What a MES(s)! A bibliometric analysis of the evolution of research on multi-energy systems

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ORIGINAL PAPER

What a MES(s)! A bibliometric analysis of the evolution of research on multi-energy systems

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Abstract Multi-energy systems combine different energy vectors (e.g. electricity, heat, cooling) and operate at different levels (e.g. building, district, and region). Although in theory, multi-energy systems should allow for lower carbon impacts compared to systems in which single energy vectors are considered individually, implementation of multi-energy systems is often difficult due to the number of technologies and actors involved and the complexity of their interactions. In this article, we conduct a bibliometric analysis based on over 20,000 articles from the Web of Science to investigate how knowledge on two important multi-energy systems, Microgrids and Smart Grids, has developed. Our findings identify areas that have been under-researched to date, offer a means of transferring learning between different multi-energy systems and provide practical guidance for the implementation of multi-energy systems.

Keywords Multi-energy systems · Knowledge development · Bibliometric analysis · Smart Grids · Microgrids

1 Introduction

Multi-energy systems (MES) integrate multiple energy vectors such as electricity, heating, cooling, fuels and transport. MES are designed to have higher technical performance, lower environmental impacts and better economic performance than systems based on single energy vectors [1]. As such, they form a central component of efforts to decarbonise the built environment. Over the past two decades researchers have been engaged in developing different MES such as Microgrids, Virtual Power Plants and Smart Grids [2]. Researchers, however, have also used other terms to describe and to conduct their work, such as distributed energy systems, intelligent power grids [3] or energy hubs [4].

Knowledge development is crucial for the successful implementation of these systems but it is also complex because of the number of technologies and actors involved as well as the complexity of their interactions. Although certain types of knowledge are specific to the components of each of these MES, there is also system-level knowledge that could potentially be shared.

In this article, we look at the knowledge development in two important examples of MES: Smart Grids and Microgrids. Smart Grids refer to a suite of technologies that allow energy networks to operate in more advanced ways, mainly based on two-way communications and vast amounts of information [5]. Microgrids combine and store distributed energy resources and interconnected loads, operating on low and medium voltage networks. They can be connected to the grid or they can be operated in island mode [1]. How distinct Smart Grids are from Microgrids or from any other MES remains unclear. Whereas some, for example, consider Smart Grids as the foundation for all other MES (e.g. the US Department of Energy), the fact that researchers appear to prefer one term over the other, suggests that the concepts differ in a meaningful way.

We first investigate how distinctly the research on Smart Grids and Microgrids has developed. We second examine the types of knowledge that have developed within these MES. We find that although the concepts are closely connected, knowledge has developed separately for the two MES. We identify three types of knowledge that have emerged: general, system-specific and integrative knowledge. Finally, we suggest that three main features of MES are likely to influ-

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ence the path of knowledge development: boundaries, scale and coordination.

2 Data and methods

To better understand how knowledge development takes places in the bodies of scientific literature of different multi-energy hubs, we focus our analysis on two of the most prominent and mature MES, namely Smart Grids and Microgrids. Our data comprises all scientific publications in English from the Web of Science that contain either the term "Smart Grid(s)" or "Microgrid(s)" (accessed on 7 January 2016). Because before 1996 researchers published almost no articles on Smart Grids or Microgrids, we begin data collection in 1996. To explore the evolution of knowledge development, we distinguish between the following four periods: i) 1996–2000; ii) 2001–2005; iii) 2006–2010; iv) 2011–2015.

To understand the extent to which knowledge development about these two MES occurs independently, we examine the number of publications unique to each MES and the number of publications that treat both MES. Subsequently, we conduct a bibliometric analysis to identify the most common keywords within a certain research field [6,7]. We use the VOSviewer software for our bibliometric analysis. The VOSviewer is a highly innovative and comprehensive approach suited for high-level analysis of large bodies of literature. So far, it has been applied in a diverse set of research areas, such as nanotechnology [8], renewable energy [9], information science [10], management [11] and scientometrics [12]. The main advantages of the VOSviewer approach in comparison to conventional reviewing methodologies is that it allows for the development of highly accurate, comprehensive and rigorous bibliometric science maps. Such science maps are analytical visualizations of relations between scientific objects based on the links between these objects. Science maps allow for the analysis of large data sets, are rigorous in content and provide detailed, interpretable, and memorable visualizations.

The bibliometric analysis allows us to identify the fields and subfields within each knowledge domain and we use this information to compare knowledge development of Smart Grids and Microgrids to identify the evolutionary patterns of knowledge, subdomains common to both MES, and domains distinct to either one of the MES. Based on our findings, we develop recommendations for future research on developed and emerging MES.

3 Results

3.1 Summary of research activity on Smart Grids and Microgrids

Table 1 provides an overview of the number of scientific publications on Smart Grids and on Microgrids between 1996 and 2015 per period. Table 1 indicates that while research on Microgrids began earlier, with 24 publications between 1996 and 2000 and 125 publications between 2001 and 2005, research on Smart Grids grew more rapidly during the same period. Already between 2006 and 2010, researchers published more scientific articles on Smart Grids, a trend that clearly extended into the period 2011 to 2015.

Table 1 Number of scientific publications for Smart Grids and Microgrids 1996–2015 per period

Time period	Smart Grids	Microgrids
1996–2000	0	24
2001–2005	5	125
2006–2010	1680	1124
2011–2015	19,324	7520

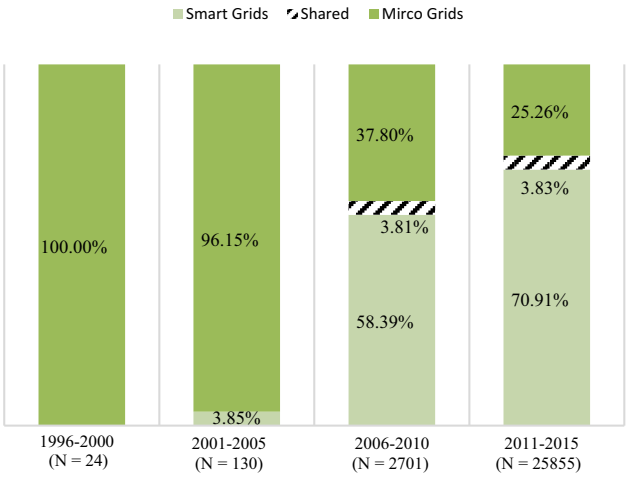

Fig. 1 Knowledge development in number of scientific publications on Smart Grids and Microgrids

How does research on Smart Grids and Microgrids relate to one another? Figure 1 shows the extent to which researchers published either uniquely on Smart Grids or on Microgrids, or developed knowledge on both MES simultaneously.

As Fig. 1 indicates, researchers began to merge knowledge on both MES only from 2006 onwards. For the period 2006–2010, we identify 103 articles (3.81 %) and for the period 2011–2015, we identify 989 articles (3.83 %) that address both MES. Thus, while researchers have recently begun to combine findings from both MES, only little learning between the two MES took place.

3.2 Types of knowledge development

Figures 2 and 3 show the terms associated with all research published over the period 1996 to 2015 for Microgrids and Smart Grids.

Figure 2 shows that the research on Microgrids forms two main clusters related to network issues (red) and to the demand-side (blue). A smaller cluster (orange) at the top of the map relates to system design. The centre of the map is empty indicating that knowledge developed in these three main areas develops independently.

Figure 3 shows research on Smart Grids. Here, too, researchers are concerned with aspects related to networks (red) and the demand-side (blue). But in the Smart Grids map, these two clusters are connected showing that research on different areas of knowledge is closely linked. Furthermore, there is a central cluster which is composed of terms associated with different types of Smart Grid actors and grid integration (yellow). This central cluster is linked to each of the other main clusters of research. A fourth cluster in the map specifically focuses on the smart aspects of the network (green).

Comparing the maps, two main messages emerge. First, common to research on both MES are two kinds of knowledge clusters. We identify general knowledge that may be shared across MES. General knowledge would include research on networks, demand-side issues and integration. Moreover, we identify system-specific knowledge; system design in the case of Microgrids and the smart side of the network in the case of Smart Grids. Second, the absence of a central cluster in the case of knowledge on Microgrids suggests that the research on Microgrids is not as integrated as research on Smart Grids.

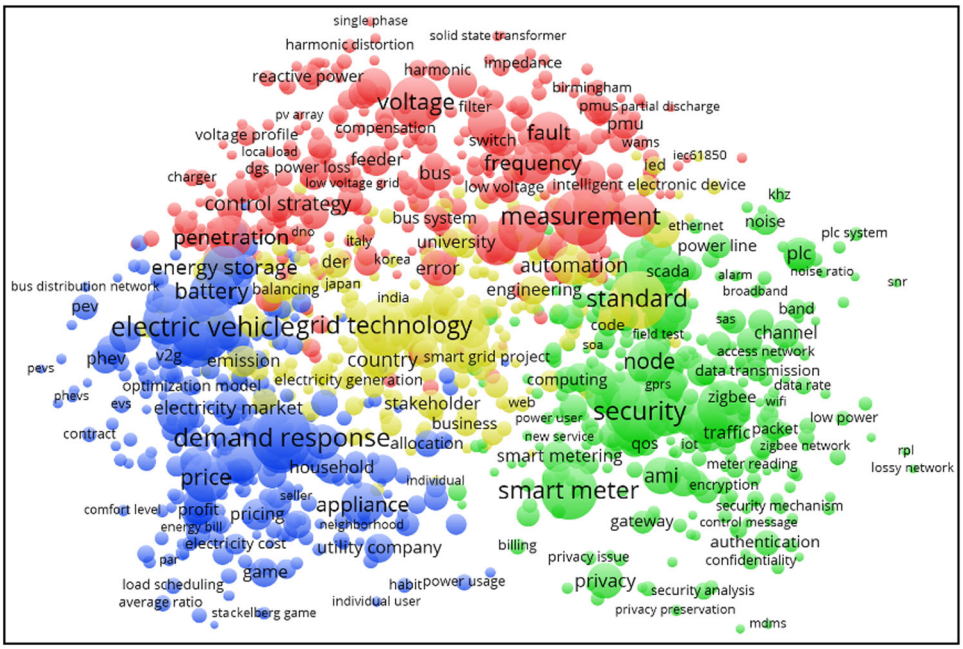

Fig. 2 Smart Grids research 1996–2015

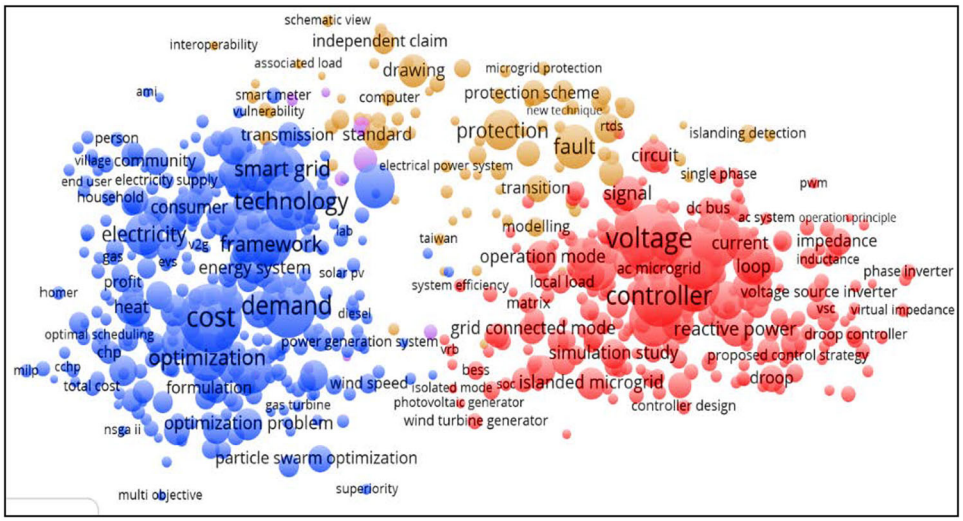

Fig. 3 Microgrids research 1996–2015

3.3 Knowledge development over time

Did knowledge develop differently for the two MES over time? Figures 4 and 5 show the development of knowledge for the two MES over the three main periods of research activity (2001–2005; 2006–2010; 2011–2015). Because, between 1996 and 2000, research on Smart Grids did not exist and research on Microgrids was too fragmented, thus we do not show these maps.

In the period 2001–2005, the research activity was highly dispersed, making it difficult to identify any clear clusters of knowledge. Since then, Microgrid knowledge development has been bipolar, characterized by two large clusters of research focused on network (red) and demand-side (blue) issues.

These two clusters have grown over time. In the most recent period (2011–2015), there is evidence of a cluster that integrates the other clusters (yellow), although the focus of the cluster is difficult to ascertain.

The research on Smart Grids started later than Microgrids, but already in the period 2006–2010 had a clearly emerging vision with fairly equally distributed knowledge clusters. Even in the early stages of knowledge development, Smart Grids research was integrated with dense clustering of knowledge and a central yellow cluster with an integrative function.

In summary, knowledge has developed differently for the two MES over time. For Microgrids, the trajectory has been from independent areas of knowledge to more connected ones. For Smart Grids, on the other hand, the integration of different areas of knowledge has been embedded in research activity from the beginning.

4 Discussion

Smart Grids are often depicted as the foundation for the implementation of many other multi-energy systems [1,7]. Although this is the case or example in how the US Department of Energy classifies Microgrid as a subcategory of Smart Grids, the research activity shows that knowledge on these MES has developed separately. From our analysis, however, it appears that there are opportunities for different MES to learn from each other. For instance, there are general clusters of knowledge that are common across MES such as those related to network issues and to the demand-side. Pooling of research efforts on these topics could be worthwhile in the future. In addition, other MES could learn from Smart Grids in developing an approach to integrate knowledge development. One explanation for our findings is that the research field on Smart Grids, starting later than that of

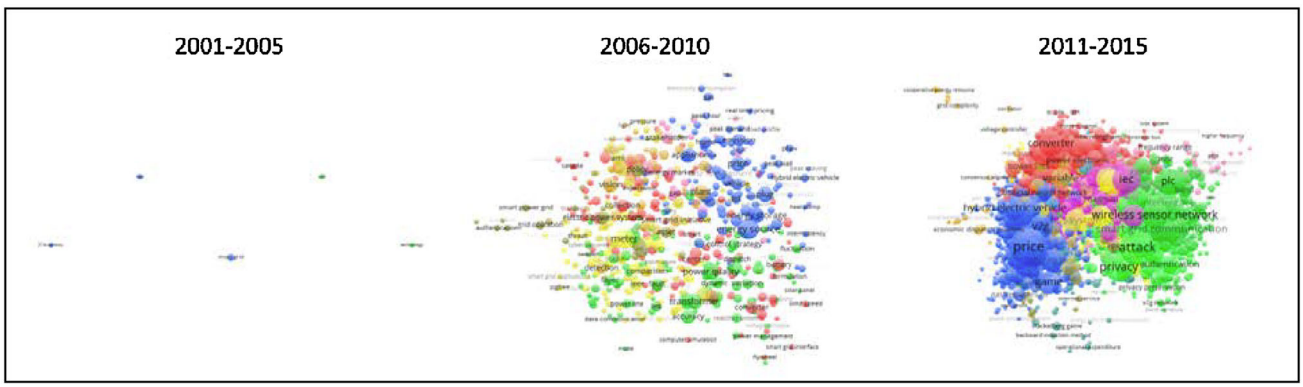

Fig. 4 Smart Grids knowledge development by period 2001–2015

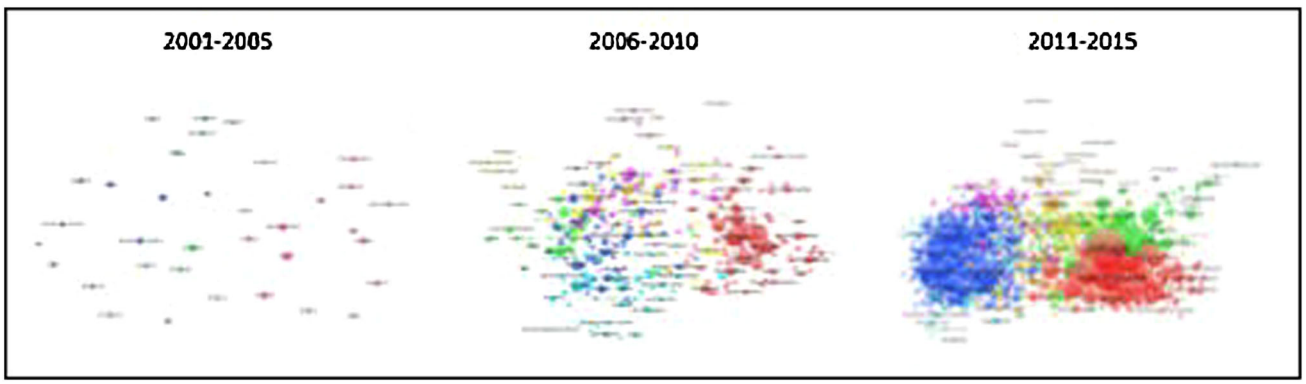

Fig. 5 Microgrids knowledge development by period 2001–2015

Microgrids, had a second-mover advantage and was able to learn from the more disconnected attempts of other fields to develop knowledge. A future direction for research would be to conceptualise how MES can learn from each other by developing clearer classifications of MES according to technological characteristics and interdependencies.

Intuitively, we might think of integration of knowledge clusters only taking place once there is a certain level of knowledge to actually integrate. The story of Smart Grids suggests, however, that knowledge does not have to first be developed in separate silos before becoming integrated. Rather, integration can be part of the vision of the field from the beginning. Future research could focus on exploring what the conditions are for this early integration of research efforts to take place and what the effects of integration might be on later implementation.

Three main features of the MES we have studied are likely to have influenced the paths of knowledge development. First, in terms of boundaries, Microgrids can be clearly defined. The boundaries for Smart Grids are less clear at least until, for example, the whole grid for a country or region can be identified as smart. There was less of a need to start out research on Microgrids with an overarching vision because the boundaries of the concept are easily defined. Second, Microgrids as the term suggests are implemented at small scales. One of the aims underlying the concept of Smart Grids by contrast is that of large-scale implementation. Third, coordination needs differ. In the case of Microgrids, one of the main priorities is the goal of independence, or at least the ability to operate the Microgrid independently. For Smart Grids, coordinating different actors and information flows is fundamental to the concept. The combined goals of large-scale implementation and coordination for help to explain the early development of integrated research efforts in the field of Smart Grids.

These three features of MES (boundaries, scale and coordination) have implications for other emerging MES. For instance, if there is a need for high coordination of actors and technologies across different scales as in the case of energy hubs, the focus of knowledge development should be on integration from the beginning. This is not to say that individual components or technologies are irrelevant or that researchers should not work towards their development. Yet, our results suggest that developing integration between these elements should be a priority from the start.

Our results have several practical implications for the implementation of multi-energy systems and for future research in this area. First, it is not enough for the actors involved in implementing MES to focus just on the individual components. Within the network of actors, there needs to be the development of capabilities for integration of technologies as well as for integration of actors. Future research should explore which actors are best placed to develop these integration capabilities. Second, universities could support MES actors in learning how to integrate. The new Master's programme in Integrated Building Systems at ETH Zurich is a step in this direction with an interdisciplinary approach and a strong focus on integration at building and urban levels. Third, it will be crucial for actors involved in the implementation of MES to be able to transfer learning from other projects. We suggest that this might be possible for general and integrative knowledge but as yet it is not clear how actors can do this in a way that improves implementation.

5 Summary

Our analysis of knowledge development on Microgrids and Smart Grids has identified that although there are links between these concepts, knowledge development has been distinct to date. We find three main categories of knowledge for MES: system-specific, general and integrative knowledge. We suggest that there is potential for MES to contribute to each others' development, particularly in the general and integrative categories of knowledge. We also show that the path of knowledge development does not have to progress from separate clusters towards efforts to integrate. In fact, as research in the field of Smart Grids has shown, integration can be embedded from early on. Our results highlight the importance and the challenges of integrating knowledge on MES. Finally, we suggest that successfully implementing a MES requires a better understanding of the kinds of system integration capabilities that actors involved in MES need.

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