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Collaborative smart grids – A survey on trends

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ABSTRACT

Smart grids are the result of a dynamic co-evolution process that leverages the integration of new technological advances in the energy systems and information and communication technologies. This process is accompanied by changes in business models, organizational structures, roles, and operating practices. In this context, collaboration among multiple entities becomes a crucial element, justifying the term Collaborative Smart Grid. The purpose of this article is to systematically review recent literature with a view to identifying trends, opportunities, and challenges regarding the application of models, approaches, and tools from collaborative networks to the energy domain.

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1. Introduction

The electrical energy systems are going through a substantial transformation while attempting to face numerous challenges of a technological, social, and policy-rated nature (Fig. 1). In this context, the notion of smart grid emerged as a result of the convergence of information and communication technologies (ICT) and energy systems [1].

In addition to a diversification of the energy sources, the need to better support demand response and address optimal assets management, energy conservation and CO_2 reduction, the next generation grid systems are bi-directional, both in terms of energy and information flows, and become "smarter", by leveraging the possibilities offered by advances in Cyber-Physical Systems, Internet of Things, sensor networks, big data, and Artificial Intelligence. To some extent, smart grids result from a co-evolution of energy systems and ICT, which also raises the need to develop new business models and organizational structures.

In spite of its recent popularity and growing number of related research works, a widely accepted definition of smart grid does not yet exist. Instead, and similar to what happens in many other emerging areas, various partial definitions are offered in the literature. An example definition by the Electric Power Research Institute [2] considers smart grid as:

> *"The overlaying of a unified communications and control system on the existing power delivery infrastructure to provide the right information to the right entity."*

This definition reflects a utility systems viewpoint and is somehow limited whereas other definitions are possible if we take into account the point of view of different stakeholders. For instance, a more comprehensive overview of the concept can be found in [1]. Various other authors have emphasized different perspectives, e.g. the engagement of consumers and other stakeholders, the role of ICT, the emergence of new value-added services and new market opportunities, etc. [3–7]. As a result, a number of elements start to gather around the concept of smart grid, as summarized in Table 1, which help to form a more comprehensive understanding of the concept.

In parallel with technological developments, an emerging characteristic in the energy sector is the involvement of multiple stakeholders – enterprises (utilities, service providers, etc.), customers, and other organizations – progressively more engaged in collaborative processes. From the technological side, as components progressively embed more intelligence and autonomy, traditional control models are also evolving towards flexible, self-organizing communities of intelligent and collaborative agents. Energy systems are becoming complex socio-technical systems which combine a variety of technical aspects and automated processes with human behavior and social/societal factors [80]. More and more the electric grid can be seen as a composition of sub-systems with increasing autonomy that need to interact, forming a system-of-systems. As such, collaboration becomes a relevant dimension in the new generation of energy grid systems. To emphasize this aspect we propose the term *Collaborative Smart Grid*. In this sense, it becomes relevant to consider the potential contribution of the discipline of Collaborative Networks [81] to the energy sector.

Some signs in recent literature already point in this direction. Therefore, the present survey intends to analyze such trends and point out further areas of convergence. The remaining of the article starts with a brief overview of the area of Collaborative Networks and a description of the methodology adopted in this survey. The main findings are then introduced, highlighting the collaborative forms, motivation for collaboration, and adopted/developed technologies and mechanisms. A discussion of the research implications and directions for further work conclude the article.

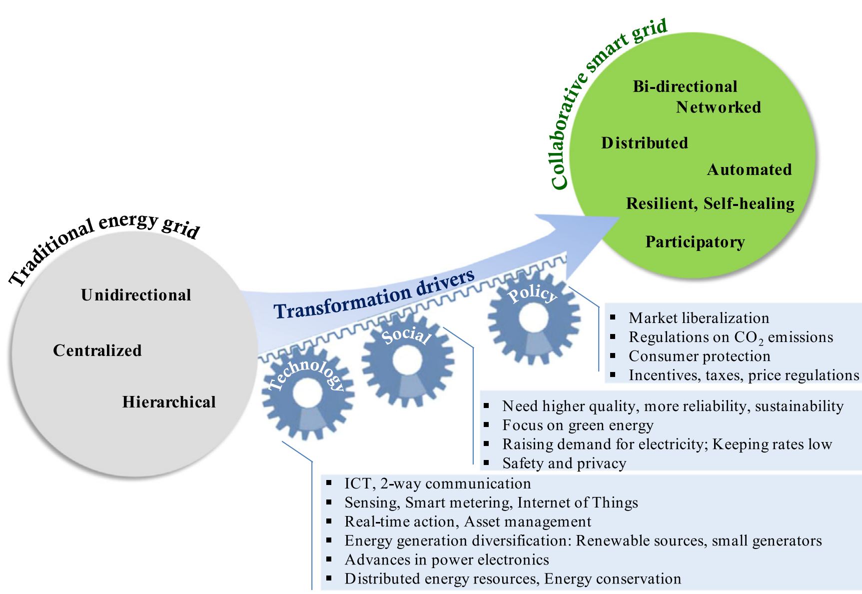

Fig. 1. Transformation of the energy system.

Table 1
Basic elements of smart grids.

Facet	Base elements and challenges
Energy generation and distribution	• Distributed generation and cogeneration • Integration of alternative sources of energy (solar, wind, biomass) • Integration of diverse energy storage technologies • Interconnected and intelligent distribution system
Control	• Distributed automation – monitoring and control; pervasive control • Self-healing and resilient systems • Topology evolution: Micro-grids/networked energy "islands" • Remote supervision • Intelligent agents, intelligent supervision
Information infrastructure	• Merge of ICT and energy grid • Two-way communications • Real-world awareness: Proliferation of sensors, smart meters, smart appliances with embedded intelligence • Adoption of technologies from Internet of Things/ Cyber-Physical Systems • Handling big data; data visualization • Interoperability, standards, and coping with legacy assets/infrastructures • Cyber security and privacy of individual data
Energy management	• Demand response – coordination of supply with demand in real-time, peak shaving, load management • Operational efficiency, dynamic optimization, forecasting and prediction • Handling the integration of electric vehicles (EV) • Dynamic energy trading, energy market structure
Value-added services	• Operation monitoring services • Maintenance-related services • Big data analytics • Cost control services • Information portals • Quality of Service; Contracting • Additional services (creating new opportunities): training, auditing, elderly care, e-health support, etc.
Participatory dimension	• Customer engagement, empowering consumers, promotion of widespread behavioral change, social computing • From consumer to prosumer • Increasing collaboration among all stakeholders • Clustering and consortia formation (home area / building, neighborhood, city level, transportation infrastructure, commercial use)

2. The area of collaborative networks

As we move towards a hyperconnected world and markets become more global, collaboration in networks is often regarded as a critical element to help companies keep competitive advantage. Sharing of resources and joining competencies through different organizational shapes according to the needs of each business opportunity, provide companies with a higher degree of agility and resilience in comparison to operating alone. As such, and as a follow up to earlier concepts of extended and virtual enterprise, the area of Collaborative Networks (CNs) has been consolidating as a new discipline along the last decade. CNs are understood as "*constituted by a variety of entities (*e.g. *organizations, people or machines) that are largely autonomous, geographically distributed, and heterogeneous in terms of their operating environment, culture, social capital, and goals, but that collaborate to better achieve common or compatible goals, and whose interactions are enabled by computer networks*" [81].

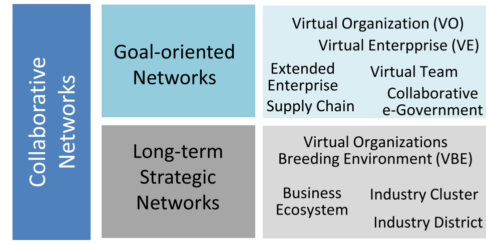

Fig. 2. Main classes and examples of collaborative networks.

Although initially predominantly present in manufacturing and supply chains [82], CNs are being adopted, in different forms, in a growing number of application domains, including services and service-enhanced products, intelligent transportation systems, elderly care, smart environments, agriculture and food industry, disaster management, education, etc. Currently a large diversity of collaborative networks forms can be observed in different domains. These organizational forms comprise two main categories [81,83], as illustrated in Fig. 2:

– *Goal-oriented networks*, typically representing temporary consortia of organizations that join resources and skills to effectively achieve a common goal, and that dissolve after the goal is achieved. The composition of such consortia is usually driven by the specific needs and constraints imposed by the identified business opportunities. The effective collaboration among such organizations is leveraged by computer networks. Examples include Extended Enterprise, Virtual Enterprise (VE), Virtual Organization (VO), (dynamic) Supply Chain, Virtual Teams, Collaborative e-government, etc.
– *Long-term strategic networks*, corresponding to alliances of organizations that aim at creating preparedness for collaboration among their members in order to enable rapid formation of goal-oriented networks in response to business opportunities. Towards this objective, participating organizations adhere to a long-term cooperation agreement and adopt common business principles and interoperable supporting infrastructures. Such networks are commonly known as Virtual organizations Breeding Environments (VBEs) [84]. Some particular cases include business ecosystems, industry clusters, and industrial districts.

Along the last two decades, and in parallel with the fast developments in Information and Communication Technologies, there has been substantial progress in terms of conceptual frameworks, models, tools, and infrastructures for Collaborative Networks [85,86]. Fig. 3 gives a brief overview of some relevant building blocks in this area.

In addition to the technological developments, considerable efforts have been put on the elaboration of models and modeling frameworks to provide a better understanding of the nature of CNs and support the development of new tools, services, and governance principles [87]. A relevant example is the ARCON reference model [88,89].

In recent years a large number of collaborative networks have been established in different application domains [90–92]. New developments in areas such as Internet of Things, Sensor Networks, Cyber-Physical Systems, Cloud Computing, and Big Data, offer new possibilities, inducing new collaborative forms and new business models, pointing to an increasing and highly dynamic interconnectivity (hyperconnected world). As such, the paradigm of collaborative networks is being adopted in many other domains, although sometimes using slightly different formulations and terminologies. The smart energy grid represents one of these

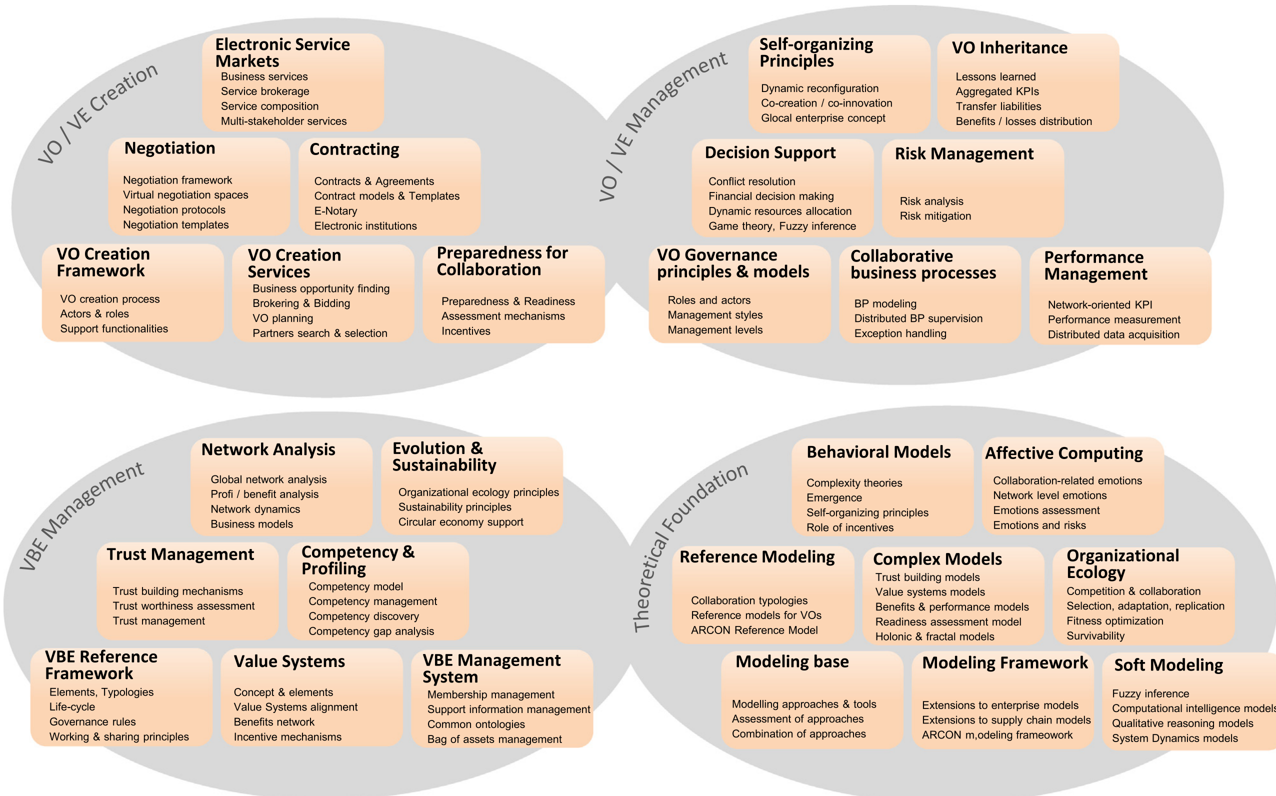

Fig. 3. Some relevant building blocks in CN research.

domains that can greatly benefit from the adoption of collaborative approaches, as identified in [92], and where many cases can already be identified, as shown in the following sections.

3. Survey approach

In order to identify and characterize trends on the application of collaborative networks concepts and methods to the smart grids area, an evidence-based approach was followed. More specifically, the performed study is grounded on the systematic literature review (SLR) method. SLR has been applied by many researchers in different fields [93,94] in an attempt to reach a systematic, replicable, and transparent process to synthetize research results and practices. However, considering that collaborative smart grids is an emerging area, not yet well structured, it is preferable to follow a light version of SLR known as systematic mapping study [95], which first attempts to know what topics have been covered by the literature, trying then to structure the area and get an overview of its scope. One of the main differences is that the research questions in systematic mapping are more general than in SLR because the purpose is to discover trends. See [95] for a detailed comparison between typical SLR and mapping studies.

3.1. Research questions

The RQs addressed by this survey work are:

RQ1. Which collaborative forms are emerging in smart (energy) grids? [*Collaboration forms*].

RQ2. Which motivators for collaboration in smart grid? [*Motivation*].

RQ3. Which technological developments enable collaborative smart grids? [*Technology and mechanisms*].

3.2. Search process and sources

An initial informal search on Google Scholar provided immediate evidence of existence of a large number of publications that could be related to the topic of study and a preliminary analysis of a sample of those papers confirmed that a systematic mapping would be an appropriate method.

For search and selection, three relevant databases were used: ISI Web of Science, IEEE Xplore, and SCOPUS. Although limiting the search to these sources naturally excluded some papers, these databases are widely used by the smart grid community and thus papers indexed in these sources are likely to have more impact and relevance in setting the trends. The search was conducted using terms such as:

> “services AND grid AND energy; value-added AND services AND grid AND energy; cooperative AND grid AND energy; collaboration AND grid AND energy; (collaboration OR collaborative) AND network AND energy AND grid”.

Since the Collaborative Networks terminology is not well assimilated yet by the smart grid community, e.g. some authors do not clearly distinguish between'collaboration’ and ‘cooperation’, it was necessary to perform the search with a number of variants of the key terms.

3.3. Inclusion and exclusion criteria

As the aim is to identify trends, the search period was limited to 2010-mid 2015. Since the term ‘grid’ is used by different communities (e.g. energy and computing), with rather different meanings, it was necessary to manually exclude those papers related to grid computing. It was also noticed that although the terms 'collaboration' or 'cooperation' would appear in some papers, their content had very little to do with collaboration. As such, it was also necessary to perform an additional manual filtering by browsing through the collected papers. As a result, a total of 79 articles were kept as the basis for this study. These articles were then read and analyzed according to the mapping protocol.

4. Main findings

4.1. Focus areas

A preliminary analysis of the selected literature allowed building a map of focus areas as shown in Table 2.

The first group of articles (category "General concept"), offer a broad discussion of the smart grid concept and its related issues, and was mainly used in the introduction section. The findings related to the other focus areas are summarized in the following sections.

4.2. Value added services

In various industry sectors there is a trend to associate business services to physical products, as a mechanism of value creation and product differentiation. This trend is often referred as "*servitization*" and led to the emergence of terms such as extended products, service-enhanced products, and product-service systems. A similar movement is starting in the energy sector.

A global overview of the transition towards value-added services in this sector is offered by [8], which state that consumers may be "*more interested in the services that can be obtained through electricity, rather than in electricity* per se". As an example, the case of transportation is provided in which there might be a shift of interest from the electric vehicle (as a physical product) to the mobility service that the car can provide. The opportunities to bundle value added services, which require collaboration among different stakeholders, and the emergence of the role of aggregator (a kind of virtual organization manager), are discussed.

Silva et al. [9] conducted a survey to better understand residential end-users and identify promising value-added services. From this study, a positive attitude of customers to collaborate in order to reduce energy costs became evident. In fact, 2/3 of the respondents seem to be willing to participate in shared interest groups, i.e. sharing energy resources with the local community. It was also found that people more easily would allow their devices to be involved in automated energy management processes, namely based on external signals such as price, than to let external parties to manage them. The importance of anonymization and other privacy protection mechanisms was also highlighted.

Table 2
Map of focus areas.

Areas		References
General concept		[1–7]
Value added services		[8–15]
Energy market / Collaboration among micro-grids		[16–22]
Customer engagement and behavior change		[23–28]
Collaboration among consumers / Social smart grid		[29–33]
Energy management	Exchange in Micro-grids	[34–39]
	Demand-response	[40–47]
	Clusters of buildings	[48–52]
	Distributed control	[53–58]
	Other cases	[59–61]
Infrastructure	Fault detection/Self-healing	[62–64]
	Communication infrastructure	[65,66]
	Electric vehicles	[67–70]
	Sensor networks	[71,72]
	Information exchange	[73–75]
	Interoperability	[75–77]
Policy and roadmaps		[66,78,79]

One specific line of works addresses services for the smart homes. Karnouskos [10] introduces a vision for a "collaborative smart grid ecosystem", which exploits intelligent networked devices and the big data resulting from those devices to develop value-added services. Examples of services include real-time energy monitoring, asset management, real-time billing, energy marketplace services, personalized information services, etc. Collaboration, including the development of appropriate business models, is seen as a core enabler for the emergence of such services. Another work on value-added services at the smart home level is found in [11], which emphasizes service level agreements among groups of stakeholders. This involves negotiation mechanisms and the use of common ontologies to facilitate agreements.

The success of value-added services in smart grid depends not only on technological aspects but also on the consideration of business challenges. Realizing this need, [12] analyze the different players involved in a smart energy ecosystem, and their collaborative partnerships and agreements. They further propose collaborative business models for this sector, using the Osterwalder Canvas model.

An extensive effort to apply collaborative networks models and mechanisms in support of multi-stakeholder services in the solar energy sector was conducted by the GloNet project [13–15]. In this project, both long-term strategic networks and dynamic goal-oriented virtual organizations were considered to support the various stages of the life cycle of a solar plant. This includes services for the specification and design of the power plant, services for the operational phase (e.g. monitoring and maintenance), as well as negotiation methods for co-design of new services.

Main characteristics in this area:

- *Collaboration forms*: Virtual organizations for service provision. In some cases there are also long-term strategic networks/VO breeding environments.
- *Motivation*: Provision of value-added services and reduction of energy costs.
- *Technology and mechanisms*: Consortia formation and negotiation associated to service design and service provision, including service level agreements and co-design processes. In some cases, cyber-physical mechanisms are used to allow resources sharing. Design of business models is also addressed.

4.3. Energy market and collaboration among micro-grids

This section addresses collaborative approaches applied to the establishment of (local) energy markets. One direction explores the new role of a class of consumers that become prosumers, and the new business relationships that can emerge. One example [16] plays with the flexibility, in terms of energy consumption patterns, that owners of large infrastructures might have. Example cases include industrial facilities, large buildings, electric vehicle fleets, residential neighborhoods, public lighting system, etc. Since this flexibility can help in more effective demand response, the authors investigate a number of scenarios for monetizing available flexibility. Although standalone users only have a small impact, a substantial impact on the grid operation in terms of load shifts may be achieved when a large number of prosumers come together. As such, they introduce the notion of prosumer virtual power plan, which resembles the concept of virtual organization used in CNs. Studied scenarios address issues such as negotiation, short term contracting, and management of the virtual organization, which may be taken by a third party service provider (the virtual organization manager). A similar idea is explored in [17], around a group of users with electric vehicles (EV). Taking advantage of dynamic energy pricing and the possibility of charging the EVs during off-peak hours and having them supplying energy to the grid during high peak periods, allows for establishing a coordinated energy trading market around an energy aggregator. Although staying at a rather theoretical level, using game theory and Nash equilibrium concepts, this study shows that higher benefits can be achieved through collaboration. Another theoretical study in the same direction and also adopting game theory is presented in [18]. The studied scenario considers groups of households with energy storage capacity, that collaborate to trade energy in real-time.

Another group of works explore cooperative game theory among micro-grids. In [19] a study of the formation of coalitions of micro-grids and different sharing rules for benefits (e.g. Shapley value) to enhance their profit is discussed. A market platform to support coordination of energy exchanges among micro-grids, which collectively form a Virtual Energy District (a kind of virtual organization) is introduced in [20].

Other works, such as [21], put more emphasis on the ICT support to the energy market and collaboration among the involved stakeholders. The development of common ontologies, as facilitators of collaboration, and applications of multi-agent systems, negotiation, and machine learning algorithms are experimented in simulation scenarios. A special case is introduced in [22], which propose a collaborative algorithm among mobile devices to balance energy consumption and computation workloads. This case uses negotiation and bargaining between buyer and seller (mobile) device agents, constituting a kind of energy market.

Main characteristics observed under this topic:

- *Collaboration forms*: Energy markets organized as collaborative coalitions or virtual power plants, a kind of virtual organization. It often exploits the roles of prosumers in contributing to balance demand response strategies.
- *Motivation*: Smoothing peak demand and creating monetary incentives for participants.
- *Technology and mechanisms*: From the energy side, bidirectional energy exchanges are assumed, often supported by distributed storage capabilities. From the conceptual side, game theory is strongly used to demonstrate the benefits of collaboration, although mostly as a theoretical exercise. Consortia formation, negotiation, and contracting algorithms are also adopted.

4.4. Customer engagement and behavior change

Works in this group aim at engaging consumers in the process of energy saving and pick demand reduction. Through games and incentives (e.g. price, penalties, social pressure), the goal is to induce a behavioral change regarding the patterns of consumption, thus modifying the pattern of energy load.

Some illustrative cases: Dmitrieva [23] introduces the EnergyRace prototype as a serious game, involving teams formed out of family members and contacts from a social network, and aiming at encouraging users to improve their energy consumption behavior. The process is based on real-time feedback and goals set collaboratively. Through team collaboration and competition among teams, the game aims at facilitating social learning regarding energy usage and saving. Morris et al. [24] present a case study of involvement of an energy utility as a peer and partner within an island community. Through creation of trust relationships and influencing community leaders, it was possible to educate consumers, leading to new consumption patterns with significant reduction of peak demands, hence limiting the increasing infrastructure costs. A complementary case, [25], is focused on the participatory processes involving multiple stakeholders in rural development. Targeting the adoption of renewable energies for improvement of the community living conditions, this study addressed the creation of participative spaces for consensus building and co-construction of new knowledge. Other cooperative approaches to reschedule demand based on pricing model are presented in [26,27]. A survey of other cases of consumer engagement and empowerment, transforming passive users into active players, is found in [28]. Reported results show an increasing emphasis towards consumer engagement in smart grids, efforts of utilities to build more trustful relationships with consumers, and the search for novel motivational factors to trigger behavioral change.

In summary, emerging characteristics under this topic include:

- *Collaboration forms*: Formation of consortia of customers at family level or neighborhood (residential community) level. In some cases involving the utility and the consumers. The creation of consortia often resorts to existing social networks.
- *Motivation*: For the customer: a combination of collaboration (inside consortia)/ competition (among consortia), social pressure, pricing/penalty incentives, and environmental concerns. For the utility: shaving picks, thus reducing infrastructure costs; in some cases leading to more accurate demand prediction.
- *Technology and mechanisms*: Social networking, game theory, connection to smart meters (access to real-time consumption and pricing information).

4.5. Social smart grid

With some points of contact with previous sections, articles in this group further emphasize collaboration among consumers for energy saving and cost reduction.

The work of Yassine [29,30] focuses on formation of coalitions of consumers to agree on and enact optimal energy consumption strategies. The approach is to have intelligent agents running in smart meters, which act on behalf of consumers. In this way, the coalitions are actually established among these agents, which act as local energy controllers. Game theory, multi-agent negotiation protocols, and incentive pricing mechanisms are used in this process, materializing a kind of self-organization and trying to balance demand with supply while maximizing benefits for the agents. Siano [31] also considers automatic interactions among smart meters and price-based incentives to collaborate in order to lower peak demands. Modeling roles and responsibilities of the various players is also addressed. Another example, at the residential micro-grid level, is found in [32]. A collaborative consumption agreement among the members of the residential community is suggested, aiming at active consumer participation in the process of reducing energy usage during peak periods without hurting consumer satisfaction. The model explores the possibility of rescheduling usage, considering the characteristics of the home appliances, and the priorities defined by the users.

Borrowing ideas from social networks and service-oriented systems, [33] introduces the term ‘social smart grid’ to represent communities of consumers that collaborate on energy sharing, consumption and storage. This work represents a clear attempt to combine the areas of smart grid and collaborative networks. As such, issues of consortia formation, identification of classes of stakeholders and their roles, contract negotiation and service-level agreements, as well as the coordination of energy consumption, establishment of energy marketplace for privately generated energy, are addressed. An agent-based simulation prototype is developed to validate the proposed models.

Main characteristics in this area:

- *Collaboration forms*: Dynamic consortia of consumers (a kind of virtual organization), typically in a confined region or neighborhood. Consumers may be involved directly or through intelligent software agents that represent them and run embedded in the metering infrastructure (a kind of collaborative cyber-physical system).
- *Motivation*: Reduce costs and support effective demand response.
- *Technology and mechanisms*: Cyber-physical system embedding intelligent agents with smart meters, access to dynamic market prices, and direct control of home appliances. Consortia formation, contract negotiation, and benefits distribution models are used.

4.6. Collaboration in energy management

This area corresponds to one of the most "popular" topics in terms of the number of publications, and cover issues of optimization, balanced demand response, and distributed control. Identified sub-categories include:

4.6.1. Exchanges in micro-grids

A number of publications address collaboration among micro-grids towards optimal energy management.

For instance, [34,35] apply game theory to dynamic formation of micro-grid coalitions, aiming at minimizing power loss, while maximizing energy transfer between micro-grids. Greedy or Shapley value based strategies are used in simulation scenarios. A method for cooperative power balancing between adjacent segments of the grid which are assumed to be self-managed, regulating their local supply-demand is proposed in [36]. This work puts a special focus on the process of EV charging (mobile energy loads) and corresponding impact on prediction and planning of local loads and inter-balancing between grid segments. Another simulation-based contribution to a quantitative evaluation of the advantages of collaboration among micro-grids, through real-time information exchange and power exchange is presented in [37]. Cooperative optimal control while considering two modes of operation for micro-grids: island mode and grid-connected mode is discussed in [38]. Another example is found in [39].

4.6.2. Demand response

This group of works relates to the optimization of demand response. They typically explore collaboration between the utility and the consumers in order to dynamically match demand and supply. The base assumption is that consumers (and their appliances) have some flexibility to re-schedule/shift their consumption in order to reduce peak demands. Dynamic pricing schemes are typically used as incentives for re-scheduling.

Application of game theory to minimize energy costs is the focus of [40]. Similarly, [41–44], and [45] also apply game theory and, in some cases, specifically Nash equilibrium, to have consumers collaborating in optimizing the scheduling of their energy consumption, taking advantage of dynamic pricing schemes. Taneja et al. [46] explore flexibility of schedulable appliances to adjust consumption patterns to intermittent (renewable) energy sources. A peer-to-peer collaboration among smart devices is introduced in [47], thus resorting to a cyber-physical system's view. The approach tries to achieve a consensus-based coordination, considering both distributed generation and responsive distributed loads that react to pricing signals received from a local price regulator.

4.6.3. Clusters of buildings

This line of work explores the possibility of forming clusters of buildings and using collaboration for energy exchange either among members of the cluster or among clusters.

In this direction, [48] introduces a collaborative decision model for multi-objective optimization based on a dynamic pricing scheme. Cooperative multi-agent systems are adopted in [49,50] to improve operation and management in smart buildings. Another case using collaboration among multi-agents for energy management in commercial buildings is presented in [51]. In this work multiple classes of agents are introduced - e.g. Central Control agent, Zone Control agent, HVAC control agent, Occupancy agent, Market agent, and Weather agent - which collaborate to achieve cost minimization. An optimal scheduling algorithm to operate clusters of smart houses is proposed in [52]. These authors also introduce the notion of "energy virtual network operator", similar to the notion of virtual organization manager, that controls the trading of energy among the clustered smart houses. This operator establishes contracts with the smart houses to operate their facilities, leading to a kind of virtual sharing of equipment.

4.6.4. Distributed control

Finally, a number of works that also pursue some forms of energy management optimization focus on control aspects.

In this line, publications such as [53–55] apply cooperative distributed control and game theory to distributed energy resources including intermittent and renewable energy (wind or solar). A cooperative multi-agent based approach to distributed control of micro-grids, aiming at optimization of costs of energy storage and exchange among them, is proposed in [56]. In this approach, each agent tries to satisfy local demand while providing maximum export to the grid under variable price conditions. Other examples of distributed control in micro-grids, but with very little on collaboration, are found in [57,58].

4.6.5. Other cases

Other miscellaneous topics related to energy management that also show collaborative approaches can be found in various sources.

For instance, [59] introduces cooperation between electric vehicles and wind-based energy resources. The approach involves aggregation of EV charging needs according to the patterns of user trips and varying storage capacity, to allow a day-ahead cooperative charging model. Also targeting solar and wind energy generation, [60] explores collaboration in a multi-agent environment, particularly the contract-net negotiation protocol and the particle swarm algorithm, for the global optimal energy distribution plan. Examples of considered agents include: wind turbine agent, battery agent, solar PV agent, and load agent. Additionally, a survey on recent progress on the application of multi-agent approaches to distributed coordination control can be found in [61].

Main characteristics under this topic:

- *Collaboration forms*: Goal oriented consortia, e.g. consortia of micro-grids, consortia of buildings/smart houses.
- *Motivation*: Optimization of energy demand-response (balancing demand supply) and costs; reduction of peak demands.
- *Technology and mechanisms*: Consortia formation, game theory, Nash equilibrium, and benefits distribution (e.g. Shapley value). Cyber-Physical Systems allow collaboration at device level. Multi-agent systems and contract-net protocol are often used as a modeling approach. Incentive mechanisms (e.g. dynamic pricing schemes) are also used.

4.7. Collaboration at the infrastructure level

As devices and sub-systems become smarter, with higher levels of autonomy, traditional "control" strategies tend to evolve to collaborative approaches. As such, a number of dimensions can be considered at this level:

4.7.1. Fault detection, cyber-attacks and self-healing

A major concern associated with smart grid infrastructures is how to deal with fault tolerance, resilience, and privacy. On one hand, pervasive sensorial capabilities and increasing embedded intelligence allow for more effective monitoring and distributed control. On the other hand, the transition towards cyber-physical systems opens the possibility of cyber-attacks to the infrastructure and violations of privacy. To face these challenges, a number of works propose new system architectures based on collaboration among the infrastructure components/subsystems.

One example is the work of Qi et al. [62], which seeks collaboration among neighboring devices to handle imprecise, missing, or incomplete information in case of problems, and thus estimate or better understand the global state of the grid. In case of faults or attacks, and supported by power-electronic and embedded intelligence, a reconfiguration of the infrastructure is launched via coordinated local actions, giving a resilience property to the infrastructure. A distributed algorithm is also introduced to detect attacks (e.g. terrorist attacks), preventing them from propagating to the whole system, through local collaboration, coordinated distributed command and control, and a distributed (grid) state estimation. With similar objectives and in the same line, [63] also proposes a reactive power management schema supported on collaboration among geographically disperse devices during power blackout situations. Collaboration, namely in terms of information exchange (allowing a distributed state estimation), facilitates the isolation of the offending/faulty unit of the system. A reconfiguration of the grid (supported by power electronics and switches) is based on a genetic algorithm to decide on resource rescheduling. Specifically focused on security against cyber-attacks, [64] briefly suggests a distributed and collaborative framework for a self-configuring and self-tuning infrastructure. The proposal relies on intelligent software agents (e.g. traffic analyzers, signal analyzers, user behavior analyzers), and pervasive sensing, communication, and control capabilities.

4.7.2. Communication infrastructure

The communications and networking infrastructure constitutes the backbone for the implementation of the smart grid. Although various works have addressed the associated technical aspects, only a few started recently to discuss issues of collaboration in this area.

For instance, [65] addresses collaboration between a telecom provider and an energy utility towards a joint development model for a shared communication infrastructure. In this study, a shared infrastructure for both broadband Internet access and smart grid communications is aimed. Issues such as the total cost of ownership, the value chain, actors and roles, are discussed. It is claimed that the proposed model supports cost savings for different optical and wireless communication technologies. In the roadmap proposed by Bui et al. [66], a combination of smart grid and Internet of Things is discussed ('Internet-based smart grid'), with a focus on networking technologies requirements (protocols, services, information interchange, standards) and web-enabled smart grid.

4.7.3. Electric vehicles

A substantial number of papers in this area present approaches for collaboration between electric vehicles (EV) and other subsystems of the grid (e.g. vehicle-to-grid, grid-to-vehicle, or vehicle-to-home) towards optimal charging strategies for the EVs. All these works are motivated by the expectation of a large number of such vehicles being introduced to the grid.

For instance, in [67], a cooperative distributed energy management approach for charging EVs is proposed. The objective is to reach optimal power allocation through local sharing of information and coordination among charging stations. The claim is that through the collaborative approach, the need for a central energy management unit is eliminated, making the system more robust against single node failures. Similarly, [68] explores information sharing among charging stations to reach optimal charging schedule, smoothing peak demands. The work of Monteiro et al. [69,70], also explores the opportunity of building collective awareness through information sharing, and the possibility of bi-directional power flows to smooth peak demands and compensate for intermittency of renewable energy production.

4.7.4. Sensor networks

The capability to timely and accurately collect information from various locations of the power grid is the base to achieve a more flexible, reliable and responsive grid. Advanced data sensing and associated processing capabilities, leading to smart sensors, play a significant role here. In order to deal with vast amounts of data collected in different geographical locations, and the limits of transmitting them to a central server, distributed processing approaches, based on collaboration among smart sensors, start to appear.

For instance, [71] introduces a collaborative processing approach to aggregate data collected from a distributed sensor network. It considers the smart grid as including several sensor networks, each one in charge of monitoring a specific section of the grid. It suggests a particular gossiping algorithm (a kind of consensus building algorithm) for data aggregation. This leads to a non-hierarchical monitoring architecture, relying on smart sensors. This distributed approach does not require the need of a central server and the transmission of raw data to a fusion center.

After making an analysis of the smart grid sensing requirements – namely to monitor energy generation, load balance, and power quality throughout the grid, detect and locate faults, or determine the equipment health status, etc. – [72] discusses the organization of sensor networks and data collection and communication requirements. Considering the increasing number of smart elements in the grid, the authors advocate the need for distributed data processing and control, and the implementation of distributed state estimation methods. For this purpose, collaborative sensing and cooperative communications are suggested. Issues of security, standardization, and interoperability are also analyzed.

4.7.5. Information exchange

Under this perspective two main challenges are addressed: (i) how to ensure trustworthy information exchange among multiple stakeholders involved in smart grids, and (ii) how to cope with the exponential growth of data from many smart devices, which requires distributed data management and cloud-based support in the context of collaboration across organizational boundaries of stakeholders (grid operators, service providers, customers).

The first challenge is discussed, for instance, in [73], which analyses issues of coordination, trust, service orchestration, service level agreements and monitoring, namely in the context of the Grid4EU project. Sankar et al. [74] also discuss the dilemma that regional transmission organizations face between sharing data for distributed state estimation and keeping data private for competitive reasons (notion of competitive privacy). A theoretical framework to quantify the tradeoff between the benefits of collaboration and the loss of privacy, namely discussing the competing goals of utility versus privacy, is introduced. Issues of information exchange across organizational borders and the need to handle big data, namely through cloud computing, are addressed in [75]. Various scenarios and needed support architectures are presented

Table 3
Implementation levels.

Areas		Simulation	Prototype	Field survey	Theory
General concept					
Value added services					
Energy market / Collaboration among micro-grids					
Customer engagement and behavior change					
Collaboration among consumers / Social smart grid					
Energy management	Exchange in Micro-grids				
	Demand-response				
	Buildings clusters				
	Distributed control				
	Other cases				
Infrastructure	Fault detection / Self-healing				
	Communication infrastructure				
	Electric vehicles				
	Sensor networks				
	Information exchange				
	Interoperability				
Policy and roadmaps					

in this work, as well as the emergence of new services. A smart grid data cloud model is then proposed under a collaborative perspective.

4.7.6. *Interoperability*

The involvement of multiple stakeholders and technologies in the development of smart grid infrastructures raises considerable interoperability challenges. Similar to what is happening in other domains, also here it is becoming clear that collaborative approaches are required when addressing complex systems integration.

One example is given by the NIST framework for smart grid interoperability [76], which discusses a conceptual reference model considering the interactions of multiple actors in different smart grid domains. Another example can be found in [77], which discusses the application to the energy sector of the interoperability research results from other sectors. This discussion is conducted under the perspective of cooperation and collaboration among regional grids. Besides the technological aspects of interoperability, also the need for the establishment of business agreements among collaborating parties is identified. Reaching compatible business processes and procedures, as well as compatible strategic objectives, are part of the requirements. The creation of incentives to build collaborative business relationships, even among competitors, is also discussed.

Main characteristics:

- *Collaboration forms*: Mainly long-term networks of (smart) cyber-physical components, with self-organizing capabilities.
- *Motivation*: Increase resilience, safety, and self-healing capabilities of the infrastructure.
- *Technology and mechanisms*: Adoption of mechanisms from the areas of cyber-physical systems, Internet of Things, and smart sensor networks, allowing embedded intelligence, self-organizing and self-healing capabilities. Frequent adoption of intelligent software agents. Mechanisms for information sharing, and distributed state estimation, allowing some form of collective awareness. Adoption of a variety of interoperability mechanisms.

4.8. *Policy and roadmaps*

The need and potential benefits of adopting collaborative approaches in smart grid are also identified in some policy documents and roadmaps. For instance, [78] discuss efficient strategies for integration of renewable energies, realizing that a high number of actors are involved in the development of new energy infrastructures, which can constitute a barrier if proper coordination / collaboration relationships among them are not established. The need to establish collaborative partnerships, including public/private partnerships and engagement of customers in achieving energy program goals is also pointed out in the American Water Environment Federation roadmap [79]. Bui et al. [66] suggest the “Internet of Energy”, combining smart grid and Internet of Things. In this work, collaborative aspects are identified at various levels, including infrastructure, smart neighborhoods, and services provision, leading to a web-enabled smart grid.

Main characteristics:

- *Collaboration forms*: Long-term strategic networks and goal-oriented virtual organizations.
- *Motivation*: Smooth integration of multiple players involved in energy infrastructures and the need to engage customers.
- *Technology and mechanisms*: Collaboration strategies and business models. Convergence between energy infrastructure and Internet (web services and Internet of Things).

4.9. *Concluding remarks*

From the above survey, some general remarks can be made:

a) *On the collaboration issues*:

- There is already an extensive awareness regarding the need of adopting collaborative networks approaches for the materialization of the smart grid.
- Various organizational forms, with predominance for goal-oriented networks, have been suggested by different authors.
- Although current proposals in smart grids already adopt several

of the approaches and mechanisms used in the collaborative networks area, and in spite of a few exceptions, the two communities have not interacted much. This is reflected in the use of different terminology for similar concepts and even some "re-invention of the wheel". A faster progress could be achieved if a greater interdisciplinary level could be pursued.

b) *On the implementation level* (Table 3):

- Most works remain at simulation level, often using simplified numeric scenarios.
- There are a few prototype implementations, but no real validation in field.
- A few works are of a different nature – field surveys – mostly conducted to identify requirements and trends.

To some extent this situation is justified by the following facts:

– Energy infrastructures are rather expensive and thus their evolution needs to be done while guaranteeing continuity of service.
– Technological evolution needs to properly take into account legacy infrastructures and devices.
– Current technological evolution in this sector, with an increasing role of ICT and CPS, brings in new players, with a different "technological and business culture".
– New business models oriented to multi-player collaboration need to be better understood.

5. Conclusions

The numerous socio-economic challenges faced by the electric energy sector, namely in terms of market liberalization, new regulations, and sustainability goals, force all players to seek new technological solutions, combined with new business models. One of the most profound transformations comes from the merging of ICT and energy-related technologies, resulting in the introduction of increasing levels of "smartness" in the grid infrastructure. In parallel with the technological evolution, an organizational transformation is happening as a result of the growing number of stakeholders involved in the sector, including new roles for the consumers. Complementarily, new business models based on engagement, behavioral change, and benefits distribution are emerging. In this evolving context, collaborative approaches become vital.

From the conducted literature survey it is evident that a good level of awareness for the need of collaborative approaches is already present in the research community. Developed simulation models show the potential benefits of collaboration, which might trigger real implementations in the near future. The evolution in ICT, combined with increasing market liberalization and tighter policy regulations, are likely to induce faster progress in this area. On the other hand, the specificity of the energy systems also raises new challenges for the Collaborative Networks area, namely in terms of combination of multiple collaboration networks (organizations, people, devices) and thus a tighter interaction between the two communities will be mutually beneficial.

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