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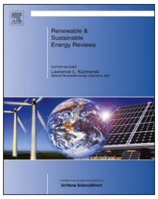

Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources

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ABSTRACT

The energy landscape is experiencing accelerating change; centralized energy systems are being decarbonized, and transitioning towards distributed energy systems, facilitated by advances in power system management and information and communication technologies. This paper elaborates on these generations of energy systems by critically reviewing relevant authoritative literature. This includes a discussion of modern concepts such as 'smart grid', 'microgrid', 'virtual power plant' and 'multi-energy system', and the relationships between them, as well as the trends towards distributed intelligence and interoperability. Each of these emerging urban energy concepts holds merit when applied within a centralized grid paradigm, but very little research applies these approaches within the emerging energy landscape typified by a high penetration of distributed energy resources, prosumers (consumers and producers), interoperability, and big data. Given the ongoing boom in these fields, this will lead to new challenges and opportunities as the status-quo of energy systems changes dramatically. We argue that a new generation of holonic energy systems is required to orchestrate the interplay between these dense, diverse and distributed energy components. The paper therefore contributes a description of holonic energy systems and the implicit research required towards sustainability and resilience in the imminent energy landscape. This promotes the systemic features of autonomy, belonging, connectivity, diversity and emergence, and balances global and local system objectives, through adaptive control topologies and demand responsive energy management. Future research avenues are identified to support this transition regarding interoperability, secure distributed control and a system of systems approach.

1. Introduction

With varied and mounting challenges facing the urban environment and its energy supply, urban energy systems have undergone increasingly rapid change from centralized systems to the distributed energy systems currently deployed and reported in research. This is due in part to the growth of smart grids (SGs) [1–6], distributed energy resources (DERs) [7–10], and their accompanying management structures [11–14], multi-energy systems (MESs) [15–21], and demand side management (DSM) [22–25]. The growing interest in these areas embodies an underlying shift in the energy landscape towards sustainability [26,27] and resilience [28–30] through distributed resources and intelligence, and management schemes integrated across energy systems and scales. However, research to date typically considers emerging energy system concepts within the current paradigm of an energy landscape dominated by centralized generation [31,32]. This paper therefore investigates whether this approach is sufficient to meet the needs of the next generation of energy systems in a landscape with a high penetration and diversity of distributed energy resources, and active consumers. Specifically, we observe that the current distributed solutions generally operate in isolation from others or under the assumption of sparse DER penetration [12,33]. We propose that this will become invalid in the near future as DER, MES and DSM penetration continue to accelerate. Therefore, continuing with this perspective will hinder the effective exploitation of renewables and other urban energy system (UES) entities, and increase barriers to entering the distributed generation landscape, as well as perpetuating several challenges. This leads to the recommendation of a new generation of energy systems which fully embraces their system of systems nature alongside valuable ICT concepts in a scalable, interoperable and secure framework. We propose that a holonic systems approach is a viable method for meeting these needs. This is introduced and discussed as an evolution of the emerging energy landscape.

After formally describing the paper's scope and our review methodology, we start by presenting classifications and descriptions of the generations of energy systems observed in the literature to date, in

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order to contextualize the high level trends described. Within the latest generation of increasingly varied and sophisticated urban energy systems, we present a taxonomy and discussion of emerging energy system concepts. This is followed by a critical comparison of recent energy management research, components and structures through a thematic review, as well focusing on the observed trends of distributed intelligence and semantic interoperability. This enables a clear understanding of the historic, current and emerging energy landscape and how the research conducted to date has paved the way for a new generation of energy systems. Next, we describe the requirements of a new generation of energy management systems, and how holonic systems meet these needs. Finally, the paper elaborates on early evidence of this approach's efficacy and lays out a number of key areas where research is required in order to transition to these future energy management systems.

2. Methodology and overview

We undertook a broad critical review of the academic literature, international standards, legislation, and key economic and political events surrounding energy systems and their management. The body of literature was then broken down into chronological and thematic groupings. Next, the current trajectory of energy management research was considered against the forecasted growth in DERs. Following the observation of new challenges and opportunities arising imminently from a mismatch in these projections, key concepts were identified to address these from related fields and novel management paradigms. The rest of this section details the scope of the review and initial observations of the subject domain.

It was apparent that as an emerging field, urban energy system (UES) management encompasses many other fields, mandating a well-considered scope. We therefore disregarded papers which only focused on national or building level energy management, or which only considered the design phase of energy systems. We also placed an emphasis on recent publications due to the accelerating change in technologies, and focused on electrical systems. Based on this, a trend of increasing popularity in the field was observed since circa 2002, as depicted in Fig. 1. The sources were filtered to those deemed most relevant and influential, to a final bibliography of circa 150 references.

Our analysis led to the observation of 3 distinct stages of the ‘state of the art’ in energy system research and implementation. These stages were: initial electrification, centralized systems and distributed systems. Fig. 2 illustrates this evolution of energy systems as well our proposed next generation of holonic energy systems, which we argue towards through this paper and elaborate in Sections 6 and 7. Before this, the history and state of the art of energy systems are discussed to aid recognition of the concepts and high level trends in the field.

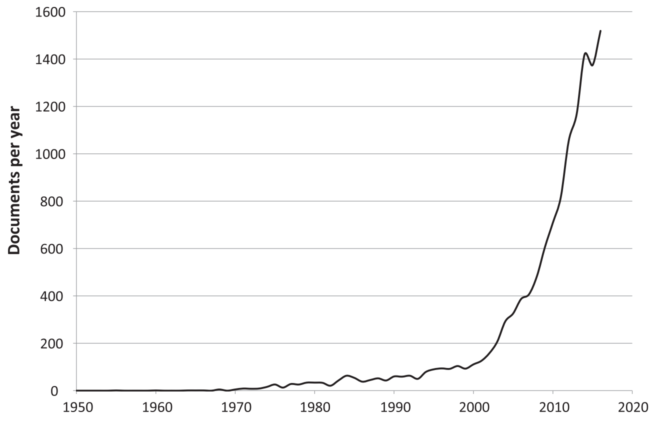

Fig. 1. Popularity of UES research over time as number of relevant Scopus articles per year.

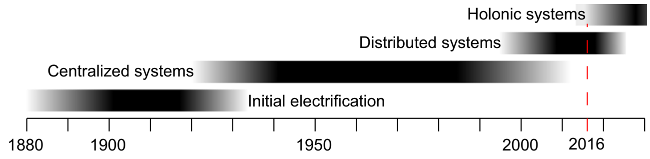

Fig. 2. Timeline of energy system evolution.

3. A brief history of energy systems

Before the discussion of the emerging energy landscape and the required future generation of energy system, this section contextualizes the high level trends observed. This manifests as a discussion of the varying technologies, management structures, and policies throughout the evolution of energy systems to date, and the forces which have caused this evolution.

3.1. Early and centralized energy systems

Following the discovery of electromagnetism and the creation of the first generators by Michael Faraday, electrification began using renewable sources, with the first public electricity supply occurring in 1881 with a water wheel as the energy source [34]. After a contested shift from direct current power stations to alternating current stations, the era of centralized power stations began circa 1890 with the completion of the first high-voltage AC coal power station in London [35]. Regional and national electric grids were rapidly developed from the start of the 20th century and were generally based on inexpensive fossil fuels. Global electrification then escalated gradually from 1900, accelerating after WW2 to reach 83% by 2010 [36]. Whilst microgeneration, renewable generation and cogeneration were prevalent in early electrical systems, the growing economies of scale offered by non-renewable national grids meant attractive electricity prices and they became the status quo in the middle of the 20th Century.

Until near the end of the Century, all national grids were public assets and hence coordinated by the state in a regulated market environment. After US encouragement to restructure the energy sector through the Public Utility Regulatory Policies Act (PURPA) of 1978 [37] and the UK's privatization of a number of other sectors, amongst other influences, the UK began the global trend of deregulating and privatizing energy markets in 1990 [38]. This caused the landscape to shift towards a more dynamic, multi-stakeholder market, although the underlying technological systems themselves remained similar until pressure towards decarbonization intensified. Despite concerns existing about the limited nature of fossil fuels, they were given little recognition in favor of inexpensive and reliable fossil fuels. Further, renewable generation technology was immature and non-hydro examples were economically unattractive to utility suppliers. Hydroelectricity however has a much more prominent place in history due to its reliability, controllability, its ability to dispatch directly to the grid and its ability to store energy, with the Hoover Dam being constructed in 1935 and hydroelectricity supplying 30% of the US's electricity demand in 1950 [40]. This is compared to negligible amounts of all other renewables until the end of the 20th century, as shown in Fig. 3.

The end of fossil-hydro systems was brought about by increasing fuel prices and increased social and political pressure towards environmental sustainability. This primarily meant a need to reduce greenhouse gas (GHG) emissions, local atmospheric pollutants and the consumption of natural resources, whilst meeting the needs of a growing and increasingly electrified population.

3.2. The conventional grid architecture

Centralized electricity systems consist of a small number of large power plants which generate higher voltage power, a high voltage

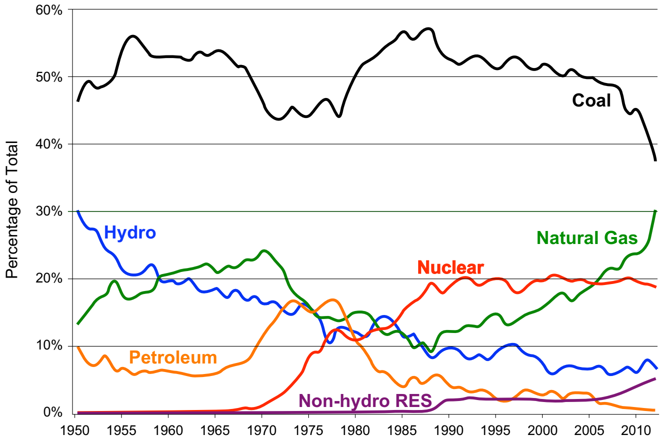

Fig. 3. Electricity generation mix of the US since 1950 [40].

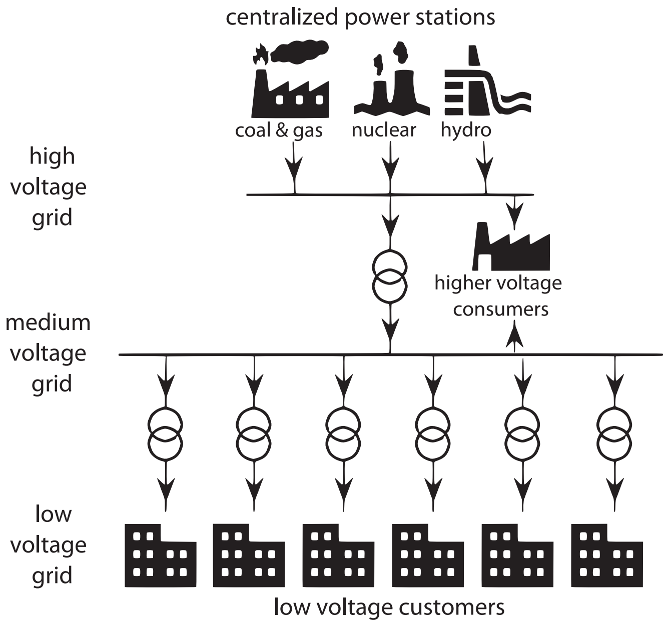

Fig. 4. The conventional grid architecture (simplified).

transmission network, transformers which produce lower voltage power for a distribution network or subtransmission, and local transformers which produce low voltage power, as shown in Fig. 4. This centralized nature is evidenced by the situation in the United States in 2005, when there were 615 coal plants [41], 103 nuclear plants and 2900 natural gas plants. These 3618 plants supplied ~90% of the electricity demand of 110 million households and 5 million commercial buildings, indicating that distributed generation was a negligible part of the industry at that time.

In this system architecture, power flows in one direction only, consumers aren’t aware of the state of the network or of others’ consumption, and producers view consumers as passive entities, and others’ assets as black boxes. The lack of predictability and load control results in the need to overproduce energy and store it as reserve capacity in case of load spikes [42]. This has increasingly wasted energy and has contributed to this approach being recognized as inefficient, alongside losses over long transmission distances and the waste of thermal energy produced during electricity generation. Whilst these concerns resembled ‘mounting environmental pressures’ at the turn of the century, sustainability was only considered to be a long term objective in energy systems of this generation, on the 5–15 year horizon [39], rather than the critical challenge it is today.

3.3. Political, legislative, and regulatory support for renewables

Key events and policies have been a core part of the growing pressure towards environmental sustainability, and contributed to the end of the fossil fuel era. For example, Agenda 21 [43], the enforcement of the United Nations Framework Convention on Climate Change in 1994 [44], the Kyoto Protocol in 2005 [45], the enforcement of the Paris Agreement in 2016 [46], and Directive 2009/28/EC [47]. These officially recognized the problem of climate change at an international level and put steps in place to mitigate humanity's contribution to it whilst adapting to its effects, and currently have near ubiquitous support from UN recognized states. These commitments to GHG emission reductions have placed an emphasis on decarbonizing the electricity sector and have been partly responsible for the pro-RES policies and incentives which have mobilized the recent shifts in the energy landscape [48]. Examples of such policies include the Energy Policy Act of 2005 [49] and the American Recovery and Reinvestment Act of 2009 [50] in the US, the Renewable Energy Law of 2005 [51] and the Golden Sun program [52] in China, and the Renewable Energy Directive [47] and Emissions Trading Scheme in the EU [53].

The roles of regulators and legislators are central in supporting renewable energy adoption. In the US, Miller and Cox reviewed regulatory issues related to variable RES [54] at varying levels of penetration, after identifying that issues are typically due to 4 main mandates. These are: facilitating new variable RES connections, ensuring adequate grid infrastructure, and ensuring both short and long term security of supply. They also highlight the key aspects of RES which regulators consider: grid operation, network deployment, levels of reserves, and allocation of integration costs. Coley and Hess conducted an insightful review into green energy laws in the US and their general opposition by Republicans [55]. For a more detailed summary of US renewable energy regulations, the reader is directed to the recent technical report by Chernyakhovskiy et al. [56].

From a Chinese perspective, concise reviews of renewable energy policies and regulations are offered by Lo [57] and Zhao et al. [58]. Zhao et al. discuss the “Renewable Energy Law” mentioned previously, and outline the main tenets of the Chinese regulatory framework circa 2011: financial subsidies, tax-based incentives, feed-in tariff policies, and technological support policies. They conclude that such incentives are strongly correlated with renewable energy developments. More recently in 2014, Lo critically reviewed relevant Chinese policies across 6 sectors, and also highlighted feed-in tariffs and direct subsidies as Zhao et al. did. Lo concludes with recommendations, such as that the government should increase RES funding further and better support small businesses by promoting energy service companies. Since then, one key policy is ‘Document 625’ in March 2016, which aimed to guarantee that all RES energy would be purchased by grid companies [59]. This continues China's attempt to become a world leader in renewables, with the goal of 15% contribution from renewables by 2020, and investing the most in renewables in 2015 [60]. For more information, the reader is directed to the forward-looking report by Qiang et al., which analyzed 35 policies using a system dynamics model and recommended carbon mitigation policies for China's 13th Five Year Plan [61], which runs until 2020.

The EU has set the ambitious target of 20% contribution from renewables by 2020 [47], has recently proposed a directive for 27% contribution by 2030 [62], and has significantly used policies and regulation to pursue the target. Böhringer et al. reviewed EU climate policies [63], concluding that the complexity of the current approach is “doomed to generate substantial excess cost”. They highlight the role of the 2005 EU emissions trading scheme as the key regulatory instrument following the Kyoto protocol and also since the 2009 Climate and Energy Package. The European Parliamentary Research Service published a report on EU promotion of RES [64], and briefly discussed existing EU policies and legislation, including the 2014 Blue Energy Action Plan (for ocean energy) and the 2016 strategy for heating and cooling. However, member states are broadly free to decide their own strategies for promoting RES towards the legally binding 2020 target, within the boundaries of other EU legislation. Haas et al. conducted a comprehensive EU-wide review of RES policies, and concluded that financial incentives for adopting specific technologies have historically been more effective than alternative approaches [65]. IqtiyaniIlham et al. recently reviewed the role of policies in European smart grids [66], and highlighted the importance of the Smart Grid Task Force as part of the Third Energy Package of 2009, and its mandate to set standards for smart meters, PEV charging, and high levels of smart grid services.

It is also pertinent to note the increasingly interconnected nature of grids. For example in Europe, a 'single energy market' has been pursued since 1996 through Directive 96/92/EC, which was superseded by Directive 2003/54/EC and finally by Directive 2009/72/EC [67]. Based on these directives, energy regulator and transmission system operators were mandated to cooperate internationally according to Regulation (EC) No 713/2009 and 714/2009. This enforced cross-border network and market integration, which promotes a system of systems behavior in modern grids and improves the ability for large RES owners to sell the energy generated by large RES units. The US, EU, and PRC have been focused on in this paper as the largest global energy consumers, and because a comprehensive and global analysis of legislations and regulations covering renewable energy is outside the scope of this paper. For further literature the reader is directed to the REN21 Global Status Report of 2016 [60] and the 2016 World Energy Outlook from IEA [68], which was based on over 3000 policies and measures.

3.4. The rise of renewables

Despite concerns over sustainability, inertia in the industry kept non-renewable systems as the status quo until circa 2005, after which the global reliance on renewable energy sources (RESs) accelerated; doubling between 2004 and 2014 [48]. Reference [69] presents a common view prior to this boom; that renewable energy sources were useful where the national grid was not possible but that they held untapped potential. The state of the art in research is however another issue; with interest in renewables accelerating circa 2000, as shown in Fig. 5.

It is important to note that whilst coal and oil reliance has been reducing, the contribution of gas to the generation mix has been increasing globally alongside renewables. This is due to its low emissions, and arguably, its simplicity to integrate with existing markets and business models. Whilst this may assist in meeting short and medium-term emissions targets, natural gas is a finite resource alongside other fossil fuels, with recent estimates predicting global depletion circa 2064 [71]. Given this, it is important to recognize the importance of renewable energy sources for long term sustainability, whilst also considering their implicit carbon impact, such as in the transportation of biomass or the production of PV panels.

Global RES policies initially caused change without disrupting the centralized paradigm, through large plants which each contributed significantly to the national grid. Large wind farms [72] and solar farms [73] as well as geothermal and biofuel plants, dominated the non-hydro renewable generation domain and have gradually supplemented conventional energy sources [48]. This started the shift towards sustainable electricity generation shown in Fig. 6, but only exchanged conventional generation units with more sustainable alternatives without changing the nature of the underlying systems.

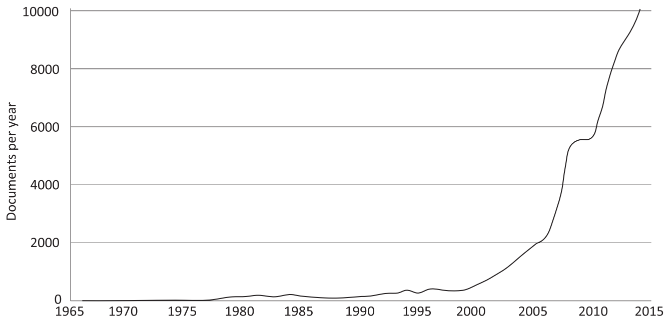

Fig. 5. Academic interest in renewable energy as number of Scopus results per year.

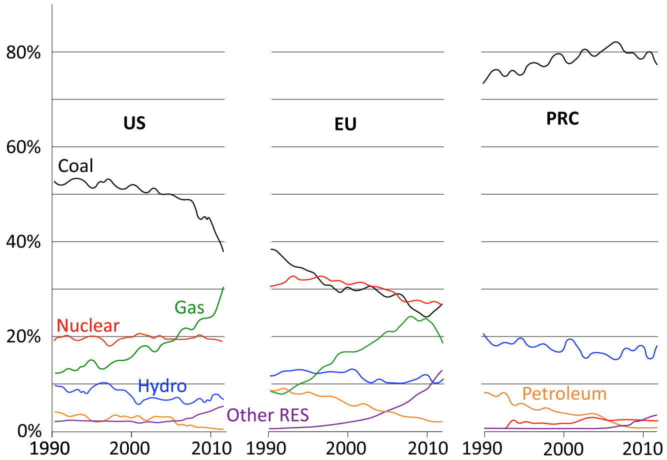

Fig. 6. Electricity production percentage per fuel source over time in three regions: US [40], EU [54], China [54] (from the left).

The management and underlying architecture of energy systems has remained centralized as shown in Fig. 7, until recently [75], with little microgeneration [74] or energy storage occurring, and consumers only acting as passive agents. Arguably, this was due to a lack of technology and incentives, which caused barriers for prosumers and small scale renewables entering the energy landscape. Regardless, the energy production share from renewable sources has increased considerably in the past 10–15 years [48].

The energy sector is now typified by large non-renewable plants, growing reliance on large renewable plants and emerging integration of distributed generation. However, the research community has moved beyond this to validate a wide variety of DER integration arrangements within centralized systems as a means to further integrate RESs and meet sustainability objectives. This has emerged through trends towards distributed generation, polygeneration, active consumers, energy storage, plug-in vehicles and virtual energy management.

The end of this generation of a gradual shift to renewables without dramatic system or paradigm reform has been brought about in the research community during the popularization of the smart grid

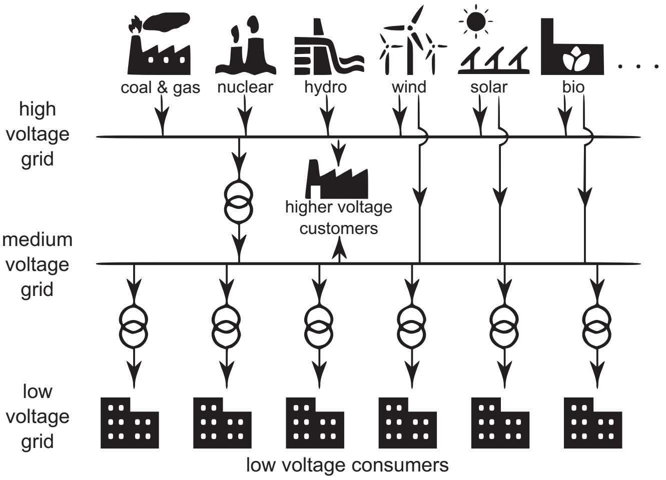

Fig. 7. The centralized grid architecture following initial investment in renewables.

concept [77]. Whilst inherently related to intelligent management, the smart grid concept is now specifically associated with the integration of modern technologies such as microgrids, distributed energy resources and virtual power plants [4]. This has somewhat coincided with the 'smart city' and 'smart planet' revolution which has manifested throughout national policies and has contributed to investment in DER technologies and management systems [78,79]. Further, recent state-backed financial incentives to invest in microgeneration technology have contributed to its accelerating uptake within the energy sector [80–82].

Energy systems have evolved from immature distributed systems, through centralized fossil fuel systems and increasingly renewable centralized systems, to the present trend of distributed renewable systems. Within research, and increasingly within industry, this new generation of energy systems is evident, and further enables the integration of renewables and other sustainability concepts. This emerging generation is introduced and discussed in the following section.

4. Distributed energy systems

This section introduces the concepts, components, policies and management structures which typify the emerging energy landscape, and the forces which have caused renewable centralized systems to evolve into distributed system. Further, this section identifies and critically appraises relevant research within each of these themes and begins an argument towards the requirement for a new generation of energy system.

4.1. Context and challenges

Energy systems are becoming increasingly distributed, due to an increasing push towards resilience and sustainability, as well as advances in DER research that enable new entrants to the electricity market [7,10,28,83]. A driving force behind DER penetration has been governmental policies and economic incentives, alongside social pressure on companies and individuals to be perceived as 'green' and progressive. DERs embody green and prosperous qualities as they include renewable energy sources, enable energy market engagement, incur less transmission losses than centralized power plants and offer the potential for intelligent management and cooperation schemes with relevant parties [84]. Also, the ability to utilize waste heat through polygeneration enables significant increases in efficiency. Further, DER integration has been assisted by its resonance with the smart city trend, due to its reliance on intelligent management and the ability to tackle large challenges at the city level [78,79]; hence we refer to recent developments primarily having occurred in urban energy systems.

The integration of DERs into the energy landscape has caused many challenges and a breadth of research has emerged, with themes being: i) the intermittent and unreliable nature of wind and solar power, ii) the changing role of passive consumers to active prosumers, iii) the integration of plug-in electric vehicles (PEVs) as a large load and storage asset, iv) ensuring quality of service (such as through ancillary services) and market stability in an increasingly complex techno-economic system, iv) the resilience of electricity supply in the face of growing populations and potential system malfunctions, and v) the integration of polygeneration units and optimization across energy carriers.

Since the push towards renewables intensified following the 2002 Earth Summit [85], the 2005 UN enforcement of the Kyoto Protocol [45] and ultimately Directive 2009/72/EC [67], the smart grid trend accelerated dramatically circa 2009 as shown in Fig. 8, and served to coagulate and invigorate DER research. This has resulted in a rich research landscape regarding a wide variety of distributed resources and structures including distributed generation units, energy storage systems, active loads, microgrids, virtual power plants, energy hubs (EHs) and plug-in vehicles, as well as a growing penetration of ICT and data-driven management, as shown in Fig. 9. As this landscape gradually becomes the status quo, it will cause a vast change in the underlying paradigm of centralized generation towards a system diverse in DERs, actors, management structures, data sources and software entities.

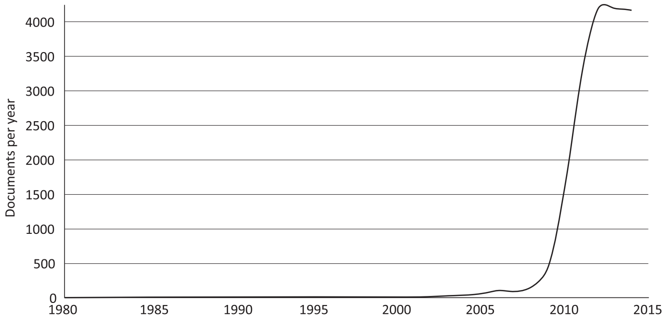

Fig. 8. Academic interest in smart grids as number of relevant Scopus results over time.

Following the growing global interest in DERs across disciplines and perspectives, a new urban energy vocabulary has emerged. However, a common understanding of this was not observed in the literature. Fig. 10 therefore presents a Universal Modeling Language (UML) class diagram which summarizes the authors' understanding of this landscape, based on the circa 500 sources considered during this review. UML is an ISO standardized language widely used within software engineering and business modeling applications, and a class diagram describes the relationships between types of object within a domain in a standardized manner [86]. The relationships used are inheritance and aggregation, implying the 'kind of' and 'part of' relationships respectively, as indicated in the figure's key. Broadly speaking, Fig. 10 can be seen to display individual components at the bottom such as generating units, then higher level concepts and aggregated terms towards the middle such as 'energy hub', and specific types of UES at the top such as microgrids. Each of the main DERs and management structures included will be discussed further throughout this section, but taxonomical aspects are discussed in the following paragraph.

Apart from 'urban energy system', the concepts presented which are less common are 'energy hub' and 'multi-energy system'. The term 'energy hub' is used to refer to multi-energy generation, conversion and storage systems and occasionally to systems which include a distribution network [87–89]. However, this paper assumes the view that an energy hub is a separate entity to the distribution network [90,91], as it can then be considered a DER node in the urban energy network. A 'multi-energy system' at the urban level is considered here as a system where energy management is integrated in some manner between carriers (such as hot water, steam, gas, cooled refrigerant, electricity and hydrogen) and includes distribution and demand elements [21]. It is also pertinent to note that storage units, including PEVs, are represented both as types of electricity demand and distributed generation, as they can act in either mode. Further, Fig. 10 only represents the main novel node and system types in urban energy networks and so doesn't include the important concept of big data, which is expected to have a large effect on the management of energy systems as ICT penetration and intelligent sensing increases within the management of these networks [92]. Further, demand side management and smart metering are very active research fields in smart grids, but are only represented here as 'active loads', as dynamic pricing schemes and knowledge flows are socio-economic concepts not easily reflected alongside technological concepts. Finally, the concept of a 'smart grid' (SG) can be considered as a descriptor of an electrical grid rather than prescriptive of what elements the grid can contain, and is used in research as an umbrella term for all the concepts depicted.

Within research, the emergence of this energy landscape accelerated alongside the smart grid trend circa 2008 and continues to the present day. This is arguably because the smart grid 'buzzword' has

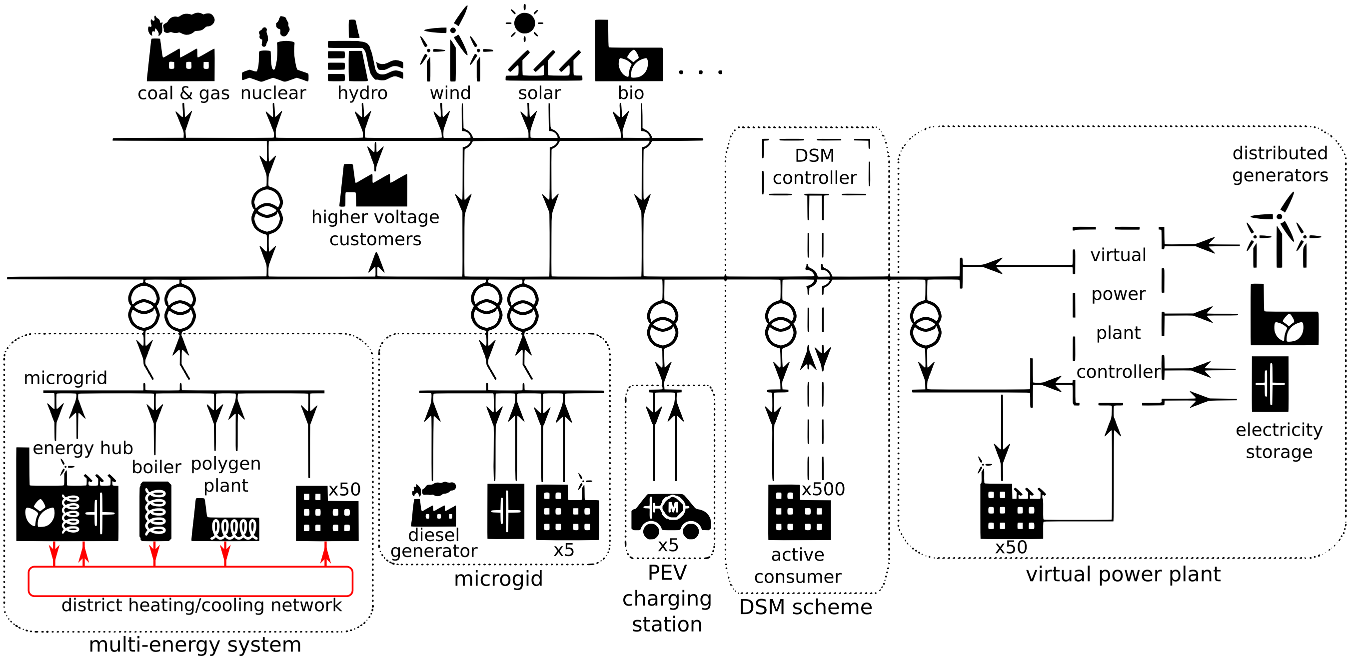

Fig. 9. The energy landscape emerging through smart grid and urban energy system concepts.

unified and invigorated several previously active but separate concepts such as microgrids and distributed generation. However, we argue that current smart grid research is still rooted in the paradigm of centralized distribution, with the aim of using these emerging technologies in an ad-hoc and isolated manner whilst primarily relying on the grid. Section 5 argues that this approach will become restrictive as DER penetration increases, but the remainder of Section 4 introduces and discusses recent research within the field, starting with each of the novel atomic elements of the emerging energy landscape in Section 4.2, followed by the key themes and management structures in Section 4.3.

4.2. Key technological components of distributed energy systems

4.2.1. Distributed generation

A core reason for the shifting energy landscape is distributed generation (DG). This refers to the production of useful energy near or at the location of its use, with power outputs significantly smaller than those typical of central plants. This includes generating plants which power districts as well as the more specific concept of microgeneration, which extrapolates the shift to even more local and small scale generation. Due to this proximity, distributed generators are connected to the distribution network without the need for transmission across large distances. Many distributed generation schemes use renewable energy, with solar and wind energy representing key growth markets, but a variety of distributed generators are available, as shown in Table 1. It is important to note that RESs can be centralized or distributed, with offshore wind farms vs micro wind turbines being clear examples of the difference. Renewable DERs mainly offer the benefits of reducing emissions and resource consumption, but various policies promote them by also offering financial incentives [42]. However, weather dependent DERs present a significant challenge of uncertainty to utility companies when they are connected to the grid, and DERs are testing the aging infrastructure's limits by using the grid in a bidirectional manner [93]. These challenges have therefore been reflected in the literature's main research goals, such as aiming to ensure reliability in interfacing with the grid whilst ensuring quality of

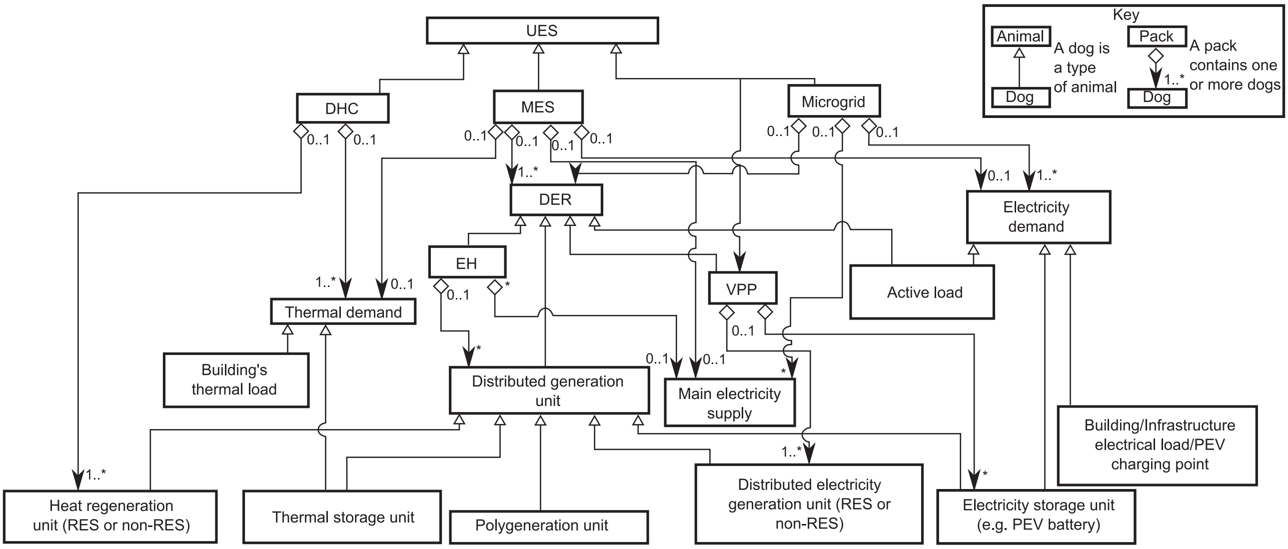

Fig. 10. Taxonomy of emerging technical urban energy and smart grid concepts.

Table 1
Examples of distributed generation.

Wind microturbine	Solar photovoltaic panel
Geothermal generator	Gas microturbine
Micro hydroelectric plant	Hydrogen fuel cell
Biomass/biogas generator	Diesel generator

service to consumers and maximizing use of renewables. DG research is at the core of the DER field and so is contained within all of the smart management structures observed, apart from some DSM strategies. We will now discuss research towards overcoming DG challenges in terms of mitigating uncertainty, ensuring resilience by optimizing DER topologies, and using advanced control structures.

Wind and solar plants are very common RES DG choices, as they are less limited in potential location than small hydro and geothermal, do not emit GHGs after installation, don’t require biomass fuel to be delivered, and are economically competitive. However, these sources of energy are subject to stochastic weather variations, so research has focused on their reliable integration. This has used energy storage solutions [94] alongside the DG units or within a microgrid [95–97] or virtual power plant [13] to present a single, aggregated connection to the grid. For example, [95] utilized multi-time-domain optimization of a microgrid containing PVs, wind turbines and batteries to reduce weather-based variation and effectively reduced CO2 emissions by 70% in real-world testing. Also promoting distributed generation but by maximizing their aggregated profit, Peik-Herfeh [98] used a point estimate method within a price based unit commitment approach in a day-ahead bidding market. Reference [99] presented a mixed-integer linear programming (MILP) model of a set of connected DG sources and maximized the network's profit, concluding that the MILP method would be scalable to larger systems, although we argue that a centralized intelligence approach to solving this would not be scalable.

Separate to the optimization of generation and system setpoints, Pilo et al. [100] and Li et al. [30] optimized the topology of connected distributed generators to achieve reduced costs and resilience respectively. Pilo et al. utilized mixed integer non-linear programming within an ‘active distribution system’ to minimize system operation costs via day-ahead scheduling and intraday optimizations, including topological network reconfigurations. Specifically regarding fault impact mitigation, Li et al. used a tree-structure algorithm to ‘island’ groups of DGs so as to minimize outage time.

The potential of islanding and aggregating DERs has been considered as the focus of microgrids and virtual power plants (VPPs) respectively. Within such structures, operational decisions at each time horizon can either be based on centralized intelligence, where all system knowledge is available and utilized at a single point, or distributed intelligence, where the knowledge is split across agents. An example of the former is [94], where a wind-PV-battery hybrid power system was managed through a supervisory controller with 5 potential modes of operation based on rules regarding the system's sensitive variables and numerical models of each component. A similar simple system approach was adopted in [96] and again in [97] but with a flywheel energy storage device and a gas microturbine within the microgrid, similar to [101,102]. Reference [103] utilized a neural network to coordinate a multi-level storage solution, but again assumed complete system knowledge and supervisory control. With only a few components, this assumption of complete system knowledge at one point is feasible, but complexity increases vastly as more DERs are included in the system's model and then again if consumers are considered as active entities; Section 5.1 discusses how distributed intelligence has been used to tackle this.

4.2.2. Polygeneration

Polygeneration refers to the production of more than one useful form of energy at a generation unit, such as the production of heat and electricity at a combined heat and power (CHP) plant. CHP plants use the waste heat produced in the electricity generation process to contribute to the heat required by a district heating network, thereby improving the efficiency of the overall energy system. Polygeneration is an umbrella term encompassing CHP units as well as combined cooling, heat and power (CCHP) plants and occasionally also the production of hydrogen as an energy carrier as shown in Fig. 11. Polygeneration itself is not a new concept, with cogeneration at steam ‘Power Houses’ occurring since the dawn of power stations [104], but recent advances in CHP technologies have led to a revival of this field of research and in the uptake of this distributed energy resource. Beyond just using waste heat, polygeneration couples the management of the local heat and electricity networks, and the national grid [19]; thereby creating a multi-energy system. Further, the use of heat and/or electricity storage allows flexibility to meet peak demand through overproduction at off-peak times [105] and the storage of energy to sell to the national grid at times of highest price, if dynamic pricing occurs [106].

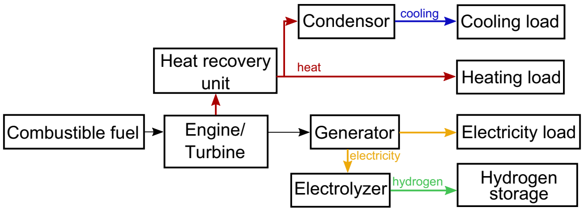

Fig. 11. Components and energy flows in an example polygeneration plant.

The main challenges of adopting CHP technologies are the associated capital and operational costs [107]. Also, integrating many micro-CHP plants greatly increases complexity due to the many energy vectors and decision variables [108]. As an example of UES research which integrates polygeneration, Lee and Kim [19] proposes a linear programming optimization of the trading of energy between the electricity and district heating systems via a CHP unit. Also focusing on CHPs but with more validation and in-depth analysis, Facci et al. [18] optimized the control of a trigeneration plant to minimize operational costs using dynamic programming based on graph theory and a black box model of the plant. These examples show that integrating CHP and RES is feasible, and is supported by the use of energy storage in a wide variety of DER arrangements. It is interesting that whilst considering users as active entities and attempting to optimize a system of systems, Kyriakarakos et al. [24] adopted a MAS approach to manage a test site's electricity, hydrogen and desalination subsystems, including demand side management. This improves on [18,19] by facilitating a more holistic solution, in that the wider system was considered, and is more applicable to the future generation of energy systems which requires such demand-responsive management.

4.2.3. Energy storage

Energy storage is the controllable and reversible conversion of useful energy to another form of energy, or the direct collection and persistence of useful energy. The main viable forms of this in distributed energy systems are indicated in [109] as pumped hydroelectric, battery storage and superconducting magnetic energy storage systems, with these and others being shown in Table 2.

As with polygeneration, energy storage is not itself a novel concept, with energy commonly being stored in hydroelectric systems by pumping water to a higher point and then allowing it to fall and drive a generator, as well as energy storage occurring in hot and cold water tanks. However, several forms of urban energy storage have been investigated recently within the DER context [109]. Of these, batteries are one of the most heavily researched technologies to store electrical energy within UESs and are increasingly used to mitigate fluctuations in output power from weather-dependent renewables, maximize re-

Table 2
Examples of energy storage technologies.

Hydrogen tank	Battery
Capacitor/supercapacitor	Superconducting magnetic energy storage
Thermal storage tank	Flywheel energy storage
Hydroelectric pumped-storage	Compressed air energy storage

newable contribution to the local generation mix and to facilitate voltage and frequency regulation [110]. This is in part due to their dramatically decreasing costs in recent years, which is also partially responsible for the recent growth of electric vehicles.

Energy storage is a common occurrence in microgrids, with almost all examples encountered in the literature of microgrids utilizing at least one form of energy storage. As well as using storage to improve the overall system's performance, it is important utilize operational strategies which balance these global objectives with local ESS objectives such as maximizing asset lifespan. For example, Abbey et al. [103] utilized a two-tier ESS to coordinate between short term and medium term energy storage, as the authors argue this offers an ideal response time and large total storage capacity to the overall system whilst improving the battery's life span. Long term energy storage can be possible through the production and storage of hydrogen via electrolysis, as was utilized in [111] in a rural stand-alone system. However, this is unlikely to be suitable in an urban environment as any excess energy produced is likely to be required nearby within a short or medium time frame. Another novel consideration is the use of thermal storage as a means to balance energy production between a district heating network (DHN) and a local electricity grid, for example [105] utilizes the DHN itself to store thermal energy and hence coordinate the optimal timing of electricity sales to the grid from a CHP unit. As batteries become more prevalent, as well as DHNs, it will be increasingly complex to balance the local goal of maximizing asset lifespan alongside the global goals of efficiency, reliability and profitability. This highlights the importance of works such as [103,105] which utilize a system of systems approach in managing complexity.

4.2.4. Plug-in electric vehicles

Plug-in electric vehicles (PEVs) are vehicles which demand, store and utilize energy from electrical systems, which includes battery electric vehicles and plug-in hybrid vehicles, and they can also return energy to the grid. They have become closely linked with the smart grid concept due to their growth within the same time period and domain. The recent boom in PEVs has led to unique challenges and opportunities within urban energy systems not seen before, as they represent a significant total quantity of load and potential storage within the system. Further, they exhibit stochastic demand profiles if not managed intelligently, which can cause large demand spikes at already peak times.

Several authors have reviewed these opportunities, challenges and the research within the field [112–115]. For example, Hota et al. [112] identifies that most relevant research falls into the categories of: scheduling the charging of PEVs, facilitating RES integration by providing storage through PEVs, optimizing PEV-electricity market interactions, and managing large PEV charging stations through smart charging. Scheduling the charging intelligently reduces the peak loads caused by many PEVs charging simultaneously and shifts this load to off-peak times such as in [116]. However, optimal charging needs to consider the potential for PEVs to act as a temporary storage device for the grid by subsequently acting in vehicle to grid (V2G) mode as in considered in [117], which minimizes both operating cost and load variation in a scenario of high DG penetration based on bidirectional energy transfer between the vehicles and grid.

The ability of vehicles to sell energy back to the grid raises the level of complexity in the system and forces one to consider the socio-economic aspects of PEV owners trading electricity. This problem has been addressed in part by [118], which recognizes that consumers may or may not be flexible in deciding their charging time, and subsequently implements a model predictive control approach to optimize charging operations under this uncertainty. This is highly beneficial, as it is important to recognize consumers not only as bidirectional nodes, but as intelligent and yet often stochastic entities. Interaction within the electricity market raises the notion of a virtual power plant [113], in that aggregating the flexibility of these vehicles enables their collective impact, and hence market position, to be greatly increased.

4.2.5. Active loads and smart metering

Smart metering refers to the digital monitoring of consumption data and its regular transmission to the energy provider, and typically enables bidirectional communication. Active loads extend this to a situation where the energy provider can control the consumption to some extent. These are grouped here as they both involve a revolutionary view of consumers as active entities through demand side management schemes, and are closely linked to the smart grid trend [119]. Arguably, this DER is unique as it is exists on the demand side and is fundamentally linked to information exchange and behavior science. Reference [119] presents a thorough survey of demand response in a smart grid environment and identifies the main benefits of integrating demand response as improved reliability of electricity systems and reduced peak load. More recently, Good et al. [120] presented a review of the barriers and enablers of demand response in smart grids, including market-based, behavioral, and technological barriers, as well as their enabler counterparts. It is interesting that they briefly praised semantics and ontologies as a technological enabler of interoperability, but stated that greater emphasis should be placed on such research, agreeing with a core argument of this paper.

By enabling communication between consumers and other energy system stakeholders, more intelligent and coordinated management schemes can be implemented. Reference [23] extends the field of demand side management to include demand response, intelligent energy systems and smart loads, and categorizes DSM schemes into the groups of energy efficiency, time of use, demand response and spinning reserve. Within demand response, interventions can involve ‘time based rate’ programs or ‘incentive based programs’ [121], where incentive based programs can be mandatory, voluntary or market clearing.

As well as these socio-technical reviews, Rahimi and Ipakchi [122] approaches demand response from an economics and ICT perspective, by indicating how demand response enables renewable integration and both market efficiency and reliability. In order to manage the complexity of demand response, participating consumers can be managed by a demand response provider; an intermediate entity between consumers and utility providers; as was modelled and scheduled by Parvania and Fotuhi-Firuzabad [123] with positive effects for grid operators. This complexity can also be managed with a multi-agent system (MAS) approach such as in [24], which managed load shedding in an autonomous microgrid.

4.3. Smart management of distributed energy resources

Towards the integration of each of the DERs discussed in the previous section, various management structures, concepts and themes have emerged within this inherently cross-domain field, although they are generally linked by the concept of developing a ‘smart grid’. Whilst this term has almost exclusively been used to describe electrical systems, the emerging energy landscape will involve multiple energy carriers linked at polygeneration and energy conversion units. Given this, the umbrella term of ‘smart grid’ is now introduced before each of the DER management concepts and their relevant research fields are discussed.

4.3.1. Smart grid

The term 'smart grid' refers to the application of greater intelligence to electricity systems, in line with the 'smart city' and 'smarter plant' concepts currently popularized in research and industry [78,79]. Specifically, 'smart grid' has been defined normatively as "the integration of power, communications, and information technologies for an improved electric power infrastructure serving loads while providing for an ongoing evolution of end-use applications" [124]. As an umbrella term, the concept of a smart grid has become linked to a variety of intelligent sensing, automation and ICT based approaches to power system management towards meeting the various challenges faced by this industry.

Primarily, smart grid research tends to consider the management of electricity systems within the current generation of increasing DER and RES penetration, active consumers and an increasing focus on resilience. Strasser et al. [125] expands on this to list the main requirements in smart grids: self-diagnostics, optimization capabilities, topological adaptability, adaptive protection, distributed management, islanding modes, ancillary service provision, demand side management, improved forecasting, self-healing capabilities and preventative maintenance. It is interesting that these authors, as well as those of other reviews [77] agree with the present authors by identifying distributed intelligence and MAS as an important paradigm, and even mention holonic systems briefly. The above list of requirements is echoed in various forms across many reviews of the field, although other mentioned requirements include consumer focus [4,126], bidirectional data and energy flow [4], market efficiency and integration [127] and higher quality of service [127].

Communication networks and standards play a fundamental enabling role in smart grids, as discussed in the review by Nafi et al. [128], who concluded that further machine to machine communication and 'software defined networking' research is advised. Communication technologies also play a key role in the cyber-physical vision of smart grids proposed by Yu et al. [129], who also emphasised the necessity of distributed intelligence and unified semantics in smart grids. As smart grids consist of a collection of related electricity management research areas, the main DER management structures and themes are now discussed in turn, as well as those related to multi-energy systems.

4.3.2. Microgrids

Microgrids are independently controlled distribution networks capable of operating in island mode [130], as shown in a simplified manner in Fig. 12. This enables them to present a single, more stable interaction with the grid, and offers resilience if the grid fails. By collecting DG, ESSs and loads within a single network and implementing an intelligent management scheme, the intermittent nature of any wind and solar DG can be mitigated and a single, more consistent load can be presented to the grid, as well as minimizing transmission losses associated with the centralized paradigm [131]. Whilst microgrid research, as with smart grids, generally considers only electrical systems, several authors have extended this to consider multi-energy microgrids [7,130,132]. The convergence of the smart grid and microgrid concepts was reviewed very recently by Yoldaş et al. [133], who distinguish between AC microgrids, DC microgrids and Hybrid AC-DC microgrids, and also discuss the role of energy storage, advanced forecasting, and communication systems in some depth.

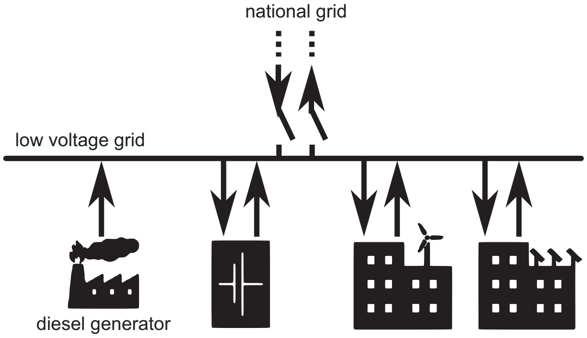

Fig. 12. Example microgrid configuration (simplified).

In general, microgrids aim to fully utilize whatever RESs they contain by storing any excess power they generate within a local storage device, and typically supplement their generation with a local dispatchable power source and/or the national grid. Research on this topic is broadly varied in goal and approach, but examples commonly focus on economic optimization in the day ahead and intra-day markets, or on ensuring system stability through real-time operational decisions [134]. Also, most examples use some form of hierarchical control, whereby a system level supervisory controller instructs component level controllers [9,94,135]. It is interesting that the control of microgrids has been attempted through the MAS approach in a plethora of research examples such as [131,136–138], to facilitate the intended microgrid characteristics of a distributed architecture, adaptability and resilience.

Microgrid operation changes distinctly between microgrids trading energy with the grid, and those either in island mode or not connected to the grid [31]. When in 'island mode', a microgrid can be modelled as a closed system such as in [139], where a microgrid's PV, WT, fuel cell, load, and storage are controlled centrally and optimized as a MILP problem in real time. The efficacy of islanding has also been shown on a real system in Hachinohe [95] and on a microgrid around a hospital [140]. However, when operating in grid connected mode, a microgrid management strategy must handle added complexity, such as in [32], which proposes an agent based framework that optimizes a typical microgrid at hourly timesteps with a 24 h horizon. This work offers the advantage of addressing the uncertainty of environmental parameters, and the added complexity of being connected to the external grid, as well as the advantages offered through MASs such as improved resilience in the face of limited information access. Another relevant work was conducted by Chen et al. [141], who consider a CHP's heating income but primarily optimize an electrical microgrid. It is an advantage that Chen et al. implement a multi-objective optimization which considers environmental impact directly via fuzzy logic and a genetic algorithm.

4.3.3. Virtual power plants

Virtual power plants are virtual entities which act between the grid and a collection of DERs to improve their operational characteristics through aggregation, and consist of dispatchable generators, stochastic generators, active loads and energy storage systems [13] as shown in Fig. 13. This definition has also been extended to explicitly include PEVs [14].

Whereas microgrids consist of a number of proximal and physically connected DERs and loads, virtual power plants facilitate DER

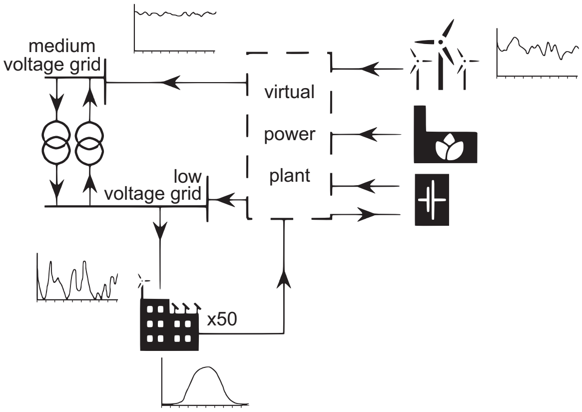

Fig. 13. Example VPP configuration to stabilize RES profiles.

integration and reliability by virtually aggregating them as an entity within the energy market through an agent interfacing with the centralized grid [142]. Further, Morales et al. [13] states that their collective management can be reduced to an economic optimization which considers the grid as an actor able to buy and sell an infinite amount of electricity in the day ahead market, and which manages stochastic generating units in real time to ensure service delivery to consumers. The former of these management tasks is elaborated in [98], which accounts for the uncertainty in the day ahead bidding market through a probabilistic price-based unit commitment method within an 18 bus system.

The assumption that virtual power plants exist only to meet economic objectives is challenged by Binding et al. [14], which indicates that two types of VPP exist: technical power plants and commercial power plants, with the former existing to meet load balancing or other technical objectives. The VPP concept has also been applied to micro-CHP clusters [143–145], thereby overlapping with the MES field and offering benefits across systems and stakeholders. As urban energy systems are likely to become more linked across energy carriers, including polygeneration and multi-energy concepts alongside virtualization would be highly beneficial.

4.3.4. Multi-energy systems

Multi-energy systems (MESs), in this context, are systems where multiple energy carriers are coordinated in an integrated manner at the urban scale through linking components, and have gained recent academic interest [15–20]. The links between these energy systems are often polygeneration plants, so the recent interest is likely due to the growing interest in CHP and polygeneration technology, alongside more systemic thinking. Fairly recently, Mancarella [21] performed a review of this trend and identified the potential energy carriers of electricity, heat, cooling, fuels and transport, and identified the concepts of energy hubs, microgrids and VPPs as potential multi-energy systems. The current authors would contest that whilst these can constitute MESs, the heating and cooling components of microgrids and VPPs are unlikely to be related to those structures' key attributes due to heat networks not typically being connected to a national network, so would argue that reserving 'microgrid' and 'VPP' for the electrical parts of UESs would simplify the terminology. In this way, Fig. 14 shows a MES consisting of a DHN and a microgrid. Further, it is important to note that whilst energy hubs are inherently multi-energy systems, they typically represent a node within an urban energy system, with multiple input and output energy vectors, such that the urban energy system itself is a multi-energy system by its primary meaning.

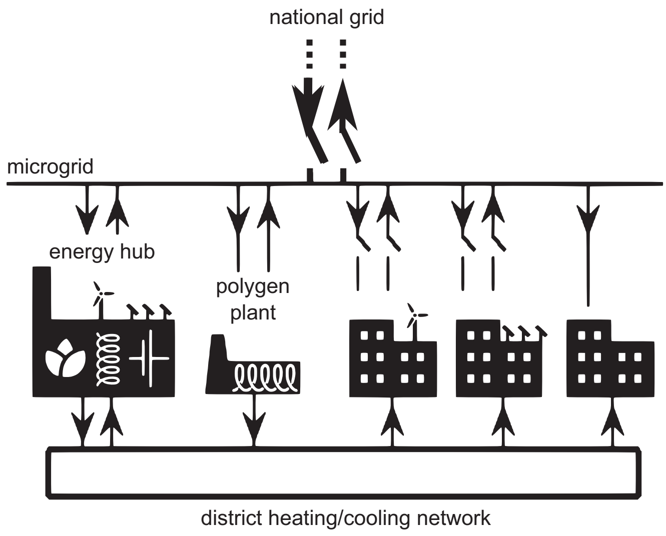

Fig. 14. Example MES configuration.

A typical example of MES research is [19], which models a MES containing a microgrid and a DHN joined by a CHP unit, and economically optimizes the energy exchange between these systems and the national grid. A more complex situation is that at the University of Genoa Polygeneration Grid [16], which consists of electricity, heating and cooling systems, and contains 11 DERs including RESs, PEVs and energy storage, which are all managed in a coordinated manner to optimize the whole system's performance and grid interaction. Unfortunately, the work only optimizes the operational cost of the system without including sustainability objectives, but it is encouraging that a system with a high penetration of 'sustainable' technologies was able to reduce operational costs by 20%. This example used centralized optimization of the system which is a drawback towards real world applicability but demonstrates the potential benefits of MESs when managed intelligently.

4.3.5. Energy hubs

Energy hubs are considered here as an urban energy network node with multiple input and output energy carriers; they are hence a multi-energy system but are considered here as a node at the urban energy system level. In this manner energy hubs are similar to polygeneration units, but differ in that they utilize multiple input energy vectors and typically consist of a more elaborate and complex internal arrangement of components, as shown in Fig. 15. Energy hubs represent a means to closely integrate systems of different energy carriers through multiple energy generating, converting and storing components. As energy hubs are often owned and operated by a single organization and are geographically dense (typically within a single building), they represent ideal locations to manage the integration of the various energy carrier networks. The benefits of this close integration are identified in [147] as increased reliability, load flexibility and efficiency gains through synergistic effects.

Several efforts towards the optimal management of energy hubs were observed in the literature [90,91,147] including works by Geidl and Andersson. The most recent of these progresses their generic model to consider interactions between energy hubs and subsequently optimizes the key management decisions of energy hubs: how much of each input should be consumed, which components should utilize these inputs to generate usable energy and how this generation process should be controlled. However, Giedl and Andersson only optimize based on financial concerns, whereas [148] develops the approach to include the 'social cost' of CO2 emissions in monetary terms and also considers maintenance costs. Whilst the energy hub concept is fairly new, it represents an interesting avenue for managing the complexity of multi-energy systems at the district level, although in order to progress it further it must be compared and considered alongside other emerging UES concepts.

4.3.6. Demand side management

Demand side management (DSM) refers to a systemic interaction with consumers and active loads to directly or indirectly affect demand profiles. Whilst active loads and demand management have been discussed previously as atomic DER concepts, these can be utilized

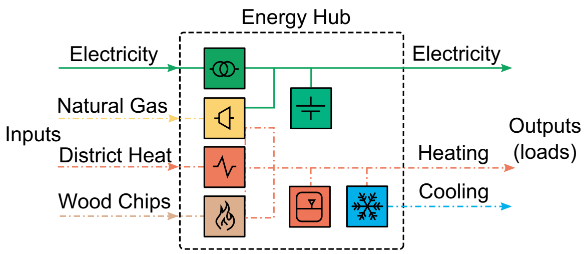

Fig. 15. Example energy hub configuration.

within socio-technical energy systems to produce a fundamentally novel form of UES, in which social implications of optimizations are accounted for and demand is considered as an active entity. However, the success of integrating consumers into the management of smart grids varies significantly depending on the perception of smart grids and the demand management scheme, as shown by Ponce et al. [149], who used signal detection theory to gauge the perceptions of users in real smart grid scenarios. Ellabban and Abu-Rub also explored the role of consumers in smart grids in a recent review [150], identifying smart consumers as one of the 3 core pillars of smart grids. They also considered consumer engagement with the grid through the lenses of various behavior models, such as the theory of planned behavior and the theory of technology acceptance.

As an example, Mohsenian-Rad et al. [151] considered automated load scheduling at the smart meter level, by using dynamic pricing to incentivize consumers whilst optimizing locally and globally, and successfully stabilized the demand profile and reduced overall system costs. These authors used a distributed algorithm, the importance of which is echoed in the DSM field in [22], where day-ahead load shifting is optimized through an evolutionary algorithm, but the authors conclude that a distributed platform is fundamental to implement such a scheme. One key intended outcome of DSM is load shifting to reduce the total generation capacity required in a system, as shown in Fig. 16. Whilst pursuing such objectives, it is critical that a consumer-focused approach is adopted to improve acceptance by consumers and competitive market-driven environments.

5. Towards ICT-driven intelligent energy management

Alongside the emerging energy system components and management structures described in the previous section, the increasing prevalence of ICT within energy management is a clear trend. This section therefore introduces and discusses recent developments within two key technologies identified within this trend; the use of distributed intelligence and agency in energy systems and an increasing emphasis on interoperability amongst ICT components. Further, this section highlights the applicability and extensibility of these technologies towards the future generation of energy systems.

5.1. Agency in energy systems

5.1.1. Introduction to distributed intelligence and multi-agent systems

A significant trend within the digitalization of energy management is the use of agency and distributed intelligence [152]. By utilizing a virtual network of intelligent and autonomous controllers (modelled as software agents) which reflects the actual network of components and abstract entities, as shown in Fig. 17, the management intelligence is modularized and hence more adaptable, resilient and scalable than in centralized approaches [153]. In a multi-agent system approach, complete knowledge of the system is not required at any individual node, but each system component acts autonomously towards a set of predefined goals to optimize the overall system's performance [135]. Software agents can interact and communicate with their environment and with other agents via predefined interfaces. The behaviors of agents are conditioned by their individual goals, which can be in cooperation or in competition with the goals of other agents. The behavior of the overall system then emerges as a result of the behaviors of its agents. By designing the agents, their interactions and their goals carefully, this emergent nature can be leveraged to optimize the performance of the overall system.

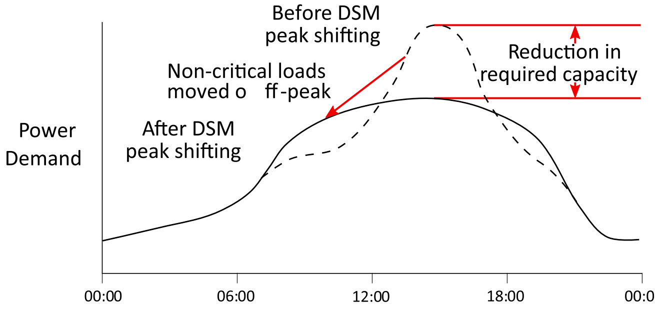

Fig. 16. Reduction in required generation capacity through DSM.

As each agent autonomously acts with the knowledge available to it, the failure or introduction of components or communication pathways does not cause total system failure, leading to the approach's powerful resilience through adaptability [29,32,33,154–158]. Further, as intelligence and computing power is provided at each agent, the approach is more scalable than centralized control as the computing power available will increase alongside the complexity of the system. However, we argue that scalability requires intelligent and dynamic topologies of agents, as complexity is likely to increase exponentially as DER penetration accelerates alongside the integration of energy carrier systems and the growth of big data.

5.1.2. Research towards agent-oriented energy management

The application of multi-agent systems and agent oriented programming to the intelligent management of urban energy networks has been the subject of significant research in the past decade and has been identified as very promising [152,159]. The benefits of a MAS approach to smart grid management were reviewed very recently by Coelho et al. [152], who concluded that this decentralization of infrastructure empowers society and reduces costs, whilst also opening new avenues for optimization of energy systems. The majority of MAS-UES literature adopts a methodology of developing device (and possibly supervisory) agents and simulating their efficacy for the authors' intended purpose in coordinating electricity supply in an example network [8,131,137,138,160,161]. This arguably began with the seminal efforts of Kok and colleagues in developing the PowerMatcher concept [134,161]; a market based electricity supply and demand matching system which aims to promote sustainability in urban energy systems. Many other authors have also utilized MASs for real time pricing and market based UES electricity coordination [33,131,138,155,162], although these typically exhibit a more simple hierarchical structure than the PowerMatcher solution and are only validated through simulation or in a lab environment.

The PowerMatcher concept has been developed and validated through the past decade [77,134,163], showing successfully that a market-based MAS can coordinate supply and demand matching, as well as considering electricity storage. However, the original PowerMatcher concept has been supplemented by several notable works. For example, several papers have specifically applied MASs to microgrids [33,131,162] and Van Dam et al. managed a collection of micro-CHP units in a VPP through agent based control [144]; a capability which was then incorporated into the PowerMatcher repertoire [164].

Whilst PowerMatcher and much other literature in this field adopt a market-based approach, several notable works utilize MASs in a different strategy. For example [8,165] place greater stress on the importance of forecasting load and demand as they believe this enables more accurate set point scheduling in advance. Several examples are also evident of MAS approaches to demand-side management (DSM) without consideration of a bidding market [8,24,166]. Further, whilst the focus of PowerMatcher is arguably the prosperity of electricity networks, several authors consider primarily the system's resilience [32,156,167]. Of these, an interesting work presented by Lagorse et al. [167] utilizes a virtual 'token' to decide which device agent is responsible for ensuring the bus voltage. 'Token' usage is also observed in a very recent and mature example on the use of hierarchical MAS management [165], and so may warrant further research. In line with

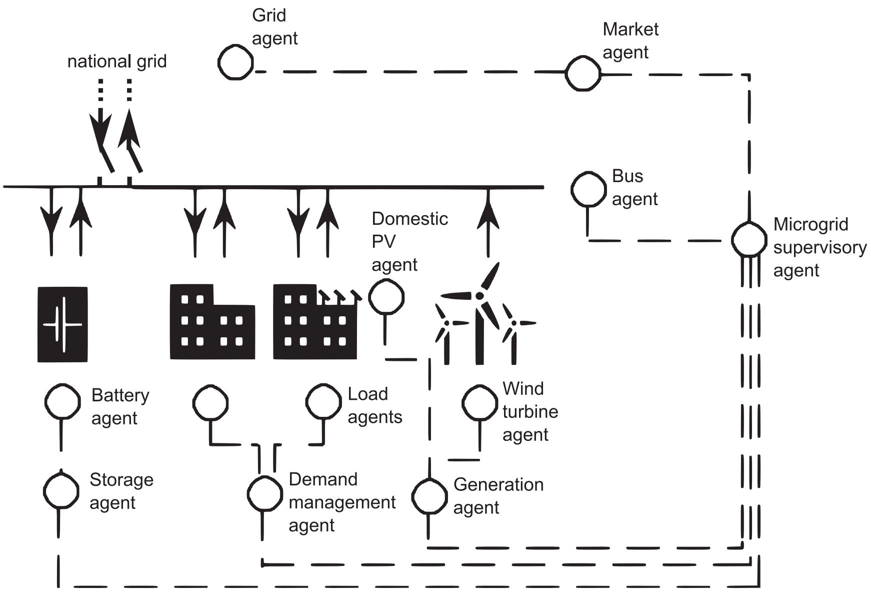

Fig. 17. Example MAS control architecture for a microgrid.

the trend of multi-energy systems, there have been extensions of the PowerMatcher approach for integrated heat and electricity systems [154], and an application of the PowerMatcher concept to a DHN [168]. A very recent and relevant work focusses on generalizing an established model of electricity networks [169] to be applicable to other energy carriers through an agent-based approach.

These examples demonstrate that urban energy management is becoming distributed across components and domains, which increases systemic complexity and heterogeneity and hence causes significant interoperability problems [124]. It is critical that the involved entities share an understanding of the domain in terms of common vocabularies and data models [170,171] in order to be able to communicate and interoperate effectively. This has been recognized within MAS approaches [156] and has manifested in examples which comply with the standards of the Foundation for Intelligent Physical Agents (FIPA) [131,137]. This is an especially interesting observation given the reliance of the FIPA standards on ontologies; a modeling approach we advocate for in the following section.

5.2. Semantic interoperability across heterogeneous energy systems and datasets

Given the emerging energy landscape's multi-disciplinary nature, along with the domain's trend towards big data and increasing complexity, interoperability between virtual artefacts is becoming a critical challenge in realizing increasingly distributed and intelligent energy systems. This section will introduce this challenge and discuss recent approaches and developments in the field.

5.2.1. Introduction to semantics in energy management

The challenge of interoperability in energy management is becoming increasingly important [124,170,172,173], and is discussed here as a problem of semantic heterogeneity between the vocabularies and data representations used by the numerous software and hardware artefacts penetrating the domain. This is to say that the conceptualizations held of the domain by people and software across disciplines and companies are often incompatible and require ad-hoc mappings and/or alignments in order for them to communicate and interoperate effectively. In line with this concern, the IEEE standards committee recently published a smart grid interoperability guide, and referred to this as interoperability of protocols, data formats and meaning [124]. This challenge will become increasingly pertinent as the volume of data and number of software artefacts involved in energy management increases alongside DER penetration, big data growth and the requirement for intelligent management [171,174–178]. Alongside the requirement for a secure framework, and the benefits of a service oriented architecture [124], the use of a common vocabulary and data model mitigates the effort required for software artefacts to communicate effectively with others in the energy management system [124,179], as shown in Fig. 18. These common models must standardize the concept descriptions and data representations within the shared domain of the software artefacts. Models which perform these knowledge modeling functions are hereby referred to as semantic models, from the models which underpin the semantic web [174].

One common type of semantic model, taken from semantic web technologies, is that of a domain ontology; a machine-interpretable description of the concepts in a domain, the relationships between these concepts and domain data and the restrictions on how these concepts can manifest [180]. This domain ontology can then be instantiated with the specific objects, relationships and data present in an instance of the domain, such as an individual energy system, to create a comprehensive knowledge base. Further, each domain ontology can re-use parts of other ontologies which map upper domains or related domains, to further facilitate interoperability and reduce development time.

Within related fields, the benefits of common data models are being widely recognized. For example, within the building construction and lifecycle management domain, open ‘building information modeling’ (openBIM) has recently boomed through the use of buildingSMART's common data model for representing building level information [181].

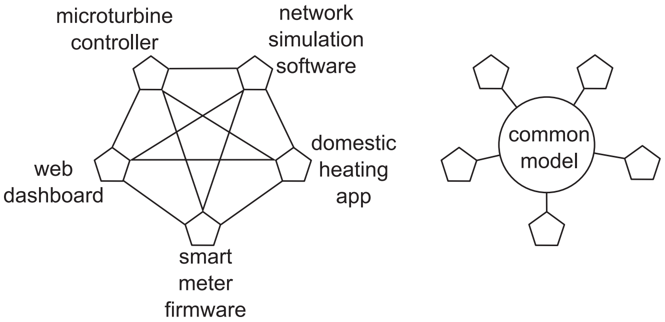

Fig. 18. Demonstration of reduced number of software mappings through a common model.

This significantly improves data utilization across handovers between the design, construction and management stages of a building's lifecycle. In the smart city field, the British Standards Institute has recently published a standard towards developing smart city data models for interoperability [182] and the Open Geospatial Consortium has released CityGML; an internationally standardized model for describing spatial and semantic information in the urban environment [183]. Finally, an understanding of the benefits of a shared ontology within multi-agent systems is commonplace and forms a central aspect of the international MAS modeling standards of FIPA [184]. Given the recent trend towards agent-oriented energy management systems, the development and use of shared domain ontologies is a natural progression.

Within interoperability in urban energy management, the most important recent development is arguably the IEEE 2030 standard [124], which provides guidelines for smart grid interoperability and delivers a 'knowledge base' of term definitions and domain descriptions through a 'Smart Grid Interoperability Reference Model'. This provides essential groundwork towards interoperability in energy systems, by facilitating a common human understanding and aiding the development of interoperable systems. Critically, the guide highlights the importance of common models in facilitating data exchange and the integration of legacy systems, and in enabling system security and performance. Further, the important role of ontological models is highlighted in ensuring a shared meaning of data, hence making the data more useful, as well as providing inference and rule-based functionality. Given this precedent and the ongoing transition of urban power systems to multi-energy systems, it is critical that energy system interoperability is addressed through research, including a focus on semantic modeling.

Despite several promising steps, these only serve to lay a foundation for semantic interoperability in energy management systems, which has been referred to as "embryonic" as of 2013 [173]. Beyond these steps, research towards a highly expressive and flexible urban energy model is necessary, as well as much research into the effective use of such a model to fully leverage its potential benefits and mitigate challenges. To this end, some examples are evident in the literature, which are discussed in the following section.

5.2.2. Towards semantic interoperability in energy systems

Whilst semantic models and their applications in the distributed energy management domain are scarce and the field is generally immature, several relevant examples were observed in the literature and are presented in Table 3.

From an analysis of these sources, a variety of intended applications within the urban energy domain were observed, which manifested as a variety of modeling approaches and resulting models. This section discusses the relevance of an existing and standardized semantic model before comparing research examples of the application of semantic models within the domain.

Before considering research examples, a critical development to discuss is that of the 'Common Information Model', which was internationally standardized (and mapped to a semantic web format) by the IEC [185]. This represents a seminal step towards establishing interoperability in the domain and is recognized as such in IEEE 2030 [124]. However, this model has some limitations and contradictions, again recognized in IEEE 2030, and fundamental parts of the specifications have now been withdrawn. Further, the model is over a decade old and is hence rooted in modeling centralized energy systems. This has led to efforts to adapt it to distributed concepts such as microgrids [186], but we argue that the interoperability described in IEEE 2030 requires a radically revised model. Finally, the CIM was designed in UML, so only represents relatively simple relationships and expressions. We argue that the greater expressivity, inference capabilities and rule applicability of ontology languages such as the web ontology language (OWL) are required for energy management in the emerging semantic web to fully leverage the potential benefit of data. The benefits of such an OWL model and the challenges of utilizing the CIM directly in this environment are acknowledged in [187].

Most of the recent examples of semantic applications in the domain were designed to facilitate the planning or analysis of urban energy systems through simulation [188,189] or information representation and exchange [190–192]. This is as opposed to the few examples where the semantic model was intended to facilitate intelligent management within a MAS [193–195] or as part of a complex event processing system [171]. Unfortunately the two MAS applications of semantic models [194,195] ([193] does not present a UES case study) are both over a decade old and appear to be little more than class structures. This leads to the conclusion that very little implementation of semantic technologies has been conducted within energy management systems rather than urban energy planning and so signifies a key requirement for future research as discussed in Section 7.

As there is likely to be significant overlap between the models used in energy system design and planning and energy system management, the models developed for the former were compared in terms of their domain coverage and the apparent modeling decisions taken. The seminal work of van Dam [193] modelled urban energy systems as socio-technical systems and hence represented dual social and technical urban energy networks with links between them in order to represent concepts such as ownership and contractual obligation. This work was later compared to the SynCity ontology developed by Keirstead et al. [192], by Keirstead and van Dam [196], who conclude that similar design choices were evident, that both ontologies modelled the technical aspects successfully, and that a common upper ontology would facilitate integration considerably. Whilst it is clear that some similarities exist between the smart grid information model (SGIM) presented by Zhou et al. [171] and the above two semantic resources, the SGIM ontology is designed to manage real-time sensor data in an event-based system and so contains a smart grid events model. This semantic management of sensor data to contextualize and enrich sensed knowledge is highly valuable and has been developed and standardized separately to the energy management domain by W3C [197].

Table 3
Semantic resources in the urban energy domain and their intended applications.

Resource name	Date	Author	Reference	Application
CityGML Energy ADE	2015	OGC	[157]	Exchange of city energy data
Energy efficient district information model (eeDIM)	2013	RESILIENT	[155]	Instantiating an energy system simulation tool
SEMANCO Energy Model	2013	SEMANCO	[158]	Urban energy planning decision support
Agent. GUI	2012	Derksen et al.	[156]	Simulation of hybrid multi-energy networks
Smart Grid Information model (SGIM)	2012	Zhou et al.	[138]	Dynamic DSM application and further SG potential
STS	2009	Van Dam et al.	[160]	Agent-based modeling of socio-technical systems
SynCity	2009	Keirstead et al.	[159]	Integrated modeling, planning and designing of urban energy systems
Common Information RDF-S Model	2006	IEC	[152]	Integration of energy management system applications
COMMAS	2004	McArthur et al.	[161]	MAS for transformer condition monitoring
PEDA	2003	Hossack et al.	[162]	MAS which provides protection engineering diagnostic assistance

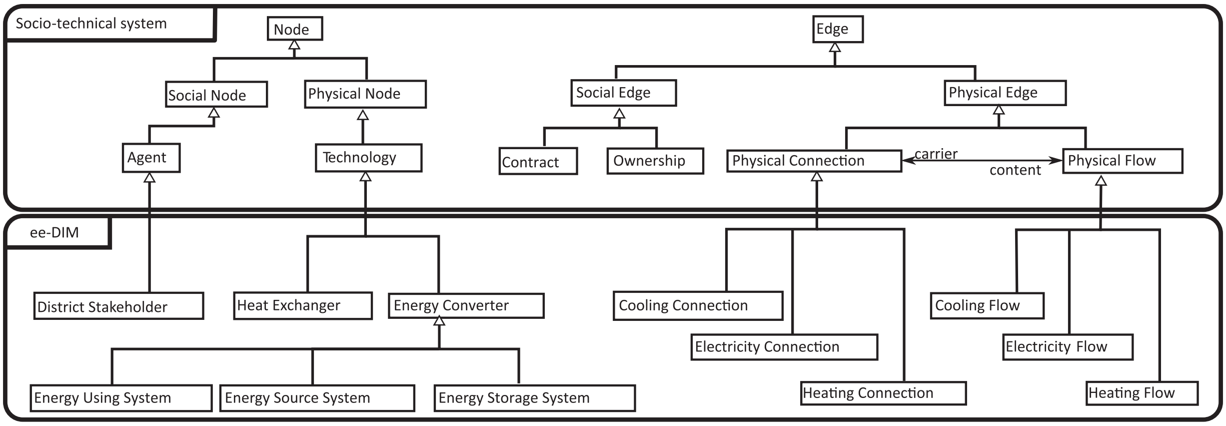

Fig. 19. Part of the eeDIM ontology, showing its reuse of the STS ontology.

Following a thorough analysis, it was clear that the CityGML Energy ADE and the SEMANCO Energy Model were intended to facilitate the representation, exchange and analysis of a broad range of city level data, primarily as a collection of components and performance metrics. In contrast, the eeDIM ontology contained more concepts specifically related to management within an electrical system or MES in an urban energy network, and reused van Dam's STS ontology to capture the duality between the social and technical network present. This indicates the eeDIM approach is more suitable for in-vivo management, whereas the Energy ADE and SEMANCO Energy Model are more suited for system planning and analysis. The eeDIM socio-technical consideration is largely missing from the other works, although a full comparison between these models is beyond the scope of this article. A sample of the eeDIM ontology and its reuse of van Dam's STS ontology is presented in Fig. 19.

5.3. Towards a new norm in energy management

This section has presented the state of the art of energy systems within research in terms of the distributed energy resources, management structures, and ICT concepts which are increasingly populating the energy landscape to create a diverse smart grid of interconnected systems, agents and domains. Given this ongoing acceleration in DER penetration, many structures such as microgrids, VPPs, energy hubs and demand side management schemes will soon coexist within cities. As the density of DERs and DER management structures increases, the potential benefit from coordination across these structures as well as the challenges associated with their integration with the grid increase dramatically. Within research to date, most authors make an implicit assumption that the intervention they are considering is acting in isolation from similar surrounding structures, as is the case in a landscape sparsely populated by DERs. However, this increasing potential for coordination within a densely populated DER landscape will require a new breed of energy system, and some authors have begun to consider interactions between management structures [12,33]. This will require a new generation of energy system, which is markedly different due to i) seamless multi-carrier energy and information exchange with neighboring DER management structures, ii) dynamic and holonic reconfiguration of DER management topologies, iii) greater reliance on distributed intelligence and automation as the status quo rather than a novelty and iv) dense penetration of DERs and active consumers being the status quo. This argument is elaborated fully in the next section as well as a recommendation of how this next generation could manifest.

6. Next generation holonic energy systems

Much research has been conducted from a smart grid perspective about how to facilitate the integration of DERs, MESs and DSM within a centralized paradigm towards sustainability, resilience and prosperity. This has laid significant foundations for their integration, and their penetration in the energy landscape is now accelerating. Given this, we argue that a tipping point is imminent whereby the prevailing landscape becomes typified by a high penetration of these concepts, in contrast to the currently prevailing assumption in research of sparse or isolated penetration. This changing landscape presents both challenges and opportunities and requires a new breed of energy system whereby the value of a system of systems approach is truly utilized, diversity is leveraged towards resilience and valuable ICT concepts are embraced in a secure framework. This section therefore extrapolates current trends beyond the emerging energy concepts presented, to the need for a new generation of energy system. This generation will be capable of intelligent interoperation across energy carriers and scales amongst dense DERs, and will rely heavily on ICT and data-driven operations. Following this, the section introduces the concept of a holonic energy system as an avenue of meeting this need and discusses the challenge of security within this ICT-driven paradigm.

6.1. The tipping point in DER penetration

As distributed energy systems continue to advance and become more affordable, their penetration within the energy landscape is likely to continue accelerating in line with current trends, examples of which are evident in Fig. 20 and [200], which shows the ongoing exponential growth of photovoltaics and electric vehicles respectively. This accelerating complexity is compounded due to the transition of consumers to active agents. The number of people able to play an active role in the energy landscape is increasing rapidly through smart metering, consumer empowerment and DSM. These trends will lead to a high density of dynamic entities, especially in urban environments, and will result in a situation where the occurrence of proximal UES entities is more likely than not, such that an environment with many nearby active UES

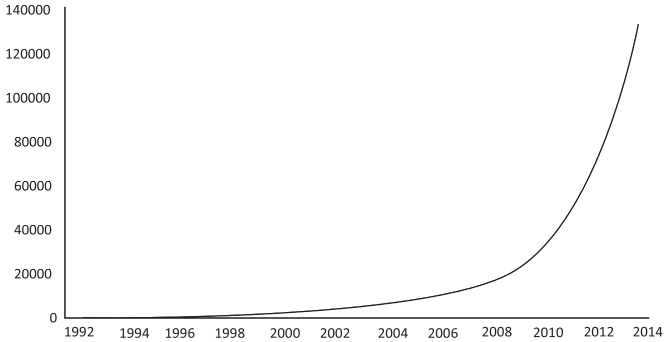

Fig. 20. Historic global PV capacity growth (MWp) [199].

entities will be commonplace. The emergence of this high penetration of UES concepts will present significant challenges in terms of management complexity, computational scalability, ICT security, data interoperability and system reliability. However, it will present equally significant opportunities through flexibility, modularity, redundancy, coordination, aggregation, new market opportunities, systemic management schemes and big data, as well as sustainability benefits from increasing RES reliance. Therefore, continuing to integrate these technologies in the isolated manner currently observed in research will limit their potential benefits and fail to meet numerous challenges, whereas utilizing a system of systems approach which meets these challenges will deliver significantly improved characteristics. For example, aggregating and coordinating adjacent microgrids, multi-energy systems, controllable loads, plug-in vehicles and virtual power plants, and dynamically reconfiguring the management topology of these structures could offer powerful new avenues to maximize the use and reliability of distributed renewables and minimize total and peak reliance on the grid.

We argue that the current paradigm of 'centralized generation with sparsely connected local generation' will fail to fully use local generation potential as the penetration of local energy solutions increases. Further, the scalability of conventional supervisory optimization is inadequate, and we argue that even the observed MAS approaches are not suitable at the scale of penetration and dynamism deemed likely. For this reason we argue that a new paradigm must emerge where interaction between DERs and UESs is commonplace in parallel to their interactions with the grid, management intelligence is highly scalable and system frameworks are able to react to weather, technical and behavioral changes. The next generation of energy system must manage these aspects dynamically and intelligently to optimize the performance of the overall energy system by balancing local and global objectives. Further, given the stochastic nature of many of these local energy solutions due to their reliance on RESs and human behavior, dynamic management of the network must be based to a greater extent on probabilistic simulations and shorter time-scale reactive management [25]. Therefore, as the energy landscape increases in complexity, we argue that a system of systems approach is required to successfully orchestrate the interplay between diverse energy components. Boardman and Sauser identified the characteristics that enable a differentiation between a system of systems and a plain system: autonomy, belonging, connectivity, diversity and emergence [198]. A UES is a system of systems according to that definition. Based on these requirements, the following section will now argue that a holonic system approach, as a manifestation of system of systems theory, is able to meet the needs of the next generation of energy systems.

6.2. Introduction to holonic energy systems

The holonic system approach is based on the concept of a dynamic hierarchy of holons, where each holon represents an autonomous and self-contained system, but can contain or be contained within other holons, as shown in Fig. 21, and the topology of this hierarchy adapts for the benefit of the super-system, or holarchy. Further, each sub-holon can change which super-holon it is a part of or become a part of multiple super holons. In this way the holonic approach is a hybrid between the distributed approach where autonomous subsystems adapt within a static framework and the centralized approach where subsystem behavior is prescribed by a supervisory controller. The concept aims to balance the objectives of individual systems and the overall system of systems, and originates from the Greek words of “holos” and “on”, meaning “whole” and “part” respectively [201]. Further, as each holon can be composed of sub-holons, these sub-holons interact through cooperation and competition to produce the emergent behavior which characterizes their super-holon; in this way the approach is again similar to multi-agent systems. This can be reflected by adopting a holonic system approach within a multi-agent system, to produce a holonic multi-agent system (HMAS) [202]. This approach differs from the conventional MAS approach, as the framework of cooperation, competition, supervision and part-whole relationships are dynamic and flexible, to balance the needs of the holons and sub-holons.

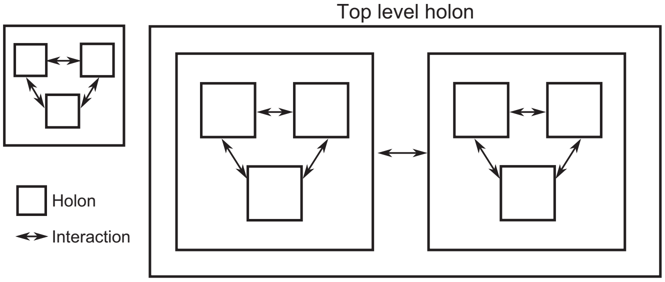

Fig. 21. Recursive architecture of holonic systems.

The holonic system approach lends itself well to the management of energy systems [202,203] as they are typically conceptualized in a hierarchical manner whereby components form a network, such as a microgrid, which in turn forms part of a larger network, and so on. However, the holonic approach also exploits the potential autonomy in each system and the flexibility of aggregation arrangement afforded by virtualization. Through the HMAS approach, the energy system can be managed by representing individual components as atomic holon-agents and grouping them dynamically into a hierarchy of supervision. This allows flexibility and scalability in an environment where the mix of online and active components varies rapidly and significantly, yet cooperation is mandatory, such as a landscape of high DER penetration. This is shown in Fig. 22, where generation and load agents are added between timesteps 1 and 2, and a load agent goes offline, resulting in a generation agent changing its super-holon to balance the computation load at each supervisor agent and a new load supervisor emerging to accommodate the additional load agents. Such a management paradigm relies on distributed intelligence, whereby microprocessors at each component receive supervisory commands from their super-holon(s), sensory data from their own electronics and interactions from neighbor holons, then perform automated analytics, and subsequently act towards predefined goals through direct electronic actuators and virtual interactions with neighbor holons.

Whilst holonic energy system research is embryonic, there are some examples of implementations which provide early evidence towards their potential. For example [202] utilized a holonic multi-agent system (HMAS) to control reactive power and provide state estimation in a grid with high rooftop PV penetration. This showed that a 3 level holarchy of 'substation', 'feeder' and 'neighborhood' holons is suitable in the described situation, where each holon is represented by an agent within the cyber-physical system. Also recently, Dou and Liu [165] utilized a hybrid hierarchical MAS approach to successfully control an energy system with high DER penetration. As early as 2009, [204] recognized that holonic models were suitable for handling the increasing volumes of data within power systems and used a HMAS to facilitate the effective collection and communication of this data. Further, the holonic system approach has been applied through distributed control to substation automation and fault protection [201]: although this manages energy at a single node in the higher level network, it demonstrates the potential of the holonic systems approach when implemented through distributed control. A different approach to the described, geographic, grouping of holons into super-holons is adopted in [205]. In this example, holons are classified as either resource holons, energy holons or service holons; thereby abstracting the aspects of the system in a different way, although we argue that this is a less intuitive representation of the system and doesn't lend itself as well to agent-based control.

Whilst this section has primarily considered electrical systems, the holonic approach could equally be applied to multi-energy systems or

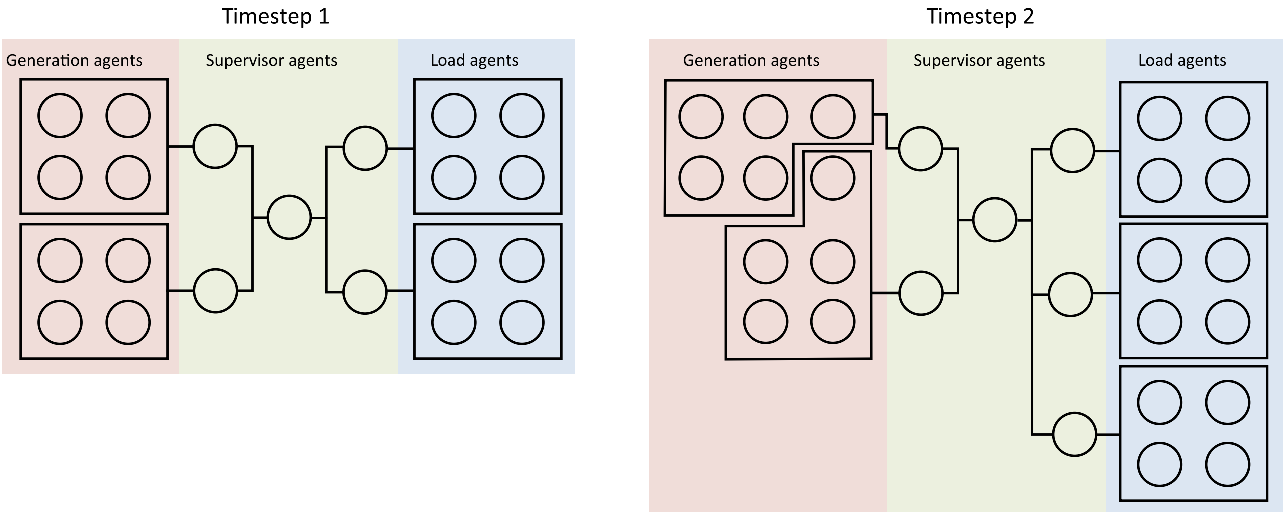

Fig. 22. Example of scalable adaptability through holonic multi-agent systems.

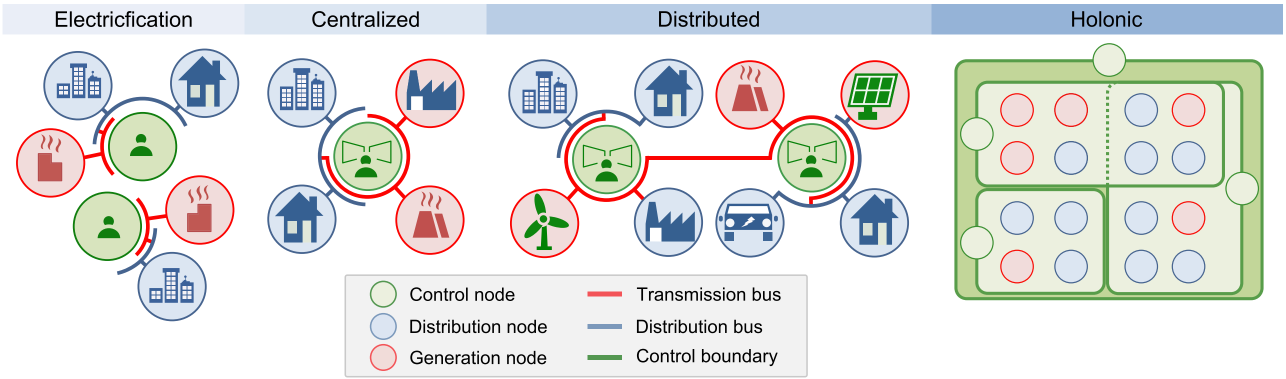

Fig. 23. Evolution of energy systems through 4 generations.

other energy carrying systems; for example, a holonic approach of grouping components into supply, demand, storage and distribution has been applied to a district heating network in [203].

6.3. The security imperative

The requirement of the next generation of urban energy systems to dynamically manage the distribution network across energy carriers and scales in terms of network topology, generation and storage optimization, and dynamic pricing, raises key cyber security concerns [124,206]. Further, Smart grid cyber security has emerged as an important topic in recent years. Three main aspects of smart grid security are discussed here: i) secure authentication, ii) secure communication and iii) information security management. Secure authentication deals with various interfaces (e.g. Home-to-Grid (H2G), Building-to-Grid (B2G), Industrial-to-Grid (I2G), Transmission and Distribution (T & D) and Business and Policy (B & P)) and is based on many existing standards and ongoing efforts on cyber security and privacy technologies in cognate domains. Efforts such as ISO 27002:2013 [207], Federal Information Processing Standard (FIPS) 201 [208], Advanced Encryption Standard (AES) [209] and Triple Data Encryption Algorithm (3DES) [210] offer some of the least cost options for strong security and high performance, but should be applied following appropriate risk assessments, and in appropriate scenarios depending on the communication resource being protected. Arguably, AES encryption with Elliptic Curve Cryptography using TLSv1.2 offers a more secure solution than 3DES, or the use of CBC in SSLv3 or TLSv1.0, which are susceptible to meet-in-the-middle attacks and BEAST attacks respectively.

Diverse communication requirements in smart grids will require the implementation of different standards. For example IEEE 802.11i and 802.16e should be implemented for wireless links, and firewalls and virtual private network (VPN) technologies such as IPSec should be used on both wired and wireless networks, as well as higher layer security mechanism such as Secure Shell (SSH) and SSL/TLS [206]. Information security management, on the other hand, is dealt with in ISO/IEC 27002 [211], which provides best practice recommendations for initiating, implementing or maintaining information security management systems (ISMS) and is aimed at the preservation of confidentiality, integrity and availability. However, these standards need to evolve as elaborated in the following section.

7. Future research directions

Research is required to support the transition to the future energy generation illustrated in Fig. 23 and described in Table 4, from the present trend of distributed energy systems to the envisioned next generation of holonic energy systems. This section therefore extends the previous description of the required energy system generation by describing the key research themes necessary for it to emerge. Specifically, three strategic research avenues are identified and discussed below: i) semantic interoperability of energy systems, ii) secure and reliable multi-agent energy services and iii) energy system of systems optimization.

7.1. Semantic interoperability and control of energy systems

The potential for semantic models to facilitate the interoperability

Table 4
Description of the generations of energy system.

Generation	Description	Reasons For Emergence
2 – Centralized systems	Electricity is produced at large power stations and transmitted at high voltage to distant loads, with increasing renewable contribution in recent years	Economies of scale enabled the production of low cost energy from abundant natural resources. National grids also aided state regulation and improved quality of service
3 – Distributed systems	DERs begin to penetrate the energy landscape, causing integration challenges and opportunities, which are gradually overcome. DERs are sparsely populated so generally exist within isolated systems	Pressure towards sustainability & resilience, alongside advancing technologies, increased the attractiveness of DG, PEVs, MESs and DSM. Various international events and policies spurred investments and research towards their integration in the centralized grid
4 – Holonic systems	DERs densely penetrate the energy landscape to form a system of systems. ICT is used to dynamically reconfigure and interoperate proximal entities	Increasingly dense DER penetration alongside ICT advances and continuing pressures will mandate DER interoperation towards further sustainability, resilience and prosperity in energy systems

of virtual artifacts and data-driven management systems was discussed previously, and represents a critical enabling step towards holonic energy systems. The diversity and prevalence of interoperating components is increasing and is leveraged as an opportunity in holonic systems, but the ability to share and fully utilize data between these components is critical for their intelligent management. The ICT penetration which is ongoing and essential for holonic energy systems therefore mandates the integration of heterogeneous data models, towards which semantic modeling has shown much promise. Specifically, the optimal coordination of distributed energy resources is a complex problem that requires intelligent control software. The components of such intelligent energy management software need to be able to retrieve and exchange data from a wide range of resources such as sensors, smart meters, actuators, building management systems (BMS), and energy managements systems (EMS). However, it is unlikely that stakeholders in a district would use the same data model or communication protocols. In fact, as it becomes commonplace for energy systems to spread across energy carriers, spatio-temporal scales and both supply and consumer-side software, communication between relevant entities will be a critical barrier towards their effective interoperation. Therefore, it is essential that further research into semantic modeling and the application of semantic models is conducted to mitigate the barriers to data-driven approaches in an energy landscape of high DER penetration and interaction. More specifically, there is a need to i) represent the autonomous nature of local energy systems and their adaptive hierarchical groupings, ii) develop semantic representations of these systems and their components to facilitate interoperability between an increasingly heterogeneous and interdisciplinary field, and iii) develop optimization strategies to leverage this systemic knowledge alongside sensory data for the dynamic organization of holons.

As mentioned earlier regarding ontologies developed for UESs, it is apparent that variations in scope, perspective or goal can cause incompatibilities between ontologies, and that the modeling of the emerging energy landscape is immature. As the UES field is consistently expanding and requires the input of experts from a broad range of fields, using multiple existing ontologies is likely and even recommended [212]. It is understandable then that many of the works considered have reflected on the interoperability of multiple ontologies, such as Catterson et al. [213] who discuss that whilst mapping ontologies is typically a manual and laborious process, an upper ontology would reduce the effort considerably. Many authors concur with this sentiment, such as Zhou et al. [171] who advocate for a framework for concept integration, Keirstead et al. [159] who desire a shared ontology for the domain, and van Dam and Keirstead [179] who reiterate towards a shared ontology and state that it would be beneficial even if not universally accepted. Key avenues for further research may be to develop semantic models of emerging UES concepts, develop and test approaches for managing the interactions of multiple ontologies, pursue a common upper ontology, and promote standards in this space.

Examples of ontology driven energy management applications are sparse and the field is immature, likely due to the complexity of ontologies and the effort required for their development. As well as the modeling research advocated, we therefore argue that further research is required on the application of existing ontologies within the field. Beyond enabling interoperability, ontological modeling enables the inference of knowledge without it being explicitly stated through the use of an inference engine, and the application of logical rules, which facilitates further inference, policy checking and enforcement. Leveraging these features in energy management systems was not observed in the literature, but represents a significant avenue for future research, alongside the validation of the approach's overall performance through deployment, such as within a service-oriented architecture. Finally, normative guidance on the best practice for developing and deploying these systems would be highly beneficial.

7.2. *Secure and reliable multi-agent energy services*

As elaborated earlier, the growth of smart grids is faced with emerging requirements for the smart integration of distributed energy resources. In this context, physical and cyber security challenges have become critical factors for the reliability and quality of supply (QoS) of energy related services [206]. Conversely, a gradual transition is occurring to demand responsive energy management enabled by smart metering infrastructures with a bidirectional flow of energy, and dynamic pricing schemes. Security problems are consistently highlighted as weak points in this new energy landscape [172,214]. There is a requirement for secure authentication of users, agents and transactions at each interface between energy devices. The number of processes is also exacerbated by the increasingly distributed nature of grids, and their underpinning communication requirements. It is therefore essential to carry out research along three avenues. Firstly, research must identify and quantify the risk of a breach of privacy and security to the systemic reliability and quality of service (QoS) caused by insecure authentication occurring in a heterogeneous environment, where legacy standards and applications need to remain in operation alongside advanced standards. Secondly, research must identify and quantify loss of data, breach of privacy and vulnerability due to the heterogeneous communication infrastructure (wireless, wired, PLC), and the impact on grid reliability and QoS. Finally, research must develop guidelines for information security management and inform related legislation and standardization.

Alongside this, energy software services which address various stakeholders' (including prosumers) needs are required. These include forecasting and simulation services, as well as responsive day-ahead and intra-day management services necessary to effectively integrate distributed energy resources, including renewables, in urban energy systems. This implies that as local renewable solution penetration increases, so too does the importance of being able to predict behaviors and adapt to changing weather and technological environments. We argue that as local RES density increases, this importance extends beyond the unit level to intelligence at the system level, where the impact of uncertainty at each node can be mitigated through the emergent behavior of adjacent DERs. However, given the assumption that DERs and consumers are active agents able to perform optimization and change their own operating parameters, a modeling approach which captures this adaptable system nature is necessary. To this end the multi-agent system approach is widely adopted, has been validated within the research field and has been increasingly tested in real-world applications. However, as the density of DERs and hence number of agents increases, the complexity of the resultant system will increase by orders of magnitude if the landscape is considered simply as a 'bag' or a fixed hierarchy of agents. Several authors have addressed this concern through hierarchical MAS solutions consisting of local manager agents, but these hierarchies are rigid, whereas the evolving landscape requires adaptable hierarchies which change with predicted generation and demand profiles and as DERs come online and go offline or fail. Instead therefore, we advocate for research into dynamically structuring groupings of agents into holons, within a holonic MAS (HMAS), to allow resources to interact with whichever nearby resources and loads present the ideal local and global benefits. Therefore, we recommend for research to further explore the application of MASs to an urban environment with a high penetration of DERs by optimizing the dynamic grouping and management of DERs within holons.

7.3. System of systems optimization of energy infrastructures

Following the ability to model and control the emergent behavior of complex distributed energy systems through a MAS approach, optimal management of the systems should be realized by systematically considering the decision space of management topologies, schemes and operating parameters. Energy system optimization is far from novel, but most approaches consider the system as a static entity, and only consider a single system rather than the emerging system of systems landscape. We therefore advocate the previously described system of systems approach of holonic energy management. Inspired by examples of recursive organization in nature, the holonic architecture is based upon the concept of a holon; a logic control entity that takes collaborative context-based decisions. Multiple holons (meta-holon) can form scalable architectures through an aggregation mechanism. For example, a Distribution Network Operator can be a holon; an aggregated cluster of DERs and loads in the grid which can make autonomous decisions as well as cooperate with other holons to make mutually beneficial decisions.

Examples of clustering objectives include local energy balancing, islanding, and blackout prevention; similar to those of microgrids, but within a paradigm more suitable to a changing environment of high DER penetration. A holonic framework has, therefore, the potential to meet the requirements of flexibility, scalability, resilience, openness and practicality. Furthermore, holonic architectures combine the advantages of distributed control (such as scalability, privacy and adaptability) and centralized control (such as feasibility, optimality and responsibility) whilst mitigating their specific drawbacks. The benefits of a holonic architecture are particularly evident when the grid needs to be healed after a disruption in service. Due to the organic nature of the holonic architecture, the grid can restore, re-organize and heal itself via alternative topologies without affecting the system as a whole. We therefore thoroughly advocate a new body of research with a view of ensuring the optimality and resilience of energy management systems through self-healing capabilities that i) promote autonomy, belonging, connectivity, diversity and emergence, ii) balance the importance of global and local objectives, iii) dynamically reconfigure to optimize the overall energy system's performance across energy carriers and scales, and iv) enable demand responsive energy management with bidirectional flow of energy, information and dynamic pricing schemes.

8. Conclusion

This paper has reviewed the evolution of energy systems from initial electrification to the emerging distributed systems, and has discussed concepts and trends within recent research. The paper then used an in-depth analysis of the domain to envision the next generation of energy systems, a paradigm which may meet the needs of this future generation, and the research required to facilitate it. Specifically, whilst the research conducted to date has produced important advances towards a decarbonized, resilient and adaptable grid, the body of work observed through this review generally considers each of the components of a future energy system in isolation. From this we can observe that each of the UES concepts such as microgrids and VPPs hold merit when applied within a centralized grid paradigm, but very little research considers the operation of these systems within the emerging energy landscape typified by a high penetration of large RESs, DERs, prosumers, seamless communication and big data. Therefore, the work conducted to date has laid significant groundwork towards future energy systems by developing and validating a range of UES solutions. However, research is now required towards the next generation of UES where diverse and distributed energy systems are dynamically interoperated through ICT penetration.

The authors argue that a system of systems approach is required to successfully orchestrate the interplay between diverse energy components in a way that promotes systemic autonomy, belonging, connectivity, diversity and emergence. This argument is crystallized through the concept of a holonic systems approach, which balances the importance of global and local objectives. We propose that the hierarchy of holons within such a system, their properties, interactions and goals, should be dynamically reconfigured to optimize the overall system's performance across energy carriers and scales. Specifically, we advocate the use of holonic multi-agent systems, as these exhibit the benefits observed in existing MAS based management systems whilst allowing further scalability and adaptability through dynamic restructuring of agents within a hybrid hierarchical-distributed management architecture.

To support the transition from the present trend of ad-hoc distributed energy systems to the envisioned next generation of holonic multi-agent energy systems, strategic research avenues were identified and discussed. These were: semantic interoperability of energy systems, secure and reliable multi-agent energy services, and system of systems optimization of energy infrastructures.

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