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A Framework for Qualifying and Evaluating Smart Grids Approaches: Focus on Multi-Agent Technologies

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ABSTRACT

New needs and emerging societal constraints have put the emphasis on the inadequacy of the actual electrical grid. Indeed, it is impossible, or at least very hard, to 1) integrate renewable energy sources at a great scale within the actual electric grid, 2) enable communications between the various power suppliers and consumers, 3) design several different services that meet the needs of a wide range of end users. A key solution to these issues consists in using Smart Grids (SG). SG can efficiently control power flows by means of Information Technology (IT). Technically, a SG consists of a power system and a bidirectional communication system. Multi-Agent Systems (MAS) constitute a possible technology that can be applied to control and monitor the operation of power grids. Moreover, MAS exhibit distribution, adaptive and intelligent features. The goal of this paper is to propose a framework of qualification and evaluation for comparison SG approaches. First, a set of features of importance for smart grids definition is identified. Then, in a second step, some criteria are given to evaluate the impact of SG on the society. Finally, these features are applied to existing MAS approaches addressing SG in order to understand and compare their different contributions.

Keywords: Smart Grids; Qualification and Evaluation; Multi-Agent Systems

1. Introduction

Nowadays, a paradigm shift occurs within energy systems [1]. New needs and constraints emerge, such as: reduced carbon dioxide emissions, greater introduction of renewable energy, diversification of power transactions, etc. These new needs and constraints have put the emphasis on the inadequacy of the actual electrical grid. Indeed, it is impossible, or at least very hard, to 1) integrate renewable energy sources at a great scale within the actual electrical grid, 2) allow communications between the various power suppliers and consumers, 3) design several different services that meet the needs of a wide range of end users.

A key solution to these issues consists in using Smart Grids (SG). SG can efficiently control power flows by means of Information Technology (IT), integrating not only the supply side but also the demand side and all the devices that allow the distribution of power. Technically, a SG consists of a power system and a bidirectional communication system. It mainly focuses on applying IT to the distribution and customer sides.

As defined in [2] smart grid is the term commonly used to refer to an electrical grid whose operation has been transformed from a twentieth-century analog technology based on the pervasive use of digital technology for communications, monitoring (e.g. sensing), computation, and control.

Emerging smart grid technology allows for fine-grained sensing and control. This enables highly flexible, efficient, and optimized operation, including full support for market-based, demand-side management and the accommodation of alternative generation sources, including sources of consumer-generated electricity. A smart grid is defined as having the following seven principal characteristics, as specified by the US Department of Energy's National Energy Technology Laboratory in its modern grid strategy [3]. A smart grid:

- enables active consumer participation
- accommodates all generation and storage options
- enables new products, services, and markets
- provides power quality for the digital economy
- optimizes asset utilization and operates efficiently
- anticipates and responds to system disturbances
- operates resiliently against attack and natural disaster

A similar smart grid vision is put forward in the document European Smart Grids Technology Platform-Vision and Strategy for Europe's Electricity Networks of the Future [4].

Over the past ten years, many research projects have addressed the smart grids and the number of projects tackling smart grids increases every year.

The goal of this paper is to propose a framework of qualification and evaluation for a comparison of every approach for smart grids. The evaluation and comparison are based on the feature analysis approach [5]. First, a set of features of importance for smart grids is identified and defined. Then, in a second step, criteria is given to evaluate the impact of the grid on the society. Finally, these features are applied to existing MAS approaches addressing smart grids in order to understand and compare their different contributions. Among the heterogeneous approaches, some are based on the Multi-Agent Systems (MAS) paradigm. MAS are a good candidate to model and implement the intelligent components of a smart grid as they exhibit autonomy, reactivity, pro-activeness and collaborative capabilities [6,7]. A workshop dedicated to agent-based approaches for energy systems (ATES) has even been created as a forum of discussion for this research since 2010. That is why authors decide to compare only MAS approaches.

This paper is organized as follows: Section 2 presents an overview of an evaluation framework for smart grids, Section 3 details the qualification framework, Section 4 presents the evaluation framework and Section 5 provides a study of the main multi-agent approaches for smart grids.

2. Evaluation Framework Overview

Significant investments have been made, especially in European Union and United States, in order to develop, demonstrate and deploy smart grids technologies. Some recent works are trying to assess the costs, performance and benefits of smart grid technologies. There is currently no established standard in this area. Among the recent initiatives, we may notably mention:

- The 2nd EU-US workshop[1] on Smart Grid Assessment Methodologies jointly organized by the Joint Research Centre and the Department of Energy on the 7th of November 2011 in Washington DC.
- The Evaluation Framework for Smart Grid Deployment Plans [8].
- The smart grid scorecard[2] that provides a listing of the required features a product must have to be compliant with a smart grid.
- The incentives to determine reliable metrics, costs, and benefits from projects related to smart grids, like in [9] and [10].

[1]See http://ses.jrc.ec.europa.eu/node/69

[2]see http://www.smartgridnews.com/pdf/Smart_Grid_Scorecard.pdf

The present article is part of this effort by providing an evaluation framework. The study focus on multi-agent approaches for smart grid. Though we decided to study multi-agent approaches for expertise reasons, it is worth noting that the proposed evaluation framework could also be used for approaches belonging to any other paradigms.

In the following two sections, we define a framework that decomposes the analysis and the comparison of smart grids into two steps. The first step aims at positioning the evaluated approaches and understand them. This step is divided into two dimensions:

Structural dimension represents the physical infrastructure of the smart grid. **Family problem dimension** defines the different classes of problems solved by the smart grid.

The second step, aims at evaluating quantitatively and qualitatively the different approaches by assessing the societal impacts of these approaches. The proposed criteria for evaluating the societal impacts are defined according to the main challenges of smart grids[3]:

Greenhouse gas reduction: How to reduce the carbon footprint of the overall supply chain? (*addressed by Environmental dimension of the proposed framework*)

Energy security: How to increase the network's capacity in order to manage a potentially diverse set of new requirements? How to provide interruption-free reliable power accommodating all generation and storage options, especially wind and solar power? (*addressed by Structural and QoS dimensions*)

Economic competitiveness & affordability: How to cost-effectively transition to a low-carbon energy system, increasing affordability? How to enable the new products, services, and markets through a flexible market to provide cost-benefit trade-offs to consumers and market participants? (*addressed by Economic dimension*)

Human integration: How to enable the consumers to actively participate by providing them with the choices and the incentives to modify their electricity purchasing patterns and behaviors (Smart metering, Advanced Metering Infrastructure)? (*addressed by Human dimension*)

For each of these challenges a set of indicators is proposed. It is not always possible to test each approach with every indicator or to obtain resources from the literature that provide results of such analysis.

3. Qualification Framework Definition

In the following, the different aspects of the framework are defined. These aspects are composed by the first (qualification) and second (evaluation) steps. The first step is detailed through two viewpoints or dimensions (structural and family problems) and the second step is

[3]Mainly according to the U.S. Department of Energy.

detailed through the societal dimension. A list of criteria (written in bold face) is presented thereafter for each dimension (structural and family problem) with the corresponding definitions and explanations.

3.1. Structural Dimension—Industry Focus

The structural dimension defines the energy infrastructure of the smart grid. The energy infrastructure consists of two highly-interrelated and complex systems: the energy physical network and the energy market [11]. These two systems and their relationships are precisely described by the ontology in [12].

First, we briefly explain the main concepts of the electric power delivery system described in the ontology.

Second we highlight questions must be answered for completely describing a power grid.

- The *producers* are responsible for generating energy.
- The *transmission system operators* are responsible for operating the transport of energy on the high-voltage interconnected system, called the transmission network, in order the ensure long-term services, like the balance of supply and demand, for instance.
- The *distributed system operators* are responsible for operating the transport of energy on medium-voltage and low-voltage energy systems in given areas. They ensure the connections of the medium-voltage and low-voltage energy networks, called the distribution networks, to the high-voltage distribution network. They also ensure the energy delivery to customers, but without including supply.
- The *suppliers* are responsible for the sale of energy to customers. In a liberalized energy infrastructure, a supplier can be a wholesale customer who purchases a commodity (for instance energy) with the purpose to sell it subsequently.
- The *households* (or customers) purchase energy for their own use.

Physical Is the network for physical delivery taken into account?

Size What is the physical network size (network voltages, number of devices, power capacity)?

The size of a network is an intricate concept and cannot be defined precisely by a single value. For completeness, a network size must contain the different voltage of the network, and the number of devices present in the network.

Storages Which types of storage systems are used (total energy, power capacity, power variation)?

Sources Which types of sources are used (renewable, capacity factor, other characteristics defined by the ontology)?

Loads Which types of loads are used (predictable, disconnectable, other characteristics defined by the ontology)?

Scalability Is the physical network scalable in real-time?

Communication Is communication between devices possible?

The new energy infrastructures have to offer a communication between distributed appliances (for example, for a demand response [13]), that is they could allow to take into account priorities on load demands or could increase the balance between consumption and production.

Microgrids Is the physical network composed of microgrids?

Microgrids [14] can be defined as parts of the energy network that comprise intermittent sources.

This approach allows for local control of distributed generation, thereby reducing or eliminating the need for central dispatch.

Islanded Is the physical network islanded?

Network type Which type of physical network is used?

The proposed approaches are validated on the basis of experiments carried out on a simulated physical network, a real network or a combination of both.

Models If simulated, which models are used for the appliances?

Timescales If simulated, which timescales are taken into account in the energy network?

Managing energy in this system implies to take into account several strong constraints.

Besides, supply and demand occurring within the physical network must always be balanced on a short timescale (milliseconds or seconds).

Commodity trade Is the network for commodity trade taken into account?

Dynamic prices Are the prices allocated dynamically between actors?

Time frames Which timescales are taken into account in the energy market?

Depending on the possible control actions, the energy balance has to be maintained at the different time frame [15]. The wholesale market and the retail market ensure energy balance at medium time frame (minutes or hours) and long time frame (days, months or years). The balancing market ensures energy balance at small time frame (milliseconds or seconds) and medium timescale.

3.2. Family Problem Dimension—Domain Focus

As stated in [16] smart grids raise many significant challenges for the AI field. Indeed, concepts and techniques will be needed to solve the numerous problems that are not solved today by the current electricity grid. Among these problems, one can cite: the maintenance of stable voltages and frequencies, supply reliability, Distributed

Energy Renewables (DER) management, heterogeneous and distributed actors, self-healing networks, ⋯

Follows some already well-identified problems.

Unit commitment The problem of unit commitment (UC) aims at finding the dispatch of available generation sources that meet the electrical load with the minimum cost. In other words, the aim is to determine the combination of available generating sources or units and to schedule their respective outputs to satisfy the forecasted demand with the minimum total production cost under the operating constraints enforced by the system [17].

Demand side management Energy demand management, also known as demand-side management (DSM) or Load Management [18], is the modification of consumer demand for energy through various methods such as financial incentives and education. Usually, the goal of demand-side management is to encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times such as nighttime and weekends. Peak demand management does not necessarily decrease total energy consumption, but could be expected to reduce the need for investments in networks and/or power plants by reducing demand peaks.

Demand Response The demand response (DR) is an extension to DSM problem. The difference lies in that demand response mechanisms respond to explicit requests to shut off, whereas DSM passively shut off when stress in the grid is sensed.

Supply and demand matching Supply and Demand Matching (SDM) is concerned with optimally using the possibilities of electricity production and consumption devices to alter their operation in order to increase the overall match between electricity production and consumption.

Vehicle to Grid The idea behind the Vehicle-to-Grid (V2G) concept, is to use the flow of power (both in input and output) of an electric vehicle. These flows can be real add-on for the electrical power grid. Indeed, these vehicles, either electric cars (BEVs) or plug-in hybrids (PHEVs), have the capability to produce AC electricity. The challenge raised by this idea is to provide electricity precisely when needed and recharge these vehicles efficiently. By communicating with the electrical power grid BEVs and PHEVs could then implement a Demand Response service.

Virtual Power Plant A Virtual Power Plant (VPP) is a cluster of distributed generation devices (such as microCHP, PV, wind-turbines, small hydro, etc.) which aggregate themselves to sell electricity. The goal of VPPs is to maximize the value for both the end user and the distribution utility by using software systems. They are dynamic, deliver value in real time, and can react quickly to changing customer load conditions. A VPP matches up a variety of distributed energy systems with intelligent demand response capabilities and aggregates those resources into an asset that acts like a centralized power plant. VPPs are similar to microgrids; however, while microgrids are very local in scope, VPPs can theoretically be deployed on a wide scale at the utility level with the ability to tap resources in real time, and with enough granularity, to control the load profiles of customers, aggregate these resources, and put them up on a trader's desk.

Self-Healing Network One of the major advantages of smart grids is to allow self-healing of the network without the intervention of technicians. This will ensure more reliable supply of electricity, and reduced vulnerability to natural disasters or attack.

4. Evaluation Framework

The points described in 3 present the upstream work for smart grid analysis. However, the objectives of the smart grids are to help companies and individuals to solve the problems due to the daily energy production and management. In order to evaluate the impact of the incoming smart grids, concepts must be defined, we integrate the concept of sustainability usually considered as a composition of Environment, Economy, and Society [19] and we also add a human dimension representing system's control and supervision capabilities.

We tried to collect them within an assessment framework combining these 4 different perspectives grouped under the umbrella term societal dimension.

4.1. The Environmental Approach

The most significant environmental impact of power generation is in the form of emission to air, ground and water. Of those emissions, the most significant in terms of impact are emission to air of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_x), methane (CH_4), nitrous oxide (N_2O) and particulates. The impact on water is more complicated, involving heat, volume and emissions. The objective of this part of our framework mainly consists in determining the benefits of a smart grid's model to reduce its carbon footprint. However, the objective can be extended to nuclear wastes or other discharges influencing environment. To reduce significant environmental impact, two main goals are easily focused:

- Reduce pollutants' emissions and wastes' production (reducing oil usage, reducing nuclear power plants, etc.).
- Lower transmission and distribution losses

The Global Warming Potential (GWP)

It is therefore, important to have indicators to evaluate the performance of a smart grid in terms of environmental impact (e.g. [20, Chapter 11]). To estimate the greenhouse gases' emission impact, the United Nations Framework Convention on Climate Change[4] (UNFCCC) sets up a cost measure, based on the environment impact of the CO_2, the Global Warming Potential (GWP) [21]. With this cost measure, one can easily evaluate the greenhouse effect of every generator on the environment, given the amount of emitted gases during production, and thus it will be easier to compare them.

The difficulty of the usage of this cost measure remains in evaluating the amount of greenhouse gases' emission, but some research has been made in this problem, and it is currently possible to find the quantity of CO_2 emitted per kWh (as [22] or in [23]).

4.2. The Economic Criteria

As an economic aspect is already included in an energy network (see 3.1), it is important to define all costs, such as investments (CAPEX), ongoing costs (OPEX) but also the revenues implied by the investments to establish the interest of the problem to be resolved.

All costs and revenues are depending on the problem to be solved. As described in 3.1, the energy market contains 3 main kinds of actors with different goals. The producer side is the well-known part of the economic approach. The pertinent elements for this actor are the cost operation and the investments of energy generators. The distribution of the energy created by the new devices also implies a cost which has to be taken into account. Adding an intelligence into a grid implies potentially a communication infrastructure. It can be interesting to manage the energy loss during the transportation. For the consumer side, the main aspects are subscription, taxes and a price of the kWh. The first and the second can vary depending on the location of the consumers, while the third also varies during time.

In [24], the authors precisely describe costs and revenues of the electricity market.

The Asia Pacific Energy Research Centre [25] provides some indicators to assess of energy efficiency from an economic perspective. They propose economic value based energy-efficiency indicators measuring the quantity of energy consumed relative to the economic/onetary value of the activity generated, denominated in a currency-related unit. This is an extension of the study published by the French Agency for Environment and Energy Management (ADEME) [26], who suggests three alternatives for comprehensively reviewing trends in energy efficiency at a sectoral or sub-sectoral level:

1) Energy Intensity

Considers whether energy, as an input to production, is used efficiently. Energy intensity's analysis is generally based on relative comparisons with established benchmarks, historical trends, or other comparable energy intensities.

2) Techno-Economic Ratios

Calculate, from an engineering perspective, the economic production associated with the unit or specific consumption of energy.

3) Energy Savings Indicators

Endeavor to measure energy savings achieved by consumers over a period. These "techno-economic effects" essentially analyze changes in the techno-economic ratios.

In [27], authors provide a step-by-step assessment framework based on the work performed by the Electric Power Research Institute (EPRI) for conducting cost-benefit analyzes of smart grid projects.

4.3. The Quality of Service Criteria

Nowadays, it would be impossible to imagine daily life without having a continuous access to energy. Offering this service to a growing number of persons and needs is very challenging. For instance, the transportation of the energy must meet numerous constraints in order to ensure power quality. Among these constraints, one can cite: nonzero frequency impedance, harmonic variations, etc.

Some statistical indicators of transmission and distributions circuits exist [28,29] for assessing the quality of such services, among the best known, we can mention:

1) MAIFI

Momentary Average Interruption Frequency Index measures the weighted average number of outages that last less than ten minutes, which occurred in a year and with reference to the total connected load.

2) ASIDI

Average System Interruption Duration Index measures the weighted average number of outages equal to or more than ten minutes, which occurred in a year and with reference to the total connected load.

3) ASIFI

Average System Interruption Frequency Index measures the weighted average number of outages equal to or more than ten minutes, which occurred in a year and with reference to the total connected load.

4) SAIDI

System Average Interruption Duration Index is the average outage duration for each customer served.

5) SAIFI

System Average Interruption Frequency Index is the average number of interruptions that a customer would experience.

6) CAIDI

Customer Average Interruption Duration Index (SAIDI divided by SAIFI).

[4]http://unfccc.int

7) SISI

System Interruption Severity Index measures the ratio of the unserved energy to the system peak load.

8) FOT

Frequency of Trippings per 100ckt-km measures the number of forced line outages (transient and permanent or sustain) initiated by automatic tripping of relay.

9) FLC

Frequency Limit Compliance refers to the percentage of time during the rating period that the system frequency is within the allowable range of 60 ± 0.3 Hz.

10) VLC

Voltage Limit Compliance refers to the percentage of the number of voltage measurements during the rating period that the voltage variance did not exceed ±5% of the nominal voltage.

Furthermore, some standards exist such as [30], which offers practice developed out of an increasing awareness of the difficulty in comparing results obtained by researchers. The Council of European Energy Regulators provides an extensive analysis on the quality of energy supply throughout Europe [31]. It provides a collection of indicators monitoring continuity of supply (interruptions), voltage quality and commercial quality used to develop a complete benchmark.

4.4. The Human Integration Criteria

From a consumer's point of view, power grid remains a black box, an unlimited amount of energy. Unfortunately, unlike fossil-fuel or nuclear based power generation, most renewable-energy sources depend upon generally unpredictable environmental factors (solar, wind, etc.). Thus, it does not suffice to replace coal or nuclear plants with solar power plants to ensure a reliable and stable energy production as consumers are now accustomed. The advent of smart grid will also require the change in consumer behavior.

This change in behavior especially requires new interface design and new ways to present information about energy usage to the user. Numerous studies have shown the impact of how to present information about energy usage impacts consumer behavior [32-37]. It appears that human behavior with respect to energy cannot be modeled only in terms of cost-effectiveness. It is directly influenced by the following factors [32]:

- Personalized information according to a user specific configuration.
- Goals and commitments.
- Constant feedback, particularly with measures of progress toward goals.
- Financial Incentives to encourage consumers to participate

Supervisory Control And Data Acquisition (SCADA) are a first step towards a monitoring interface that could participate in user behavior change.

IEC PC 118[5] is working on a standard covering the architecture of smart grid user interface, function and performance requirements of demand side systems, information exchange interfaces among demand side systems/equipment, with the aim to support applications, such as a demand response.

4.5. Summary Statement

This evaluation Framework gives 4 criteria to evaluate the impact of smart grid on the society. In this section, we will describe numerical criteria to evaluate and compare approaches solving the same problem in the same structure. The criteria defined below are not the only to evaluate a grid but they represent the improvement of the future grid as defined in the Section 2.

- The Global Warming Potential (GWP) appears to be the best existing factor to evaluate the environmental aspect of a smart grid.
- The economic factor is depending of the vision of the future grid, but all aspects rely on the price of the energy. The money (dollar, euro, etc.) is thus the obvious factor to compare several grids.
- The Quality of Service (QoS) has two perspectives, the first is the feeling of the end-users about the grid (with MAIFI, CAIDI, etc.) and the second is the network stability (with FLC, VLC, etc.). These perspectives are linked, as the first can be seen as the result of the second.
- The Human Integration (HI) is the hardest criterion to quantify. The simplest way to evaluate the human interaction with the grid is the number of settings that users can modify.

Smart grids of the same domain (see Section 3) can be evaluated quantitatively and qualitatively following these criteria to offer a comparison of the result.

5. MAS Approaches

In this section, we conduct a comparative study of the main multi-agent approaches for smart grids using the qualification and evaluation framework previously defined. After over ten years of research, indisputable progress has been made. Indeed, recent approaches are more and more efficient but the benchmark results show that many efforts are still required to offer a truly comprehensive toolbox of approaches for smart grids.

The qualification of the framework can globally be set even if the structural dimension is not completely defined. On the other side, the evaluation framework cannot be used with the current analysis of the studied technologies because of the lack of numerical data. This is one of the

[5]International Electrotechnical Commission, see http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:8701,25

point highlighted by this paper.

5.1. GridAgent

Developed by Infotility, the Grid Agent [38,39] Enterprise Agent Manager (EAM) Suite is the main user interface which provides centralized management and works in conjunction with a suite of pre-configured agent types, specialized editors, applications, and reporting alerting tools, including: An out-of-the-box, complete agent management collection included specialized property editors: RateEditor, ModelEditor, and RuleEditor, PlanningEditor Preconfigured visual information and analytic tools include: EventManager, Smart Dashboard, Resource Viewer, SmartFilter, Cost Manager.

The GridAgent framework implements several types of agents: "Sense and Control" and "Resource" Agents who have analytic methods to calculate optimal response based on pricing signals. "Planning and Optimization Agents manage Distributed Energy Resources (DER) devices under various operational scenarios such as optimal microgrid control strategies. "Blackboard" Agents can store databases (from several media, like Internet or the MAS).

GridAgent also offers human interactions and network protection.

This Suite is developed for managing distributed energy resources and can be used for large-scale integration of distributed energy and renewable-energy resources into real distribution systems.

Its evaluation following the given criteria are in **Table 1**.

5.2. Homebots

Homebots [40,41] is an approach that deals with the smart distributed equipment management in a house. It is based on a multi-agent system, the agents of which are

Table 1. Grid agent evaluation.

Structural Dimension	
Physical	Yes
Size	The system is created to manage energy network supplying 24,000 network transformers in 63 secondary networks. It has to manage the 3G/SOF including the DER, consider substation load transfer, application of HVDC, higher distribution voltage (27 kV, 33 kV, 33+kV), minimal secondary voltage, company-deployed mobile DER assets
Storage	smart charging of PHEV
Sources	Dispatch of distributed and renewable generation
Loads	Loads present in buildings like home or company (e.g. HVAC)
Scalability	Yes, agents are "plug and play"
Communication	Yes, agents play roles, which are the ability to send and receive set of messages, FIPA compliance, could use IP
Microgrids	Yes, the system enables the ability to create on-the-fly "aggregate" blocks of capacity for presentation to the energy markets.
Islanded	Yes, the system enables the ability to create intelligent islanded grid
Network type	Real, an example is presented in [39]
Commodity trade	Yes
Dynamic prices	Yes, the demand response algorithm is based on market transactions
Time frames	unknown
Family Problem Dimension	
Demand Response	Aggregation of capacity (*i.e.* consumption). Ability to shift or curtail load or dispatch local generation. Assume that each agent has a planning execution cycle.
Societal Evaluation Criteria	
Environment	Reduce energy consumption during peak thanks to load shifting and load shedding and also use Renewables.
Economic	Each agent in the system attempts to choose among available alternatives according to the criterion of minimum operating cost
QoS	Using DER, which has the potential to provide reactive power (generated close to loads) to maintain grid voltage stability
Human	expected to operate over a large range of hardware platforms and sites (such as PDA)

directly linked to one specific equipment. The management process is based on a computational market, which can be considered as a multi-agent systems sub-field, involving specific agents.

In this context, every load is represented by an interactive load agent, the preference and needs of which are translated into a utility function. The agents are grouped taking into account the topology of both the electrical grid and the communication system.

The utility function is embodied by a utility interface agent. This helps to provide an interface between the utility and the load management system even if the time scales for the different kind of agents (load and utility) are not necessarily the same. In the market management paradigm, the utility interface agents can be considered as a local utility salesperson. This utility agent can thus be directly manipulated in order to make the system go in on a specific way. The utility function is computed taking into account several elements such as: load model, load's current state, utility contract, user model, expected evolution of the local market.

The Homebots evaluation following the defined criteria is made in **Table 2**.

5.3. IDAPS

IDAPS [42] is a distributed smart grid concept proposed by Advanced Research Institute of Virginia Tech. The agents in the IDAPS MAS work in collaboration to detect upstream outages and react accordingly to allow the microgrid to operate autonomously in an islanded mode. The proposed MAS consists of:

- A control agent who monitors the system voltage, detects problems and sends signals to the main circuit.

Table 2. Homebots evaluation.

Structural Dimension	
Physical	No
Size	From one house to several houses.
Storage	Not defined.
Sources	Not defined, the only source for the system is the main grid.
Loads	House classical loads (wash machine, lights, etc.). Each is represented by one agent who decides to connect the load or not.
Scalability	yes, depending on the loads used.
Communication	The communication is made indirectly through the market exchanges.
Microgrids	Indirectly yes but not really mentioned
Islanded	No
Network type	In [41], both are mentioned but only simulations are presented.
Models	everything is integrated into utility function.
Timescales	Not detailed (expressed in time units)
Commodity trade	Yes
Dynamic prices	Yes, Homebots is based on market computational market economies.
Time frames	The utility function includes both local agent timescale and market timescale in the prediction that has to be taken into account.
Family Problem Dimension	
Adaptation to power production	Two examples of adaptation to power shortage are presented. In the first, the adaptation is made thanks to utility function. In the second, the adaptation is made by influencing the energy price.
Societal Evaluation Criteria	
Environment	Not available.
Economic	Minimizing energy cost based on market evolutions.
QoS	Not taken into account
Human	Human interaction can be made indirectly by influencing the market.

- A DER agent who is responsible for storing associated DER information and monitoring and controlling DER power levels.
- A user agent who acts as a customer (user or load) gateway.
- A database agent who is responsible for storing system information.

IDAPS is realized with Zeus [43] multi-agent system platform, which is FIPA-compliant.

This work aims at demonstrating a practical implementation of multi-agent systems in a smart grid located at a distribution level. It also demonstrates that the agent's capability can be considered as a software alternative to a traditional hardware-based zonal protection system for isolating a microgrid. IDAPS separates the multi-agent system (developed with Zeus) and the microgrid hardware (developed with Matlab/Simulink).

The evaluation of IDAPS is presented in **Table 3**.

5.4. IDEaS Project

The IDEaS Project has been focusing on the following problem families since its advent:

- Adaptive Home Heating ([45])
- Demand Prediction ([46,47])
- Demand-Side Management ([48,49])
- Electric Vehicles ([50-52])
- Energy Exchange ([53-55])

Table 3. IDAPS evaluation.

Structural Dimension	
Physical	Yes
Size	Circuit 9 of Virginia Tech: a residential distribution circuit at or below 12.47 kV, 34 laterals with 117 transformers serving 780 customers.
Storage	Battery Model from Matlab-Simulink 2009 [44]
Sources	Solar photovoltaic, wind turbines, microturbines, fuel cells
Loads	Typical residential needs: Lighting, Freezing, Refrigeration, Clothes Drying, Cooking, Water Heating, Space Cooling
Scalability	Yes
Communication	Yes, TCP/IP or Internet Protocol
Microgrids	One microgrid
Islanded	No, but it could be in emergency situations
Network type	Both
Models	Mathematical Formulae, Equations
Timescales	Milliseconds and hours
Commodity trade	Yes but adopting the "supply-driven-demand" approach instead of the traditional demand-driven-supply approach.
Dynamic prices	Yes
Time frames	Minute, Hour and Day. Electricity price ($/kWh) can vary from every minute to every hour;
Family Problem Dimension	
Supply-Driven-Demand Management	An IDAPS microgrid employs a bulletin board that represents an electricity market place for electricity buyers and sellers to transact business in. However, instead of matching the supply with the demand and producing market clearing prices, end-use customers make a decision, whether to buy electricity or not for their deferrable demand according to the real-time electricity pricing information offered by suppliers in the grid.
Societal Evaluation Criteria	
Environment	Not available
Economic	Not available
QoS	No real indicators, just follow grid's voltage and frequency. Response time within about half an electrical cycle (*i.e.* less than 0.008 second for a 60-Hz system) from detecting the fault to stabilizing the grid
Human	Done thanks to their "User Agent" that makes features of an IDAPS microgrid accessible to users. A user agent monitors voltage, current, active and reactive power consumption at each critical and non-critical load. It also allows users to control the status of loads based on priority pre-defined by a user. It retrieves real-time information and displays all relevant information on an electronic console on the end-user premises. This may include price ($/kWhr), quantity (kWhr) and duration (clock time) of electricity available for purchase, as well as electricity pricing information.

- Exposure in Auction Markets ([56])
- Micro-storage ([57,58])
- Virtual Power Plants ([59])

As examples, only two articles proposed within the IDEaS Project will be evaluated below using our framework. The first article tackles a problem of demand-side management. The second article deals with virtual power plants.

Demand-Side Management: A decentralized demand-side management model is proposed and evaluated in [48]. Such a model aims at optimizing the deferment of loads so as to maximize the comfort in the home and minimize energy cost. The proposed method can be evaluated on the basis of the criteria shown in **Table 4**.

Virtual Power Plants: Although the production of energy with Distributed Energy Resources could potentially reduce reliance on conventional power plants, they lack the capacity, flexibility and controllability to participate in a cost-efficient way for demand supply, both in the physical electricity network and in the electricity market. The creation of Virtual Power Plants (VPP), that is entities that manage a set of DERs, has been suggested in recent years to cope with the previous quoted drawbacks. In [59], the emergence of cooperatives of VPP composed of small-to-medium size renewable electricity producers is controlled with a game-theoretic approach using a pricing mechanism and a scheme allocating payments within the cooperatives. **Table 5** evaluates the proposed

Table 4. IDEaS project evaluation: demand-side management.

Structural Dimension	
Physical	Yes
Size	Composed of 5000 homes, using load profiles of 26 M homes in the UK.
Storage	Not required for this kind of problem.
Sources	Not required for this kind of problem.
Loads	Deferrable loads, including shiftable static loads (like washing machines and dishwashers) and thermal loads (like fridges, boilers and radiators) and non-shiftable static loads (lighting and cooking).
Scalability	It has been shown in the article that the proposed approach can scale well
Communication	Surely but not described.
Microgrids	Represented by *smart homes*.
Islanded	Irrelevant for this kind of problem.
Network type	Simulated.
Models	Mathematical models are used for the loads.
Timescales	One decision per day and per agent.
Commodity trade	Demand-side management and pricing are dynamical and influence each other.
Dynamic prices	They are allocated dynamically, using the Real-Time Pricing (RTP) based on the macro-model of the UK electricity market, but not between actors.
Time frames	Market prices are predicted for every next day over 100 experiments.
Family Problem Dimension	
Decentralized Demand-side Management	The proposed approach consists in coordinating large populations of agents. Each agent controls and adapts the deferrable loads of a *smart home* so as to maximize the comfort and minimize energy costs. The adaptive mechanism embedded in every agent is composed of two processes. First, a Widrow-Hoff learning mechanism is used to gradually adapt the deferment of the loads based on predicted market prices for the next day. Second, a stochastic mechanism is used to reoptimize the thermal load profiles on any particular day with a probability.
Societal Evaluation Criteria	
Environment	Minimizing carbon emissions.
Economic	Minimizing energy cost.
Quality of Service	Not taken into account.
Human Integration	Selecting which loads can be deferred.

Table 5. IDEaS project evaluation: virtual plants.

	Structural Dimension
Physical	Yes.
Size	The network has a nominal capacity of 17.5 MW and can supply 12000 homes.
Storage	Not mentioned.
Sources	24 simulated wind turbines are used with profiles coming from real data of the Sotavento experimental wind farm in Spain.
Loads	Not available.
Scalability	No.
Communication	No.
Microgrids	Yes: the microgrids are represented by the cooperatives of VPP.
Islanded	Yes: only the wind turbines supply the demand.
Network type	Simulated.
Models	Analytical models are used.
Timescales	Slots of hours are used.
Commodity trade	Yes.
Dynamic prices	The prices are allocated dynamically between the cooperatives of VPP and the distribution network.
Time frames	Per hour.
	Family Problem Dimension
Virtual Power Plants	Virtual Power Plants represent collections of Distributed-Energy Resources (like storage systems or renewable-energy capacitor) that can be used more efficiently to meet load demand within an electricity supply network. Several techniques based on game theory are proposed in this article for forming and maintaining cooperative VPPs and for allowing them to reliably communicate their production to the electricity grid.
	Societal Evaluation Criteria
Environment	Not taken into account.
Economic	Not taken into account.
Quality of Service	Not taken into account.
Human Integration	Not taken into account.

technique using our framework.

5.5. PowerMatcher

The PowerMatcher [11] is one of the outcomes of the Smart House/Smart Grid European FP7 project[6]. It consists in a coordination mechanism that aims the balancing of demand and supply in (possibly multi-level) microgrids integrating Distributed Energy Resources. These microgrids are defined as clusters of sources and loads. The PowerMatcher mechanism implements supply and demand matching (SDM) using a multi-agent system and a market-based control approach. The PowerMatcher technology can be the basis of a Virtual Power Plant (VPP). The qualifying and evaluation of PowerMatcher is presented in **Table 6**.

[6]http://www.smarthouse-smartgrid.eu/

Within a PowerMatcher cluster, the agents are organized into a logical tree. The leafs of this tree are a number of local device agents and, optionally, a unique objective agent. The root of the tree is formed by the auctioneer agent, a unique agent who handles the price forming, *i.e.*, the search for the equilibrium price.

Follows a description of the three pilots.

- Netherlands

Twelve have a combined heat and power (CHP) plants with high efficient 1 kW boilers running on natural gas. The other 13 have a hybrid heat pump that combines an air-to-water heat pump with condensing boilers. All 25 houses have smart meters from Itron. Each house has twelve square meters of PV paneling for a total capacity of 1400 W peak. Ten houses have a smart washing machine and dishwasher from Miele. One house has a plug-in hybrid Toyota Prius car and two others each has an

Table 6. Power matcher evaluation.

Structural Dimension	
Physical	Yes
Size	Mass application (Hoogkerk, the Netherlands), mix of domestic clusters and selected grid segments (Mannheim, Germany), reaction to critical situations (Meltemi, Greece).
Storage	Electricity storage is present in the form of batteries.
Sources	Stochastic operation devices are present in the form of photovoltaic (PV) solar cells and small-scale wind turbines; classical sources are also present depending on the field test.
Loads	Deferrable loads, Shiftable static loads and classical loads depending on the field pilot.
Scalability	Yes it is one of the goals of the PowerMatcher.
Communication	The communication is implemented by a smart metering approach and via web services.
Microgrids	Yes the inherent structure defined by the PowerMatcher is hierarchical and allows to decompose a grid into smaller interacting grids in a VPP fashion.
Islanded	Yes, it was one of the constraints of the third field test.
Network type	Both simulated and real network were used.
Models	The appliances are simulated according to energy profiles drawn from well-known sources
Timescales	The simulator timescale/frequency is one second.
Commodity trade	Is the network for commodity trade taken into account? Yes/No
Dynamic prices	The prices are allocated dynamically, using the Real-Time Pricing (RTP) based on the macro-model of the UK electricity market, but not between actors.
Time frames	Market prices are predicted for every next day.
Family Problem Dimension	
SDM	The basic mechanism underlying PowerMatcher consists in answering the Supply and Demand Matching problem. The logical structure used also allows to tackle the VPP management problem.
Societal Evaluation Criteria	
Environment	Concerning the societal viewpoint RES and batteries have been used in pilots. Some initial results show that the use of PowerMatcher may bring from 14% to 21% of CO_2 reduction.
Economic	The peak reduction has been quantified at 4.49% (annual average) for the Greek pilot.
QoS	There is no evidence of the Quality of service issue in the available documents.
Human	The clients are integrated as real actors via the prosumer concept. Indeed, each house of the Netherlands pilot has a Home Energy Management (HEM) box, which implements the local energy management strategy of the house.

all-electric Volkswagen Golf car. One house has a standard lead-acid battery to store solar energy for later use.

- Germany

The installation of the smart meters has been done during spring 2010. The installation of first system prototypes at the end customers' premises have first started at "very friendly user's" homes. Afterwards, all BEMIs will be rolled out during October and November, so that the field trial operations can start. Meltemi comprises 220 cottages, which are fully inhabited in the summer (from May to September) and mostly empty in winter. A typical cottage in the camp is a single floor building of 70 m^2 surface. Most of the cottages are more than 30 years old.

- Greece

The whole camp is supplied by a 3-phase medium-to-low voltage substation. The maximum load consumption of the site is approximately 220 kW. Furthermore, a 40 kW diesel generator is present. Finally, PV systems are installed in some of the houses as well in the entrance of the camping. The total installed capacity is 6 kWp.

6. Conclusions

This paper presents a framework for qualifying and evaluating smart grids approaches. This contribution is mainly based on a comparative study that is conducted based on an assessment framework analyzing each approach. The comparison is only possible for approaches that have same structure and same objective, thus the paper first provides focus on structural dimension and problem dimension to bring together approaches, then gives societal evaluation criteria in order to compare these different approaches.

This study aims at defining a cartography of the existing contributions to smart grid and analyze their strengths and weaknesses. Our objective was not to determine which approach is the best among the chosen ones. Such a choice would be dependent on many conditions specific to the deployment context. However, the survey presented in this paper should help a stakeholder with the comparison of the defined features. The reader should be aware of the following limits of this work:

- The results presented in this work for all chosen approaches are based on the available documentation (articles, technical reports and presentations). We may have missed some elements and could not be absolutely sure that the presented information is complete.
- The study is theoretical. There was no real experimentation to test the different approaches.
- The features defined for the analysis and comparison were influenced by the current state of the art of the domain which is still in its infancy. Future works may improve these features and go further.

Future directions for this work may consist in deploying a website in order to store the presented results, enable new experiments and the addition of new features.

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