BRAIN. Broad Research in Artificial Intelligence and Neuroscience
ISSN: 2068-0473 | e-ISSN: 2067-3957
Covered in: Web of Science (WOS); PubMed.gov; IndexCopernicus; The Linguist List; Google Academic; Ulrichs; getCITED; Genamics JournalSeek; J-Gate; SHERPA/RoMEO; Dayang Journal System; Public Knowledge Project; BIUM; NewJour; ArticleReach Direct; Link+; CSB; CiteSeerX; Socolar; KVK; WorldCat; CrossRef; Ideas RePeC; Econpapers; Socionet.

2020, Volume 11, Issue 4, pages: 201-230 | https://doi.org/10.18662/brain/11.4/149

The State of the Art in Smart Grid Domain: A Network Modeling Approach

Waseem AKRAM[1]*,
Saba NOOR[2],
Awais MANZOOR[3]

[1] COMSATS University Islamabad, Pakistan,
imwaseem.khan@yahoo.com
Corresponding author

[2] Lahore Garrison University, Lahore, Pakistan

[3] COMSATS University Islamabad, Pakistan

Abstract: *Agent-based computing and multi-agent systems are important tools in the domain of smart grid. Various properties of agents like self-organization, co-operation, autonomous behavior, and many others allow researchers to well represent the smart grid applications and models. From past few decades, various research attempts have been made in the smart grid domain by adopting the agent-based computing technology. The research publications are growing in number which makes it difficult to locate and identify the dynamics and trends in the research. Scientometric analysis is a useful tool to perform a comprehensive bibliographic review. It allows not only to understand the key areas of research but also provide visual representation of each entity involve in the research. In this study, we provide a detailed statistical as well as visual analysis of agent-based smart grid research by adopting complex network-based analytical approach. The study covers all scientific literature available online in Web of Science database. We are interested in identification of key papers, authors, and journals. Furthermore, we also investigate core countries, institutions, and categories.*

Keywords: *smart grid; multi-agent systems; network modelling; scientometric analysis.*

How to cite: Akram, W., Noor, S., & Manzoor, A. (2020). The State of the Art in Smart Grid Domain: A Network Modeling Approach. *BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 11*(4), 201-230.
https://doi.org/10.18662/brain/11.4/149

Introduction

From past few decades, agent-based computing has received a great deal of attentions in the smart grid domain. The agents have various behaviors like atomicity, communication, self-organization, co-operation etc. By developing agent-based models, one can easily represent any complex adaptive systems where the agent's features are main concerns.

In scientific literature, a number of studies have been done on the smart grid by making use of agent-based computing technology. Some of the key examples are as following. For example it is applied for demand response in (Kim, Zhang, Van Der Schaar, & Lee, 2016; Siebert, Sbicca, Aoki, & Lambert-Torres, 2017), smart home management (Dusparic, Harris, Marinescu, Cahill, & Clarke, 2013; G. Wang et al., 2017), electric vehicle chagrining and discharging (Golpayegani, Dusparic, Taylor, & Clarke, 2016; Jannati & Nazarpour, 2017; Yao, Lim, & Tsai, 2017). The agent-based smart grid systems can also be noted for appliance scheduling (Muralitharan, Sakthivel, & Shi, 2016), storage management (Ju et al., 2018; Lamedica, Teodori, Carbone, & Santini, 2015; Shirzeh, Naghdy, Ciufo, & Ros, 2015). These studies have shown the importance and utility of agent-based computing technology in the domain of smart grid.

One key problem in scientific literature is that the research is growing very fast. From different countries and organization researchers make their contribution in the smart grid domain. In literature of smart grid, there are also several surveys and reviews papers, which provide a detailed analysis of the domain, available techniques, and tools. Some of the examples of surveys can be seen in (Rehmani, Davy, Jennings, & Assi, 2019; Risteska Stojkoska & Trivodaliev, 2017; Siano, 2014). Although there are numerous surveys and reviews in the domain, there exist one key problem that researchers are unable to understand and locate trends and dynamic of the domain. Another problem with these surveys is that they are outdated and target a specific requirement of the study. These surveys are unable to cover all the published work.

A network modeling approach is a useful tool for bibliographic reviews. It allows not only the visual analysis but also a detailed statistical analysis of the domain. However, to the best of our knowledge, currently there exists no study on bibliographic analysis of the agent-based smart grid research.

In this paper, we provide a detailed survey of the smart grid domain from agent-based perspective. We cover all studies currently available in the domain on Web of Science database. This study adopts the network modeling approach- an approach of cognitive agent-based computing framework. The approach allows developing a network model, thus allows better understanding the domain in the form of network. Our key focus is on the analysis of key papers, journals, authors. We are also interested in the analysis of core countries, institutions, and categories.

Methodology

Data collection:

The dataset was collected from the Thomson Reuters web of knowledge database in the period of 1992 to 2019. The input data was retrieved on 7 November 2019, by using extended topic search of smart grid domain from agent technology perspective. The following search key words were used in data collection.

- Agent-based modeling of smart grid
- Multi-agent systems in smart grid
- Modeling and simulation of smart grid

We performed bibliographic search in different web of science databases included SCI-Expanded, SSCI, and A&HCI. Our results included different documents types such as articles, reviews, letters, and other editorial materials published in English language. Each record includes full information as document titles, author names, abstracts, and cited references. Our dataset contains a total of 3884 records. By addition of cited references, a total of 36317 nodes were counted.

Tools and method:

In this paper, we have adopted CiteSpace- a scientometrics analysis tool (Chen, 2014, 2016). The tool allows visual analysis of the citation network. It uses different colors that highlight details information about nodes and links of the citation network. CiteSpace offers tools and techniques for developing various complex networks based on years, time slice, centrality, and clustering. The developed network can be analyzed and various details information can be collected about a research domain. For example, based on the extracted network, we can get information about core authors, documents, and journals. Additionally, we can also analyze the top country, institutions, and category of a specific research topic and domain.

The research method followed in our study is adapted from (M. A. K. Niazi, 2017). The methodology diagram is shown in Figure 1. First, we start by collecting bibliographic data of marketing domain from the web of science. For visual analysis, we use the CiteSpace network modeling tool.

Our analysis starts by developing network clusters. It is followed by an analysis of Journals in order to identify core Journals of Marketing domain. Our next research objective is to identify top articles, and most cited authors in marketing research studies. Additionally, our next focus is on the identification of core country, category, and institutions.

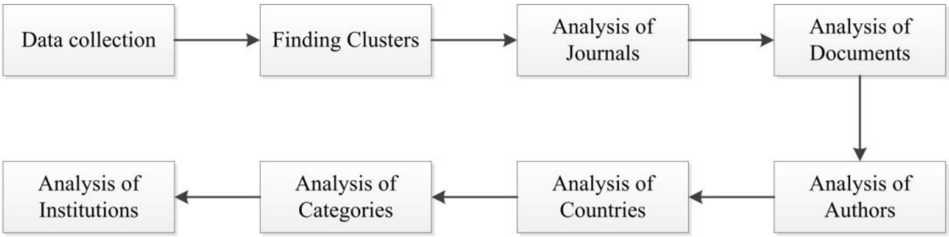

Figure 1: Research method for bibliographic analysis of Marketing research adopted from (Farooq, Khan, Niazi, Leslie, & Hussain, 2018)

Results

We start with a basic look at the overall picture of bibliographic data retrieved from web of science. Figure 2 shows total publications by year. As we can see here, the use of agent technology in smart grid starts primarily in 2007. The research gradually was rising and in the period of 2015 to 2019 the research achieved a great attention from research community in the domain. In this period, more than 550 different research publications were observed.

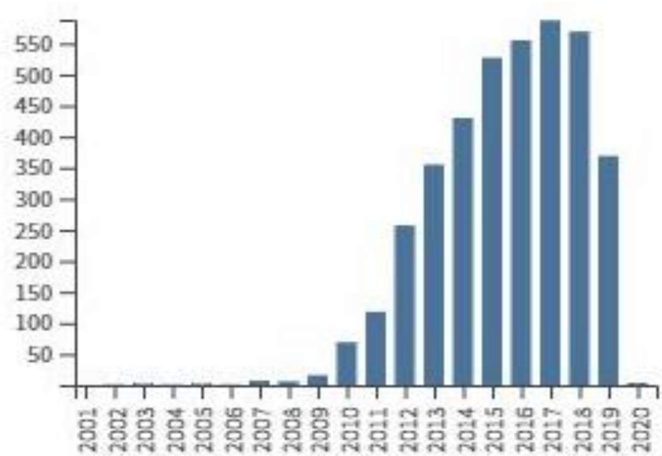

Figure 2: Total publications by year
(Authors analysis on collected data from WoS)

The popularity of any research domain is based on number of citation of documents. Thus, we also needed to observe the citation phenomena in the domain in order to get deep insights of the domain advancement. Figure 3 shows total citations by year in smart grid domain using agents' technology. Here, we can see that the citation starts with a very small number and gradually rising to almost 1000 citations in the year of 2018.

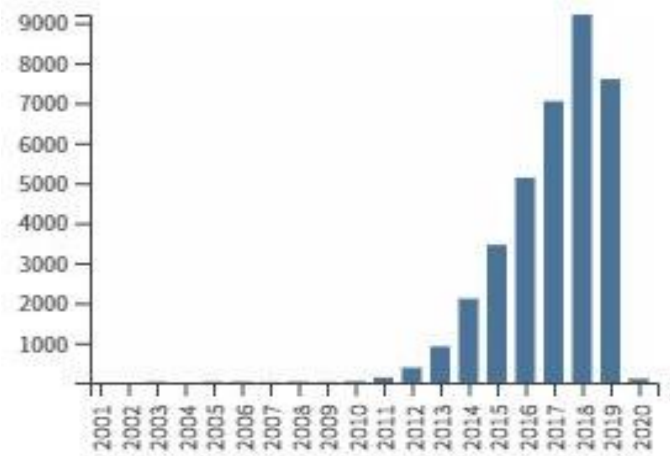

Figure 3: Total citations by year
(Authors analysis on collected data from WoS)

1. Identification of the largest cluster

In this section, we present our first analysis to observe the big picture of the domain. In Figure 4 top clusters are displayed is a visual form. These clusters are formed using CiteSpace analysis tool. Each cluster is named based on index terms.

In agent-based smart grid research, researchers work on different aspects of the domain. Here, we can see that the hottest area of research is "demand response management in the smart grid". Next, machine learning techniques and agent-based systems are adopted in the domain. These techniques are utilized to develop an energy efficient system. Other research topics are voltage regulations and electric vehicles management. The detailed analysis of the largest clusters is given in the following.

In Table 5, frequency-based document analysis is given. Here, we notice that the article (Mohsenian-Rad, Wong, Jatskevich, Schober, & Leon-Garcia, 2010) has the highest frequency among all cited articles. Next, (Fang, Misra, Xue, & Yang, 2012) is the most cited article in the domain. Following by (Palensky & Dietrich, 2011), (Farhangi, 2010), (Gungor et al., 2013) and (Siano, 2014). These are top documents based on frequency in the smart grid domain.

The detailed summary of the top clusters can be found in

Table **1**. Cluster #0 contains 80 nodes in the year 2011. The mean silhouette score of this cluster is 0.626 indicate high homogeneity in the cluster. Cluster #1 has 50 node and 0.861 silhouette score in 2009. The mutual terms of this cluster are electric vehicles, charging and discharging. Cluster #2 has 49 nodes with 0.807 silhouette score which indicates homogeneity in the cluster. The average year of this cluster is 2014. Cluster #3 has 42 nodes and 0.784 silhouette score in the year 2009. This cluster shares research mostly on power line communication. Cluster #4 has 40 nodes and 0.719 silhouette score which indicate the homogeneity in the cluster in the year 2010. The terms controllable and smart home are used in this cluster. The next top cluster contains 23 nodes along with 0.764 silhouette score. The average year of this cluster is 2008. Mostly papers in this cluster share noise reduction term.

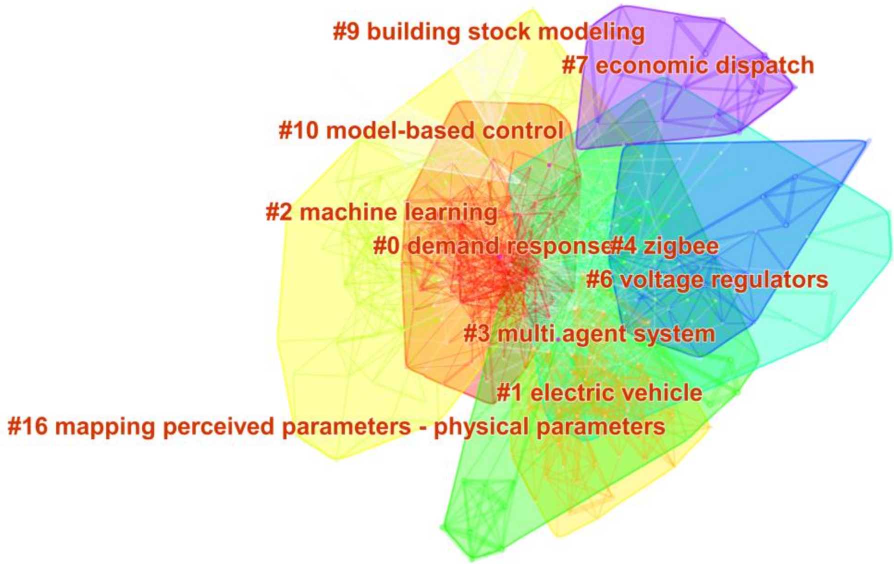

Figure 4: Top clusters by index terms
(Authors analysis on collected data from WoS)

Table 1: Summary of top clusters
(Authors analysis on collected data from WoS)

ClusterID	Size	Silhouette	mean(Year)	Label (LLR)	Label (MI)
0	80	0.626	2011	demand response home energy management, smart energy hub, appliance scheduling ,demand-side management	distributed storage, scheduling problem, bacteria foraging optimization
1	50	0.861	2009	electric vehicle, smart charging	double control, ev group, coordinated charging and discharging
2	49	0.807	2014	machine learning, power markets, smart contract	electric power network, accuracy, cyber-security, incentive-based demand response
3	42	0.784	2009	multi agent system, micro-grid	power system automation, power line communication
4	40	0.719	2010	Zigbee, smart home grid	controllable load
5	23	0.764	2008	voltage regulators	Powerline, noise reduction

Table 2: Top document based on citations
(Authors analysis on collected data from WoS)

Citation counts	Reference
164	Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 320
118	Fang X, 2012, IEEE COMMUN SURV TUT, 14, 944
115	Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 120
96	Palensky P, 2011, IEEE T IND INFORM, 7, 381

95	Farhangi H, 2010, IEEE POWER ENERGY M, 8, 18
89	Gungor VC, 2011, IEEE T IND INFORM, 7, 529
85	Siano P, 2014, RENEW SUST ENERG REV, 30, 461
74	Zimmerman RD, 2011, IEEE T POWER SYST, 26, 12
66	Ipakchi A, 2009, IEEE POWER ENERGY M, 7, 52
65	Mcarthur SDJ, 2007, IEEE T POWER SYST, 22, 1743

Table 3: Top document based on bursts
(Authors analysis on collected data from WoS)

Bursts	References
12.66	Mcarthur SDJ, 2007, IEEE T POWER SYST, 22, 1743
12.44	Dimeas AL, 2005, IEEE T POWER SYST, 20, 1447
11.68	Siano P, 2014, RENEW SUST ENERG REV, 30, 461
10.46	Olivares DE, 2014, IEEE T SMART GRID, 5, 1905
9.25	Kempton W, 2005, J POWER SOURCES, 144, 268
9.05	Deng RL, 2015, IEEE T IND INFORM, 11, 570
8.78	Kempton W, 2005, J POWER SOURCES, 144, 280
8.38	Vardakas JS, 2015, IEEE COMMUN SURV TUT, 17, 152
8.33	Eddy YSF, 2015, IEEE T POWER SYST, 30, 24
8.26	Albadi MH, 2008, ELECTR POW SYST RES, 78, 1989

Table 4: Top document based on centrality

Centrality	References
0.16	Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 320
0.12	Pipattanasomporn M, 2009, POW SYST C EXP 2009, 0, 1
0.10	Zimmerman RD, 2011, IEEE T POWER SYST, 26, 12
0.09	Farhangi H, 2010, IEEE POWER ENERGY M, 8, 18
0.08	Fang X, 2012, IEEE COMMUN SURV TUT, 14, 944
0.08	Clement-nyns K, 2010, IEEE T POWER SYST, 25, 371
0.08	Moslehi K, 2010, IEEE T SMART GRID, 1, 57
0.06	Ipakchi A, 2009, IEEE POWER ENERGY M, 7, 52
0.06	Galli S, 2011, P IEEE, 99, 998
0.06	Palensky P, 2011, IEEE T IND INFORM, 7, 381

Table 5: Top document co-citation based on frequency in agent-based smart grid research (Authors analysis on collected data from WoS)

Frequency	Author	Year	Source
164	Mohsenian-rad AH	2010	IEEE T SMART GRID
118	Fang X	2012	IEEE COMMUN SURV TUT
115	Mohsenian-rad AH	2010	IEEE T SMART GRID
96	Palensky P	2011	IEEE T IND INFORM
95	Farhangi H	2010	IEEE POWER ENERGY M
89	Gungor VC	2011	IEEE T IND INFORM
85	Siano P	2014	RENEW SUST ENERG REV
74	Zimmerman RD	2011	IEEE T POWER SYST
66	Ipakchi A	2009	IEEE POWER ENERGY M
65	Mcarthur SDJ	2007	IEEE T POWER SYST

2. Analysis of journals

Our next analysis is to identify the core journals of the domain. This can be noticed in Figure 4. The pink ring around the nodes in the network shows that there one node in the network with more than 0.1 centrality. "IEEE Transaction on Smart Grid" has the largest number of highly cited publications. The second largest number of publications is associated with the "IEEE Transaction on Power Systems".

Table 6 shows the list of top ten journals based on citation counts. We can note here that the top venue for smart grid research is IEEE Transaction on Smart Grid and IEEE Transaction on Power Systems. These journals are mostly relevant to the research topic of "Agent-based smart grid". Other journals like IEEE Transaction on Power Delivery, Renewable Sustainable Energy Review, IEEE Industrial Electronic, and Applied Energy are also representing relevance in the research of "Agent-based smart grid".

Table 6: Top journals based on citation (Authors analysis on collected data from WoS)

Citation	Abbreviated Title
1868	IEEE T SMART GRID
1776	IEEE T POWER SYST
774	IEEE T POWER DELIVER
700	RENEW SUST ENERG REV

677	IEEE T IND ELECTRON
654	APPL ENERG
649	P IEEE
647	ELECTR POW SYST RES
631	IEEE T IND INFORM
576	INT J ELEC POWER

Figure 5: Top journals based on centrality
(Authors analysis on collected data from WoS)

Table 7 shows top journals based on centrality. “Nature” has the highest centrality value of 0.26 among all the other journals in the domain. “IEEE Transaction on Smart Grid”, and “IEEE Transaction on Power Systems” have same centrality value of 0.17 and listed at second and third position respectively. We also noticed that “Renewable and Sustainable Energy Review”, “Lecture Notes in Computer Science”, and “IEEE Transaction on Power Systems” are also some of the top journals of the “Agent-based smart grid” research.

Table 8 shows the list of top journals based on frequency. Here, the results are sorted according to the frequency of the publications and show different set of key journals. By frequency analysis of top journals, it can be noticed that "IEEE Transaction on Smart Grid" is at the top having 1868 frequency value. "IEEE Transaction Power Systems" and "IEEE Transaction Power Delivery" follow with 1776 and 774 frequency values respectively. This is followed by "Renewable Sustainable Energy Review", "IEEE Transaction Industrial Electronic" and "Applied Energy" with frequencies 700, 677, 654 respectively. Next "Power IEEE" has published 649 articles. "Electric Power System Research", "IEEE Transaction Industrial Informatics", "Int. Journal of Electrical Power" and "Energy" journals are also top venues of "Agent-based smart grid" research.

Table 7: Top journals based on centrality

Centrality	Journal Name
0.26	NATURE
0.17	IEEE T SMART GRID
0.17	IEEE T POWER SYST
0.11	RENEW SUST ENERG REV
0.10	LECT NOTES COMPUT SC
0.10	IEEE T POWER SYSTEMS
0.10	P IEEE INT C SYST MA
0.09	IEEE T POWER DELIVER
0.09	IEEE J SEL AREA COMM
0.09	P IEEE POW EN SOC GE

Table 8: Top journals based on frequency
(Authors analysis on collected data from WoS)

Frequency	Source
1868	IEEE T SMART GRID
1776	IEEE T POWER SYST
774	IEEE T POWER DELIVER
700	RENEW SUST ENERG REV
677	IEEE T IND ELECTRON
654	APPL ENERG
649	P IEEE
647	ELECTR POW SYST RES
631	IEEE T IND INFORM

576	INT J ELEC POWER
542	ENERGY

3. Analysis of categories

Our next focus is on the analysis of different categories in the "agent-based smart grid" research. Figure 6 shows the network of top categories. The detailed analysis of the subject categories is shown Table 9, Table **10** and Table 11.

The top ranked category by centrality is “Engineering”, with centrality of 0.40. The second one is “Engineering, Electrical and Electronic, with centrality of 0.22. The third and fourth are “Computer Science and Information Systems” and “Science and Technology”, with centrality of 0.11. The fifth is “Physics” with centrality of 0.10. It is followed by “Computer Science”, “Energy and Fuels”, “Computer Science and Artificial Intelligence”. It is observed that the category “Computer Science and Interdisciplinary applications” has the lowest value of centrality among all other categories.

Next, we present an analysis of burst in subject categories.

Table **10** shows top categories based on burst. Here, it is noticed that "Computer Science, theory and methods have the highest burst in 2009. Next, there are two categories related in different time span that are "Engineering, environmental", and "Computer science, hardware and architecture". It is followed by "Environmental Science and Ecology", with bursts of 3.66. The last one is "Mathematics and Interdisciplinary applications", with bursts of 3.57.

We also analyzed top categories based on frequency. It is shown in Table 11. Through frequency analysis of different categories, we come up with the almost same set of results. Here, again "Engineering" has topped the list with 2744 articles. It is followed by "Engineering, Electrical and Electronics" with 2397 published articles. It is noticed that "Energy and Fuels", and "Computer Science" have close frequency value. Through frequency and centrality analysis, it is observed that the smart grid research is mostly related to the engineering, mathematics, and computer science.

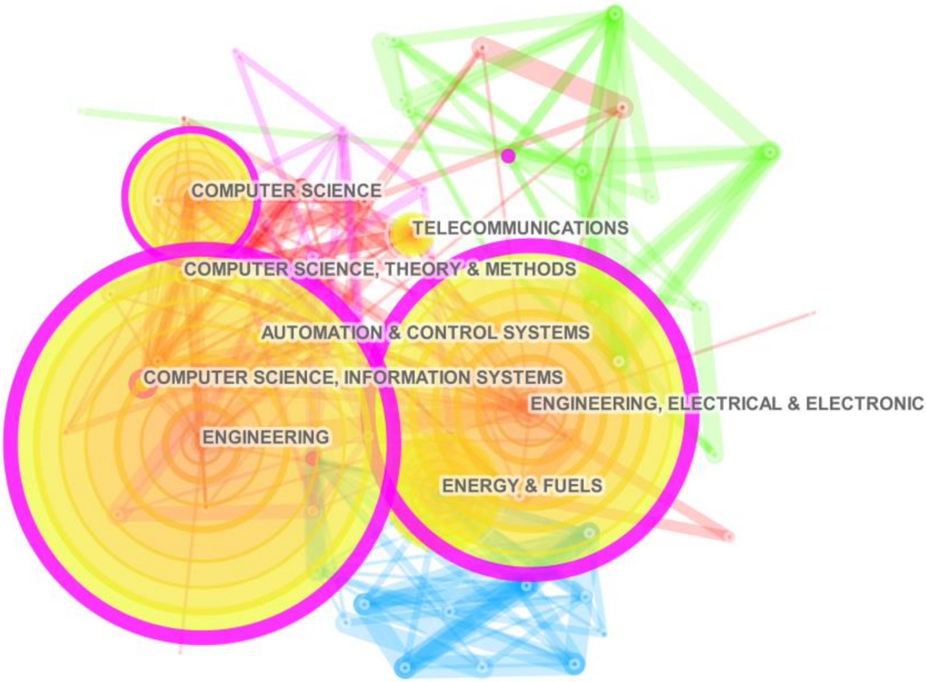

Figure 6: Top categories network
(Authors analysis on collected data from WoS)

Table 9: Top categories based on centrality
(Authors analysis on collected data from WoS)

Centrality	**Category**
0.40	Engineering
0.22	Engineering, Electrical and Electronics
0.11	Computer Science and Information systems
0.11	Science and Technology
0.11	Physics
0.10	Computer Science
0.08	Energy and Fuels
0.08	Engineering and Mechanical
0.07	Computer Science and Artificial Intelligence
0.06	Computer Science and Interdisciplinary applications

Table 10: Top category based on burst
(Authors analysis on collected data from WoS)

Bursts	Category	Year
14.04	Computer Science, theory and methods	2009
5.86	Engineering and environmental	2013
5.57	Computer Science, hardware and architecture	2009
3.66	Environmental Science and ecology	2010
3.57	Mathematics and Interdisciplinary applications	2014

Table 11: Top category based on frequency
(Authors analysis on collected data from WoS)

Frequency	Category
2744	Engineering
2397	Engineering, Electrical and Electronics
1150	Energy and Fuels
1081	Computer Science
475	Telecommunication
359	Automation and Control systems
338	Computer Science, theory and methods
335	Computer Science and Information system
241	Computer Science, hardware and architecture
238	Computer Science and Artificial Intelligence

4. Analysis of countries:

In this section, we present an analysis of the agent-based smart grid research across different countries. Figure 7 shows network of top countries based on centrality. Here, different countries are shown in a visualized form that is involved with agent-based smart grid research. Thus the network shows the top country is United States of America. This is followed by some other countries such as Germany, England, France, Canada, and China.

The top ranked item by citation counts is USA in 2000, with citation counts of 856. The second one is China (2010), with citation counts of 709. The third is Canada (2010), with citation counts of 243. The 4th is Germany (2000), with citation counts of 231. The 5th is Italy (2012), with citation counts of 211. Next, India, Iran, England, Australia, and France are also listed top in countries based on citation.

Table 12: Top countries based on citation
(Authors analysis on collected data from WoS)

citation counts	references	cluster #
856	USA, 2000, SO, 0, 0	3
709	PEOPLES R CHINA, 2010, SO, 0, 0	2
243	CANADA, 2010, SO, 0, 0	1
231	GERMANY, 2000, SO, 0, 0	0
211	ITALY, 2012, SO, 0, 0	0
185	INDIA, 2012, SO, 0, 0	2
165	IRAN, 2013, SO, 0, 0	1
155	ENGLAND, 2011, SO, 0, 0	1
149	AUSTRALIA, 2010, SO, 0, 0	1
126	FRANCE, 2010, SO, 0, 0	0

Table 13 shows the list of top countries based on centrality. The top ranked item by centrality is USA, with centrality of 0.32. The second one is Germany with centrality of 0.15. The third is England, with centrality of 0.15. The 4th is France with centrality of 0.14. The 5th is Canada with centrality of 0.12. It is followed by China with centrality of 0.11. The 7th is Australia with centrality of 0.07.

Figure 7: Network of top countries
(Authors analysis on collected data from WoS)

Table 13: Top countries based on centrality
(Authors analysis on collected data from WoS)

Centrality	Country	Year
0.32	USA, 2000	2000
0.15	Germany	2000
0.15	England	2011
0.14	France	2010
0.12	Canada	2010
0.11	China	2010
0.07	Australia	2010
0.07	Portugal	2010
0.07	Turkey	2012
0.06	Italy	2012

Table 14: Top countries based on frequency
(Authors analysis on collected data from WoS)

Frequency	Author
856	USA
709	China
243	Canada
231	Germany
211	Italy
185	India
165	Iran
155	England
149	Australia
126	France

5. Analysis of Institutes

In this section, we present visual analysis of top institutions on agent-based smart grid research. Figure 8 shows top institutions in a visual form. Here, we can see that Tsuinghua University is the most central as well as highly cited node among all other institutions. North China Electric Power University, Delft University of Technology, Chinese Academy of Science, and COMSATS University Islamabad, Pakistan are also among top institutions in the agent-based smart grid research.

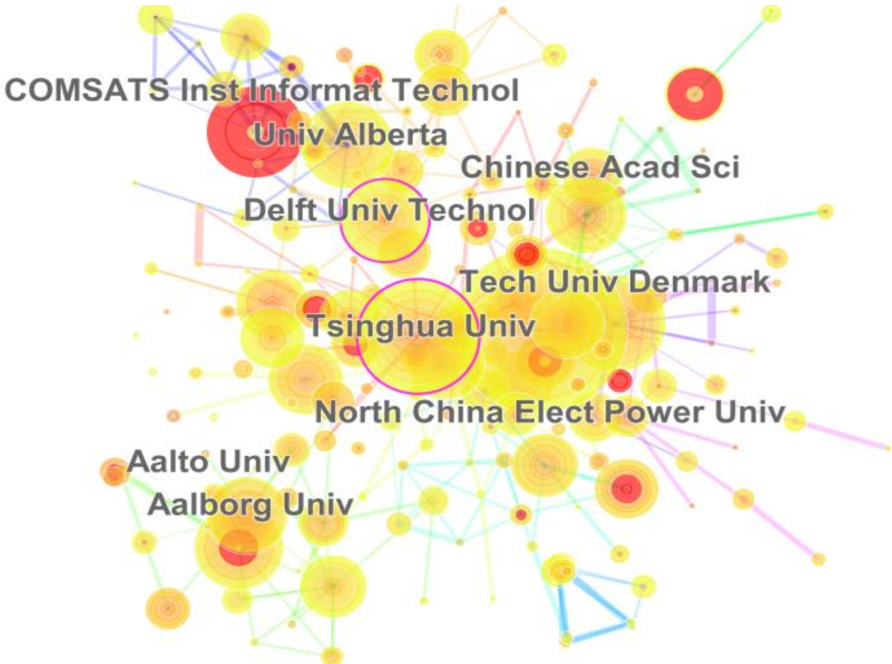

Figure 8: Network of top institutions
(Authors analysis on collected data from WoS)

A visual analysis of the history of the burstness of top institutions is shown in Figure 9. This shows the list of those universities that are active in the agent-based smart grid research. Here, we see that Pecific NW NatLab has the strongest and longest citation burst among all other institutes from 2010 to 2016. It is followed by University of Auckland and University of Tennesse. It is found that National University of Singapor and Sherif Univeristy of Technology have shortest citation burst.

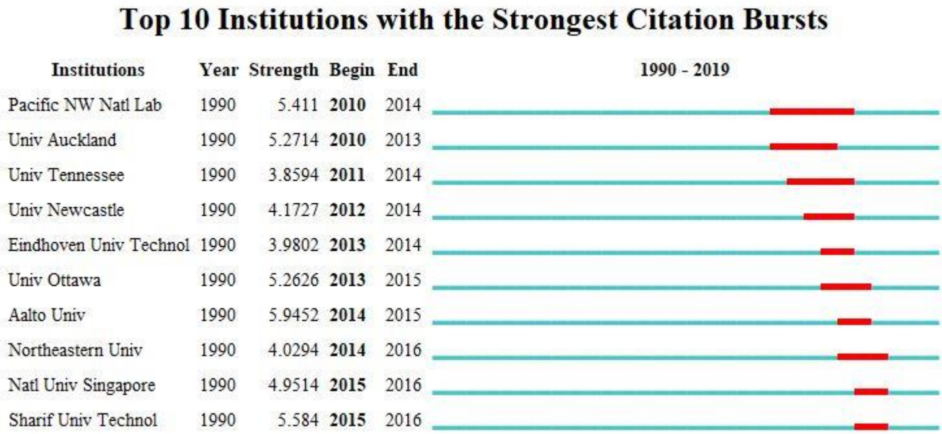

Figure 9: Citation burst of top institutions
(Authors analysis on collected data from WoS)

Next, we present an analysis of top institutions based on centrality. This has been shown in Table 15. The top ranked item by centrality is Tsinghua University with centrality of 0.13. The second one is Delft University of Technology, with centrality of 0.12. The third is Tech University Denmark, with centrality of 0.09. The 4th is University Alberta with centrality of 0.09. The 5th is Chinese Academy of Science, with centrality of 0.08. The 6th is Islamic Azad University with centrality of 0.07. The Aalborg University, Southeast University, Politecn Milan and Nanyang Technology University have centrality of 0.06 and lowest positions on the list.

Table 15: Top institutions based on centrality
(Authors analysis on collected data from WoS)

Centrality	Institutions
0.13	Tsinghua University
0.12	Delft University Technology
0.09	Tech University Denmark
0.09	University Alberta
0.08	Chinese Academy Science
0.07	Islamic Azad University
0.06	Aalborg University
0.06	Southeast University
0.06	Politecn Milan
0.06	Nanyang Technology University

Our next focus is on the analysis of institutions based on frequency of publications. This has been shown in Table 16. It can be noted that North China Electrical Power University has the highest rnaking with the frequency of 63 publications. Tsinghua University is followed by Technical University of Denmark with the frequency of 43 and 37 respectively. Next, COMSATS Institutes of Information Technology has 35 published articles. Next, the list shows University of Alberta and Aalto University. It is observed that Tianjin University has lowest publication frequency among others.

Table 16: Top institutions based on frequency
(Authors analysis on collected data from WoS)

Frequency	Institutions
63	North China Elect Power Univ
43	Tsinghua Univ
37	Tech Univ Denmark
35	COMSATS Inst Informat Technol
33	Univ Alberta
32	Aalto Univ
31	Delft Univ Technol
29	Chinese Acad Sci
29	Aalborg Univ
27	Tianjin Univ

6. Analysis of co-author

In this section, we present an analysis of author co-citation network. In Figure 10, the co-author network has been shown. The detailed analysis is given in Table 17 and Table 18.

The top ranked item by citation counts is Nadem Javaid (Javaid et al., 2015) with citation counts of 47. The second one is Zita Vale (Silva et al. 2012) with citation counts of 26. The third is Zahoor Ali Khan (Javaid, Ilyas, et al., 2015) with citation counts of 21. The 4th is Tiago Pinto (Barreira et al., 2013) with citation counts of 17. The 5th is Valerity Vyatkin (Chia-han Yang et al., 2013) with citation counts of 16. The 6th is Zhu Han (Saad et al., 2012) with citation counts of 15. The 7th is Sebastian Lehnhoff (Hinrichs et al., 2014) with citation counts of 13. Next, Gulnara Zhabelova (Zhabelova & Vyatkin, 2012) and Hugo Morais (Silva et al., 2012) have citation counts of 11.

The top ranked item by bursts is Jamil Y. Khan (Nafi & Khan, 2012) in 2012, with bursts of 5.31. The second one is Gulnara Zhabelova (Zhabelova & Vyatkin, 2012) with bursts of 4.38. The third Valerity Vyatkin (Chia-han Yang et al., 2013) with bursts of 4.29. The 5th is Husheng Li

(Meng et al., 2011) with bursts of 4.15. The 6th is Jason Brown (Brown & Khan, 2012) with bursts of 3.46.

Table 17: Top author by citation count
(Authors analysis on collected data from WoS)

Citation counts	Author
47	Nadeem Javaid
26	Zita Vale
21	Zahoor Ali Khan
17	Tiago Pinto
16	Valeraity VyatkinV
15	Zhu Han
13	Sebastian Lehnhoff
11	Umar Qasim
11	Gulnara Zhabelova
11	Hugo Morais

Table 18: Top authors by burst
(Authors analysis on collected data from WoS)

bursts	references	Year
5.31	Jamil Y Khan	2012
4.38	Gulnara Zhabelova	2010
4.34	Umar Qasim	2015
4.29	Valerity V. Yatkin	2010
4.15	Husheng Li	2011
3.46	Jason Brwon	2012

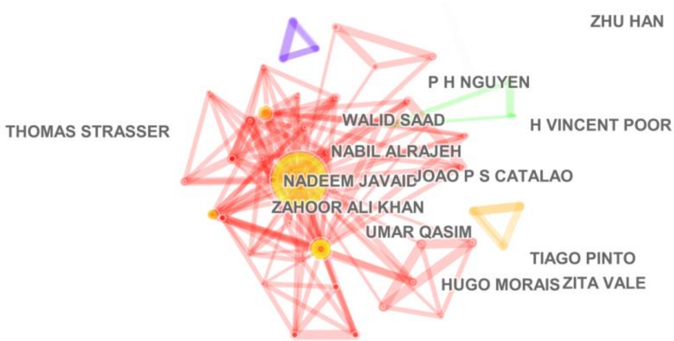

Figure 10: Network of top co-authors
(Authors analysis on collected data from WoS)

7. Analysis of cited authors

This section presents analysis of the cited-authors network. Figure 11 shows network of cited-authors in the domain. This network consists of 394 cited authors along with 7203 links. It is important to note here that there is a problem in the dataset. The CiteSpace identified a cited-author named as "Anonymous". In terms of frequency it is a most cited and central node in the network. However, on searching online we found no such author with this name. The detailed analysis is discussed as following.

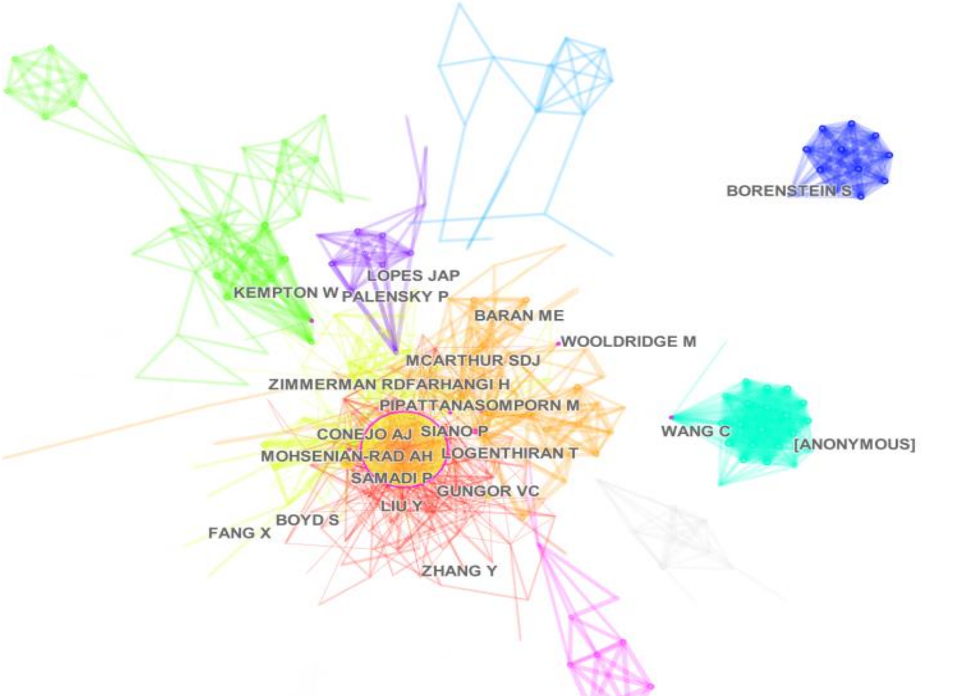

Figure 11: Network of top cited authors
(Authors analysis on collected data from WoS)

The top ranked item by centrality is (C. Wang & Mahadevan, 2011) with centrality of 0.16. The second one is (Amin, 2011) with centrality of 0.15. The third is (Rahimi & Ipakchi, 2010) with centrality of 0.14. The 4th is (Shao, Zhang, Pipattanasomporn, & Rahman, 2010) with centrality of 0.13. The 5th is (Kersting & Green, 2011) with centrality of 0.12. The 6th is (Bouxsein et al., 2010) with centrality of 0.12. The 7th is (Rudd, McArthur, & Judd, 2010) with centrality of 0.11. The 8th is (Dimeas & Hatziargyriou, 2010) with centrality of 0.09. The 9th is (Lopes, Soares, & Almeida, 2011) with centrality of 0.09.

Table 19: Top cited-authors based on centrality
(Authors analysis on collected data from WoS)

Centrality	References	cluster #
0.16	Wang C, 2011, SO, 0, 0	5
0.15	Amin SM, 2010, SO, 0, 0	1
0.14	Ipakchi A, 2010, SO, 0, 0	2
0.13	Pipattanasomporn M, 2010, SO, 0, 0	1
0.12	Kersting WH, 2011, SO, 0, 0	3
0.12	Boyd S, 2010, SO, 0, 0	2
0.11	Mcarthur SDJ, 2010, SO, 0, 0	1
0.10	[Anonymous], 2010, SO, 0, 0	0
0.09	Hatziargyriou N, 2010, SO, 0, 0	1
0.09	Lopes JAP, 2010, SO, 0, 0	2

Table 20 shows the list of top cited-authors based on frequency. As discussed above, there exists a problem in the dataset. The tool identified a cited-author with the name “Anonymous” with the most 1030 citations. However, by searching on internet, we found no such author. Next, Mohsenian-rad (Mohsenian-Rad & Leon-Garcia, 2011) is on second number with 273 citations. Gungor VC (Supriya, Magheshwari, Sree Udhyalakshmi, Subhashini, & Musthafa, 2015) is on third position with 169 citations. This is followed by Logenthiran T (Logenthiran, Srinivasan, Khambadkone, & Aung, 2010) with 151 citations. Next, Mcarthur SDJ (Rudd et al., 2010), Pipattanasomporn M (Shao et al., 2010), Feng X (Huang, Cui, Yin, Zhang, & Feng, 2017), Samadi P (Samadi, Schober, & Wong, 2011), and Palensky P (Palensky & Dietrich, 2011) are also listed as top cited-authors based on frequency.

Table 20: Top cited-authors based on frequency
(Authors analysis on collected data from WoS)

Freq	**Author**
1030	[Anonymous]
273	Mohsenian-rad AH
169	Gungor VC
151	Logenthiran T
149	Mcarthur SDJ
146	Pipattanasomporn M
143	Fang X
134	Samadi P
126	Palensky P

Summary of results

In this paper, we have adopted CiteSpace (a scientometric analysis tool) for different of analysis on the agent-based smart grid research. The key focus of this review was to give an overview of the emerging trends and dynamic of the domain over time. In the following section, we discuss our key findings.

Firstly, through cluster analysis, we found that cluster #0 was the largest cluster containing 80 nodes in the average year of 2011. The mutual index terms in this cluster were demand response, smart home and appliance scheduling. The articles by Mohsenian-rad AH, 2010 Fang X, 2012, are the key turning points in the domain.

Our next analysis was to identify key journals, authors, countries, institutions, and subject's categories. Our analysis produced various interesting results. Next, we discuss these analyses.

In the analysis of key journals, we noted that the "IEEE Transaction on Smart Grid" has the largest number of highly cited papers in this domain. This journal also has most number of published articles in the domain. The journal "Nature" is the most central journal in the list.

In the top cited-author analysis, we noted that "Wang C., 2011" has the strongest burst among all authors in the list. We also performed analysis of most cited authors and found that "Wang C, 2011" is mostly cited authors in the research of agent-based smart grid. His area of research is smart grid, physical system, wireless sensor network, and security.

In the top countries analysis, we noted that "USA" is top country among all others based on frequency as well as citation. Others countries like China, Canada, Germany, and France are also actively work in the domain.

On the analysis of top institutions, we noted that "Pacific NW NatLab" has strongest and longest citation burst in the duration of 2010 to 2014. Based on frequency, "North China Elect. Power University" is on the top among all other institutes. Based on centrality score, "Tsinghua University" has top the list.

The analysis of top categories showed that the category "Engineering" leads over other categories with frequency 2744 and 0.40 centrality value. Category analysis showed that the work on agent-based computing of smart grid is multi-discipline. Engineer, computer scientist, physician, and environmental scientists all are working the domain.

Conclusions

In this paper, we have presented a detailed bibliographic review on agent-based smart grid research. The bibliographic data was collected from WoS database during the period of 1992 to 2019. The dataset was contained all journals, conferences, and workshop research work.

Our review showed various interesting results. The analysis showed that the domain gain significant research interest in 2007. Wang C, 2011 is most cited author in the domain. From journal perspective, the most cited journal is IEEE Transaction on Smart Grid. It contributed highest number of publications in the domain. The USA is most productive country in the domain while Pecific NW NatLab is most cited institute among all other institutions. In the category analysis, we found that this domain is multi-disciplinary domain. Researchers from engineering, computer science, and environmental science are working the smart grid research by using agent-based computing technology.

The possible extension of this work can be to explore the demand response, smart home, electric vehicles research topics of the domain.

References

Amin, S. (2011). U.S. grid gets less reliable [The Data]. *IEEE Spectrum*, *48*(1), 80–80. https://doi.org/10.1109/mspec.2011.5676396

Barreira, D., Garganta, J., Pinto, T., Valente, J., & Anguera, T. (2013). Do attacking game patterns differ between first and second halves of soccer matches in the 2010 FIFA World Cup? In *Science and Football VII: The Proceedings of the Seventh World Congress on Science and Football* (pp. 193–198). https://doi.org/10.4324/9780203131879

Bouxsein, M. L., Boyd, S. K., Christiansen, B. A., Guldberg, R. E., Jepsen, K. J., & Müller, R. (2010, July). Guidelines for assessment of bone microstructure in rodents using micro-computed tomography. *Journal of Bone and Mineral Research*, Vol. 25, pp. 1468–1486. https://doi.org/10.1002/jbmr.141

Brown, J., & Khan, J. Y. (2012). Performance comparison of LTE FDD and TDD based Smart Grid communications networks for uplink biased traffic. *2012 IEEE 3rd International Conference on Smart Grid Communications, SmartGridComm 2012*, 276–281. https://doi.org/10.1109/SmartGridComm.2012.6485996

Chen, C. (2014). The CiteSpace Manual version 0.77. *College of Computing and Informatics*, *103*(3), 1–84. Retrieved from http://cluster.uschool.drexel.edu/~cchen/citespace/CiteSpaceManual.pdf

Chen, C. (2016). CiteSpace : a practical guide for mapping scientific literature. In *Novinka*. Retrieved from http://cluster.cis.drexel.edu/~cchen/citespace/books/

Chia-han Yang, Gulnara Zhabelova, Chen-Wei Yang, & Valeriy Vyatkin. (2013). Cosimulation environment for event-driven distributed controls of smart grid. *IEEE Transactions on Industrial Informatics*, *9*(3), 1423–1435. https://doi.org/10.1109/TII.2013.2256791

Dimeas, A. L., & Hatziargyriou, N. D. (2010). Multi-agent reinforcement learning for microgrids. *IEEE PES General Meeting, PES 2010*. https://doi.org/10.1109/PES.2010.5589633

Dusparic, I., Harris, C., Marinescu, A., Cahill, V., & Clarke, S. (2013). Multi-agent residential demand response based on load forecasting. *2013 1st IEEE Conference on Technologies for Sustainability, SusTech 2013*, 90–96. https://doi.org/10.1109/SusTech.2013.6617303

Fang, X., Misra, S., Xue, G., & Yang, D. (2012). Smart grid - The new and improved power grid: A survey. *IEEE Communications Surveys and Tutorials*, Vol. 14, pp. 944–980. https://doi.org/10.1109/SURV.2011.101911.00087

Farhangi, H. (2010). The path of the smart grid. *IEEE Power and Energy Magazine*, *8*(1), 18–28. https://doi.org/10.1109/MPE.2009.934876

Farooq, K., Khan, B. S., Niazi, M. A., Leslie, S. J., & Hussain, A. (2018). Clinical decision support systems: A visual survey. *Informatica (Slovenia)*, *42*(4), 485–505. https://doi.org/10.31449/inf.v42i4.1571

Golpayegani, F., Dusparic, I., Taylor, A., & Clarke, S. (2016). Multi-agent Collaboration for Conflict Management in Residential Demand Response. *Computer Communications*, *96*, 63–72. https://doi.org/10.1016/j.comcom.2016.04.020

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2013). A Survey on smart grid potential applications and communication requirements. *IEEE Transactions on Industrial Informatics*, *9*(1), 28–42. https://doi.org/10.1109/TII.2012.2218253

Hinrichs, C., Lehnhoff, S., & Sonnenschein, M. (2014). *A Decentralized Heuristic for Multiple-Choice Combinatorial Optimization Problems*. https://doi.org/10.1007/978-3-319-00795-3_43

Huang, X., Cui, Y., Yin, G., Zhang, B., & Feng, G. (2017). Preparation and Thermal Properties of Capric-palmitic-stearic Acid/Expanded Graphite Composite Phase Change Material for Energy Storage. *Cailiao Daobao/Materials Review*, *31*(7), 52–56. https://doi.org/10.11896/j.issn.1005-023X.2017.014.011

Jannati, J., & Nazarpour, D. (2017). Optimal energy management of the smart parking lot under demand response program in the presence of the electrolyser and fuel cell as hydrogen storage system. *Energy Conversion and*

Management, *138*, 659–669. https://doi.org/10.1016/j.enconman.2017.02.030

Javaid, N., Ahmad, A., Nadeem, Q., Imran, M., & Haider, N. (2015). iM-SIMPLE: iMproved stable increased-throughput multi-hop link efficient routing protocol for Wireless Body Area Networks. *Computers in Human Behavior*, *51*, 1003–1011. https://doi.org/10.1016/j.chb.2014.10.005

Javaid, N., Ilyas, N., Ahmad, A., Alrajeh, N., Qasim, U., Khan, Z. A., … Khan, M. I. (2015). An efficient data-gathering routing protocol for underwater wireless sensor networks. *Sensors (Switzerland)*, *15*(11), 29149–29181. https://doi.org/10.3390/s151129149

Ju, L., Zhang, Q., Tan, Z., Wang, W., Xin, H., & Zhang, Z. (2018). Multi-agent-system-based coupling control optimization model for micro-grid group intelligent scheduling considering autonomy-cooperative operation strategy. *Energy*, *157*, 1035–1052. https://doi.org/10.1016/j.energy.2018.06.097

Kersting, W. H., & Green, R. K. (2011). The application of Carson's equation to the steady-state analysis of distribution feeders. *2011 IEEE/PES Power Systems Conference and Exposition, PSCE 2011*. https://doi.org/10.1109/PSCE.2011.5772579

Kim, B. G., Zhang, Y., Van Der Schaar, M., & Lee, J. W. (2016). Dynamic pricing and energy consumption scheduling with reinforcement learning. *IEEE Transactions on Smart Grid*, *7*(5), 2187–2198. https://doi.org/10.1109/TSG.2015.2495145

Lamedica, R., Teodori, S., Carbone, G., & Santini, E. (2015). An energy management software for smart buildings with V2G and BESS. *Sustainable Cities and Society*, *19*, 173–183. https://doi.org/10.1016/j.scs.2015.08.003

Logenthiran, T., Srinivasan, D., Khambadkone, A. M., & Aung, H. N. (2010). Multi-Agent System (MAS) for short-term generation scheduling of a microgrid. *2010 IEEE International Conference on Sustainable Energy Technologies, ICSET 2010*. https://doi.org/10.1109/ICSET.2010.5684943

Lopes, J. A. P., Soares, F. J., & Almeida, P. M. R. (2011). Integration of electric vehicles in the electric power system. *Proceedings of the IEEE*, *99*(1), 168–183. https://doi.org/10.1109/JPROC.2010.2066250

Meng, J., Yin, W., Li, H., Hossain, E., & Han, Z. (2011). Collaborative spectrum sensing from sparse observations in cognitive radio networks. *IEEE Journal on Selected Areas in Communications*, *29*(2), 327–337. https://doi.org/10.1109/JSAC.2011.110206

Modeling and Simulation of Complex Communication Networks. (2019). In M. A. Niazi (Ed.), *Modeling and Simulation of Complex Communication Networks*. https://doi.org/10.1049/pbpc018e

Mohsenian-Rad, A. H., & Leon-Garcia, A. (2011). Distributed internet-based load altering attacks against smart power grids. *IEEE Transactions on Smart Grid*, *2*(4), 667–674. https://doi.org/10.1109/TSG.2011.2160297

Mohsenian-Rad, A. H., Wong, V. W. S., Jatskevich, J., Schober, R., & Leon-Garcia, A. (2010). Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid. *IEEE Transactions on Smart Grid*, *1*(3), 320–331. https://doi.org/10.1109/TSG.2010.2089069

Muralitharan, K., Sakthivel, R., & Shi, Y. (2016). Multiobjective optimization technique for demand side management with load balancing approach in smart grid. *Neurocomputing*, *177*, 110–119. https://doi.org/10.1016/j.neucom.2015.11.015

Nafi, N. S., & Khan, J. Y. (2012). A VANET based intelligent road traffic signalling system. *Australasian Telecommunication Networks and Applications Conference, ATNAC 2012*. https://doi.org/10.1109/ATNAC.2012.6398066

Niazi, M. A. K. (2017). Towards A Novel Unified Framework for Developing Formal, Network and Validated Agent-Based Simulation Models of Complex Adaptive Systems. *ArXiv*, p. 275.

Palensky, P., & Dietrich, D. (2011). Demand side management: Demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics*, *7*(3), 381–388. https://doi.org/10.1109/TII.2011.2158841

Rahimi, F., & Ipakchi, A. (2010). Demand response as a market resource under the smart grid paradigm. *IEEE Transactions on Smart Grid*, Vol. 1, pp. 82–88. https://doi.org/10.1109/TSG.2010.2045906

Rehmani, M. H., Davy, A., Jennings, B., & Assi, C. (2019). Software Defined Networks-Based Smart Grid Communication: A Comprehensive Survey. *IEEE Communications Surveys and Tutorials*, *21*(3), 2637–2670. https://doi.org/10.1109/COMST.2019.2908266

Risteska Stojkoska, B. L., & Trivodaliev, K. V. (2017). A review of Internet of Things for smart home: Challenges and solutions. *Journal of Cleaner Production*, Vol. 140, pp. 1454–1464. https://doi.org/10.1016/j.jclepro.2016.10.006

Rudd, S., McArthur, S. D. J., & Judd, M. D. (2010). A generic knowledge-based approach to the analysis of partial discharge data. *IEEE Transactions on Dielectrics and Electrical Insulation*, *17*(1), 149–156. https://doi.org/10.1109/TDEI.2010.5412013

Saad, W., Han, Z., Poor, H. V., & Başar, T. (2012). Game Theoretic Methods for the Smart Grid: An overview of microgrid systems, demand-side management, and smart grid communications. *Ieeexplore.Ieee.Org*. Retrieved from https://ieeexplore.ieee.org/abstract/document/6279592/

Samadi, P., Schober, R., & Wong, V. W. S. (2011). Optimal energy consumption scheduling using mechanism design for the future smart grid. *2011 IEEE International Conference on Smart Grid Communications, SmartGridComm 2011*, 369–374. https://doi.org/10.1109/SmartGridComm.2011.6102349

Shao, S., Zhang, T., Pipattanasomporn, M., & Rahman, S. (2010). Impact of TOU rates on distribution load shapes in a smart grid with PHEV penetration. *2010 IEEE PES Transmission and Distribution Conference and Exposition: Smart Solutions for a Changing World*. https://doi.org/10.1109/TDC.2010.5484336

Shirzeh, H., Naghdy, F., Ciufo, P., & Ros, M. (2015). Balancing energy in the smart grid using distributed value function (DVF). *IEEE Transactions on Smart Grid*, *6*(2), 808–818. https://doi.org/10.1109/TSG.2014.2363844

Siano, P. (2014). Demand response and smart grids - A survey. *Renewable and Sustainable Energy Reviews*, Vol. 30, pp. 461–478. https://doi.org/10.1016/j.rser.2013.10.022

Siebert, L. C., Sbicca, A., Aoki, A. R., & Lambert-Torres, G. (2017). A behavioral economics approach to residential electricity consumption. *Energies*, *10*(6), 1–18. https://doi.org/10.3390/en10060768

Silva, M., Morais, H., & Vale, Z. (2012). An integrated approach for distributed energy resource short-term scheduling in smart grids considering realistic power system simulation. *Energy Conversion and Management*, *64*, 273–288. https://doi.org/10.1016/j.enconman.2012.04.021

Supriya, S., Magheshwari, M., Sree Udhyalakshmi, S., Subhashini, R., & Musthafa. (2015). Smart grid technologies: Communication technologies and standards. *International Journal of Applied Engineering Research*, *10*(20), 16932–16941. Retrieved from https://ieeexplore.ieee.org/abstract/document/6011696/

Wang, C., & Mahadevan, S. (2011). Heterogeneous domain adaptation using manifold alignment. *IJCAI International Joint Conference on Artificial Intelligence*, 1541–1546. https://doi.org/10.5591/978-1-57735-516-8/IJCAI11-259

Wang, G., Zhang, Q., Li, H., McLellan, B. C., Chen, S., Li, Y., & Tian, Y. (2017). Study on the promotion impact of demand response on distributed PV penetration by using non-cooperative game theoretical analysis. *Applied Energy*, *185*, 1869–1878. https://doi.org/10.1016/j.apenergy.2016.01.016

Yao, L., Lim, W. H., & Tsai, T. S. (2017). A Real-Time Charging Scheme for Demand Response in Electric Vehicle Parking Station. *IEEE Transactions on Smart Grid*, *8*(1), 52–62. https://doi.org/10.1109/TSG.2016.2582749

Zhabelova, G., & Vyatkin, V. (2012). Multiagent smart grid automation architecture based on IEC 61850/61499 intelligent logical nodes. *IEEE Transactions on Industrial Electronics*, *59*(5), 2351–2362. https://doi.org/10.1109/TIE.2011.2167891