is presented, giving information about which scale of percentages are reached in terms of national roll-outs. We also include additional references in order to depict the status of smart meter roll-outs in different countries and present a more complete picture.

2.1. Work Performed by JRC and Status of Smart Metering

The Third Energy Package approved in 2009 required European countries to roll out smart metering by 2020 for 80% of the electricity end-customers. To take into account specific cases, governments could carry out a cost–benefit analysis to be completed and communicated to the European Commission by 3 September 2012. The JRC analyzed such cost–benefit analyses for smart meters roll-out and published its benchmarking report back in 2014; the main outcome is summarized in Figure 1 below.

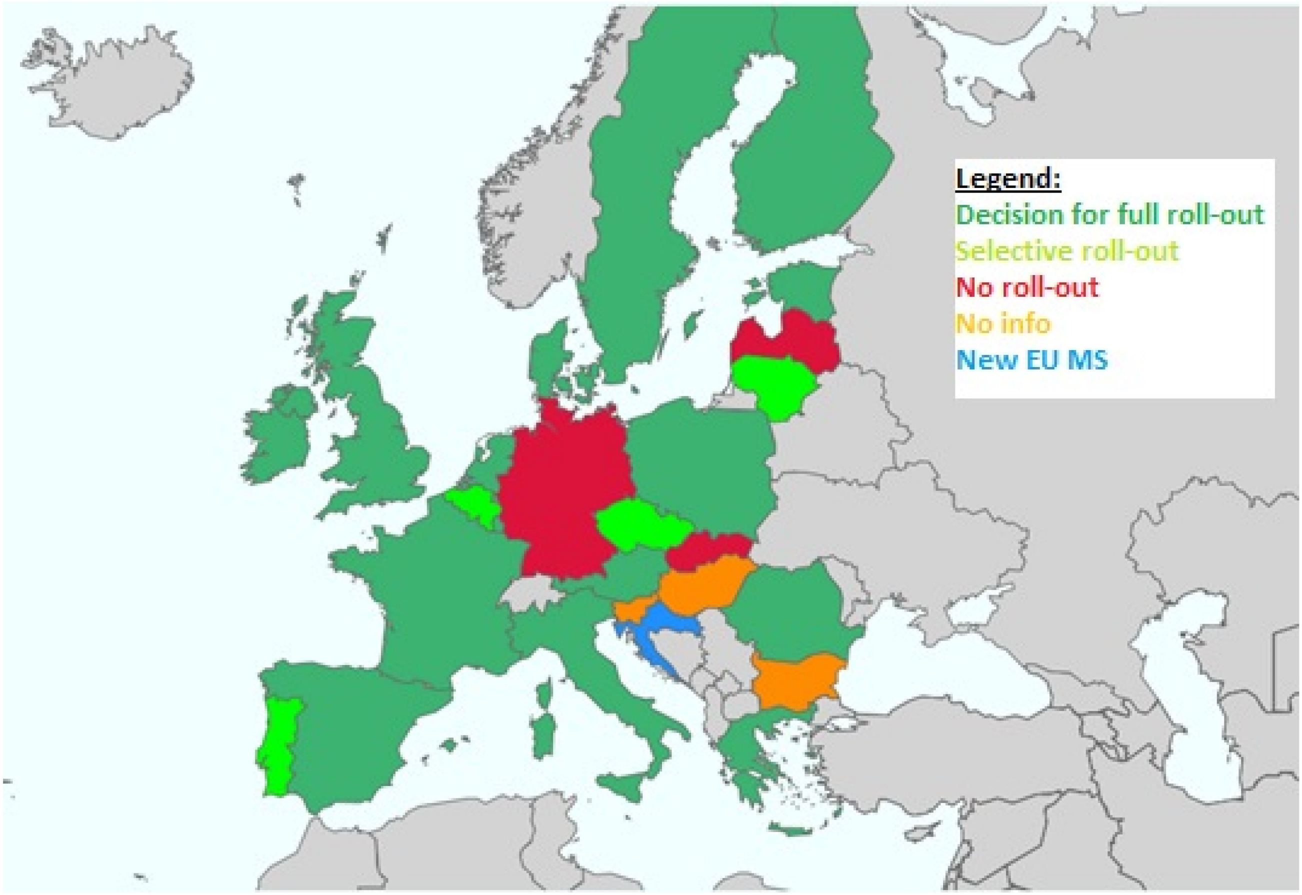

Figure 1. Results of national cost–benefit analyses for smart metering roll-out in 2014, Source: [1].

According to the latest information available to the JRC, beyond Finland, Italy and Sweden that had already completed well before 2014 the roll-out for virtually all electricity customers, only Bulgaria and Hungary had not completed or communicated their CBA. For the rest, in most of the countries that performed a CBA this latter turned out positive

(Austria, Denmark, Estonia, France, Greece, Ireland, Luxemburg, Malta, Netherlands, Poland, Romania, Spain, and the UK). In seven countries, however (Belgium, the Czech Republic, Germany, Latvia, Lithuania, Portugal, and Slovakia), the CBAs turned either negative or inconclusive, thus giving a red light for a smart meter roll-out by the year 2020. Finally, in Germany, Latvia and Slovakia a smart meter roll-out resulted positively in terms of economic costs just for specific segments. To sum up, at the time (2014) European countries had engaged to a smart meter roll-out of around 200 million electricity metering points by the year 2020 resulting in an investment of around 35 million euros [6].

The JRC then continued to monitor the evolution of national roll-out plans in its bi-annual Distribution System Operators (DSO) Observatory [2,3], and updated data as communicated by European Distribution System Operators to the JRC are presented in the last sub-section of this section. It is interesting to notice that 25% of the DSOs that took part in the survey of the [3] report have achieved more than 99% of the smart meter roll-out. Half of the DSOs have achieved around 12–50% of their smart meters roll-out, while the remaining 25% have practically not implemented a wide-scale smart meter roll-out. It is estimated that circa 23 million smart meters are needed so as to reach the 80% goal for smart meters roll-out.

It should be noted that additional references have been taken into account in order to complete the picture of the roll-out status in all the Member States. Before showing the graphs and tables depicting the current situation, we refer to similar works carried out recently giving information about the smart meter roll-out status. In the last sub-section of this section, we present the results overall.

2.2. Similar Works

In 2019, a consultancy consortium led by Tractebel in Belgium took over the follow-up of the work initiated in 2014 by the JRC. The scope was to depict the extent to which the European countries had realized their scheduled smart meter roll-outs and to assess their progress in alignment with the targets set by the Third Energy Package.

The report stated that there had been slow progress until the time the report had been written; thus a penetration rate of 43% was foreseen to be achieved by the year 2020, resulting in 123 million smart meters instead of a 72% penetration rate, as stated in the initial roll-out plans. In the report, it was also stated that a 92% penetration rate with 223 million smart meters installed was foreseen to be achieved by 2030. For the work to be realized and for drafting the state of play of roll-outs in the Member States, a questionnaire was forwarded to the National Regulatory Authorities (NRAs), which covered several parts, among others the cost–benefit analysis and the state of play of smart meters deployment. Based on the answers, a dedicated country fiche was compiled [4].

The results showed in this report are included in the following sub-section together with the outcomes of the JRC work, where a comparative analysis is made, and conclusions are drawn.

In addition, we also take into account the report in [5] published by the European Union Agency for the Cooperation of Energy Regulators (ACER), and entitled "Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2020". There is a section in this report dedicated to the smart meter roll-out situation. It gives information about the range of percentages reached by national roll-outs. Although the information is precise for some countries, only generic information is presented for other countries, i.e., that they have accomplished less than 50% of their national roll-outs, without giving more information about the exact situation.

2.3. Graphs and Tables Representing the Current Situation

Here, we present the situation regarding the roll-out of smart meters in the Member States as well as the results from the CBAs. Tables 1 and 2 show the numbers referring to the smart meter roll-out penetration mainly based on the JRC Distribution System Operators Observatories, the report from the consortium led by Tractebel and the ACER report. As it can be seen, various sources are considered in order to give the most up-to-date situation regarding the smart meter roll-out situation in Europe. In addition, as shown in Table 1, additional sources are considered, so as to complete the picture of the smart meter roll-out. For the extraction of the numbers for the column "Situation of roll-out", we considered the most accurate and most recent sources of information. Much information has been extracted from the ACER report, which has been the most recent source of information (published only in November 2021). However, for some countries, only generic information is given, i.e., that less than 50% of the roll-out has been completed. Therefore, we present more precise numbers from other sources. Such information regards mainly countries that are behind with the roll-out plan. In addition, it has been clear that some countries had completed the roll-out already since 2018 or earlier. For these countries, it is concluded that the roll-out remains complete.

Table 1. Status of smart metering roll-out in countries that decided for a wide-scale roll-out, Source: [2], unless otherwise stated.

Country	Wide-Scale Roll-Out Plan—JRC Estimated	Wide-Scale Roll-Out Plan—According to [4]	Situation of Roll-Out—Estimated by JRC	Situation of Roll-Out—According to [4]
Austria	Yes	Yes	29% [5]	11.8%
Croatia	Yes [1]	Yes [1]	n.a.	2.3%
Denmark	Yes	Yes	80% and higher [5]	69.1%
Estonia	Yes	Yes	100%	98.9%
Finland	Yes	Yes	100%	99.8%
France	Yes	Yes	80–90% [5]	22.2%
Greece	Yes	Yes	37%	2.6%
Italy	Yes	Yes	100%	98.5%
Latvia	Selective	Yes	50–70% [5]	36.3%
Luxembourg	Yes	Yes	80–90% [5]	25.2%
Malta	Yes	Yes	80–90% [5]	97%
Netherlands	Yes	Yes	85.2%	46.5%
Poland	Yes—Official Decision pending	Yes	1–11.5%	8.3%
Portugal	No	Yes	50–70% [5]	25%
Romania	Yes—Official Decision pending	Yes	12–14%	4.8%
Slovenia	Yes	Yes	80–90% [5]	58.2%
Sweden	Yes	N/A	90–100%	100%
United Kingdom	Yes	Yes	28% [7]	19.9%

[1] Croatia completed its CBA in 2017.

Table 2. Status of smart metering roll-out in countries that do not have an official positive outcome for their wide-scale roll-out, Source: [2] unless otherwise stated.

Country	Wide-Scale Roll-Out Following CBA/Estimated by JRC	Wide-Scale Roll-Out Following CBA—According to [4]	Situation of Roll-Out (2020)—Estimated by JRC	Situation of Roll-Out—Estimated by [4]
Belgium	No	Yes/inconclusive	N/A	N/A
Czech Republic	No	No	Pilot projects	N/A
Germany	Selective	No	2–15%	N/A
Hungary	N/A	N/A	N/A	1%
Ireland	Yes [2]	No	0%	N/A
Lithuania	No	Inconclusive	NA	2.4%
Slovakia	Selective	Inconclusive	18%	5.1%
Spain	No CBA	No CBA	80–90% [8]	93.1%

[2] the positive result is depicted here because in 2014, Ireland had a positive CBA result.

From the above tables, it can be observed that there have been few changes in the CBA results among the Member States (the UK is also considered in the analysis). However, there are some countries that have passed from a negative outcome (or an outcome that decided for selective roll-out) to a positive one, like Portugal and Latvia, whereas there is Ireland that has passed from a positive outcome to a negative one.

It is also noticed that the numbers referring to the percentage penetration according to the JRC work and the work carried out by the consortium led by Tractebel differ for some countries. This is explained because the latter report mainly refers to residential and SMEs (small and medium enterprises) smart meters, whereas the data from the DSO observatory refer to smart meters also installed in industries. An example here is Greece, where most industries are equipped with smart meters, whereas a lot needs to be undertaken in the residential sector. Specifically for Greece, the tender for a massive smart meters roll-out needs to be published again in 2022; thus, no wide-scale roll-out has taken place yet. However, as for 2018 data, there were smart meters installed in industries, and thus, the number of massive smart meters roll-out has not been above zero. We presume that the number declared in 2018 for the smart meter roll-out has remained the same since no other actions have been taken. Another reason for the diversification is the fact that the latter column of both tables refers to data obtained as of July 2018, whereas in the JRC work, we include some more references.

The information included in the above tables is depicted in Figures 2 and 3. Figure 2 gives a visual idea of how the situation is regarding the smart meter roll-out decision, based on the information from all sources (where a "yes" is reported from a source, it is considered that the CBA was concluded positive). Some differences are observed with respect to the result of the CBAs when comparing the main sources, we have in the above tables. However, it should be noted that the DSO observatory data is based on the replies of the DSOs, if not the 2014 analysis of the smart metering benchmarking. Therefore, some minor changes in the decisions may not have been correctly depicted, like for example in Slovakia, where in [2] the decision is noted as "selective", whereas in [4] it is noted as "inconclusive".

On the other hand, Figure 3 shows the progress of smart meter installation in European countries. Various sources have been considered for extracting the numbers regarding the smart meters roll-out in European countries. It can be observed that the smart meter roll-out situation deviates a lot in different countries.

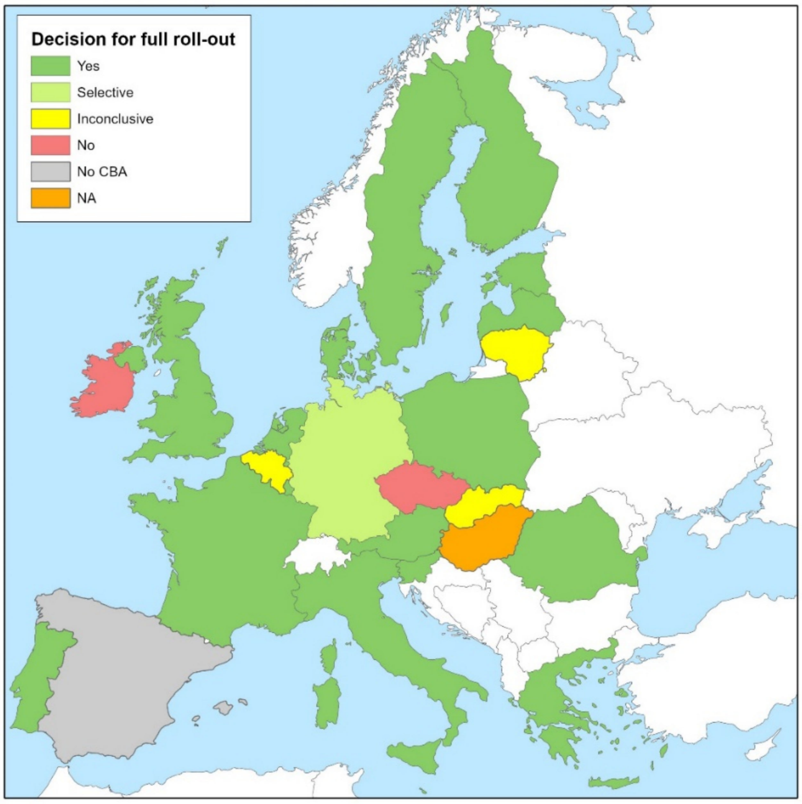

Figure 2. Information on national smart meter roll-out decision.

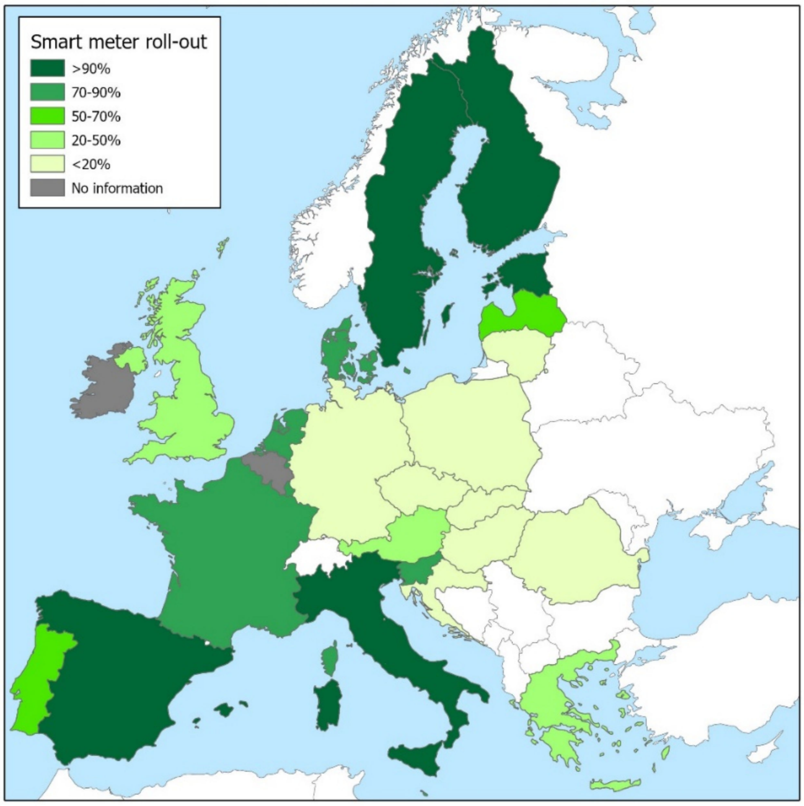

Figure 3. Progress on national smart meter roll–outs.

The figures presented here illustrate that the expected objective of 80% of electricity end-customers equipped with smart meters by 2020 is not at hand, although some remarkable progress has been made. A new intervention of the European legislator through the Clean Energy for All Europeans legislative package was therefore necessary to give a novel impulse to smart metering and achieve the target of at least 80% of electricity end-customers covered.

3. Description of the Clean Energy Package

The "Clean Energy for all Europeans" is a set of legislative proposals put forward by the European Commission at the end of 2016 with its final stages of approval taking place in June 2019. It is made up of eight different pieces of legislation, each one disciplining a specific aspect of the European energy system.

Smart metering has been addressed in the directive on common rules for the internal market in electricity, revising the 2009 directive, which contained the target for European countries to perform a smart meter roll-out for a minimum of 80% of the electricity end-users by the year 2020, provided that the respective cost–benefit analysis turns a positive result. After 2009, a Communication by the European Commission also reiterated such specific targets for the smart metering roll-out and has provided guidance on how to perform the cost–benefit analyses.

3.1. Provisions to Enable Smart Metering Roll-Out in Europe

After almost 10 years from this landmark provision, the new directive remarks the importance of smart metering in delivering energy efficiency and empowering consumers by enabling their active participation in the electricity market. For the first time, it is underlined that the smart meter itself is a tool, certainly powerful, which however needs to be coupled with consumer energy management systems to deliver its benefits. Some new crucial aspects are also introduced; the smart metering should be interoperable, and its operation should respect the rules on data protection (Art. 19). In this article it is also reiterated that the responsibility to roll out smart meters stays with the governments of countries part of the European Union: they shall ensure that the roll-out takes place.

Concerning the costs and benefits of the roll-out of smart meters, the directive states some important principles: first of all, part of the smart meter roll-out costs is attributed to the consumers (but such contribution should be transparent and non-discriminatory). The benefits stemming from the smart metering roll-out should be considered along the whole value chain, therefore accruing for the positive impacts on all types of involved stakeholders (electricity companies, consumers, energy services providers, national regulatory bodies, etc.).

The newly amended directive provides also for a specific commitment in case the cost–benefit analysis supporting a government's decision on whether to roll out smart meters or not is negative: in this case, a re-assessment is required at least every 4 years, or even more recently if significant changes in the conditions considered in the CBA occurred. This provision, therefore, maintains the roll-out option substantially open to all countries, also to those who at this stage decided against it.

Another interesting statement contained in the directive concerns the expected lifetime of already installed smart meters: in order to guarantee that the current devices enable the functionalities of market participation by consumers, the maximum lifetime is set at 12 years from the moment the directive enters into force. In this way, all smart meters currently installed in Europe shall be substituted at the latest in 2031. The summary of the main provisions on the characteristics of smart meters introduced by the Clean Energy Package is presented in the Table 3 below.

Table 3. Summary of main provisions on SM systems introduced by the Clean Energy Package.

Characteristics of SM According to the New Directive
• Smart meters should be coupled with energy management systems • Part of smart meters costs should be attributed to consumers • A revision of a negative roll-out decision and the relevant CBA should be performed at least every 4 years. • Already existing smart meters should be replaced within 12 years from the moment the Directive enters into force

3.2. Smart Meters' Data and Data Management

Concerning the functionalities of smart metering, the main issues addressed by the directive are certainly those of privacy and cybersecurity. In particular, the directive provides for a principle of proportionality when ensuring the cybersecurity of SM and consequently an adequate treatment of the data gathered: the costs associated with guaranteeing cybersecurity should be proportionate to the rest of the SM installation, therefore not posing an additional economic burden to the wide-scale roll-out. The smart metering data-related functionalities according to the New Directive are shown in Table 4.

Table 4. Summary of main provisions on SM systems introduced by the Clean Energy Package.

Smart Metering Data-Related Functionalities According to the New Directive
• Smart meters send information about consumption to end-users: historical consumption and near real-time consumption • Smart meters should be aligned with privacy, data protection and cybersecurity law rules • Smart meters should send information about the electricity generated by prosumers and inserted into the grid • Smart meters data are owned by the consumers and can be transmitted to third actors • Smart meters' functionalities regarding consumption readings should become known when they are installed or a priori. • The predefined resolution for time, set by the electricity market, should be followed regarding consumption and/or generation smart meter measurements

As the final aim is to empower consumers, the data concerned are not only consumption/generation data, but also any other information that may allow the consumer to switch suppliers remotely, to be managed respecting the EU legislation on data protection.

Data protection is one of the main concerns when dealing with the SM roll-out, and for this reason, the roll-out plans have the option to identify dedicated Compliance Officers in the companies managing SM data, with the task of ensuring that the privacy, cybersecurity, and appropriate treatment is respected and access of consumers to their own data is ensured at no cost.

3.3. Interoperability

Looking at the future possible evolutions of SM, a new requirement is set in terms of Interoperability of the SM systems and services: in this way, a company can offer services related to SM and energy management to any European consumer, regardless of its location, and thus contributing to creating a unique electricity market for the whole Europe. The interoperability is therefore intended not only in terms of technical capabilities of the SM, which should be able to measure and connect to any appliance in a *smart home*, but also to provide information, energy provision contracts and pricing options across any border within the European Union.

For interoperability purposes, the type of smart meters and the communication protocols that those meters support is of vital importance. As has been demonstrated in [9], there are various technologies supported by smart meters in Europe. ZigBee and NB-PLC technology are two popular solutions for transmitting smart meter data to the Neighborhood Network Access Point (NNAP—data concentrator). On the other hand, wireless cellular technologies are popular for transmitting such smart meter data further to the control center. The paper presented a review on the smart meter technologies used by different countries for their smart meter roll-outs as well as a review on the technologies used by projects based on smart metering infrastructure. The results have shown that different countries were using different technologies for their roll-outs or their smart grid projects; i.e., in Italy, Spain, Germany, France, Sweden different technologies have been reported. For more details, the reader is directed to [9]. As a result, it can be deduced that interoperability issues may arise with the different technologies supported by smart meters. Such interoperability issues might be dealt with in case the Advanced Metering Infrastructure (i.e., data concentrators, head-end systems, meter data management systems) could support smart meters with different technologies. Given the importance of the topic, it is fundamental to monitor the smart meter technologies along with the national roll-outs. This is left as a task for investigation for the future when the smart meter roll-outs will be mature in more European countries and during future data collection for this scope.

4. What to Measure and How? The Foreseen Impact of the "Clean Energy for All Europeans" Package

How to Measure the Evolvement of Smart Metering Roll-Out in EU after the Implementation of the Clean Energy for All Europeans Legislative Package

The methodologies adopted in CBAs vary, while the JRC have prepared a specific methodology to be followed, which entails specific steps and can be found in [1]. The benchmarking report elaborated by the JRC back in 2014 identified several indicators to compare the different cost–benefit analyses performed by the EU countries for their respective smart metering roll-out plans.

Such indicators are:

- The form of market model: who is the provider of the smart meter device, who is the responsible party for the roll-out, what the final customers pay in order to be equipped with the smart meter;
- The costs incurred for the roll-out by all the relevant stakeholders. In this sense, two operations need to be performed: one is the consideration of the same categories of costs, second is their evaluation for a well-defined list of stakeholders (ideally, they should be the same across all EU states). Comparing roll-out costs that take into account different components might be misleading;
- Benefits, as costs, should be grouped into specific categories as recommended in the smart metering cost–benefit analysis guide developed by JRC [10]. As specified in the report, a matrix can help in identifying which costs and benefits accrue to which stakeholder group. A key benefit item is the visibility of the distribution network to DSOs, so they will be able to decrease the budget related to maintenance and network functionality and ultimately benefit the consumers who pay a tariff for the distribution system. Other long-term benefits should take into account the improved network monitoring and management, and localization of energy losses.
- The functionalities of the smart meters. Such functionalities have been identified by the Smart Grid Task Force Expert Groups promoted by the European Commission and gathering the experts in the field. Although there is an evident trade-off between the number of functionalities allowed by the smart metering device and the benefits calculated in the CBAs analyzed so far by the JRC, such a relationship should be carefully assessed.

However, the use of the CBA itself poses some critical points. First, the CBAs are all different: while the differences, e.g., in time horizons are somehow easy to overcome thanks to appropriate discounting, some others are nearly impossible to neutralize. In this sense, the limits of the benchmarking should be understood from the very beginning: some smart metering points might be more expensive because they allow for specific innovative solutions, or because for their roll-out a massive improvement of the existing distribution grid is required. So, all these are parameters to be taken into account when performing a CBA.

5. SM Projects in EU

5.1. Smart Grid Projects in Europe

Over recent years, there have been many investments in smart grid R&I projects. They have been analyzed in the Smart Grid Projects Outlook [6], where the smart grid projects with at least one European partner have been listed and described. This has been a periodic exercise carried out by our team. In fact, the report in [6] has been a follow-up of the equivalent published in 2014 [11]. A later update of this exercise has been published in late 2021, entitled: "Smart Grids and Beyond: An EU research and innovation perspective" [12].

According to [12], there are 407 smart grid projects realized or ongoing in Europe with total investments that reach 3.08 billion euros, whereas there are 5986 organizations involved.

Figure 4 depicts the situation.

Figure 4. Smart grid projects in Europe, as extracted from [12].

The distribution of the projects throughout Europe is shown in Figure 5. With red dots, the demonstration projects are visible, whereas with green dots, the research and development projects are visible.

With the use of [6,12] and the online options available, we are able to obtain information about smart grid projects and their topic of investigation. In this section, we give an idea of the research performed with respect to smart meters and their applications and the way this research has been evolved over the recent years; thus, showing the trends in the field.

The trends in smart meter research are closely related to the smart meter national roll-outs. Therefore, it is interesting to see the correlation of such research with the latest updates regarding the national roll-outs, as these are presented in Section 2. The most recently published report on the European smart grid projects shows information about the categories of such projects. These categories are namely [12]:

- Smart Network Management;
- Demand Side Management;

- Integration of distributed generation and storage;
- Integration of large-scale RESs and storage;
- Smart City;
- E-mobility.

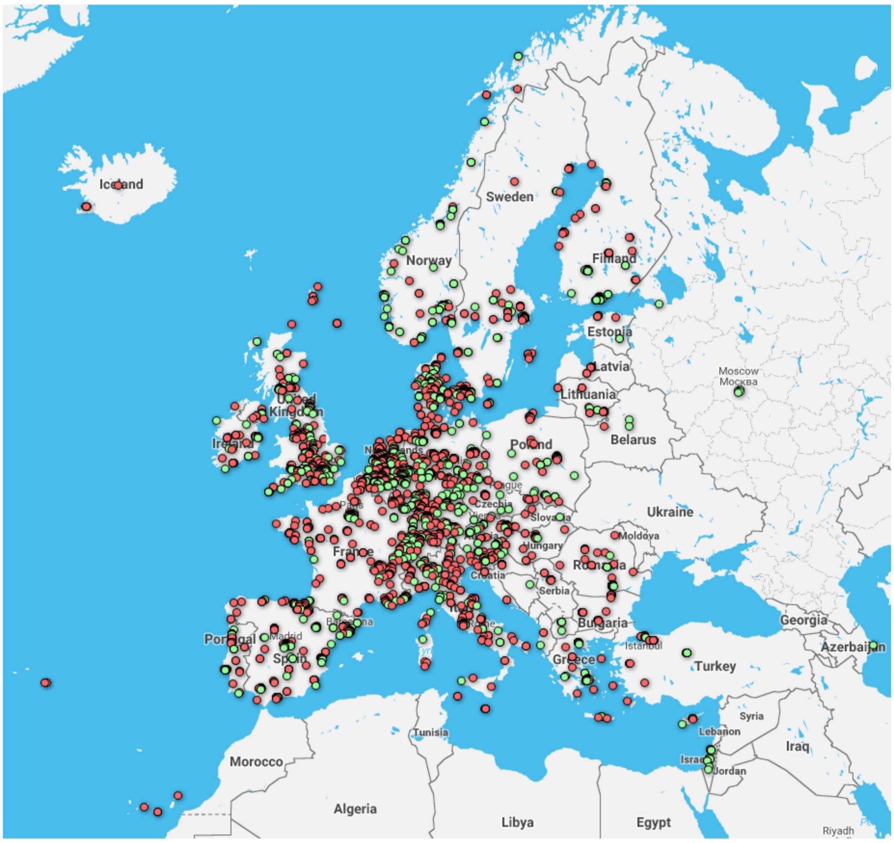

Figure 5. Distribution of smart grid projects in Europe, Source: [12].

The first two categories are directly linked with smart meters installation, whereas smart city category smart projects can also be linked to smart meters deployment. According to [12] there are 162 projects related to Demand Side Management, which gather 22.41% of the total funding. On the other hand, there are 65 projects related to Smart Network Management, gathering 16.78% of the total budget. For smart cities, the equivalent numbers are 23 projects and 19.33% of the total budget. As it can be concluded from the numbers, the progress made with respect to national smart meter roll-outs, as this is described in Section 2, has proved to be fruitful in the sense that numerous projects and investments have been based on wide-scale smart meters implementation. In the following, we give details about projects involving smart meters implementation. The distinction before and after 2014 is related to the timing of the first benchmarking of cost–benefit analyses being published.

5.2. Projects Dealing with Smart Metering Applications—Before 2014

In [9] an analysis of the smart grid projects was been made, focusing on smart metering applications and the telecommunications technologies that were used for the national roll-outs by several member states. As it can be concluded by [9], 50 projects had been identified from the Smart Grid Project Outlook 2014 [11], that deal with smart meter applications. The findings of [9] are summarized as follows:

- In 15 out of 50 projects, the research is focused on ways to reduce energy consumption in buildings or houses. Energy monitoring and management are performed for this scope. Particularly in four projects, public buildings like schools and sports facilities are examined in terms of energy consumption and efficient management.

- In 19 out of 50 projects the topic of investigation is RES integration, whereas, in five of these projects, RES have been manufactured for the project's realization.
- In 20 out of 50 projects grid and energy management is dealt with, including topics like grid control and automation, grid optimization. It is noteworthy that 10 of these 20 projects address the subject of RES integration, studying the influence it has on the grid this energy distribution.
- Six projects address grid monitoring through smart meters.
- Two projects deal with microgrids.
- There are three consultation projects.

5.3. Projects Dealing with Smart Metering Applications—After 2014

One of the tools available along with the Smart Grid Project Outlook 2017 gives the possibility to categorize the projects according to their topic of research. However, as it is mentioned in the report itself, the smart meter domain is not included in the database, since in many Member States, smart metering installations have accomplished a mature level. Nevertheless, it is worth surveying the level of smart meter penetration in Europe and the development of smart grid projects can give us a hint on this direction.

In total, 206 new smart grid projects have been initiated after 2014 and many of them examine smart metering applications. In addition, there are many projects that are based on the analysis of smart meter/smart grid data and propose techniques to improve the supporting networks and ways to handle the amount of data more effectively. Here, we provide some hints on the projects that:

- Explicitly mention the utilization of smart meters;
- Explicitly mention the utilization of smart meter data;
- Refer to applications where smart meters would be key elements for their successful implementation;

The added value of this work is that we provide information about the smart metering applications status regarding the smart grid projects, which is not explicitly mentioned in the Smart Grid Projects Outlook. This information can give feedback on the maturity of the technologies with respect to smart metering applications. Furthermore, the usefulness of the smart meters is highlighted, and it stressed the importance of smart meters for the transition into the smart grid. Such information, along with the benchmarking of smart meter roll-out can give us an idea of how close we are to actually realizing the smart grid applications that will help in the energy transition.

At this point, we give a short description of the smart grid projects that deal with smart meters (smart meters implementation, smart meters playing a key role in local energy communities, etc.). As it can be seen, there are 61 projects that are relevant to smart metering applications. It should be noticed that the list is not exhaustive; more projects are likely to be dealing with smart metering issues or to be based on smart metering applications. In this work, we list the ones that were easier from their description found in [13] to deduce such information. The following tables show a short description of the projects and a categorization according to their topic. It should be noted that the categorization is indicative; some projects may handle issues with respect to more than one category. The categories chosen for the projects are derived as follows:

- Smart metering applications—projects that deal with the smart meters implementation or development of different smart meter features for advanced services;
- Demand Response (DR) applications—projects that deal mainly with the facilitation of DR and are based on smart meter usage;
- Smart cities/smart home/smart building development—projects that deal with one of these topics either focusing on the consumer part (consumer involvement) or the network part (management of a smart city district or building);

- Grid monitoring applications—projects that deal with grid management/grid monitoring issues and smart meter usage can facilitate this goal;
- Data management issues—projects that deal with techniques related to data traffic management, like the increased traffic of data created by the implementation of smart meters;
- Other applications—we have identified projects that deal with EV charging issues and cyber security issues.

As it can be observed from Table 5, for the projects described here, smart meters are a fundamental part of each project. Specifically for one project (FLEXMETER), new smart meters are developed for the project's needs.

Table 5. Smart Metering Applications.

Project	Scope/Short Description
ELIZE	Provide electricity to remote zones offering intelligent generation and consumption. Smart meters are brought to the consumer level.
FLEXMETER	Development of a new smart meter that addresses objectives like energy improvement, CO_2 reduction. This will allow for innovative services for prosumers, like analysis of energy consumption, and for DSOs, like fault detection and network balancing.
INNOEM	Software that analyses the total consumption is developed; energy consumption of electric devices is identified from smart meter consumptions.
SAGA	Smart meters with advanced cyber security capabilities are developed.
SMART-NRG	Smart metering applications are addressed; 2-way smart meter communication is developed; energy consumption is managed; a protocol stack is developed comprising of: communication and networking; smart energy management; security and protection.
SMART-UP	Goal: to use smart meter readings and a home display to lower residential consumption; training to vulnerable customers is offered for this purpose.
USmartConsumer	Smart meter usage is conducted; households are expected to create savings in their consumption.

As it can be concluded from Table 6, there are a lot of projects that use smart meter data to implement demand response services. It is obvious that smart meters can facilitate demand response and determine the flexibility of consumers. For many of these projects, smart meters are an important element for the project's execution.

Table 6. Demand Response/Flexibility applications.

Project	Scope/Short Description
ACE	Residential demand response reinforcement.
AnyPLACE	Develop a modular smart meter platform to facilitate demand response for residential customers. Public acceptance is also studied.
DREAM-GO	Focus on demand response.
DR of the future Swedish building stock	The potential of building stock in DR is examined.
EMPOWER	Creation of a platform with the inclusion of ICT solutions for facilitation of microgrids and DR for homes; Real-time communication through the platform for effective management of energy.
Flex4Grid	Prosumer generation and demand flexibility is aimed at; effective data management; pilot sites are used equipped with smart meters.
FlexNett	Verify flexibility of consumers/prosumers, real-time monitoring and management of distribution networks.
KDRP	To facilitate DR; second by second-meter readings are used for this scope.
NOBEL GRID	DR is addressed; consumers are benefiting from cheaper prices in energy.
P2P-SmarTest	Improve demand-side flexibility; advanced ICT technologies are used for real-time control; optimization of energy flows through a peer-to-peer concept; methods are developed to handle traffic of smart meters.
SEMIAH	DR in households is addressed; smart grid services in households are provided.
Smart Planning	Network capacity and flexibility usage by customers and suppliers is facilitated.

Table 6. *Cont.*

Project	Scope/Short Description
SmarterEMC2	The impact of DR and VPP is studied; the ability of telecommunication networks to handle a massive amount of data is examined.
SmartGridEnable	LV network monitoring system to support DR management systems.
SOLENN	Facilitation of Demand Side Management (DSM) is performed; handling of collective data from smart meters for over 10,000 dwellings is performed.
Tiko	Aggregation of residential electrical loads is undertaken; a pool of such loads is used for DR purposes.
Vulnerable customers and energy efficiency	Involvement of fuel poor and vulnerable customers in the smart grid and in particular in demand response applications is performed; benefits are examined.

From Table 7 it is observed that smart meters can be a pillar for smart buildings and smart cities. They can help in measuring and monitoring the consumptions, thus improving the system's management.

Table 7. Smart cities/smart building applications.

Project	Scope/Short Description
CITYFIED	Develop a strategy for the smart city of the future: grid management improvement; clustering of cities; integration of distributed electricity generation; links with ICTs and mobility.
CityOpt	Design, Management of energy systems in cities and neighborhoods.
City-Zen Amsterdam	Improve the interaction of district heating, local energy generation, energy efficiency for housing; Integration of flexible open infrastructures.
CITIES	To create an integrated center covering important aspects of the energy sector, i.e., gas, power, district heating and cooling. Interactions between such elements are improved through the use of ICT tools.
Esslingen: Smart Energy City	Smart neighborhoods: monitoring of energy efficient operations.
FUTURE ALLEY-SUSTAINABLE LIFESTYLES	Design smart grids in residential areas; Electricity consumption will be measured for 2 years and tenants' behavior will be studied.
GrowSmarter	Smart cities are the target; ICT solutions are employed, smart grid heating is addressed and smart waste handling.
IDEM	Tenant-aware system for energy control; control of the building is achieved.
IJENKO	Services for consumers in smart homes are developed; internet of energy and internet of everything for service providers are addressed.
ITI	Interface between Virtual Power Plant (VPP) and Energy Management System (EMS) is developed.
SCDA	Smart buildings are targeted; ICT integration in buildings; involvement of customers in the smart grid.
SINFONIA	Smart city districts are addressed; effective use of energy in districts.
Virtual Private Home	A tool for residential users is developed; the tool is connected to third-party smart meters and home devices; energy savings by consumers are targeted at.

As it can be observed from Table 8, smart meters can contribute to data collection, and they can facilitate network management, whereas they play a fundamental role in many projects since they facilitate grid monitoring. Network automatization is also an action that can be facilitated through smart meters.

Table 8. Grid Monitoring and control applications.

Project	Scope/Short Description
ENERGIE	Evaluation of network state; measurement values are used (current, voltage) plus an algorithm for missing data.
FERROHUB	Management of power flow to and from the network with innovative solutions like storage units, PV inverters; improvement of the grid stability.
Future Grids	New technologies for accurate measurement systems for voltage and current; smart meters are used to monitor power supply between networks.

Table 8. *Cont.*

Project	Scope/Short Description
grid-control	The project examines the application of smart meters cross-functionally, on the smart grid, smart market and smart home; technical plus economic issues are examined.
i-sare	A microgrid is created, composed of: transformer; batteries; storage in capacitors; EVs; loads
MAS2TERING	ICT platform for the monitoring and optimal management of LV distribution grids.
Rennes Grid	Control electricity consumption so as to integrate RES.
Scalable and reliable real time control of power flows	Management of power consumed or produced by the grid; Information is exchanged in real-time between grid resources.
SCISSOR	Security in the grid is aimed at; SCADA monitoring is applied; data collection and data protection is applied.
SEAS	Monitoring and forecasting energy consumption; ICT solutions are used for this purpose.
SELFNET	Network management is aimed at; the network needs to be automated without any labor-intensive network management tasks.
SmartRuralGrid	Management of electricity distribution networks; integration of local RES is performed; prosumers interconnection is performed.
SYNAPS	Monitoring of LV network is performed; smart sensors are used; fault location identification is achieved.
UPGRID	Advanced operation and exploitation of LV networks are conducted; smart grid monitoring is performed; active consumer awareness and participation are targeted.

Table 9 summarizes the projects that deal with data traffic. Smart meters are responsible for a huge amount of traffic created in the network. It is obvious that there are projects that deal with how to handle the traffic created from a large-scale smart meter implementation, implying that there are supporting technologies and techniques for a potential roll-out.

Table 9. Data management.

Project	Scope/Short Description
Dynamic topology data in distribution grids	Develop an integrated framework for algorithms that deal with data exchange between DSO, aggregator, metering provider, etc.
EnergyLab Nordhavn platform for development of smart city energy solutions	Energy management data of smart cities; defining behaviour of future buildings.
FLEXICIENCY	Offering of new services, flexibility, monitoring, energy control;Near real-time smart meter data are available.
Optimized Distribution Grid Operation by Utilization of Smart Metering Data	Smart meters data processing; analysis for distribution grid operation.
SMART I.E.S.	Smart meter data are analyzed; communication interfaces to customers are created through smart metering results.
Smart Meter Data Analytics for Automated energy Consulting	Electricity load profiles are used for determining household parameters and properties.
VIMSEN	One of the goals: develop smart data metering techniques suitable for the virtual micro-grids.

Table 10 summarizes the usage of smart meters in other fields, like EV charging and cyber security issues, showing that the benefits from smart meters can be visible to multiple fields in the smart grid domain.

Table 10. Other applications: EV charging, cyber security.

Project	Scope/Short Description
ChargeFlex	Improve EV charging capacity through smart management of demand response
INCH	Plug-in electric vehicles (PEVs) and their smart charging; precise metering of energy consumption
SPARKS	Smart Grid Cyber security issues are studied; focus on areas like smart meters is given

As it can be observed from Tables 5–10, there are at least (the list is not exhaustive) 7 projects (11%) that deal with smart metering applications (development of smart meters with advanced characteristics or implementation of smart meters), 17 projects (28%) that deal with demand response or flexibility issues, 13 projects (21%) that examine smart home/building or smart neighborhood issues, 14 projects (23%) for grid monitoring, 7 projects (11%) that examine data management issues, 1 project studying cyber security in smart meters.

From the analysis made, some conclusions about the smart grid research trends can be concluded. For example, it is observed that the interest in grid monitoring and grid management remains a high priority for smart grid projects; for such purposes, smart meters can play a key role, since they can offer data about the grid consumption. Smart home/building and smart cities are also a topic on which smart meters can be of vital importance since it is an element that can contribute to the home–smart home transformation. It is worth noticing that DR is a topic that becomes popular lately and this is depicted by the number of projects that deal with it. There have been at least 17 projects initiated in the period 2014–2017, which shows a trend towards the investigation of demand response or flexibility aspects. Another topic that is also gaining attention is data traffic management. This can be explained because smart meters have already been implemented in some member states, thus issues following this vast implementation have come out. Indeed, smart meters are responsible for a massive amount of data communicated through the smart grid; therefore, studies related to data handling are necessary.

In general, the trend from the smart grid projects not only shows the importance of smart meters as a fundamental element of the smart grid, but also suggests the development of integration of solutions going beyond the smart meter as a simple device. These technologies make use of smart meters, build upon the metering infrastructure and explore further their potentials to offer advanced services, like demand response or grid management. The smart grid projects trend shows that the scientific interest gets to be shifted to applications that take for granted the usage of smart meters. Consequently, it is evident the necessity of smart meters implementation in order to make use of advanced applications.

6. Future Work and Discussion

6.1. Monitoring the Digital Energy System Evolution with Focus on Smart Metering Integration and Citizen's Energy Communities

The work presented in this paper is based on the monitoring work conducted by the JRC on the electricity distribution system developments and on the Smart Grid R&I projects throughout Europe. This periodic mapping of the electricity ecosystem will be continued by the JRC as the digitalization of the energy system represents one of the main trends and challenges for the energy transition. New versions of the power system observatories are under preparation, with updated information on the distribution systems, the smart grid projects and the smart grid laboratories worldwide.

Along with this, "horizontal" scanning exercises, additional "vertical" studies are being conducted and/or planned—among others—on smart metering applications/integration, citizen's energy communities and consumer vulnerability issues. This would allow the JRC to identify gaps and inform the policy-making in the context of the European Green Deal put forward by the European Commission.

In addition, as future work, it is intended to monitor the technologies of smart meters used along with the national smart meter roll-outs. Since smart meter technologies can play a vital role in interoperability issues, and given the fact that continuous monitoring is needed as smart meter roll-outs status changes in continuation, it is important to have periodic data collection for this scope. This is left as a task for periodic investigation during future data collection.

6.2. Discussion

Smart meters are a key factor in the realization of consumer-centered digital energy systems. They have attracted both scientific as well as legislative interest. In this paper, we show the main results of the cost–benefit analyses carried out by the Member States in order to carry out a smart meter roll-out or not. It is clear that smart meters have been the point of discussion even before 2014, when the first study was performed depicting the status of the smart meter roll-out in the European Member States and the CBAs carried out by them.

Recently, the Clean Energy Package was adopted, where provisions to enable smart metering roll-out are clearly stated. The main provisions of the newly adopted directive on common rules for the internal market for electricity are described. In general, two of the main objectives of the Clean Energy Package are: (A) empowering of customers; (B) achieving energy efficiency and network management. There are several points mentioned in the Clean Energy Package that are important for future smart meter roll-outs or updating the current smart meter status. Table 11 lists the main points and links them to the overall objectives.

Table 11. Main points regarding smart metering applications as highlighted in the Clean Energy Package (CEP).

n.	Smart Meter Important Points According to CEP	Linking to Objectives
1	Smart meters linked to Energy Management System(s)	A, B
2	Cyber security techniques to be implemented	A
3	Smart meter data availability plus near real-time access	A
4	Interoperability	B
5	Smart meters account for generation input in the grid by prosumers	B
6	Update smart meter systems (at most after 12 years)	B

On the other hand, apart from the legislative interest, smart metering applications have attracted scientific interest as well, as proved by numerous smart grid projects focusing on system integration and interoperability. Reassuming Section 5, where smart grid projects linked to smart metering applications are described, Table 12 lists the issues attracting more interest.

Table 12. Main points of interest regarding smart metering applications as indicated by the smart grid projects analysis.

n.	Smart Meter Thematic Areas According to Smart Grid Projects	Linking to Objectives
i	Smart Meter applications including reaching remote zones, linking to a Home Display and Cybersecurity issues	A, B
ii	Demand Response/Demand Side Flexibility	A, B
iii	Smart Cities and Smart Buildings	A
iv	Grid monitoring for energy management	B
v	Data Management	A

A certain match is observed between the legislative acts and the interest areas of the smart grid project proponents. First of all, the important areas of smart metering applications respect the overall objectives of the Clean Energy Package. Furthermore, there is a clear link between the main points as listed in Table 11 and the thematic areas, as listed in Table 12. In particular, point n. 1 is linked to the thematic area (i) and (iii); point n. 2 is linked to the thematic area (i); point n. 3 is linked to the thematic area (v); point n. 5 is linked to the thematic area (iv); point n. 6 is linked to the thematic area (i). It should be noted that Demand Response/Demand Side Flexibility is a topic that has also attracted legislative interest through the Smart Grid Task Force Expert Group for the Deployment of Demand Side Flexibility [14].

As a result, it can be concluded that in this paper we give the main points/topics that concern smart metering applications as these emerge from the newly adopted Clean Energy Package and in convergence also with the thematic areas of smart metering related projects. These points should be taken into consideration for future national plans for smart meter roll-outs or for updates of such national plans. In this paper, we give an insight into the importance of smart meters for the future smart grid and provide incentives for performing a constructive CBA that can lead to advanced smart meter roll-outs.

7. Conclusions

In this paper, we provide an up-to-date overview of smart metering for electricity end-customers in Europe. First of all, data from benchmarking of the cost–benefit analyses performed in 2014 by the JRC are presented, clarifying the roll-out plans that each European country is set to achieve by 2020. These data are complemented by information gathered by the JRC in 2018 and 2020 through surveys administered to European Distribution System Operators, as well as additional sources, like the benchmarking report on smart metering by a consortium led by Tractebel and an ACER report on the results of Monitoring the Internal Electricity and Natural Gas Markets. Such data clarify the current situation before entering into the force of the "Clean Energy for all Europeans" legislative package and its provisions for smart meters.

Following this assessment, we delve deeper into the "Clean Energy for all Europeans" legislation recently approved, which provides specifications for smart metering systems and smart metering data functionalities. In addition, we present the data from smart grid projects focusing on the integration and applications of smart meters initiated in Europe before and after 2014, where the first benchmarking analysis took place. Thus, the maturity of technologies that can support smart metering applications is discussed and the importance of smart meter usage is depicted. We complement the analysis by reporting the emerging trends in research with respect to smart grid projects. We also show that the main points highlighted in the newly adopted legislation converge with the thematic areas examined by smart grid projects. In particular, data show a trend to go beyond the smart meter as a simple device, but instead build upon the smart metering infrastructure and explore further their potential to offer advanced services for the smart grid. The current work shows overall the status of smart metering applications today and gives hints for its future evolution in the light of the "Clean Energy for all Europeans" legislative package.

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