Implementing Digital Twins in Energy Systems: Meta Analysis of the State of Art and Evolution

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December 4, 2021

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Abstract. Energy System is a critical Infrastructure that is categorized in Cyber-Physical-Social Systems because of the integration of computerized control systems and consumption patterns of the society, with Physical entities of production, transmission, and distribution. Cutting-edge technologies, sustainable development, and Digitization of the essential services of the society disclose emerging issues to the energy systems. Digital Twin(DT) is a state-of-the-art technology that is employed to deal with the complexity of Cyber-Physical-Social systems and brings Energy IoT(EIoT) into action. The current study investigates the implementations of DT in the Energy Systems Domain. The search results from three digital libraries (SCOPUS, WOS, IEEE) unveiled the freshness of the topic, which has been started in this sector since 2018. This article is a Meta Data Analysis, which is the primary phase of a Systematic Literature Review that carries out on DT implementations in Energy Systems. The results of statistical analysis that combine the results of multiple scientific studies shows the most studied features, applications, and gaps in the body of knowledge.

Keywords: Digital Twins · Energy Systems · Smart Energy System · Cyber-Physical Systems · Cyber-Physical-Social Systems · Data Driven Model · Smart Grid · Power Systems · Artificial Intelligence · Machine Learning.

1 Introduction

The rapid growth of digitization [13], Industry 4.0 [32], and IoT [33] have changed the energy demand and production pattern. This trend is not limited to the industry but already got in people's daily life. It means the traditional Cyber-Physical energy systems transform into Cyber-Physical-Social systems. Accordingly, human settlements are becoming smart cities, and sustainable development turned into a hot issue. Alongside sustainable development, socio-technical and socio-ecologic transformations resulted in the need of a sustainable and reliable energy system (ES). In the current article, the energy system is composed of all kind of energy sources (Fossil fuel and renewable sources), components to produce and store the energy (Electricity and Thermal energy), delivery (Distribution and transmission), and end-users consumption or production behavior [38], regardless of the scale of the system. The energy system is considered a complex system, which is a vital infrastructure of the society. The reliability of this critical system is crucial [23] and an effective way to operate in an optimal state is to automate it. Recent studies pinpoint the effectiveness of forming a smart energy system [10]. The first study on efficiency of Energy Systems (ES) by making it "smart" was published in 1983 [11]. Huebler and Rush probed implementing smart meters and robots in ES.

Digital Twin (DT) is a technology paradigm to computerize and eventually create a smart system. The trigger of using DT as a virtual archetype of a Physical Entity (Ph. E) goes back to 2010 when the creation of an avatar in a virtual world was raised to model the human relations [22]. Notwithstanding, DTs were born into social science, but it found its way in industry space in 2011 through a structural simulation that aimed to predict the working life of an aircraft[30].

It lasted until 2018 to have the first look at ESs through DTs lens [28]. Tucker et al. evaluated the ES as a Cyber-physical system (CPS) employing DTs. They focused on risk reduction in the system; thereafter, the attempts to solve other issues in ES using DTs acutely escalated. Although conducted investigations are precious, they were mostly undertaken in diverse domains; however, the focused researches started in 2018 significantly revealed the gaps in the body of knowledge of the topic. There are different definitions in literature for DT which are mostly derived from the application and scope of employing DT. In current article, the definition adapted from [20] and "Digital Twin Consortium" [8], then customized regarding the Cyber-Physical-Social Systems(CPSS) in ES scope is:

> Digital Twin is a component of CPSS that couples with the physical real-world entities and the stakeholders through a bidirectional communication channel to present the state of the entire system, to store data, to monitor the system and to automate its operation, employing Artificial Intelligence and Data-Driven Decision Support Systems (DDDSS).

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Bearing in mind that the Cyber-physical-Social Energy System (CPSES) is a cutting edge contrivance in smart grids and efficient energy systems, the present paper examines the relevant literature to summarise reliable results of Digital Twins (DTs) implementation on the grounds of conducted researches. The specific objective of the current SLR is to collect, summarize and assess the produced body of knowledge associated with implementing Digital Twins in energy systems functioning, maintenance and process improvement. This study has been conducted to answer four specific research questions (RQ):

- RQ1: What are the most studied domains/features of DT within ES?
- RQ2: What are the most studied applications of DT within Energy Systems ?

– RQ3: Which are the gaps of DT body of knowledge in ES?

To assure protecting the review process from bias, clarity and validity are considered along with the suitability [7] as the principal attributes of the current review. The results unveil that the implementation of DTs in energy systems is a fresh topic; nevertheless, the effectiveness of DTs applications caught the scholars' attention and the publications are increasing sharply. In the next section, the methodology of this study will be explained in detail. Section 3 is devoted to the discussion of the work and section 4 is for the conclusions and further works.

2 Methodology

2.1 General structure

The structure of the paper may follow the format suggested by Smith et al [26], whereas the outline of the steps of SLR, is adopted from an approved approach [27]; the keyword selection follows the process which is already implemented by SLR in engineering scope [2]. The general structure of this study includes two main phase. First, The primary search to collect principal information about state-of-the-art; and second search following the SLR to answer the research questions. Figure 1 reports the outline of the steps illustrated below.

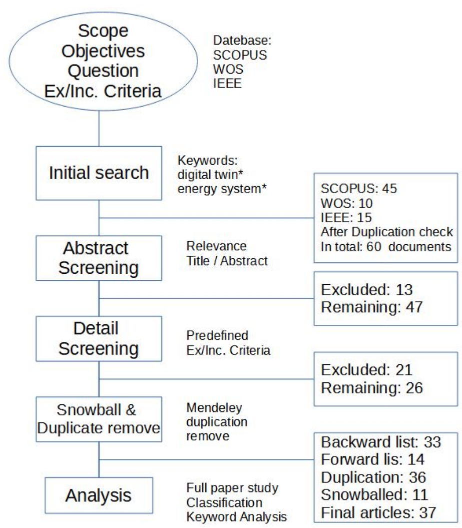

Fig. 1. Outline of the SLR steps

2.2 Sources

We have used three digital libraries (SCOPUS, WOS, IEEE) to carry out the Document Search. Current article investigates the implementation of DTs in energy systems engineering. The main scope is the complex energy systems; therefore, all literature that is associated with implementing DT, the maturity level of sub-systems, energy system of systems as a complete unit, evaluating/analyzing and improving the efficiency of system are included in search process. Search area is focused on Engineering along with Social studies. Document type is not a limit in this study; and the following document types are included: Article, Conference Paper, Review, Book Chapter, Book.

2.3 Searching

In second phase, three searches have been done to define the background and primary keywords for next phase. First, search in SCOPUS has been conducted to identify the keywords of the search string in Second phase. Energy System is considered a complex system composed of Cyber, Physical, and Social active elements; therefore, the second pilot search has been done using the following string: TITLE-ABS-KEY ("energy system*" OR (("Complex systems" OR "cyber*physic*") AND "energy")) AND "digital twin*". Last search was done using less Boolean operators. The comparison of the first 15 papers of the result list shows that the second search string is effectively comprehensive.

Following search strings are used to create the first list of articles to feed SLR approach: **SCOPUS:** TITLE-ABS-KEY ("energy system*") AND "digital twin*" **WOS:** #1 TI=("digital twin*" AND "energy system*") #2 AK=("digital twin*" AND "energy system*") #3 AB=("digital twin*" AND "energy system*") Final result through combination: #3 OR #2 OR #1 Databases= WOS, BIOABS, BCI, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO Timespan=All years Search language=Auto **IEEE:** "Abstract":"digital twin*" AND "energy system*" OR "Document Title":"digital twin*" AND "energy system*" OR "Author Keywords":"digital twin*" AND "energy system*"

2.4 Review Selection

The primary search string unveils the freshness of the topic. The first paper published in 2018. In 2021 the search provides following results: 45 documents in SCOPUS, 10 documents in WOS, 15 documents in IEEE. All documents are reviewed in the first phase after duplication remove and integrating all three databases results. The First Screening is done based on the relevance of the topic to the scope of the SLR and prospective response that a document can provide for the research questions(RQs). Beside screening, and according to the RQs, following information will be extracted for evaluation of the results:
RQ1: The fields and features that are studied more. **RQ2:** Set keyword to the application, clustering, and make a network to identify the interrelations. **RQ3:** The features that studied less according to the following criteria: frequency of the keyword usage, the set of keywords which are used together, relation between the articles through appearance of keywords used in common

In the second screening, the Inc./Ex. Criteria are considered to keep/eliminate the paper from review process. The main goal of this stage is detail screening of the documents involving criteria listed in Table 1. In Table 1 the type of each Criteria and its attribute is described. The next three columns identify the reference section that will be investigated employing each criteria to Keep/Eliminate the document.

Table 1. Inclusion(Inc.)/Exclusion(Ex.) criteria - Mthd.:Methodology, Abst.:Abstract, Strt.:Document Strucutre

Type	Criteria Description	Abst.	Mthd.	Strt.
Inc.	English			X
Inc.	All Doc. Type			X
Inc.	All Source Type			X
Inc.	All Subject area			X
Ex.	Doc. without focus on DTs implementation in Practice	X	X	
Ex.	No defined Method of DTs implication		X	
Ex.	Less than 1500 words		X	
Ex.	Short Report, Essay, Extended Abstract			X
Ex.	Doc. does not answer any RQ	X	X	

The Third stage of the current SLR is conducting a systematic snowballing. The outline of the steps follows the process introduced by Wholin to identify the relevant research papers from a selected st of papers[35]. Both Forward and Backward iteration are employed in this study aim to efficient snowballing. Figure 2 illustrates the outline of the steps of snowballing. the result is shown in a matrix in Appendix A.

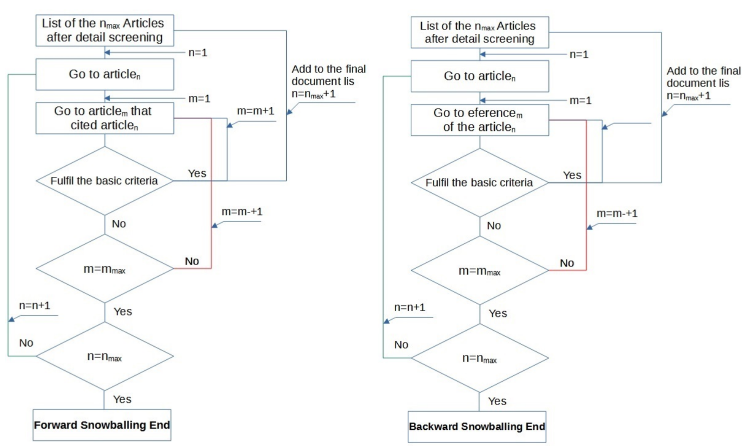

Fig. 2. Left: Forward snowballing, Right:Backward snowballing

2.5 Methods and Tools

Tools During conducting the current review, diverse tools utilized in connection with the needs. Advanced Search engines of ASOPUS, WOS, IEEE employed to collect the primary set of documents. For Snowball iterations we used Google Scholar search engine. Zotero is used for reference management; Microsoft Excel and various libraries of Python are utilized for statistical analysis and data visualization. To create and analyze the network, Gephi is used.

Clustering Clusters are made in order to find the relation between the articles regarding the keywords. To avoid adverse effect of the diversity of keywords and create a common concepts, the keywords are categorized in 18 clusters. 18 keywords are not included in any of the clusters because of having no relation with any of the other clusters and no repetition or similar keywords. The clusters are shown in Figure 2. This network will provide a new perspective on the relation between attainments, challenges, and applications from the keywords of the articles lens. the The clusters will be made out of the similarity of the keywords from conceptual and technical aspect.

Table 2. Keyword clusters

Simulation/Modeling	***Digital Twin***	***Energy Systems***	***Analysis/Methods***	***Building***
Real-time Simulation	Ditital Twin	Power and Energy Systems	Root Cause Analysis	Building energy
Co-Simulation	digital shadow	industrial energy systems	Network analysis	Built Environment
Power System Simulation	***cyber physical system***	Urban energy systems	data stream analysis	building information modelling
simulation and analysis	Cyber-Physical Energy System	power system	Time series analysis	whole building energy analysis
simulation computing tasks	cyber physical system	Power system testing	hybrid analysis and modeling	indoor air quality
mathematical model	***Digitalisation***	Power system dynamics	fault prediction	construction
ontological model	IoT	Heating systems	transient state estimation	***Sustainabile development***
modelling	Energy Internet	thermal power plants	Diagnostics	Sustainability
model-free	industry 4.0	Innovative energy services	Anomaly Detection	Climate change
load modeling	digitalisation	distributed energy resources	scheduling management method	SDG
Computational modeling	semantic web	system integration	generative design	Urban areas
real-time systems	online monitoring and control	Energy generation	Forecasting	Regional Development
real-time	power grid online analysis	Energy efficiency	Demand side management	Cities
Computer Science/Control	Grid online analysis	energy research	state evaluation	Renewable energy
inmemory computing	***AI***	Power electronics	task assignment mechanism	renewable energy sources
parallel computing	Machine Learning	Energy management	probabilistic logic	Technology development
edge computinge	Neural Network model	***Security***	anomaly detection	***Asset Management***
Computer architecture	Temporal Convolution Neural Network	Cyber Security	Complex event processing	power transformer
closed-loop	Artificial Intelligence	security assessment	model reduction	transmission and transformation assets
distributed control	Data Mining	security constraint dispatching	Predictive models	Power stations
Shared Memory	defective text mining	***Data/Big Data***	probabilistic logic	Fuel cells
long short-term memory	intelligent technologies	big data analytics	**Smart Grid**	Turbines
Transport	***IT***	big data cybermetrics	smart cities	Control Center
Transport energy	Information and Communicator Technology	Data acquisition	smart energy	life cycle assessment
Transport	Information and Communicator Technology	Data Analytics	smart grid	***Industry***
Standards	Interprocess Communication	data-driven	networked microgrids	Industrial Systems
		physical knowledge		Manufacturing

Keyword Analysis A Treemap is constructed regarding the exact Author Keywords derived from a hierarchical network with Keywords as criteria and Articles as alternatives. The Treemap shows the most studied aspects and the gaps in the body of knowledge of implementing DTs in ES. The main purpose is recognising the gaps and subsequently the future challenges to fill these gaps. A network is constructed using the Author Keywords clusters. This network is created to identify the communities (related studies) through the inter-relation of the introduced keywords. on the first step, the network is segmented through modularity of the nodes[6]. Modularity identify if the edges in a community is significant. By definition, the Modularity defined by Formula 1 [14]:

$$Q = (\text{fraction of edges within communities}) - (\text{expected fraction}) \tag{1}$$

$$Q = \frac{1}{2m} sum \sum_{C \in P} \sum_{i,j \in C} [A_{i,j} - P_{i,j}] \quad (2)$$

$$\text{if } P_{i,j} = \frac{\langle K \rangle}{2} \text{ , Then} Q = Q_{unif} \quad (3)$$

$$\text{if } P_{i,j} = \frac{K_i K_j}{2m} \text{ , Then} Q = Q_{conf} \quad (4)$$

where A: adjacency matrix, i-j: the number of the nodes, K: degree of the node, m: total number of nodes, C: comunity, P: partition. in directed networks, Formula 1 is slightly changed to following[14]:

$$Q = \frac{1}{2m} \sum_{C \in P} \sum_{i,j \in C} \left[A_{i,j} - \frac{K_i^{in} K_j^{out}}{2m} \right] \quad (5)$$

The ForceAtlas2 algorithm (spatial layout algorithm) is employed for network construction. ForceAtlas2 is the improved version of ForceAtlas within force-directed algorithms[12]. The Clustering Coefficient of the entire network is calculated to see the completeness of the connections of the nodes with neighbors. If all of the neighbor nodes are connected the Average Clustering Coefficient is equal to 1. in current study, it shows the relation between the articles. If Average Clustering Coefficient is 1, all of the articles are connected together. Gephi uses Watts-Strogatz algorithm to calculate the Average Clustering Coefficient[15]. Watts-Strogatz algorithm is a built-in function of Gephi that uses Formula 7[34]where n is total vertices, Ci is local clustering coefficient(Formula 6).

$$C_i = \frac{\text{maximum number of possible links in neiborhood}}{numberof \text{maximum number of possible links in neiborhood}} \quad (6)$$

$$\bar{C} = \frac{1}{n} \sum_{i=1}^{n} C_i \quad (7)$$

Eigen vector centrality is the last method that is used from statistic library of Gephi. This function is used as the a measure of node importance in a network. We utilized directed network mode with 100 iteration In current study. Eigenvector centrality in this study illustrate the importance of an article within the network of the articles. in this approach, first a vector b0 created randomly. b0 is an approximation to start iterations.

$$b_{k+1} = \frac{Ab_k}{\|Ab_k\|} \quad (8)$$

Then considering the Recurrence Relation (Formula 8), vector b will be multiplied by the given diagonalizable matrix A. after normalization this process repeats and bk converges to an eigen vector.

2.6 Quality Assessment of Reviews

Clarity The structure of the selection is structured in a systematic way, in which, the general procedure of data extraction, document search method including the Databases, Search Strings, and screening criteria is explained in Section 2;

Validity Both kind of the biases in SLR are considered and avoided through following strategies. Selection Bias: Including a document depends on the relevance, Inc/Ex Criteria which are listed in Subsection2.3. Publication Bias: Current SLR searched the documents through 3 databases -SCOPUS, WOS, IEEE- without any exclusion regarding the type of the document.

Auditability The procedure is repeatable in the same scope through explained terminology; it means, following the outline of the steps in searching and selection subsections of Methodology will be resulted in the same list of documents.

3 Results and Discussion

The advance search in digital libraries (Section 2) provided us 45 document from SCOPUS, 15 documents from IEEE, and 10 documents from WOS as initial results. After applying Duplication Check 60 item remained, which unveil that employing DTs in ES is a pioneering technology that started to be investigated from 2018. Nevertheless the rapid growth of the publications chronologically shows the interest of the scholars about the mentioned cutting-edge technology.

The initial search report and the detail of snowballing is available in Appendix A. After Screening process, the final results for full paper study are 37 articles.

The Treemap of the keywords is shown in Figure 3.The Treemap shows that Data Analytics, cyber-Physical Systems, Internet of the things, and Smart Grid are used more than the other keywords. This map unveils the importance

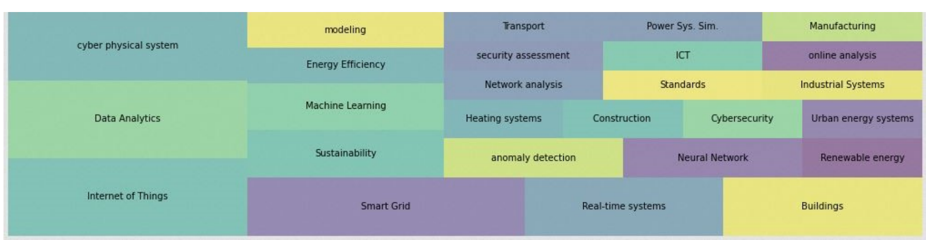

Fig. 3. Treemap of the original keywords belong entire group of final articles

of these concepts in DT; even a deeper view on the entire system from technical lens depicts the interrelation of this keywords. DT is data-driven replica of a physical entities. Therefore, the behavior of digital replica is derived from information that is processed and transformed through Data Analytics[24]. In energy systems, DT is operating as system of systems because its functioning is based on two main systems along with communication means between them. Cyber entities in digital side, and physical entities in energy system side form a complex system. Scholars suggested different architectures for this complex system that will be analyzed and discussed in future studies; It worth mentioning that all architectures consider a communication layers to clarify the communication means and protocols. The Internet of Things IoT in Treemap illustrate that most of the articles adopt internet in order to exchanging data between Cyber and Phicical entities within a Cyber-Physic system[25]. Energy Internet of Things (EIoT) [21] is a particular type of IoT concept utilized in the energy infrastructure. To bring in EIoT in action, the Ph.E is embedded with diverse sensors that povide data for Data Analystics and feed them in AI algorithms aims to make real-time decisions. This process create a smart system which in energy sector is called Smart Grid[19]. This grid could be a smart house energy grid[3], a group of smart houses as a smart city[31], or the whole electricity and thermal power distribution, and transmission grid plus transportation in a country[16].

194 keywords are extracted from the articles. Because of the diversity of the terms that Authors are used for same general concept (sustainable energy and renewable energy), different terms that share common feature (Both Deep Learning and predictive Analytics are methods of Machine Learning), abbreviation (IoT and Internet of Things), or annotating the phrasal names (Cyber-Physic and Cyber Physic), we clustered the original keywords in 18 predefined categories (Figure 2)(18 keywords are used in a individual concepts that cant be in the predifined family groups). The combination of this keywords(in couples) are studied to see which terms are used together the most Figure 2. The occurrence of couple of Keywords shows the "Digital Twin , AI" and "Energy Systems, Digitalisation" are studied in the same articles more than the other combination of the words 4. It has two significant meanings. First, DT is a solution of digitalization of Energy Systems; second, AI is heart of the DT and the biggest advantage of DT in comparison with difference between traditional simulation methods, monitoring and control systems and SCADA. The Network Analysis of the articles -using the keywords as relation vector- is the last analysis of the final articles list. There three two main objectives in performing this analysis in current study. First, grouping the articles in a significant way regarding to keywords to future studies; Second, Finding the most related articles to go deeper in investigation and extract information on applications, implementations, advancements, and advancements of DT in this articles(Which will be discussed in Section 4-7); Finally, to seek for the gaps and less studied topic regarding the network and relation between the articles. Figure 5 illustrate the sub-networks inside the general network of the studies and relation between the studies. In order to have a detect the communities inside the general network, Modularity index is employed[6]. The calculation parameters are Randomize Mode: On, Use edge weights: On, Resolution: 1.0; and the results shows (Figure 6-Left) Modularity: 0.155, Modularity with resolution: 0.155, and Number of Communities: 3. Figure 5-right shows that there are 3 main sub-network inside the entire list. Nevertheless, the relation between the articles connected network with Avg. clustering Coefficient of the entire network equal to 0.44. that means articles are not well connected, but the articles in yellow are the least related articles to the others [[37], [18], [1], [5]]. Among the articles in the list one article is focused on enhancing Cyber security and another one is focused on Smart Grid Security. It

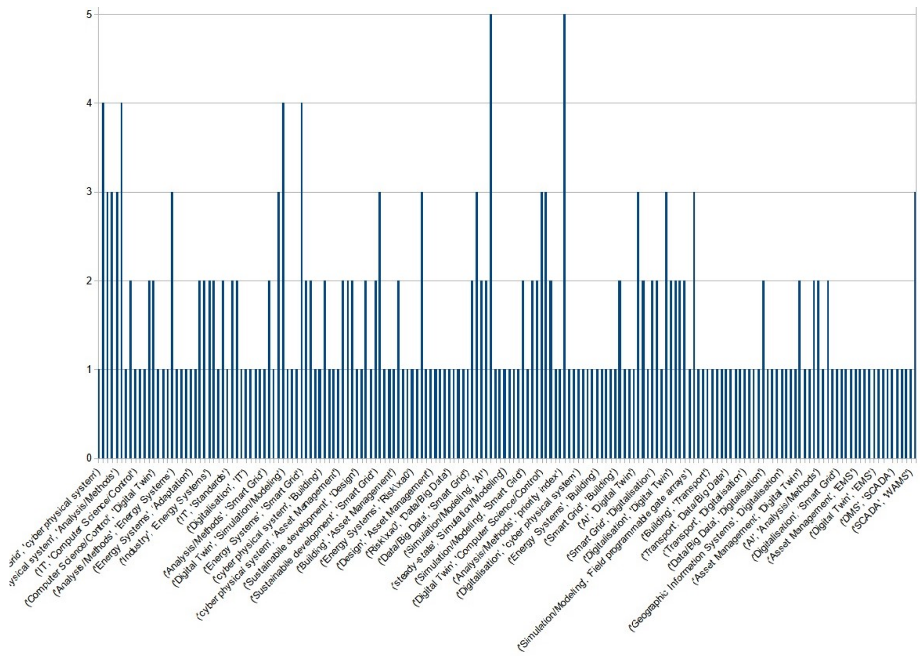

Fig. 4. Occurrence of the combination of the two keywords in the final articles

could be a significant gap that the other articles did not addressed security issue beside there main focus as much as the other aspects. C25TDM9E (the ID and full description of the papers are available in AppendixA) is about the potential applications of DT. Last but yet significant, F3L5P2R3, is focused on the real-time online analysis; since online analysis is a key attribute of the recent trends and is a requirement of IoT, real-time online analysis should be a subject to more studies in the future to construct the EIoT body of knowledge, which is not well standardized yet. Moreover, aims to identify the most important nodes within the general network EigenVector Centrality is calculated in Directed Network Interpretation mode (Figure 6-Right). EigenVector Centrality with Number of iterations: 100 and Sum change: 0.004222422889210424 used to extract the node importance. regarding this index, [39] and [29] from the red sub-network, and [17] and [20] from green sub-network are the most important nodes in the network. In the future studies we will probe the Applications and implementation from Technical aspects, Advancements and finally challenges and future research area of Energy Systems Digital Twin (ESDT), extracted from final list of the articles of current article.

DT is rather novel technology, however its applications are growing in different sectors. The first application of DT goes back to 2010 when NASA utilized DT as virtual replica of a spacecraft[9]. Other than aerospace, DT is widely used

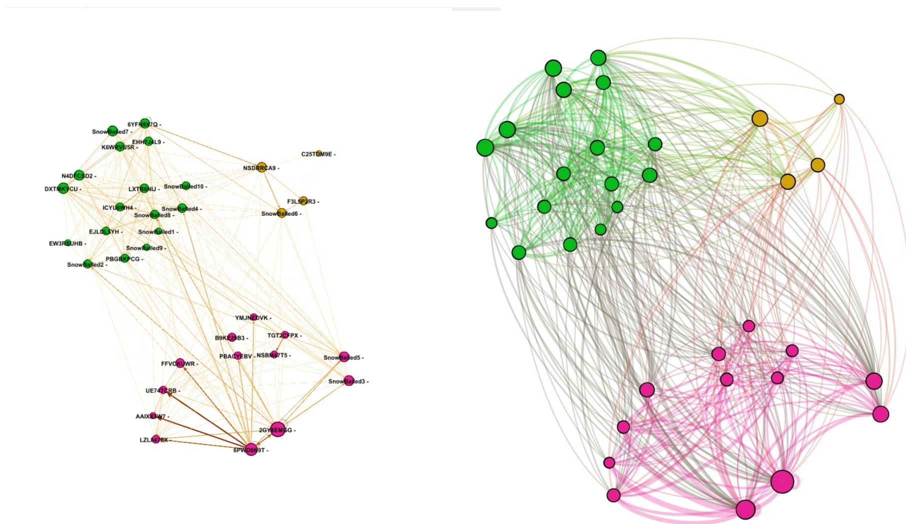

Fig. 5. Left: Network of the articles with the Code of the article(Appendix A) and its edges; Right: Sub-networks within the entire list with all of the edges(The filtered edges are in grey)

in Diverse applications; however, DT usage in energy systems is rather recent. Figure 7 illustrate the main applications in the scholars in a Sunburst diagram.

Figure 7 shows that DT is widely applied in Energy Management, Maintenance and Smart Grids. Quite the opposite, even if the scholars mentioned Cloud Technology, it was not the particular focus of the studies. On the other hand, due to established legislation on Co2 emission, UN Agenda 2030 etc., the environmental factors of energy production become a must. This fact imposed the energy planners to think about socio-ecologic transition in ES. However, Figure 8 illustrate that the potentials of DT to enhance sustainability and resilience of the energy system is not studied well. Only two researches studied the renewable and sustainable energy energy[4]and one articles investigated multi energy systems[36].

4 Conclusion

In the context of a systematic review, the current article answers three main research questions through statistical analysis of published scientific literature. **RQ1:** DT is studied the most in smart grids/micro-grids, Cyber-Physical systems, and smart buildings; the results unveil that the most important feature of DT is real-time interaction between the digital and physical entities. Last but yet important, the results prove that "Internet of The Things" has the potential to facilitate the implementation of DT by providing bidirectional communication between the entities. **RQ2:** Energy Management, Maintenance, security,

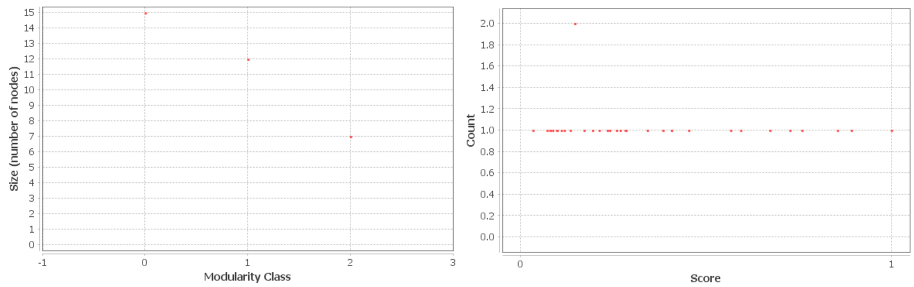

Fig. 6. Left: size Distribution of Modularity; Right: Eigenvector Centrality Distribution

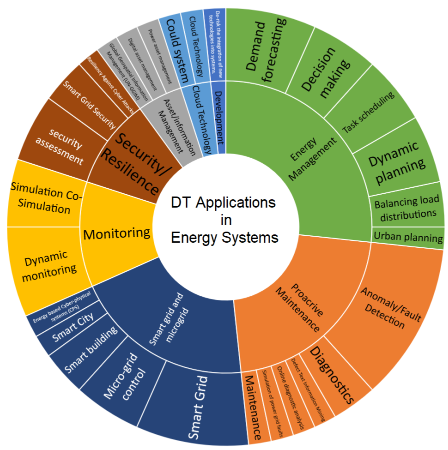

Fig. 7. DT applications in Energy systems

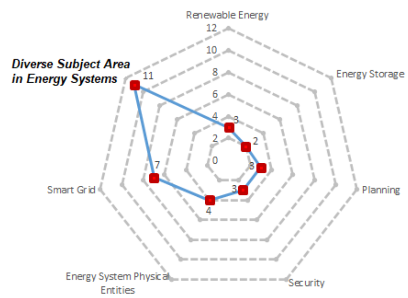

Fig. 8. DT applications in Energy systems

and resilience are the most common applications of DT in ES. **RQ3:** The results uncovered significant gaps in the literature. The most important gap is the lack of implementing DT in integrating renewable energy resources with the existing systems, while just three articles are studying renewable energies. On the other hand, most of the articles mentioned the problem of fluctuating energy resources (wind and solar energy); However, only two articles considered Energy Storage, which is a potential solution for this issue. Finally, integrating cutting-edge technologies such as cloud computing with DT is still in the infancy stage.

Since the current article is a primary study to open up research lines for future works, the next study will focus on the technical aspects of implementing DT in ES. Future study will cover the DT architectures, DT platforms, AI, and in particular employed Deep Learning algorithms, and the challenges of bringing DT into action in energy scope.

References

1. A. Saad, S. Faddel, T. Youssef, O. A. Mohammed: On the implementation of IoT-based digital twin for networked microgrids resiliency against cyber attacks. IEEE Transactions on Smart Grid **11**(6), 5138–5150 (2020). https://doi.org/10.1109/TSG.2020.3000958
2. Aghazadeh Ardebili, A., Padoano, E.: A literature review of the concepts of resilience and sustainability in group decision-making. Sustainability **12**(7), 2602 (2020). https://doi.org/10.3390/su12072602
3. Akbari-Dibavar, A., Nojavan, S., Mohammadi-Ivatloo, B., Zare, K.: Smart home energy management using hybrid robust-stochastic optimization. Computers & Industrial Engineering **143**, 106425 (May 2020). https://doi.org/10.1016/j.cie.2020.106425, `https://doi.org/10.1016/j.cie.2020.106425`
4. Andryushkevich, S.K., Kovalyov, S.P., Nefedov, E.: Composition and application of power system digital twins based on ontological modeling. In: 2019 IEEE 17th International Conference on Industrial Informatics (INDIN). vol. 1, pp. 1536–1542 (2019). https://doi.org/10.1109/INDIN41052.2019.8972267
5. Atalay, M., Angin, P.: A digital twins approach to smart grid security testing and standardization. In: 2020 IEEE International Workshop on Metrology for Industry 4.0 IoT. pp. 435–440 (2020). https://doi.org/10.1109/MetroInd4.0IoT48571.2020.9138264
6. Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E.: Fast unfolding of communities in large networks. Journal of statistical mechanics: theory and experiment **2008**(10), P10008 (2008)
7. Booth, A., Papaioannou, D., Sutton, A.: Systematic approaches to the literature. Systematic Approaches to a Succesful Literature Review (2012)
8. Consortium, D.T.: The definition of a digital twin (Feb 2021), `https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin.htm`
9. Glaessgen, E., Stargel, D.: The digital twin paradigm for future nasa and us air force vehicles. In: 53rd AIAA ASME ASCE AHS ASC structures, structural dynamics and materials conference 20th AIAA ASME AHS adaptive structures conference 14th AIAA. p. 1818 (2012)
10. He, B., Li, J., Tsung, F., Gao, Y., Dong, J., Dang, Y.: Monitoring of power consumption requirement load process and price adjustment for smart grid. Computers & Industrial Engineering **137**, 106068 (Nov 2019). https://doi.org/10.1016/j.cie.2019.106068
11. Huebler, J., Rush, B.: Vesta-gas distribution system for tomorrow and today. osti.gov (1983)
12. Khokhar, D.: Gephi Cookbook. Packt Publishing (2015)
13. Ku, C.C., Chien, C.F., Ma, K.T.: Digital transformation to empower smart production for industry 3.5 and an empirical study for textile dyeing. Computers & Industrial Engineering **142**, 106297 (Apr 2020). https://doi.org/10.1016/j.cie.2020.106297
14. Lambiotte, R., Delvenne, J.C., Barahona, M.: Laplacian dynamics and multiscale modular structure in networks. arXiv preprint arXiv:0812.1770 (2008)
15. Latapy, M.: Main-memory triangle computations for very large (sparse (power-law)) graphs. Theoretical Computer Science **407**(1), 458–473 (2008). https://doi.org/10.1016/j.tcs.2008.07.017

16. Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V.: Smart energy and smart energy systems. Energy **137**, 556–565 (Oct 2017). https://doi.org/10.1016/j.energy.2017.05.123
17. M. Milton, C. D. L. O, H. L. Ginn, A. Benigni: Controller-embeddable probabilistic real-time digital twins for power electronic converter diagnostics. IEEE Transactions on Power Electronics **35**(9), 9850–9864 (2020). https://doi.org/10.1109/TPEL.2020.2971775
18. M. Zhou, J. Yan, X. Zhou: Real-time online analysis of power grid. CSEE Journal of Power and Energy Systems **6**(1), 236–238 (2020). https://doi.org/10.17775/CSEEJPES.2019.02840
19. Markovic, D.S., Zivkovic, D., Branovic, I., Popovic, R., Cvetkovic, D.: Smart power grid and cloud computing. Renewable and Sustainable Energy Reviews **24**, 566–577 (2013). https://doi.org/10.1016/j.rser.2013.03.068
20. Massel, L., Massel, A.: Development of digital twins and digital shadows of energy objects and systems using scientific tools for energy research. In: Stennikov V.A., Voropai N.I., Filippov S.P., Yusifbeyli N.A., Sereter B., Changwei P., Lin F.-J., Negnevitsky M., Rehtanz C., Yoon J.-Y. (eds.) E3S Web Conf. vol. 209. EDP Sciences (2020). https://doi.org/10.1051/e3sconf/202020902019, journal Abbreviation: E3S Web Conf.
21. Muhanji, S.O., Flint, A.E., Farid, A.M.: eIoT. Springer International Publishing (2019). https://doi.org/10.1007/978-3-030-10427-6
22. Puig, J., Duran, J.: Digital twins. In: IMSCI 2010 - 4th International Multi-Conference on Society, Cybernetics and Informatics, Proceedings. vol. 2, pp. 28–31. International Institute of Informatics and Systemics, IIIS (29 June-2 July 2010), `www.scopus.com`, cited By :2
23. Rocha, P., Siddiqui, A., Stadler, M.: Improving energy efficiency via smart building energy management systems: A comparison with policy measures. Energy and Buildings **88**, 203–213 (2015). https://doi.org/10.1016/j.enbuild.2014.11.077
24. Runkler, T.: Data analytics : models and algorithms for intelligent data analysis. Springer Vieweg, Wiesbaden, Germany (2020)
25. da Silva, F.S.T., da Costa, C.A., Crovato, C.D.P., da Rosa Righi, R.: Looking at energy through the lens of industry 4.0: A systematic literature review of concerns and challenges. Computers & Industrial Engineering **143**, 106426 (May 2020). https://doi.org/10.1016/j.cie.2020.106426, `https://doi.org/10.1016/j.cie.2020.106426`
26. Smith, V., Devane, D., Begley, C.M., Clarke, M.: Methodology in conducting a systematic review of systematic reviews of healthcare interventions. BMC medical research methodology **11**(1), 1–6 (2011). https://doi.org/10.3390/su12072602
27. Szvetits, M., Zdun, U.: Systematic literature review of the objectives, techniques, kinds, and architectures of models at runtime. Software & Systems Modeling **15**(1), 31–69 (2016). https://doi.org/10.1007/s10270-013-0394-9
28. Tucker, D., Pezzini, P., Bryden, K.M.: Cyber-physical systems: A new paradigm for energy technology development. In: ASME 2018 Power Conference collocated with the ASME 2018 12th International Conference on Energy Sustainability and the ASME 2018 Nuclear Forum. vol. 1. American Society of Mechanical Engineers, Power Division (Publication) POWER (2018). https://doi.org/10.1038/421805a, `www.scopus.com`, cited By :3
29. Tucker, D., Pezzini, P., Bryden, K.: Cyber-physical systems: A new paradigm for energy technology development. In: ASME Power Div Publ POWER. vol. 1. American Society of Mechanical Engineers (ASME) (2018).

https://doi.org/10.1115/POWER2018-7315, journal Abbreviation: ASME Power Div Publ POWER
30. Tuegel, E.J., Ingraffea, A.R., Eason, T.G., Spottswood, S.M.: Reengineering aircraft structural life prediction using a digital twin. International Journal of Aerospace Engineering (2011). https://doi.org/10.1155/2011/154798, www.scopus.com, cited By :270
31. Ullah, R., Faheem, Y., Kim, B.S.: Energy and congestion-aware routing metric for smart grid AMI networks in smart city. IEEE Access **5**, 13799–13810 (2017). https://doi.org/10.1109/access.2017.2728623
32. Özer Uygun, Aydin, M.E.: Digital transformation: Industry 4.0 for future minds and future society. Computers & Industrial Engineering **157**, 107362 (Jul 2021). https://doi.org/10.1016/j.cie.2021.107362
33. Wang, J., Lim, M.K., Wang, C., Tseng, M.L.: The evolution of the internet of things (IoT) over the past 20 years. Computers & Industrial Engineering **155**, 107174 (May 2021). https://doi.org/10.1016/j.cie.2021.107174, https://doi.org/10.1016/j.cie.2021.107174
34. Watts, D.J., Strogatz, S.H.: Collective dynamics of 'small-world' networks. Nature **393**(6684), 440–442 (Jun 1998). https://doi.org/10.1038/30918, 10.1038/30918
35. Wohlin, C.: Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering. EASE '14, Association for Computing Machinery, New York, NY, USA (2014). https://doi.org/10.1145/2601248.2601268, 10.1145/2601248.2601268
36. X. Tang, B. Sun, H. Yang, X. He, J. Chen, Y. Song, X. He: Dynamic scheduling management method for multi-energy system digital twin simulation computing tasks. In: 2020 10th International Conference on Power and Energy Systems (ICPES). pp. 606–612 (2020). https://doi.org/10.1109/ICPES51309.2020.9349724, journal Abbreviation: 2020 10th International Conference on Power and Energy Systems (ICPES)
37. X. Zhang, K. Li, D. Li, M. Zhong, W. Huang: Digital twin in energy internet and its potential applications. In: 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2). pp. 2948–2953 (2020). https://doi.org/10.1109/EI250167.2020.9346967, journal Abbreviation: 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)
38. Yang, S., Wu, J., Yang, X., Liao, F., Li, D., Wei, Y.: Analysis of energy consumption reduction in metro systems using rolling stop-skipping patterns. Computers & Industrial Engineering **127**, 129–142 (Jan 2019). https://doi.org/10.1016/j.cie.2018.11.048
39. Yang, Y., Li, X., Yang, Z., Wei, Q., Wang, N., Wang, L.: The application of cyber physical system for thermal power plants: Data-driven modeling. Energies **11**(4) (2018). https://doi.org/10.3390/en11040690, publisher: MDPI AG

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