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Review

The Status of Research and Innovation on Heating and Cooling Networks as Smart Energy Systems within Horizon 2020

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Abstract: The European Union is funding scientific research through the Horizon 2020 Framework Programme. Since the key priorities for the next few decades are the reduction in carbon emissions and the enhancement of energy system conversion efficiency, a collection of the most recent research projects can be beneficial to researchers and stakeholders who want to easily access and identify recent innovation in the energy sector. This paper proposes an overview of the Horizon 2020 projects on smart distributed energy systems, with particular focus on heating and cooling networks and their efficient management and control. The characteristics of the selected projects are summarized, and the relevant features, including the energy vectors involved, main applications and expected outputs are reported and analyzed. The resulting framework fosters the deployment of digital technologies and software platforms to achieve smart and optimized energy systems.

Keywords: European research projects; horizon 2020; digitalization; smart district heating and cooling networks; energy efficiency; intelligent management and control; optimization

1. Introduction

Over the last couple of decades, the attention on the anthropogenic impact on the environment has increased and research and actions aimed for sustainable development and climate change mitigation have become widespread [1]. In this context, the European energy scenario has been subjected to a progressive transformation from fossil-based to sustainable and renewable-based systems [2]. According to Bertelsen and Mathiesen [3], the most significant consumer of energy is the heating and cooling sector making up nearly 50% of the total primary energy consumption in Europe. Many areas with high population density still adopt individual thermal energy production sources that are powered by fossil fuel in 70% of residential end-users. Hence, there is a relevant potential for decarbonization and improvement in the air quality offered by options that have still not been fully exploited, such as district heating and cooling networks (DHC) and energy efficiency in buildings.

A more rational use of energy can be achieved if the concept of smart energy systems, as defined by Lund et al. [4], is considered. According to the latest accepted meaning, it consists of a holistic approach that integrates the energy sectors and infrastructures (e.g., electricity, heating and cooling, and natural gas), and identifies optimal solutions by benefitting from their synergies and interconnections. This can lead the way to sustainable and renewable future energy systems but also adds new challenges to the existing issues deriving from the integration of discontinuous and distributed resources into the current infrastructure. Indeed, smart energy systems are more complex and, for this reason, their design, management, and optimization require innovative methods and models. In this regard, the novel instruments for digitalization and modern technologies such as the Internet-of-Things (IoT) can be exploited to address this complexity and make energy systems smarter [5]. For instance, the availability of large datasets of energy consumption, demand and operating parameters can be advantageous in the development of predictive models and optimal strategies to reduce the impact of energy use on the environment.

These topics are at the forefront of scientific and technological research, but the state-of-the-art context is still fragmented and constantly evolving. Most review reports regarding the transformation of the energy sector take into consideration only the scientific papers submitted to journals and/or conference proceedings [6,7]. These analyses hardly include the research and innovation projects funded by national and international agencies and institutions. Alternatively, other reviews mainly focus on specific aspects such as the forecasting of energy consumption in buildings by means of data-driven approaches based on neural networks [8]; the optimization of energy exploitation in the transportation sector [9]; and the control architectures and management strategies for smart grids [10]. A descriptive summary of support activities from the European Union (EU) on energy efficiency in heating and cooling was published in 2016 [11], but it should be further updated. Another report from the Low Carbon Energy Observatory [12] gives suggestions for research priorities by comparing the objectives of national and international projects.

The scope of this paper is to provide a comprehensive overview of the research and innovation projects funded by the EU as part of the Horizon 2020 Framework Programme. The focus of the study is heating and cooling distribution networks, which are regarded as highly promising in improving air quality and environmental conditions especially in urban areas, within the context of smart energy systems. Special attention is paid to the inclusion of smart management and control strategies, since they are paramount to achieving the digitalization and interconnection of the energy networks. The most relevant projects are reviewed, catalogued and analyzed according to their goals, outputs and characteristics. A summary of such work actions can be helpful for researchers and practitioners in the energy sector for several reasons:

- to summarize the most recent innovations from the point of view of original research, as a result of the cooperation of partners from different countries and realities (e.g., research organizations, companies, and public bodies);
- to explore the potential of public engagement (i.e., participation of the public in energy-related research [13]), usually not included in technical papers, in the identification of technical solutions that are more attractive for customers;
- to keep track of the most recent practical research applications, since international projects often propose the demonstration of technologies in operative environments up to market uptake;
- to provide an overview of the results obtained by coupling scientific research and industrial development;
- to identify the research gaps partially addressed or not yet considered;
- to understand the direction of the global interest and to locate (i) future funding opportunities and (ii) profitable collaborations for addressing new challenges in the energy sector.

2. The Current European Context

This section aims to summarize the current framework of the research and innovation projects funded by the European Union. Firstly, it outlines European policy over the past few decades, which aims to promote the transition toward a better society by funding research in key fields, such as the energy sector. Secondly, it lists the main findings of the projects concerning the transition toward a smart energy scenario that have already been concluded as part of the previous funding programme. Finally, the objectives and key information of the latest major funding programme are described in order to give a full picture of the context into which this review is integrated.

2.1. European Policy for Research and Innvation

The Energy Challenge is universally recognized as one of the key priorities to be addressed in the present and future, in order to reduce carbon emissions and mitigate climate change. Since 2007, the European Commission has set fundamental targets. The first step was the adoption of the Strategic Energy Technology Plan (SET-Plan) in 2008 [14]. This document is the principal decision-making support tool for energy technology policies in the EU and aims to accelerate the transition toward a low-carbon and sustainable energy scenario. The first key goals established by the SET-Plan for 2020 were the well-known 20-20-20 goals:

- a 20% reduction in carbon dioxide emissions;
- a 20% share of energy from renewable energy resources;
- a 20% improvement in energy efficiency by reducing primary energy consumption.

Over the past few years, with the target year of 2020 approaching, the progress has been monitored and the strategies have been updated. This resulted in the Clean Energy for All European package [15] which establishes more ambitious objectives for the Energy Challenge up to 2030:

- the renewable energy target is set to 32%;
- the energy efficiency target is increased to 32.5%.

A more long-term goal of the SET-Plan is to limit the rise in temperature of the planet (as an effect of global warming) to no more than 2 °C before 2050, and also to reduce EU greenhouse gas emissions to between 80% and 95% [16]. These are essential in order to fulfill the Paris Agreement of the United Nations Framework Convention on Climate Change held in 2015 [17]. All these measures highlight the importance that the European Union authorities have recently given to research in the energy field through funding opportunities.

In general, all scientific disciplines are addressed by the Framework Programmes (FPs), which are the main financial tools of the EU for providing support to research activities. The fundamental objectives of these opportunities are (i) to link research institutions (e.g., academia and research centers) and industrial research; (ii) to create networks for cooperation and promoting the exchange of ideas, methodologies and tools; and (iii) to foster the actual application of innovation to all areas of society. Each of the first six FPs, from 1984 to 2006, lasted for a period of five years. The 7th and 8th Programmes, instead, ran for seven years and saw a substantial budget increase. More details on these tools, with a focus on the impact on district energy, are given in in the following sections.

2.2. Previous Projects

During the previous Seventh Framework Programme for Research and Technological Development (FP7), for the years 2007 to 2013, some research projects were funded with a focus on DHC as well as smart techniques for its management and control. Since these projects have recently concluded, it is worth mentioning some interesting results from this first set of actions:

(1) The CELSIUS initiative is a collaborative project that gathered the expertise and research from a large partnership to demonstrate innovative solutions for integrated heating and cooling in cities and to accelerate sustainable development. The main output is the Celsius Wiki [18], a web resource launched in 2016 that aims to be a source of knowledge and inspiration for cities and utility companies interested in district heating and cooling networks. The platform provides an overview of strategies for planning energy systems as well as the recent innovations concerning all issues of energy use, from efficient supply to smart system integration.
(2) The Energy IN TIME project aimed to develop a smart energy simulation based control method to reduce energy consumption in non-residential buildings [19]. The main output is a control tool for building energy management systems which is automatically and remotely operated. For this purpose, dynamic simulation building models with predictive models of user behavior

are integrated with adaptive algorithms for real-time control. The project entirely focused on the end-user side of the energy system. The extension of the method to energy networks could be promising.

(3) The CITYOPT project [20] aimed to create a set of applications and guidelines to make planning, design and operation of energy systems more efficient. The main output is a toolset for the optimization of urban districts comprising a simulation layer (specific for decision support) and a real-time layer, designed for demonstration and monitoring.

(4) The READY project aimed to demonstrate a whole city approach for increasing sustainability and renewables uptake, starting from the retrofitting of buildings to the implementation of information technologies in district energy. For instance, one of the main outputs is a short-term heat load forecasting tool based on machine learning and suitable for large district heating networks [21].

This brief overview describes the preliminary steps to exploit and spread smart multi-source energy systems in European countries. Since more work is required to reach state-of-the-art technologies and the commercialization stage, these topics are central also in the following European funding programme, which is laid out in Section 2.3.

2.3. The Horizon 2020 Programme

The EU is currently supporting research through the most recent Framework Programme for Research and Technological Development FP8, known as Horizon 2020. It is the biggest EU Research and Innovation Programme ever started with nearly EUR 80 billion of funding available over 7 years, from 2014 to 2020 [22]. Aligned with the European Union strategy for 2010–2020, Horizon 2020 aims to contribute to the realization of a knowledge- and innovation-driven society and is oriented toward the key priority for 2020: intelligent, sustainable and inclusive growth. The programme is divided into three macro-areas, called "pillars" [23]:

- The "Excellent Science" pillar aims to develop long-term skills for the next generation of science, technology, researchers and innovation. This includes funding for talented individual researchers from the European Research Council (ERC), support for collaborative research on future and emerging technologies, innovative training and career opportunities through the Marie Sklodowska-Curie Actions and development of an integrated European research infrastructure.
- The "Industrial Leadership" pillar aims to accelerate technological development and help small- and medium-sized enterprises (SME) grow into leading companies. The main goals are: support for the development and demonstration of advanced technologies in the fields of Information and Communication Technologies (ICT), nanotechnology, biotechnology and space, as well as access to risk finance.
- The "Societal Challenges" pillar addresses the major issues society is going to face in the near future. Such challenges are related to public health, food security, climate action, intelligent transportation, and "Secure, Clean and Efficient Energy".

The latter has been conceived "to support the transition to a reliable, sustainable and competitive energy system", since it is recognized as one of the major challenges of the near future [13]. The work programmes in Horizon 2020 are biannual in order to allow a better preparation of applicants. Therefore, three major phases can be identified for the "Secure, Clean and Efficient Energy" challenge throughout the duration of the programme:

- Work Programme 2014–2015. This first call for proposals was structured in three specific research areas: "Energy Efficiency" applied to buildings, industry, heating and cooling and their integration with ICT; "Competitive Low-Carbon Energy" such as renewable energy sources; and "Smart Cities and Communities".
- Work Programme 2016–2017. Similarly, the second part contributed to the two focus areas of "Energy Efficiency" and "Competitive Low-Carbon Energy".

- Work Programme 2018–2020, which was recently published and is currently open for proposals. This call includes the contribution to the focus area "Building a low-carbon, climate resilient future" with special attention paid to energy efficiency and global leadership in renewable energy solutions for implementation at the energy system level.

In particular, increasing attention is given to DHCs, which offer the opportunity to improve the air quality of urban environments by means of (i) the efficient, smart and cheaper distribution of thermal energy and (ii) the integration of multiple resources, including renewables. This is specified, for instance, by two calls for proposals from different work programmes: firstly, the call EE-13-2015 [24] requires to develop the new generation of intelligent heating networks by means of innovative metering, control and optimization tools; secondly, the call LC-SC3-RES-8-2019 [25] supports cost-effective solutions for heating networks with at least a 50% share of renewable energy sources to be tested in operational environments. A large number of universities, research centers, private companies and public bodies answered these and other calls giving rise to innovative research projects.

In order to have a broader idea of the purpose and methodology of each considered project, it is beneficial to make a further distinction according to the funding scheme adopted within the Horizon 2020 framework:

- Research and Innovation Action (RIA): these actions aim to establish new knowledge and to explore the feasibility of new technologies and solutions. They typically include small-scale development, testing and validation of a prototype in a laboratory or simulation environment.
- Innovation Action (IA): typically guided by industrial partners, these actions aim to improve, demonstrate and validate a state-of-the-art idea on a large scale, in order to show its feasibility and convenience for the market.
- Coordination and Support Action (CSA): these actions primarily consist of accompanying measures and complementary activities that aim to improve the networking and cooperation between programs in different countries. These actions include standardization, dissemination, awareness-raising and communication.

The main difference between the former two funding schemes is the value of the Technology Readiness Level (TRL). The TRL is an indicator that defines the maturity level of a given technology, providing a common understanding of its status and addressing the entire innovation chain. It is based on a scale from 1 to 9: lower values of TRL typically represent basic research or proofs of concept (i.e., RIA), while higher values are indexes of more mature products that approach the status of manufacturing or commercialization (i.e., IA). Figure 1 shows the definitions of the TRLs and their correspondence with the two main funding schemes described above. It is more common for IA to have larger consortia and more industrial subjects in the partnership than RIA. This can be justified by the companies' interest in achieving a product ready to be introduced on the market and by their ability to speed up the demonstration and manufacturing process.

The opportunities within Horizon 2020 outlined above are going to end in 2020. The next FP approved by the EU is named Horizon Europe and is even more ambitious than FP8, with a total funding higher than EUR 100 billion and a similar duration of seven years, from 2021 to 2027 [26]. It is expected to pursue clearly defined targets in five mission areas, including "Climate-neutral and smart cities" [27]. Hence, the research topic targeted in the present work is expected to be at the forefront of innovation also over the next decade.

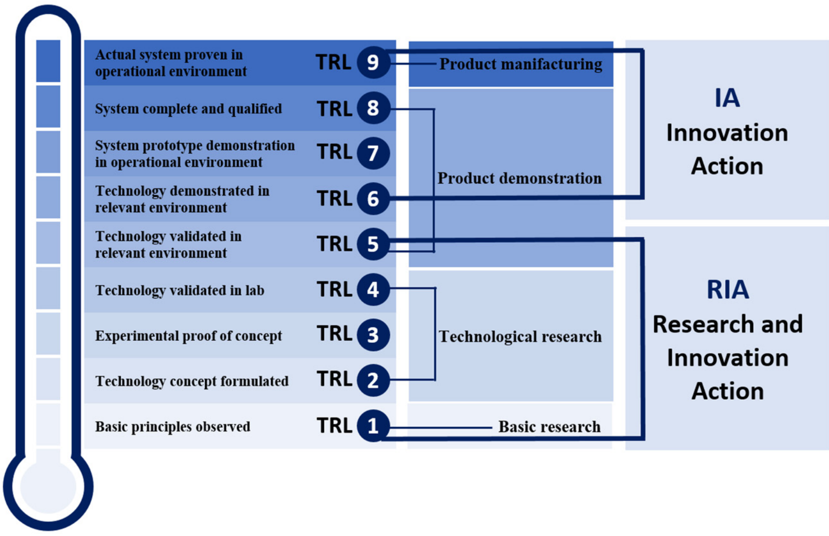


Figure 1. Technology Readiness Level definition.

3. Research Method

As stated above, the present study aims to give an overview of the research and innovation projects funded by the Horizon 2020 Programme that are relevant to the "Secure, Clean and Efficient Energy" challenge and, in particular, to smart district energy systems. This can be done by selecting the work actions focused on smart energy, smart grids, digitalization of the energy sector, smart control, and optimization of energy systems and intelligent technologies for districts and buildings.

Nonetheless, the construction of a map of Horizon 2020 projects may be a challenging task, as the projects are often large and involve partners from different countries and backgrounds. Moreover, individual work packages are distributed to different research groups, thus preliminary results and public information may be difficult to find. In addition, some characteristics, methods, or outputs of the projects are not detailed in the general description. Therefore, a constant update of the available information is required to identify their features correctly.

Two recent articles with a similar scope are available in the literature. Moseley [28] highlights and addresses this issue presenting a detailed and comprehensive review of recent and ongoing Horizon 2020 research, innovation and market uptake projects on "smart buildings". Firstly, a definition of the "smartness" of a building is identified as its technological readiness to manage itself efficiently, and to interact with its occupants and the wider energy environment. Keeping these criteria in mind, the author examines the tasks, scopes, and innovations focusing on building automation, demand response, energy management, and ICT interfaces for energy efficiency at building level. The outcome of this paper is a useful summary and comparison of 42 relevant Horizon 2020 actions funded within the calls for proposals of the years 2014, 2015, and 2016. The paper, published in 2017, cannot include the most recent developments of the programme. Moreover, the interactions between the building and the global energy system as well as the potential innovations at district level are excluded, as they are beyond the scope of the paper. On the other hand, Longo et al. [29] present a review of the ongoing and concluded projects that study energy poverty in households and vulnerable consumers from the perspective of energy provision, in order to understand the common framework and future trends to solve this issue in an international context. The work collects 43 relevant projects spanning over the FP7 and Horizon 2020 Programmes. Furthermore, it identifies the most recent calls of 2019 as the turning point in the recognition of energy poverty as an issue to be addressed with specific calls, common specifications, and standardized measures.

These studies are relevant to the considered application field. Nevertheless, they do not involve the energy systems more broadly. In the present context, it is essential to investigate the entire energy system in a holistic way, its interactions and connections, and the innovative methods to improve its efficiency. Moreover, with Horizon 2020 coming to an end, a summary of all the funded actions can be of interest. This is proposed, for instance, in [30], which gives a quantitative outline of the European research regarding the concept of Smart Cities.

The present work adopts a method similar to the aforementioned papers, with a focus on the development of smart tools and approaches for heating and cooling energy systems, comprising district level, building level, and their integration with other energy carriers.

Firstly, a close examination of the Community Research and Development Information Service, also known as the CORDIS portal [31], was carried out. This portal is the primary reference for information on every EU-funded project in different programmes and calls over the past two decades. It includes the general description and, when applicable, results in brief for each available project. The search was conducted with the following keywords and their combinations: District Energy; District Heating and Cooling; Smart Energy System; Optimization; Intelligent Control and Management; Predictive Control; Energy Sector Integration; Digitalization. Special attention was paid to projects that involve Model Predictive Control (MPC), as this is a well-known efficient control strategy for chemical and industrial processes but its further application to district energy still has to be explored to a greater extent [32].

The characteristics of the projects selected as relevant to the scope of the paper were scrutinized in depth by referring to the dedicated website. In particular, the analysis focused on the subdivision of the projects in work packages (WPs), on the demonstration case studies—when applicable—and on the published dissemination material (such as deliverables and reports). In some cases, the website contained a section dedicated to the related projects, which share the objectives, applications, or part of the consortium. These were further examined in order to identify and include additional work actions in the analysis that were not obtained during the preliminary search phase. Moreover, science databases were explored for potential publications (e.g., conference or journal papers) from the main research groups involved in the projects, in order to track the preliminary results of the ongoing projects as well as the outcomes of those already concluded.

The material and documentation were collected in a database that can be periodically updated with new information and current results when they become available. Each action was represented by a project profile sheet that gathered the following data:

- name and acronym;
- project website and logo;
- grant agreement and total funding;
- start and end dates of the project activities;
- partnership, divided between private companies, research institutions, universities, public bodies, and others;
- general description and main goals;
- location of the demonstration sites;
- preliminary results and current status.

Regarding the goals and activities carried out or expected, the main features—relevant to the development of smart energy systems—were highlighted for each selected project. These features, detailed in Table 1, include (i) energy vector, (ii) major application, (iii) project output, (iv) purpose and methodologies. This defines a comprehensive research and innovation framework that can be exploited to identify scientific and technological gaps to be considered for future activities. The discussion of this framework is outlined in Section 4.

4. Results and Discussion

The search described in Section 3 resulted in 58 work actions funded within all three Work Programmes of Horizon 2020. All the selected projects are relevant to the topics of this search in at least one work package. The general characteristics that identify each project, such as funding scheme, total funding amount, coordinator country, and dates, are collected in Table A1, while their relevant features are reported in Table A2, both in Appendix A. The discussion and analysis of both of these aspects are given in the following sections.

4.1. General Information

The analysis of the general information of the Horizon 2020 research projects on smart energy systems can improve the understanding of where and when the majority of the funding has been directed. As shown in Figure 2, the coordinators of the projects come from 13 different countries, situated in western or northern Europe, where typically thermal networks are more widespread. The only exception is represented by the TOPAs project, which is coordinated by a private company from Israel. The two most represented countries are Spain and Italy, where the former coordinates 14 projects (almost one quarter of the total) and the latter coordinates 11 projects (about 19%). The United Kingdom coordinates six projects (10%), while participants from France and Belgium are responsible for five (8.5%) and Germany for four (7%) projects. Sweden, Finland, Denmark, the Netherlands and Austria have two projects each, while Ireland and Israel, cited above, coordinate one of the selected actions each.

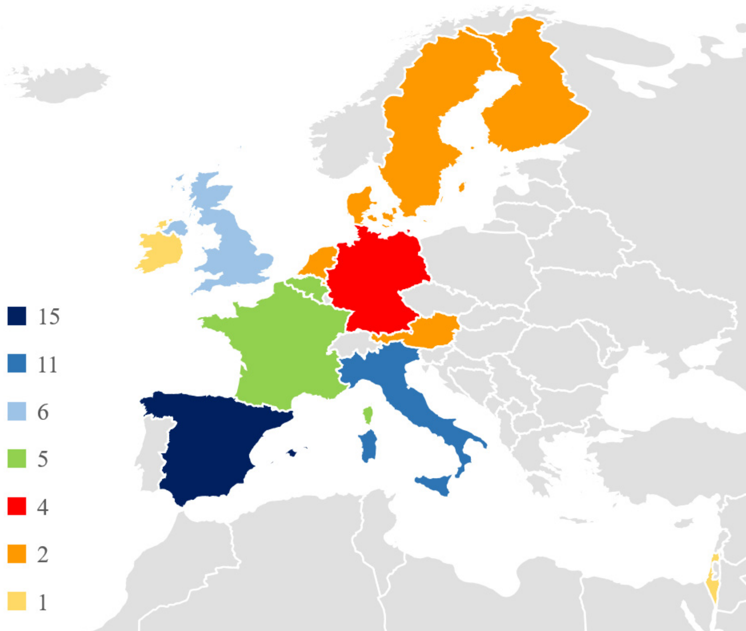


Figure 2. Number of projects per coordinator country.

These considerations are confirmed by Figure 3, which gives a representation of the number of projects that partners from the different countries are contributing to. The most represented country is again Spain, as it participates in almost 70% of the selected projects (39). Germany and Italy follow with 37 and 35 projects, respectively, while France and Belgium each participate in 30 work actions, and the United Kingdom in 29. Nonetheless, it is possible to notice that the most part of the European countries are involved in studies and demonstration activities on smart energy systems: Denmark and the Netherlands (19), Sweden (17), Austria (15), Ireland (14), Switzerland (13), Poland (12), Greece (11), Finland and Czech Republic (10 each), Croatia (9), Romania (8), Serbia (7), Slovenia and Portugal (6 each), Hungary, Bulgaria, Cyprus, and Turkey (4 each), Norway, Estonia and Latvia (3 each), Lithuania, Luxembourg, and Bosnia–Herzegovina (2 each), and North Macedonia and Ukraine (1 each). Furthermore, there is the contribution of Israeli partners in three projects and Indian partners in one project. The latter is not shown in Figure 3 for clarity.

Table 1. Features for the selection of the research and innovation projects that involve smart energy systems.

Feature		Explanation
Energy vector		This identifies the energy carriers the project works on: thermal power, cooling power, electricity, or natural gas.
Application	Grid/District	The project's activities are applied at grid or district level, generally involving a multi-source complex energy system.
	Building	The project's activities are applied at building level.
Main Outcome	Software/Platform	The scope of the activity is to create a software package, a platform, a web application, or a framework for researchers and industries.
	Model/Library	The scope of the activity is to create a model or a library of models for the effective simulation of buildings or district energy system components.
	Optimization tool	The activity comprises the development of an optimization algorithm or the solution of optimization problems for minimizing an objective (e.g., cost, total energy consumption).
	Business model	The activity aims to create a new business model for the industrialization or exploitation of the concept.
Purpose	Planning	The purpose of the project is to perform long-term (yearly) planning and scheduling of the system.
	Sizing/Design	The sizing or design of the distribution grid, generation systems and loads, additionally considering the topology, are carried out.
	Retrofitting	The purpose of the project is the evaluation of adding innovative technology to existing systems for refurbishment.
	Real-time control	Innovative intelligent control strategies are implemented and tested.
	Monitor/Management	System monitoring through smart meters and sensors and overall system management to achieve a given goal is performed.
	Diagnosis	The methodology is developed to perform system diagnosis or fault detection.
	MPC	The Model Predictive Control technique is applied: the control action is optimized based on the future behavior of the system predicted by a dynamic model.
Other	Machine learning	Machine Learning and Artificial Intelligence techniques are used for the classification and identification of models by exploiting the available data on the system.
	Forecasting	The forecasting of weather conditions, energy demand or other external disturbances are implemented.
	LCA/LCC	Life Cycle Analysis or Life Cycle Cost are performed to evaluate the global environmental or economic impact of the system.
	Demand Response	Demand Response strategies are integrated in order to adjust energy demand to match the supply through engaging customers and promoting behavior that is beneficial to the system.
	Peak shaving	Strategies for the elimination or leveling of the peak loads are evaluated.
	Storage	Energy storage is accounted as a key component to improve the flexibility of the system.
	RES	There is specific reference to the integration of Renewable Energy Sources (RES) as one of the goals of a work package.

As far as the distribution of the projects over time is concerned, Figure 4a,b show the number of actions per start year and end year, respectively. Almost all the projects (i.e., 85%) considered relevant to this analysis started from 2015 to 2017, while only eight started in 2018 and 2019. This is also due to the fact that recently started projects are still in the preliminary phases and do not yet have reports or, in some cases, a website. Therefore, the periodic update of the project database is a way to include more actions and improve the results of this analysis with new available knowledge. On the other hand, almost 70% of the projects are still ongoing, while the remaining 30% concluded their research in 2017 (1), in 2018 (5) and more recently in 2019 (12). This indicates that, during the next few years, an increase is likely to be seen in publications and reports once the results from the demonstration of the proposed new technologies are available.

It is also interesting to analyze the distribution of the projects depending on the funding schemes cited in Section 2.3, in order to give an estimation of the maturity level that these technologies are expected to reach. According to Figure 5, only seven projects, equal to 12% of the total, are Coordination and Support Actions. The most part of the selected projects are instead IA or RIA with the former equivalent to 52% (30) and the latter to 36% (21). This distribution shows that the available funding for smart energy systems is mostly dedicated to technologies demonstrated at least in a relevant or operative environment (TRL 6 or 7, with reference to Figure 1).

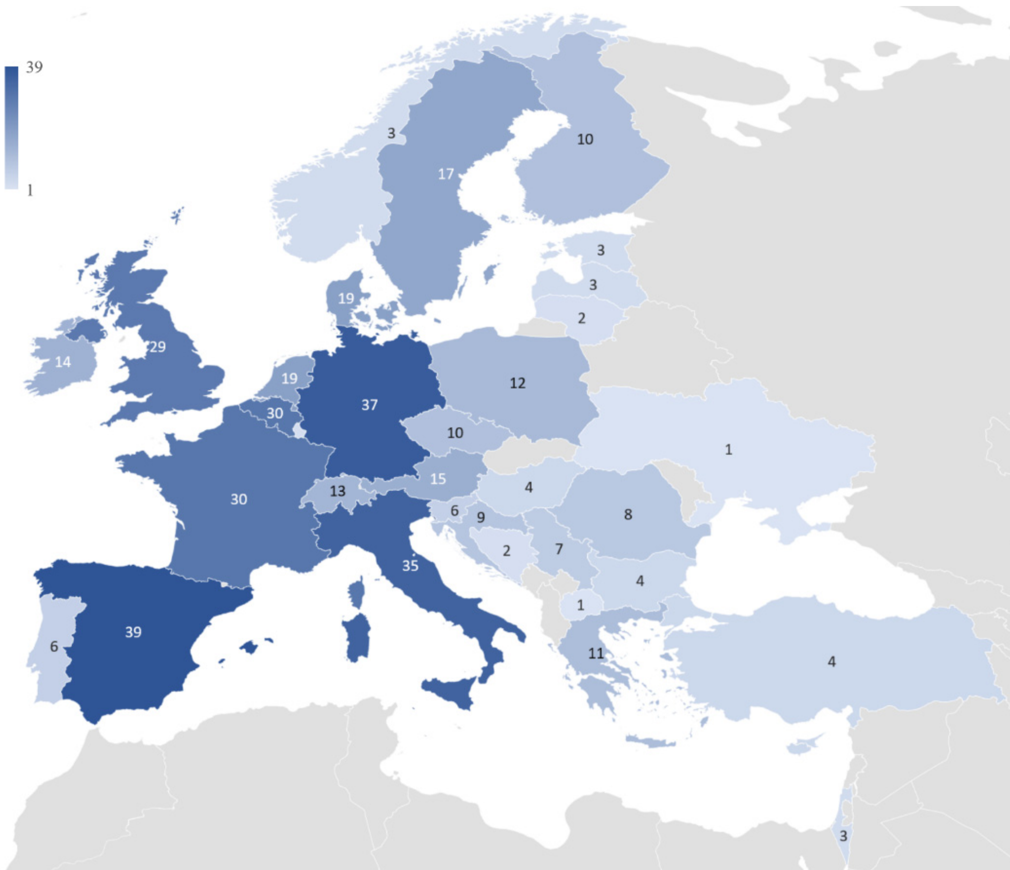
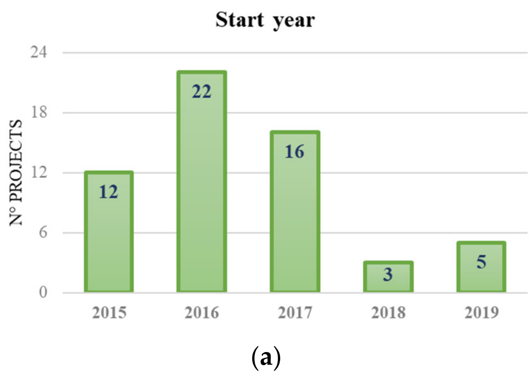


Figure 3. Number of projects per participating country. In addition, India participates in one project (not shown).



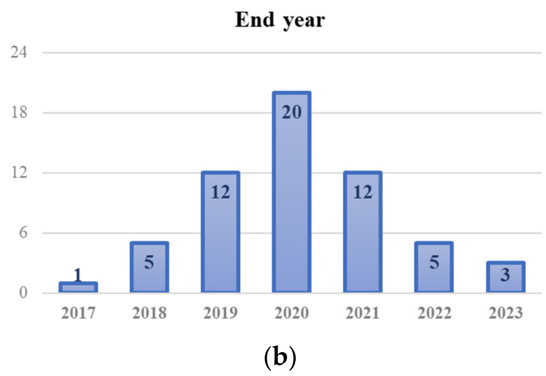


Figure 4. Number of projects per (**a**) start year and (**b**) end year.

This is of key importance since the spread of smart and integrated energy networks throughout Europe is possible if innovative technologies, once demonstrated, become available at a commercial level. Nonetheless, feasibility studies and testing in laboratory (TRL 1 to 5, as in Figure 1) are also considered relevant to allow new concepts to be proposed and, potentially, further carried out in future actions. In this regard, an interesting case is that of the STORM project, followed by the TEMPO project, both coordinated by the same institution. The former is an RIA and developed a smart controller for district heating and cooling with the features of load forecasting and thermal peak shaving [33]. The latter is an IA aimed to extend the functionalities of the STORM controller and bring it forward in the path toward market readiness.

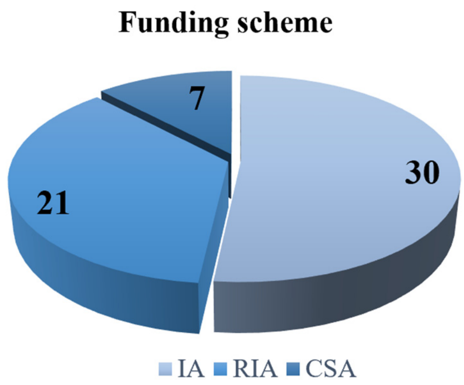


Figure 5. Number of projects per funding scheme: IA Innovation Action; RIA Research and Innovation Action; CSA Coordination and Support Action.

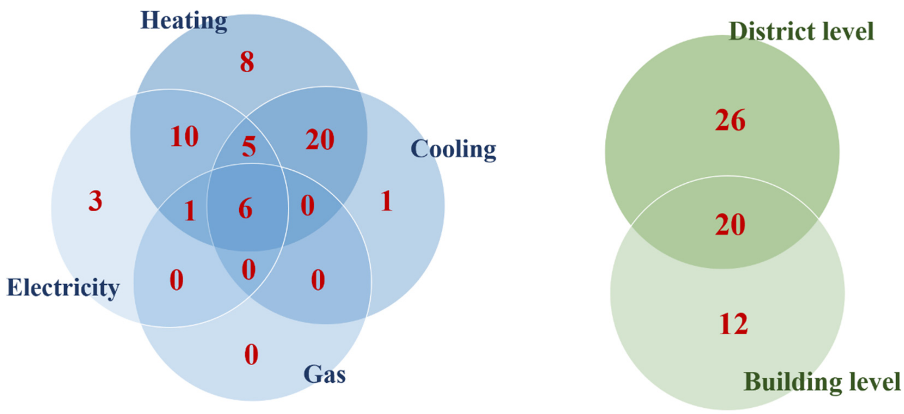
4.2. Project Features

After summarizing the general characteristics of the selected work actions, it is important to analyze their specific features (with reference to Tables 1 and A2) in order to outline the outcomes and improvements expected in the coming years, and to understand the methods that should be further explored.

Figure 6a represents the number of projects that explicitly consider heating, cooling, electricity, or gas, or a combination of these, as energy vectors. Since the analysis is mainly dedicated to smart thermal networks, the most exploited vector is heating which is combined with cooling technologies in 20 projects. In general, district heating is more widespread than district cooling. This is confirmed by the fact that, out of the selected projects, only INDIGO [34] is entirely aimed to improve planning, control and management of a district cooling network. Only three projects are fully dedicated to smart methods and technologies for the electric grid, while 22 projects integrate electricity with thermal vectors. Overall, six actions attempt to tackle a global urban energy system by exploiting the synergies between heating, cooling, electricity, and natural gas at the same time. These are promising steps toward the development of an efficient "network of networks", in which sector integration allows the energy to be stored and converted into the most convenient form, depending on the external conditions. However, this should be further explored with more research and demonstration activities.

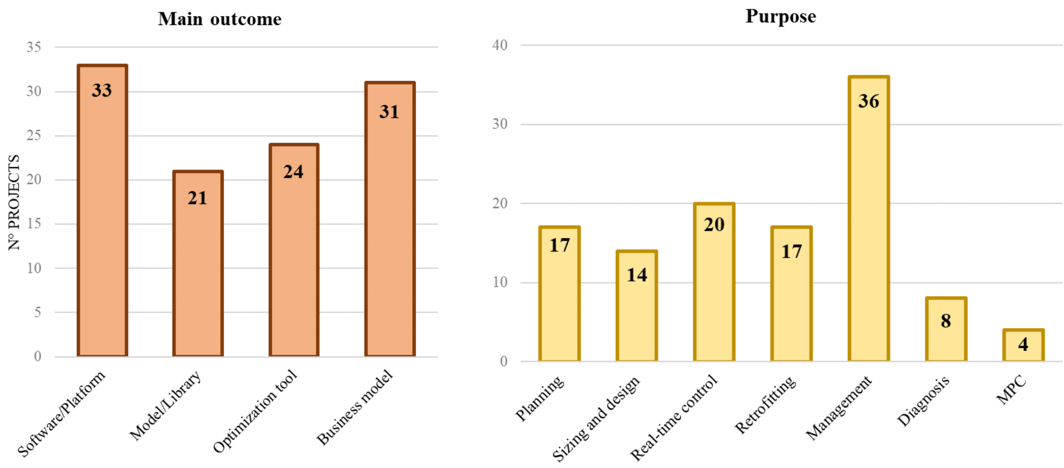
Figure 6b depicts the distribution of the projects depending on their main application. As expected, most works focus on the districts (26), while fewer develop technologies that are applied to single buildings (12). Nonetheless, 20 projects integrate the building level with the district level, showing a significant interest in providing methods that can be implemented to an energy system in its entirety, from energy conversion to end-user supply.

The analysis of the main outcomes and purpose of the projects is depicted in Figure 7a,b, respectively. More than half of them (33) aim to build a software package, a web platform, or an application that can efficiently help researchers and stakeholders increase knowledge on complex energy systems. This shows the trend toward the digitalization of the sector, in opposition to the conventional approaches typically based on the experience of the system operators. The development of models or a library of models that can accurately simulate the behavior of energy systems is another important aspect that is proposed by 21 projects. These models can also be used to promote the future exploitation of the technologies, allowing them to be evaluated and replicated to systems other than the project demonstrations sites. Likewise, optimization algorithms with the scope of minimizing energy consumption or cost are implemented in 24 work actions.



(**a**) (**b**)

Figure 6. Number of projects per (**a**) energy vectors involved (**b**) and main application.



(**a**) (**b**)

Figure 7. Number of projects per (**a**) main outcome and (**b**) principal purpose of the study. The detailed explanation of the features is reported in Table 1.

Lastly, the importance of tackling smart energy networks not only with reference to technical and engineering issues, but also from an economic point of view is shown by the large number of projects that include the creation of new business models for the actual market evaluation of smart technologies. Indeed, a ready business model is paramount to (i) make them attractive to investors, consumers, and stakeholders in general and (ii) foster the increase in TRL.

As can be seen from the outlook on the project features in Table A2, the selected work actions hardly focus on a single target, as a multi-stage and multi-disciplinary approach is fundamental for making energy networks smart. System management or monitoring with sensors, in order to obtain real-time data for digitalization, is achieved by more than 60% of the projects (36). In 20 projects, one of the main goals is the development or testing of a smart real-time control strategy, which shows the importance of system control in improving efficiency. However, predictive controllers (i.e., MPC) are only proposed in four cases. The production planning (e.g., day-ahead scheduling or load allocation) of multi-source energy networks and the retrofitting of existing systems, typically buildings, are both achieved by 17 projects, while the development of efficient methodologies for designing or sizing new systems in an optimal way is the purpose of 14 work actions. A limited number of projects (8) focuses on diagnosis and fault detection. Understanding the most common faults in district heating networks and adopting the right approaches to overcome them, however, can help decrease the operating temperatures and, therefore, increase system efficiency, as shown for instance by the TEMPO consortium [35].

The additional features analyzed in this work can be of particular significance as they all represent innovations for energy systems. The number of projects tackling such features is shown in Figure 8. As expected, more than 70% (42 out of 58) of the selected projects contemplates explicit goals, work packages, or activities for the integration and efficient management of RES in the energy systems. This is essential for the development of the new generation of DHC [2] and smart energy systems [4], for which the combination of waste heat recovery and alternative sources is required. Another key element is the integration of storage technologies to decouple supply and demand (as they are seldom simultaneous) and to increase the flexibility of the system by scheduling production when it is more convenient from an energy consumption or cost perspective. This is tackled by 21 actions (36%). The exploitation of IoT and machine learning technologies is carried out by 18 projects, typically to perform load forecasting (14 projects), which is highly influenced by the external conditions. This is essential especially in thermal networks, where the dynamic behavior is slower compared to the power grid. For this reason, an energy efficient production has to be planned in advance in order to correctly answer the load variations. On the other hand, network flexibility can also be enabled on the consumer side by promoting Demand Response (DR), i.e., shaping the demand of the end-users to match the optimal management of the network. This can be proposed for any energy carrier involved in the energy system. The DRIvE project [36], as well as seven other research projects, study DR technologies that are feasible when advanced ICT platforms, optimization algorithms, and real-time control architectures are implemented [37].

Fewer works perform LCA studies (six work actions) involving future scenario analyses with a long-term perspective. Only three projects implement thermal peak shaving, which has the ability of reducing the fluctuation of thermal demand and, therefore, achieving a more stable operation of the production plants (e.g., potentially avoiding the frequent start-up of auxiliary equipment). For this reason, it should be more widely addressed in future funding opportunities.

All the projects and features analyzed in the present paper are finally collected together in the interconnection map depicted in Figure 9, similarly to [12].

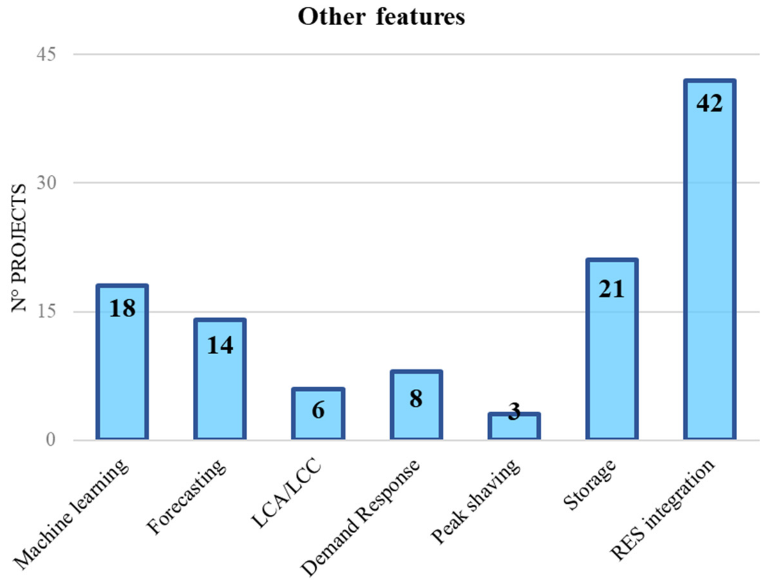


Figure 8. Number of projects per other features included in the project activities. The detailed explanation of the features is reported in Table 1.

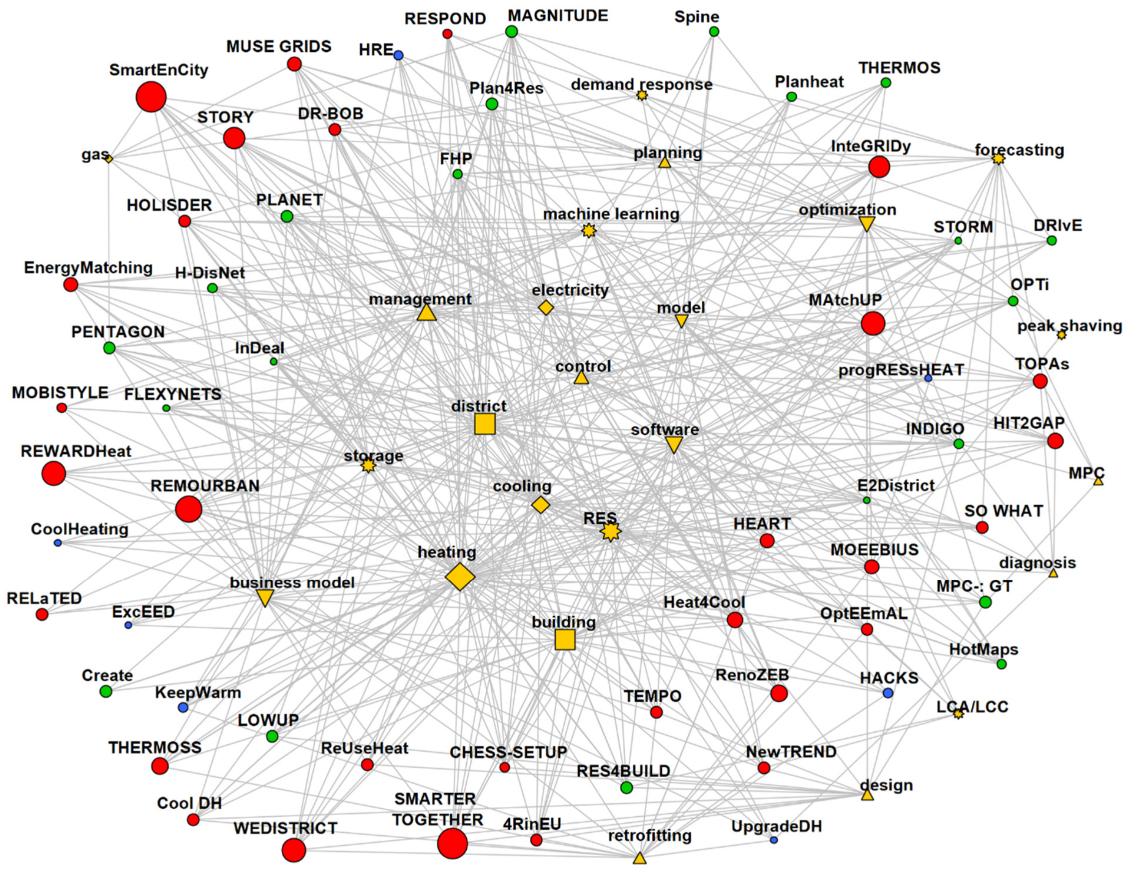


Figure 9. Interconnections between the selected projects and their relevant features. The circles represent the projects (red for IA, green for RIA, blue for CSA), with the size proportional to the funding amount. The yellow symbols represent the features, with the size proportional to the number of interconnections with the projects. The detailed explanation of the features is reported in Table 1.

The circles correspond to the selected Horizon 2020 projects with the diameter proportional to the amount of funding (with reference to the data collected in Table A1). The color of the circle indicates the type of funding scheme, where red, green and blue stand for IA, RIA and CSA, respectively. Each project is linked to the involved features, represented by the yellow symbols. The shape of the symbols corresponds to a different feature category with reference to Table 1 (i.e., diamond for energy vector, square for application, inverted triangle for main outcome, triangle for purpose and star for other features). The size of each symbol is proportional to the number of interconnections and, consequently, to the number of projects that directly tackle the feature. The largest cluster of characteristics include heating applications at district and building level by means of software packages, simulation models, and business models, with the purpose of smart management and control, often involving machine learning and RES integration. Since they are key issues of smart DHCs, this is coherent with the scope of this work. Promising features such as demand response, peak shaving, MPC, and fault detection for heating networks are on the edges of the map and deserve future in-depth analysis. It also emerges from the graph that the projects with the largest budgets, in some cases higher than EUR 10 million, are all IA and involve technology demonstration on a large scale.

The comparative analysis outlined in this section resulted in some final thematic considerations concerning the real-time control of the system. Apart from the already cited STORM project [33], other interesting outputs are as follows:

- the INDIGO project develops an MPC for the generation, distribution and consumption levels of district cooling systems and provides a library of models for detailed information on the physical phenomena occurring in the components [38];
- the OPTi project [39] proposes an integrated toolset for user-centric optimization of DHCs, adopting the MPC strategy and advanced modeling techniques;
- the TOPAs project designs centralized and distributed MPCs suitable for controlling the temperature in separate areas of single building environments, and compares the related performances [40];
- the FLEXYNETS project [41] aims to test different control strategies by means of a small-scale experimental test rig that emulates a real thermal network;
- the E2District project deploys a novel management framework for district heating systems with a large number of tools and the aim of lowering the distribution temperature [42].

4.3. Other Projects

In the framework of the international funding opportunities, the ERA-Net Cofund scheme [43] can be of further interest for the deployment of smart energy systems. Indeed, 32 transnational projects were funded under the Smart Grids (SG+) Joint Calls from 2015 to 2017 while 23 other actions were funded under the Smart Energy Systems (SES) Joint Call in 2018 [44].

These calls have the prerequisite that the funded actions adopt the three-layer model, consisting of three categories—i.e., stakeholders, market and technology—to be integrated in the smart grid/energy environment. As a matter of fact, the interrelation and combination of these three layers can improve the assessment and uptake of smart energy systems [45]. In particular, it is recommended to tackle the problems from a multidisciplinary point of view, by coupling market analysis, social acceptance and consumer need with the technical aspects.

The first calls were more focused on the power grid, as shown for instance by the ReFlex project, which developed use-cases for flexibility in smart grids and published a guidebook for their replication [46]. In the following opportunities, heating networks and sector coupling are becoming more attractive. The DISTRHEAT project, funded as part of the call in 2018, aims to develop a scalable predictive controller for DHCs suitable for fast replication at any scale, from an individual building to a city network [47].

Thus, despite the smaller partnerships and budgets involved in these actions, these calls should not be underestimated since they fund research on specific topics of the energy sector, and promote multidisciplinary evaluation and testing. Furthermore, the ERA-Net SES Initiative promotes communication and networking between different project partnerships by organizing conferences, webinars and follow-ups. This aims to create a broad network of institutions, companies and other participants engaged in the field of smart energy systems.

4.4. Drivers and Guidelines

The overview outlined above is a comprehensive picture of the current status of research and innovation projects. This section provides some general indications and guidelines for future developments that can be derived from these results.

Firstly, it is possible to identify some key features that should drive research and innovation on smart DHCs:

- Digitalization. The worldwide context has evolved toward an interconnected and data-driven system, dominated by more efficient tools and devices from the ICT world as well as by data mining and machine learning techniques. This creates opportunities also for the energy sector, which can benefit from these new technologies in order to achieve more sustainable energy systems by means of the smart management of low-carbon sources (e.g., renewables and waste heat) and predictive maintenance. In this regard, one of the greatest potentialities is offered by real-time optimal control methods, which require online data processing and computationally efficient algorithms. While they were not applicable in the past, nowadays they are enabled by the latest developments in programmable controllers, innovative software and hardware architectures. These methods reinforce physics-based system modeling, which is in any case essential in accurately representing the occurring phenomena and understanding the system behavior. Overall, digitalization is beneficial for smart energy systems and should be pursued by means of the synergic match between physics-based representation, available data, and software.
- Integration. The most part of the projects summarized in this paper involves only one or two energy domains. The integration of all energy vectors (i.e., electricity, heating, cooling, natural gas), on the other hand, allows synergies to arise between these domains. Indeed, the conversion of energy into the form that is most cost-effective or energy-efficient for the global system (depending on the actual boundary conditions) will lead to optimal exploitation of renewables and energy saving. It is paramount to invest and research on enabling technologies, such as energy conversion devices (e.g., Power-to-Gas and Power-to-Heat) and optimal ways to control their integration. Furthermore, the integration should be seen also from a social point of view, as positive interactions between producers, consumers, networks and infrastructures could improve the management of smart energy grids.
- Decarbonization, toward a 100% renewable energy system that requires storage technologies to be strongly implemented. When dealing with energy storage, it is necessary to focus not only on proper storage devices, but also on unconventional storage concepts, e.g., building envelopes, frozen food, and controllable load in industry.
- Last, but not least, resilience, which is currently of utmost relevance due to the COVID-19 containment measures that have greatly affected the energy scenario and that may have repercussions in future years [48]. Similarly, the global energy system will have to be able to adapt to other unpredictable global events that might occur in the future.

All these trends have already been identified as strategic lines for the Horizon Europe programme. Finally, it is also possible to delineate some general guidelines aimed to assist specific actors of the energy sector in future research and innovation:

- Policy makers, who are responsible for defining the priorities for the next calls [16], shaping funding opportunities and updating roadmaps [49–51]. The prospect of smart approaches and available renewable technologies is vast, but most are still at a preliminary phase. In the light of this, policy makers and investors should stimulate the work actions that demonstrate the feasibility of these technologies in operational environment (i.e., IA). They should also promote the formation of experimental areas where more smart technologies can be integrated, tested and exploited jointly [52], and where limitations (e.g., due to interferences between different technologies) and opportunities (e.g., due to synergies between technologies) can be observed. Overall, the leading trend for the next few years is to rely on strong and well-defined partnerships in order to actualize innovation. Another fundamental aspect that should be included in future opportunities is social and economic research. As a matter of fact, the spread of digital technologies might be limited by opposition from consumers. Hence, investigating social acceptance, accessibility and affordability, as well as creating new business and behavioral models in order to engage the customers in innovation, will determine win-win solutions for consumers, producers, network providers and investors.

- Energy system designers, who should adopt an integrated holistic approach to system development. Indeed, they should focus on the optimization of the entire energy system (also with LCA and evaluation of the environmental performance in the long term) and not of individual components, by considering design and operation at the same time with the help of system digital twins and simulation platforms. The designers should also consider the limitations (e.g., the current power grid capacity) and opportunities (e.g., increasing the share of renewables and waste heat recovery) given by the evolution of the energy context. It is important to propose solutions with high potential for replication, but also to adapt and exploit the new tools made available by research and innovation in order to retrofit the existing systems.
- Researchers, who should deeply investigate the applicability of digital technologies in theory and practice. It is paramount to move from technological research to product demonstration in relevant and operational environments, in order to bring innovation to the market. One of the key priorities is to develop new interactive platforms for decision-making, energy network management and cross-sector integration. It is also important to focus on methods which, in the presented projects, have not been addressed to a significant extent. Real-time control is still raw and outdated in most DHCs, therefore the implementation of MPC strategies, enabled by new developments in ICT and optimization, deserves more attention. Other promising approaches include peak shaving and demand response, which should be exported to thermal networks. Finally, researchers should not underestimate social and economic research in order to cover user needs and involve the end-users in identifying more profitable solutions.

5. Conclusions

This paper proposes an overview of the most recent research projects, funded by the European Union within the Horizon 2020 Framework Programme, with the aim of making district energy systems smarter. An in-depth search of the CORDIS portal, the database of the European Union projects, followed by the analysis of websites, reports and publications resulted in the selection of 58 relevant work actions. The general information and specific features regarding energy vectors, applications, and outcomes were collected in detailed tables. Special regard was given to the projects involving the optimization, control and management of district heating and cooling networks. The analysis of the data made it possible to draw quantitative and qualitative considerations from the selected Horizon 2020 work actions as follows:

- the projects on smart energy systems are mainly coordinated by partners in western and northern Europe, even though almost every European country contributes to the innovation;
- it is reasonable to expect a large number of publications and data available from technology demonstration, as most of the projects are still ongoing;
- there is increased interest in the integration of electricity, heating, cooling, and natural gas sectors, in order to exploit their synergies and interconnection/storage technologies in an optimal way;
- similarly, about one third of the projects tackles both district and building levels, considering the system from production to consumption;

- software applications with model libraries, digital technologies, and business models are key elements of the future smart energy systems;
- a few projects that address real-time control obtained promising results from predictive control strategies, which deserve further testing;
- additional funding opportunities such as the ERA-Net Smart Energy Systems Joint Calls are regarded as relevant since they foster sector integration and the inclusion of social and economic aspects in innovation.

Overall, this framework establishes a starting point for the evaluation of future technologies, research gaps and funding opportunities within the next Horizon Europe research and innovation programme.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CSA	Coordination and Support Action
DHC	District Heating and Cooling
DR	Demand Response
EU	European Union
FP	Framework Programme
IA	Innovation Action
ICT	Information and Communication Technologies
IoT	Internet-of-Things
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
MPC	Model Predictive Control
RES	Renewable Energy Sources
RIA	Research and Innovation Action
SES	Smart Energy Systems
SET-Plan	Strategic Energy Technology Plan
SME	Small to Medium-sized Enterprise
TRL	Technology Readiness Level
WP	Work Package

Appendix A

This appendix reports the general information and specific features of the 58 resulting projects.

Table A1. General information of the selected projects funded by the Horizon 2020 Framework Programme.

Project	*Title*	*Grant Agreement*	*Funding Scheme*	*Funding [€]*	*Coordinator Country*	*Start Date*	*End Date*
4RinEU	Robust and Reliable technology concepts and business models for triggering deep Renovation of Residential buildings in EU	723829	IA	4,627,954	Italy	01/10/2016	30/06/2021
CHESS-SETUP	Combined Heat System by using Solar Energy and heaT pUmPs	680556	IA	3,703,706	Spain	01/06/2016	31/05/2020
Cool DH	Cool ways of using low grade Heat Sources from Cooling and Surplus Heat for heating of Energy Efficient Buildings with new Low Temperature District Heating (LTDH) Solutions	767799	IA	5,291,186	Denmark	01/10/2017	30/09/2021
CoolHeating	Market uptake of small modular renewable district heating and cooling grids for communities	691679	CSA	1,664,340	Germany	01/01/2016	31/12/2018
Create	Compact Retrofit Advanced Thermal Energy Storage	680450	RIA	5,914,658	Netherlands	01/10/2015	30/06/2020
DR-BOB	Demand Response in Blocks of Buildings for Energy Systems	696114	IA	5,136,770	United Kingdom	01/03/2016	31/08/2019
DRIvE	Demand Response Integration tEchnologies: unlocking the demand response potential in the distribution grid	774431	RIA	3,955,259	Spain	01/12/2017	30/11/2020
E2District	Energy Efficient Optimised District Heating and Cooling	696009	RIA	1,999,849	Ireland	01/02/2016	31/07/2019
EnergyMatching	Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimise EU building and district load matching	768766	IA	6,994,120	Italy	01/10/2017	31/03/2022
ExcEED	European Energy Efficient building district Database: from data to information to knowledge	723858	CSA	749,633	Italy	01/09/2016	30/09/2019
FLEXYNETS	Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS	649820	RIA	1,999,364	Italy	01/07/2015	31/12/2018
FHP	Flexible Heat and Power, Connecting heat and power networks by harnessing the complexity in distributed thermal flexibility	731231	RIA	3,823,606	Belgium	01/11/2016	31/10/2019
HACKS	Heating And Cooling Know-how and Solutions	845231	CSA	2,159,045	France	01/09/2019	31/08/2022
H-DisNet	Intelligent Hybrid Thermo-Chemical District Networks	695780	RIA	2,699,895	Belgium	01/06/2016	31/12/2019
HEART	Holistic Energy and Architectural Retrofit Toolkit	768921	IA	6,638,687	Italy	01/10/2017	30/09/2021
Heat4Cool	Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system	723925	IA	7,934,578	Italy	03/10/2016	02/10/2020
HIT2GAP	Highly Innovative building control Tools Tackling the energy performance GAP	680708	IA	7,914,590	France	01/09/2015	31/08/2019
HOLISDER	Integrating Real-Intelligence in Energy Management Systems enabling Holistic Demand Response Optimization in Buildings and Districts	768614	IA	5,052,547	Spain	01/10/2017	30/09/2020
HotMaps	Heating and Cooling: Open Source Tool for Mapping and Planning of Energy Systems	723677	RIA	2,996,870	Austria	01/10/2016	30/09/2020

Table A1. *Cont.*

Project	*Title*	*Grant Agreement*	*Funding Scheme*	*Funding [€]*	*Coordinator Country*	*Start Date*	*End Date*
HRE Heat Roadmap Europe	Building the knowledge, skills, and capacity required to enable new policies and encourage new investments in the heating and cooling sector	695989	CSA	2,113,482	Denmark	01/03/2016	28/02/2019
InDeal	Innovative Technology for District Heating and Cooling	696174	RIA	1,992,726	United Kingdom	01/06/2016	28/02/2019
INDIGO	New generation of Intelligent Efficient District Cooling system	696098	RIA	2,960,853	Spain	01/03/2016	30/09/2020
InteGRIDy	Integrated Smart GRID Cross-Functional Solutions for Optimized Synergetic Energy Distribution, Utilization Storage Technologies	731268	IA	15,840,275	Spain	01/01/2017	31/12/2020
KeepWarm	Improving the performance of district heating systems in Central and Eastern Europe	784966	CSA	2,098,497	Germany	01/04/2018	30/09/2020
LOWUP	LOW valued energy sources UPgrading for buildings and industry users	723930	RIA	4,086,245	Spain	01/11/2016	30/04/2020
MAGNITUDE	Bringing flexibility provided by multi energy carrier integration to a new MAGNITUDE	774309	RIA	3,999,058	France	01/10/2017	31/03/2021
MAtchUP	MAximizing the UPscaling and replication potential of high level urban transformation strategies	774477	IA	19,452,329	Spain	01/10/2017	30/09/2022
MOBISTYLE	MOtivating end-users Behavioral change by combined ICT based tools and modular Information services on energy use, indoor environment, health and lifestyle	723032	IA	2,407,910	Netherlands	01/10/2016	30/06/2020
MOEEBIUS	Modeling and Optimization of Energy Efficiency in Buildings for Urban Sustainability	680517	IA	7,288,383	Spain	01/11/2015	30/04/2019
MPC-: GT	Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems	723649	RIA	4,263,701	Belgium	01/09/2016	31/08/2020
MUSE GRIDS	Multi Utilities Smart Energy GRIDS	824441	IA	7,430,784	Italy	01/11/2018	31/10/2022
NewTREND	New integrated methodology and Tools for Retrofit design towards a next generation of Energy efficient and sustainable buildings and Districts	680474	IA	5,732,388	United Kingdom	01/09/2015	31/08/2018
OptEEmAL	Optimized Energy Efficient Design Platform for Refurbishment at District Level	680676	IA	4,748,859	Spain	01/09/2015	28/02/2019
OPTi	Optimization of District Heating and Cooling systems	649796	RIA	2,100,130	Sweden	01/03/2015	30/04/2018
PENTAGON	Unlocking European grid local flexibility through augmented energy conversion capabilities at district level	731125	RIA	4,437,834	United Kingdom	01/12/2016	30/11/2019
Plan4Res	Synergistic Approach of Multi-Energy Models for an European Optimal Energy System Management Tool	773897	RIA	3,905,060	France	01/11/2017	31/10/2020

Table A1. *Cont.*

Project	*Title*	*Grant Agreement*	*Funding Scheme*	*Funding [€]*	*Coordinator Country*	*Start Date*	*End Date*
PLANET	Planning and operational tools for optimising energy flows and synergies between energy networks	773839	RIA	3,999,695	Italy	01/11/2017	31/10/2020
Planheat	Integrated tool for empowering public authorities in the development of sustainable plans for low carbon heating and cooling	723757	RIA	2,999,400	Italy	01/10/2016	31/01/2020
progRESsHEAT	Supporting the progress of renewable energies for heating and cooling in the EU on a local level	646573	CSA	1,728,305	Austria	01/03/2015	31/10/2017
RELaTED	REnewable Low TEmperature District	768567	IA	4,755,475	Spain	01/11/2017	31/10/2021
REMOURBAN	REgeneration MOdel for accelerating the smart URBAN transformation	646511	IA	24,754,878	Spain	01/01/2015	30/06/2020
RenoZEB	Accelerating Energy renovation solution for Zero Energy buildings and Neighbourhoods	768718	IA	8,708,051	Spain	01/10/2017	30/09/2021
RES4BUILD	Renewables for clean energy buildings in a future power system	814865	RIA	4,999,702	Germany	01/05/2019	30/04/2023
RESPOND	Integrated demand REsponse Solution towards energy POsitive NeighbourhooDs	768619	IA	3,693,615	Spain	01/10/2017	30/09/2020
ReUseHeat	Recovery of Urban Excess Heat	767429	IA	4,894,330	Sweden	01/10/2017	30/09/2021
REWARDHeat	Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks	857811	IA	19,023,298	Italy	01/10/2019	30/09/2023
SmartEnCity	Towards Smart Zero CO2 Cities across Europe	691883	IA	31,874,538	Spain	01/02/2016	31/07/2021
SMARTER TOGETHER	Smart and Inclusive Solutions for a Better Life in Urban Districts	691876	IA	29,801,762	France	01/02/2016	31/01/2021
SO WHAT	Supporting new Opportunities for Waste Heat And cold valorisation Towards EU decarbonization	824441	IA	4,195,357	Italy	01/06/2019	31/05/2022
Spine	Open source toolbox for modelling integrated energy systems	774629	RIA	3,729,988	Finland	01/10/2017	30/09/2021
STORM	Self-Organising Thermal Operational Resource Management	649743	RIA	1,972,126	Belgium	01/03/2015	31/03/2019
STORY	Added value of STORage in distribution sYstems	646426	IA	15,353,840	Finland	01/05/2015	30/04/2020
TEMPO	TEMPerature Optimisation for Low Temperature District Heating	723649	IA	4,997,041	Belgium	01/10/2017	30/09/2021
THERMOS	THermal Energy Resource Modelling and Optimisation System	723636	RIA	2,902,480	United Kingdom	01/10/2016	30/06/2020
THERMOSS	Building and district thermal retrofit and management solutions	723562	IA	8,796,474	United Kingdom	01/09/2016	29/02/2020
TOPAs	Tools for Continuous Building Performance Auditing	676770	IA	6,139,296	Israel	01/11/2015	31/10/2018
Upgrade DH	Upgrading the performance of district heating networks in Europe	785014	CSA	1,999,667	Germany	01/05/2018	30/04/2021
WEDISTRICT	Smart and local reneWable Energy DISTRICT heating and cooling solutions for sustainable living	857801	IA	19,273,573	Spain	01/10/2019	31/03/2023

Table A2. Relevant features of the selected projects funded by the Horizon 2020 Framework Programme.

	Energy Vector				*Application*		*Main Outcome*				*Purpose*							*Other Features*						
Project	***Heating***	***Cooling***	***Electricity***	***Gas***	***Grid/District***	***Building***	***Software/Platform***	***Model/Library***	***Optimization Tool***	***Business Model***	***Planning***	***Sizing/Design***	***Retrofitting***	***Real Time Control***	***Monitor/Management***	***Diagnosis***	***MPC***	***Machine Learning***	***Forecasting***	***LCA/LCC***	***Demand Response***	***Peak Shaving***	***Storage***	***RES***
4RinEU	✓	✓				✓	✓			✓		✓	✓											✓
CHESS-SETUP	✓	✓	✓		✓	✓	✓		✓	✓		✓			✓								✓	✓
Cool DH	✓	✓			✓	✓				✓		✓	✓											✓
CoolHeating	✓	✓			✓					✓														✓
Create	✓					✓																	✓	✓
DR-BOB			✓			✓	✓		✓	✓				✓	✓						✓		✓	
DRIvE			✓		✓		✓								✓				✓		✓			✓
E2District	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓		✓		✓			✓	✓
EnergyMatching	✓		✓		✓	✓			✓	✓					✓			✓						✓
ExcEED					✓	✓	✓			✓					✓									
FLEXYNETS	✓	✓			✓			✓		✓				✓	✓								✓	✓
FHP	✓		✓		✓	✓	✓	✓	✓	✓	✓			✓	✓				✓				✓	✓
HACKS	✓	✓				✓	✓						✓											
H-DisNet	✓	✓			✓			✓		✓				✓				✓					✓	✓
HEART	✓	✓	✓			✓	✓				✓		✓		✓			✓	✓	✓				✓
Heat4Cool	✓	✓	✓		✓	✓			✓	✓		✓	✓	✓	✓			✓			✓			✓
HIT2GAP	✓	✓	✓			✓	✓	✓							✓	✓		✓	✓					
HOLISDER	✓		✓	✓	✓	✓			✓	✓					✓			✓			✓		✓	
HotMaps	✓	✓			✓		✓	✓			✓										✓			✓
HRE Heat Roadmap Europe	✓	✓			✓			✓	✓	✓	✓													✓
InDeal	✓	✓			✓	✓	✓								✓			✓	✓				✓	✓
INDIGO		✓			✓		✓	✓	✓		✓	✓		✓	✓		✓	✓	✓					✓

Table A2. *Cont.*

Project	*Energy Vector*				*Application*		*Main Outcome*				*Purpose*							*Other Features*						
	Heating	*Cooling*	*Electricity*	*Gas*	*Grid/District*	*Building*	*Software/Platform*	*Model/Library*	*Optimization Tool*	*Business Model*	*Planning*	*Sizing/Design*	*Retrofitting*	*Real Time Control*	*Monitor/Management*	*Diagnosis*	*MPC*	*Machine Learning*	*Forecasting*	*LCA/LCC*	*Demand Response*	*Peak Shaving*	*Storage*	*RES*
InteGRIDy			✓		✓		✓		✓	✓	✓				✓				✓		✓		✓	✓
KeepWarm	✓	✓			✓					✓			✓		✓									✓
LOWUP	✓	✓				✓						✓		✓									✓	✓
MAGNITUDE	✓	✓	✓	✓	✓		✓	✓	✓	✓				✓	✓				✓					✓
MAtchUP	✓		✓		✓	✓				✓	✓			✓	✓	✓							✓	✓
MOBISTYLE						✓	✓			✓					✓			✓						
MOEEBIUS	✓		✓		✓	✓		✓	✓	✓			✓	✓		✓			✓	✓		✓		✓
MPC-: GT	✓					✓		✓	✓			✓		✓			✓							✓
MUSE GRIDS	✓	✓	✓	✓	✓				✓		✓			✓	✓			✓					✓	✓
NewTREND					✓	✓	✓	✓		✓		✓	✓							✓				✓
OptEEmAL	✓	✓			✓		✓		✓			✓	✓					✓		✓				
OPTi	✓	✓			✓		✓	✓	✓					✓			✓	✓	✓		✓	✓		
PENTAGON	✓	✓	✓	✓	✓	✓	✓								✓			✓					✓	✓
Plan4Res	✓	✓	✓	✓	✓		✓	✓	✓		✓				✓									✓
PLANET	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓				✓								✓	✓
Planheat	✓	✓			✓		✓				✓								✓					✓
progRESsHEAT	✓	✓	✓		✓						✓													✓
RELaTED	✓				✓										✓									✓
REMOURBAN	✓		✓		✓	✓	✓			✓	✓		✓		✓									✓
RenoZEB	✓		✓			✓	✓						✓	✓	✓			✓						
RES4BUILD	✓		✓			✓		✓		✓		✓			✓					✓			✓	✓
RESPOND	✓		✓		✓	✓			✓					✓	✓						✓			
ReUseHeat	✓	✓			✓					✓	✓	✓												
REWARDHeat	✓				✓					✓				✓									✓	✓

Table A2. *Cont.*

Project	*Energy Vector*				*Application*		*Main Outcome*				*Purpose*							*Other Features*						
	Heating	*Cooling*	*Electricity*	*Gas*	*Grid/District*	*Building*	*Software/Platform*	*Model/Library*	*Optimization Tool*	*Business Model*	*Planning*	*Sizing/Design*	*Retrofitting*	*Real Time Control*	*Monitor/Management*	*Diagnosis*	*MPC*	*Machine Learning*	*Forecasting*	*LCA/LCC*	*Demand Response*	*Peak Shaving*	*Storage*	*RES*
SmartEnCity	✓	✓	✓	✓	✓	✓				✓	✓		✓		✓	✓								✓
SMARTER TOGETHER	✓		✓		✓	✓	✓			✓		✓	✓					✓						✓
SO WHAT	✓	✓			✓		✓												✓				✓	✓
Spine					✓		✓	✓	✓		✓													
STORM	✓	✓			✓	✓		✓	✓					✓	✓			✓	✓			✓	✓	✓
STORY	✓		✓		✓			✓		✓				✓	✓				✓				✓	
TEMPO	✓				✓	✓	✓		✓	✓		✓	✓		✓	✓								✓
THERMOS	✓				✓		✓	✓	✓		✓				✓									
THERMOSS	✓	✓			✓	✓	✓						✓		✓									
TOPAs	✓					✓	✓	✓	✓					✓	✓	✓	✓	✓						
Upgrade DH	✓				✓					✓			✓			✓								✓
WEDISTRICT	✓	✓			✓		✓					✓	✓		✓								✓	✓

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