Energy Reports 7 (2021) 997–1015

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review

Abiodun E. Onile [a], Ram Machlev [b], Eduard Petlenkov [c], Yoash Levron [b], Juri Belikov [a,*]

[a] Department of Software Science, Tallinn University of Technology, Akadeemia tee 15a, 12618 Tallinn, Estonia
[b] The Andrew and Erna Viterbi Faculty of Electrical Engineering, Technion—Israel Institute of Technology, Haifa, 3200003, Israel
[c] Department of Computer Systems, Tallinn University of Technology, Akadeemia tee 15a, 12618 Tallinn, Estonia

ARTICLE INFO

Article history:
Received 30 November 2020
Received in revised form 12 January 2021
Accepted 27 January 2021
Available online 13 February 2021

Keywords:
Recommender systems
Demand side management
Energy efficiency
Digital twins
Innovative energy services

ABSTRACT

Innovative solutions targeting improvements in the behavior of energy consumers will be required to achieve desired efficiency in the use of energy. Among other measures for stimulating consumers' behavior changes based on attention triggers, personalized recommendations are essential to enhance sustainable progress towards energy efficiency. In light of this challenge, the current study focuses on innovative energy services that are based on intelligent recommendation systems and digital twins. We review several trends associated with the modeling and diffusion of energy services, taking into account the positive interrelationships existing between recommendation provisions and demand-side consumer energy behavior. This is achieved by means of a content analysis of the state-of-the-art works, focusing on the IEEE Xplore and Scopus databases. Based on this review, we present new empirical evidence to validate data-driven twin technologies as novel ways of implementing consumer-oriented demand-side management via sophisticated abstraction of consumers energy behaviors, and identify various barriers associated with the adoption of energy services, especially as they relate to the implementation and overall adoption of the digital-twins concept. Lastly, we use the review to summarize a coherent policy recommendations related to the wide-spread adoption of the digital-twins concept, and demand-side management solutions in general.

Contents

* Corresponding author.
E-mail addresses: abiodun.onile@taltech.ee (A.E. Onile), ramm@ee.technion.ac.il (R. Machlev), eduard.petlenkov@taltech.ee (E. Petlenkov), yoashl@ee.technion.ac.il (Y. Levron), juri.belikov@taltech.ee (J. Belikov).

https://doi.org/10.1016/j.egyr.2021.01.090

List of abbreviations

AI	Artificial intelligence
ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
CE	Cost of energy
DG	Dispatch generators
DNN	Deep neural network
DR	Demand response
DSM	Demand side management
DT	Digital twins
EMS	Energy management system
ES	Energy services
ESCOs	Energy service companies
GHG	Green house gas
HVAC	Heating ventilation and air conditioning
IES	Innovative energy services
IoT	Internet of things
LED	Light emitting diode
NILM	Non-intrusive appliance load monitoring
PRS	Personalized recommendations system
RET	Renewable energy technologies
SDG	Sustainable development goals
SMEs	Small to medium-sized enterprise
SVM	Support vector machine

1. Introduction

Energy consumption in the recent decades has been on the rise and can be associated with electricity being a convenient substitute to fuel (oil and gas), acting both as primary and secondary sources of energy (Chalvatzis and Rubel, 2015). This makes the electricity sector a leading contributor to Green house gas (GHG), and also the sector generating the highest concentration of emission per source, when compared to those recorded by other sectors (Malmodin et al., 2010). An agenda of sustainable development is essential for transitioning into an energy efficient economy, and will entails measures not limited to technologies and policies, but also to innovation as specified by the Sustainable development goals (SDG) of the United Nations (Hills et al., 2018). At the EU level, meeting the European CO2 emission reduction target by 2030 will require changes in the behavior of European consumers (Koroleva et al., 2019). Additionally, measures in the form of international agreements such as the European Emission trading Scheme or the Kyoto Protocol, are also geared towards mitigating the impact of climate change (Delzendeh et al., 2017). Adopting these measures on the other hand poses challenge for the consumers as they sometimes lack requisite technical expertise, monetary and time resources to implement such conservation measures. The implication is that the responsibilities of operations associated with the power systems have been left solely to ill-equipped consumers which promotes the use of energy managers, contract consultants and Energy services (ES) companies to better manage their consumption profile. In spite of these efforts, energy related activities in the EU have steadily increased, owing to rapid innovation in the electronic industry and consumer demand for comfort and efficient ES, leaving the designated observers in an uncomfortable position (Kowalska-Pyzalska, 2018). To this end, there is an increasing need to rethink the concept of energy conservation, with necessary measures put in place. The question however is not whether consumers should be equipped with smart energy solutions and measures such as innovative policies or ES, but rather how these solutions will be deployed.

In particular, Innovative energy services (IES) are an important requirement in the quest to overcome challenges associated with energy inefficiency with intents of supporting consumers transition into actions geared towards energy sustainability. Similarly, digital technologies have advanced tremendously in the recent decades heralding the birth of Digital twins (DT), creating ways for a real-time synchronization and monitoring of the energy system via computerized and virtual world modeling of service, resulting from data, information and consumer behavior (Stark et al., 2017; Brosinsky et al., 2018). Most of all, a better understanding of consumer behaviors is required to speculate their energy consumption pattern, which is an important feature for achieving reduction in energy consumption. Successful transition into energy-relevant behavioral change can be facilitated by intelligent recommendations. Intelligent recommendation system provides information associated with the selection of alternative cause of action allowing consumers to be directed to services that are customized for them in a large space of potential alternatives (Aguilar et al., 2017). This approach has found application in the electronic commerce industries where recommendation system suggests recommendation tips that help consumers conveniently achieve their goal for energy optimization. The introduction of personalized recommendation to Demand side management (DSM) holds immense potential to enhance consumers' energy efficiency.

It is worthy of note that only few publication contains evidence describing association linking energy consumer, energy conservation, DT and recommendation system. From the literature perspective, a review of incentives and barriers towards the adoption of IES based on consumers' environmental behavior has been presented, which identified intention-behavior gap as major problem towards such adoption (Kowalska-Pyzalska, 2018). In-spite the knowledge of benefits associated and consumers willingness to adopt IES, it does not automatically translate into certain desired behavior giving way to intention-behavior gap (Kowalska-Pyzalska, 2018). A similar work which addresses energy conservation behavior in group of agents using economic behavior model based on theory of cellular automata has been presented (Tetiana et al., 2018). This work is limited in scope as it solely addressed consumer economic and social behavior. In addition, work Irizar-Arrieta et al. (2020) presents an approach utilizing human computer interactions for the improvement of energy consumption with a focus on energy efficiency. Existing solutions attempting to explore the concept of consumer-oriented energy efficiency models are PEAKapp (2017), SOCIALENERGY (2017) and IntelliSOURCE. These solutions are however heavily customized for utilities' administrative users rather than ordinary energy consumers. It can be concluded that energy supply in the future will be characterized by economy and consumer-focused, rather than generation dominated (Chalvatzis and Rubel, 2015).

In light of the challenges mentioned above, the current study focuses on innovative ES that are based on intelligent recommendation systems and digital twins. Unlike the approach adopted in Chalvatzis and Rubel (2015), Kowalska-Pyzalska (2018), Tetiana et al. (2018), PEAKapp (2017) and SOCIALENERGY (2017), this study focuses on the trends associated with the modeling and diffusion of IES, taking into account the positive interrelationships existing between recommendation provisions and demand-side consumer energy behavior. This is achieved by means of a content analysis of the state-of-the-art works, focusing on the IEEE Xplore and Scopus databases. Based on this review, we present new empirical evidence to validate data-driven DT technologies as novel ways of implementing consumer-oriented DSM via sophisticated abstraction of consumers energy behaviors, and identify various barriers associated with the adoption of IES, especially as they relate to the implementation and overall adoption of the digital-twins concept. Lastly, we use the review to summarize a coherent policy recommendations related to the wide-spread adoption of the digital-twins concept, and demand-side management solutions in general.

The rest of the paper is organized as follows. Section 2 discusses the idea of intelligent ES. Section 3 provides an overview of data modeling and digital twinning, while Section 4 discusses the recommendation features and energy saving tools. Section 5 presents an analysis of the results, and Section 6 concludes the paper.

2. Overview of innovative energy services for consumer-oriented design

In this section, IES is being discussed by exploring various components of consumers driven innovative models and their linkages to energy efficiency services based on behavior alterations at the consumer end.

2.1. Energy services

The concept of ES can be associated with how effectively demand side reduction and management can be understood, anticipated and modeled (Fujimori et al., 2014). Business model that encourages selling functions provided by energy has found appealing acceptance especially among consumers. Similarly, retreating from the fundamental business of selling energy (Morley, 2018) into servitization (Plepys et al., 2015), has seen Energy service companies (ESCOs) being identified with the tasks of selling a range of "efficiency services" in form of advice, energy saving deliveries, and equipment installations, based on performance contracts (IEA, 2013; Mourtzis et al., 2018). Although the term "energy services" has sparked various debates in scientific literature, the work Fell (2017) tried to clarify this discrepancy revealed that the differences associated with the term could be associated with different field of science and approach for energy usage.

Recent reviews on the idea of ES have been presented in Fell (2017), Kalt et al. (2019). The work Fell (2017) reported that, ES are functions that require energy for their execution acting as a means towards achieving a desired state or end services. Work (Morley, 2018) presented a review focusing on the socio-cultural and dynamic nature of ES referred to as meta-services, which are not only determined via energy provision, governance or consumption but also by other organizations that are not providing energy, with intent to efficiently stabilize the level of demand for ES.

2.2. Innovative energy services

Energy services providers are experiencing transition on global scale (Kowalska-Pyzalska, 2018). In most cases, this transition is aided by the availability of smart technological solutions allowing energy consumers to freely assume an active role in the energy market. These services form the building blocks of a rapidly advancing digital energy ecosystem providing opportunity for digitally compliant consumers and progressive/forward thinking utilities to make a claim. Effective transition of the energy system towards sustainability therefore calls for innovation among others factors such as economic, technology and policy (Hills et al., 2018; Onile et al., 2020). Innovation has been defined as act of using iterative design process, deployment, improvement, and testing to put ideas into practical use (Grübler and Wilson, 2013; Miremadi et al., 2018). It has also been seen as the basis of all activities and can originate from both internal factors such as: inconsistencies, technical demands, situations relating to force majeure and market and industrial changes; external factors on the other hand includes: globalization, world digitization, identification of new knowledge area and changes in recipients (Rudskaia and Rodionov, 2018). In order to achieve the UN SDG agenda of 2030 for sustainable development, there is need for innovation geared towards energy conservation. Innovation in energy system provides a workable option for addressing challenges associated with energy security in the face of increasing electricity demand coupled with problems of environmental degradation (Miremadi et al., 2018) and economic challenges (Chalvatzis and Rubel, 2015). Similarly, innovation in the energy sector will be required in order to meetup with the Paris agreement aiming at 1.5 °C reduction and the energy for all agenda of the Sustainable Development Goals. Additionally, a "Mission Innovation" and investment to double R&D for expediting action on the uptake of clean energy have also been signed by the G20 (King, 2017; Bak, 2017). The need for innovative, persuasive, deep and swift transformation from the classical approach for resourcing, transforming, consuming energy is therefore imminent (Geels et al., 2017; Wilson and Tyfield, 2018). Recent reviews of IES have been presented Bigoloni and Filipponi (2017), Kowalska-Pyzalska (2018), Gaspari et al. (2017).

In this paper, the concept of IES was compiled, based on the recent literature and understanding of consumer-oriented approach. A consumer-oriented model which utilizes intelligent components to non-intrusively provide recommendations capable of influencing consumers behavior to adopt energy saving options (Paukstadt et al., 2019; Mrazovac et al., 2012) in categories such as: Social (Soc), Economic (Eco) and Technical (Tech) was considered. For example, in order to capture a comprehensive estimation of energy wastage we explored the identified IES model using two major tools (contributing technologies) which include: DT recreation of energy consumers (see Section 3), and recommendation system to provide actionable insight (see Section 4). Previous works selected for review in Sections 3 and 4 are directly related to "recommendation systems" and "energy services". Fig. 1 describes the schematics layout of the study. It depicts consumers' consumption data and DT modeling with broader discussion in Section 3 and their associated recommendations with further discussion in Section 4.

In what follows, this section further elaborates on various aspects of innovation in the energy sector.

Technological innovations: The ecosystem of innovation describes the environment where interactions associated with flow of technologies and knowledge occur (Kotilainen et al., 2016). Digital technologies have been seen to be effective as an enabler of innovation across various economic sectors. The concept of digitization in the energy sector has helped in stabilizing the transmission grid simply by stabilizing reserve from fluctuating energy sources such as solar and wind (European Union, 2018). Connecting objects at the micro level using Internet of things (IoT) opens an unprecedented gateway allowing electric devices to contribute to the energy system building even bigger ecosystem for the distributed energy resources. Thus, digital innovation in the energy industry aided by the emergence of the IoT has provided convenient approach for integrating non-human elements in the managerial strategies of the digital innovation and its respective ecosystem (Kolloch and Dellermann, 2018). In previous research, Bergek et al. (2015) worked on technological innovation system and its interactions with the wider context structures. The paper Yang et al. (2019) proposes the analysis of energy technical innovation from the renewable energy and fossil energy point of view. It was reported that the impact of

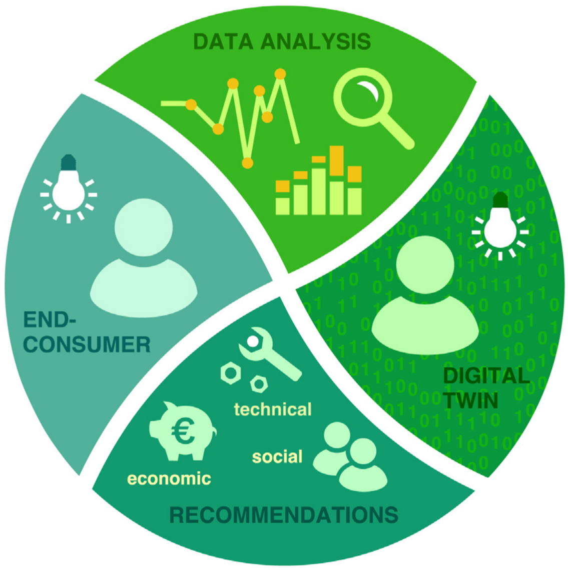

Fig. 1. Overall scheme of a common consumer-oriented framework for recommendation of innovative energy services.

innovation technology on fossil energy exceeds that of renewable energy when considering price, making the renewable energy price fall below the optimal rate while placing demand on the requirement of price mechanism for the development of renewable energy technology in China. It was further identified that the government policy support has to be an enabler for the development of the proposed technical innovative technology. Meanwhile, recent academic literature has payed close attention to system concept approach to policy making and innovation systems (Sharif, 2006). Innovation in the energy sector requires established set of indicators for evaluating energy performance in relation to the innovation system (Miremadi et al., 2018; Borup et al., 2013). The work (Miremadi et al., 2018) identified about 120 indicators (categorized as policy, impact, input, output, structural and systematic indicators) associated with four criteria (availability, understanding, relevance and measurability) used to describe notable weaknesses among available indicators. At the technology level, 90 indicators were used to match seven functions available for system technological innovations which could also be used to generate policy recommendations.

Although, traditional approach based on expert advice has been considered as effective but it is rarely scalable to meetup with large number of consumer (Starke et al., 2017). Research targeting persuasive technology, however indicated that technical innovative solutions holds the clue to helping consumers achieve their energy efficiency goals.

Economic innovation for energy: Rational use of energy produces economic development and to satisfy such demand for development, energy consumption needs to undergo structural upgrading and innovation funding for better economic benefits (Foxon, 2013; Jabbour et al., 2015; Ma, 2019). From the political point of view, funding framework for low carbon innovations based on low-carbon economy can be provided by government to integrate environmental policy and innovation policy which can be developed from divergent point of view (Willis et al., 2007). Successful adoption of corporate actions and the use of carbon-low Eco-innovation in the fight against climate change, relies on the nature of resources and support available to organization (Polzin, 2017).

Work (Bridge et al., 2013) reported that energy system and the concept of spatial differentiation has implication on growth and development of the economy. Innovation associated with the energy sector are developed from various clusters that are geographically defined (Baptista and Swann, 1998; Cooke, 2001). These clusters are seen as global locus for low carbon energy innovations and can be considered as a major point for hitching regional economic fortune. Work Jabbour et al. (2015) described the application of Eco-innovation to sustainable supply chain for a low-carbon economy. Similar study presented by Ma (2019) identified optimized economic model for industrial innovation based on economy of clean and renewable energy (geothermal energy) as key contributor to sustainable economic development.

Social innovation for energy: Social innovation will be required to effectively transition into low carbon energy system (Hewitt et al., 2019; Selvakkumaran and Ahlgren, 2020; Wittmayer et al., 2020). This includes activities associated with social goals for achieving community general well being and civic empowerment. More often than not, the technical and social aspect of energy system have been researched separately, the later however is crucial to the adoption and acceptance of such innovation by the society. Work Abbar et al. (2018) presented innovation model based on city neighborhood and social networks for the adoption of Renewable energy technologies (RET). They came up with a twitter based constraints obtained from censor geography of Qatar. The rate of RET innovation diffusion was later determined using a combination of twitter network and household diffusion patterns based on adapted linear threshold technique for spreading information. A collection of key citizen motivated renewable energy solutions and operational criteria termed as community energy viewed in the lens of social innovation has been surveyed in Hewitt et al. (2019). Work Kotilainen et al. (2016) addressed the function of residential prosumer in instituting innovation in energy ecosystem to ensure flexibility in the energy system of the future. Their proposed social-technical and diffusion approach targets the implementation of government actions towards slowing down climate change on global scale and enhancing advancements in technology in ICT and consumer electronics. Finally, study presented in Wittmayer et al. (2020) focused on the application of social innovation in the context of socio-technical energy systems.

Innovation diffusion in itself is a process associated with spreading of the innovation within a period of time. Innovation can therefore be adopted among a group of people referred to as innovators, primary adopters, secondary adopters and sluggards (Kotilainen et al., 2016). The theory associated with the diffusion of innovation has been focused on the analysis of social network, allowing build up of peer pressure resulting from a positive feedback from initial benefactors of such innovation (Abrahamson and Rosenkopf, 1997; Abbar et al., 2018). With significant interconnection with eco-innovation and environmental policies, demand side innovation policies have also been seen to proffer solution targeted towards overcoming difficulties relating private market innovation diffusion. A study on consumer innovation diffusion for sustainable energy solutions using small-scale RET has been presented (Hyysalo et al., 2017). Their investigation revealed a 34% consumer adoption rate based on "innovative peer diffusion". Work Kahma and Matschoss (2017) presented the idea of smart ES in the light of innovative technology diffusion. The author further described innovation adoption as a concept of technological diffusion noting that the probability of success or failure (non-use) of novel technologies depends on its ability to permeate the energy market. To solve this problem, work (Clausen and Fichter, 2019) observed innovation diffusion based generalized inhibition and driving factors. Similarly, work Vaidyanathan et al. (2019) presented a study on multi functional and analytic framework of renewable energy technology innovation diffusion for energy deficient communities based on decentralized innovations (Vargo et al., 2020). Fig. 2 describes the adoption rate

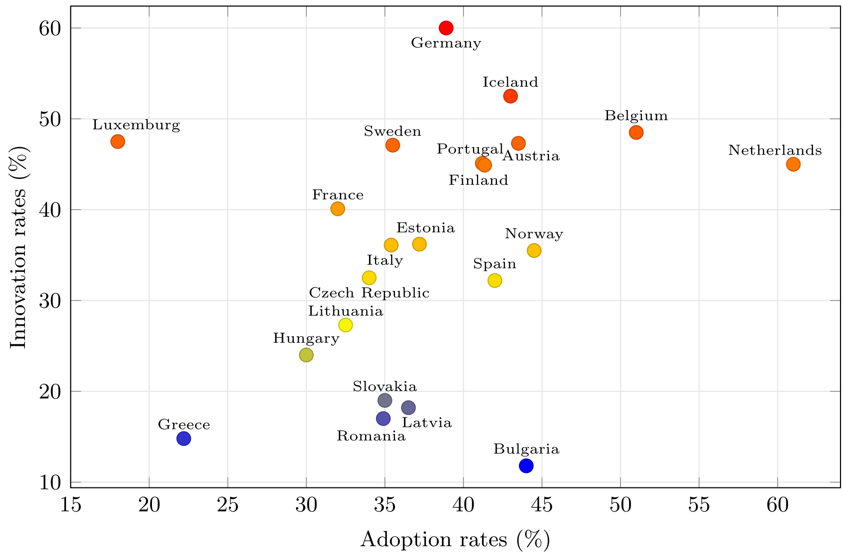

Fig. 2. Innovative services adoption rate.

of innovation services across EU member state (Autant-Bernard et al., 2010).

Energy services for basic consumer (in perspective): Energy is not consumed simply by purchasing it, but rather must be converted from nature into forms that provide services such as power to appliances (Haas et al., 2008; Kaygusuz, 2011; Fell, 2017; Morley, 2018; Rinkinen and Torriti, 2019). In general, effective use of energy is associated with provision of services such as ventilation, heating, lighting and motive power (WHO, 2018). The following paragraphs describe examples of ES.

Lighting: Irrespective of income or class, illumination is considered as an essential need for life, making it the major source of energy expenditure and a significant portion of consumer budget. This paragraph describes various services in lighting with the goal of optimizing energy consumption. The work of Polzin et al. (2016) described the application of innovative end use energy demand reduction technologies associated with energy efficiency services in municipalities using Light emitting diode (LED) street lighting. Another work focusing on low cost energy efficiency compact fluorescent lamps with promises to reduce GHG emission and overall energy demand has been presented (Figueroa et al., 2019). An approach utilizing the application of ICT and LED in achieving deep energy savings for outdoor street lighting based on life-cycle services and energy data was presented by Pandharipande et al. (2019). Similarly, smart lighting services are often seen to incorporate different levels of energy savings. In line with this, work (Cacciatore et al., 2017) identified three unique heuristics incorporated in smart lighting based on the technology deployed in lamps. An approach implementing IoT alongside the WWW integrated lighting promises to provide energy efficient lighting (Murthy et al., 2015).

Cooking: Immense potentials for energy savings lie in services associated with cooking and heating for consumers across various income class or group (Strydom et al., 2020). Study revealed that about 2.3 billion people do not still have access to clean cooking services while projecting that about 2.5 million pollution related deaths on yearly basis may be recorded by 2030 (Batchelor et al., 2019; WHO, 2018). In the same vein, the SDG7, promotes reliable and affordable, modern cooking services and technologies (Karanja et al., 2019; UN United Nations Sustainable Development Goals, 2018). Cooking services provided using electricity holds potential for disruptive transformation for households. Residents do not only enjoy benefits associated with less exposure to dangerous emissions but also experience a cleaner cooking environment when electric cooking is deployed. Research into the development of modern energy cooking services based on energy storage and off-grid has been described in (Batchelor et al., 2019). A transition from conventional cooking approach into the use of battery electric enabled eCook (Batchelor et al., 2018; Brown and Sumanik-Leary, 2016; Brown et al., 2017) and renewable such as the hybridized solar electric stove proves the technical viability of renewable in cooking as modern and cleaner option.

Heating and Cooling: Innovative services with application to Heating ventilation and air conditioning (HVAC) are requirements for ensuring a productive and healthy environment for occupants while paying attention to measures for attaining reduction in energy consumption and its associated cost. In order to attain desirable energy saving feat, it will be required to deploy energy technologies and systems that optimizes energy consumption some of which includes heat/energy recovery ventilators, evaporative cooling, night time radiative cooling, etc. Ma et al. (2019). Meanwhile, the following systematic reviews have investigated innovative action in heating and cooling. A study conducted using air handling unit for achieving energy savings subject to the introduction of energy efficiency measures was presented by Shea et al. (2019). Cooling was achieved by pumping air through cooling coils located in the air handling unit for cooling the air while heating requirements were implemented by varying the supply of cooled air for heating demand of various zones allowing reduction in excess usage of energy. In order to meet the information demand associated with heating system, integrated information services framework based on open group architecture and service oriented software architecture has been considered to eliminate the challenges associated with information island in central heating systems allowing for efficient sharing of information and provides integration control.

3. Data modeling and digital twinning

This section presents an overview of various tools and supporting technologies for consumption reduction based on modeling consumers as DT in the IES framework (see Fig. 1) presented in Section 2.

3.1. Digital twinning

Digitization has recorded highly pervasive association and increased integration with modern energy systems resulting into increasing and effortless connectivity between virtual machines, data and their physical environment. DT can be described as front runner of Industry 4.0 and virtual representation of a rare or real-life assets such as services, products or machine with the models that are capable of achieving behavior alteration (Uhlemann et al., 2017; Yan et al., 2018; Rasheed et al., 2020) using real-time data and intelligent analytics (Brosinsky et al., 2018; Fuller et al., 2020) supported with visualization software (Zhou et al., 2019) and interfaces which generates information associated with the state of the machine (Karanjkar et al., 2018) such as performance metrics, machine operation state, energy consumption, product quality targeting improvements in energy system efficiency. The term DT was originally conceived in Grieves (2015) and has been strategically rated as one of the top ten technologies of year 2018 (subject to predictions on future trends in research) with a potential to attain a 15 billion dollar market target by 2023 (Khajavi et al., 2019).

A consumer-oriented DT framework can be derived from modeling methodology that integrates historical loads and social media (meta) data analysis, short/long-term energy forecasting, machine learning models, and data visualization to achieve DT recreation of energy profile of consumers based on energy behavior pattern (Havard et al., 2019). This approach is underpinned by interoperation of advanced load prediction and analytic models. This way consumers are required to possess less technical knowledge of the energy system, rather advanced intelligent, analytic models extract knowledge from the digital signature of electricity consumption. A review has been presented in Brosinsky et al. (2018) focusing on developments and the application of DT to the control of power system. Work (Francisco et al., 2020) explains the application of DT with respect to energy benchmarking as an approach to getting informed about optimal energy decision making towards better strategies for energy retrofitting and real-time energy managements. A multilayered approach energy efficient model based on DT modeling of energy consumption has been presented by Andryushkevich et al. (2019), Lu et al. (2019). Work (Andryushkevich et al., 2019) further used ontological modeling language for recommendation provision in digital decentralized energy sector. A DT application platform for smart-grid using online analysis of the power grid has been presented (Zhou et al., 2019). Recent implementation of this concept in the energy sector includes Honeywell Forge APM-Asset Performance Management software for energy monitoring (Honeywell, 2019), HVDC Light DT and Edge based available peak power an ABB solution for PV module (ABB, 2020).

Key enabling technologies: To achieve significant reduction in energy consumption at the consumer end using DT framework, it is important to describe key technologies (Qi et al., 2019; Fuller et al., 2020) and parameters supporting the described framework. The input to the DT model is the output obtained from the data gathering and insight stage, with an output targeting energy reduction. Similarly, it is important to present the key enabling technologies associated with the smooth running of the described architecture. These include IoT platform, energy forecasting, and advanced data analytics.

IoT framework: Application of information technology such as the IoT coupled with smart devices enabled with the ability to obtain data produced during a product's lifetime, and supported by the data mining ability of Artificial intelligence (AI) are all paving the way for a new era of data driven product design, manufacturing and service (Tao et al., 2017). The IoT platforms which generate data from physical system in real-time combined with historic data set provided from previous energy consumption are all utilized in the development of DT concept (Ruohomaki et al., 2018). Similarly, technologies such as Energy Internet (Hong et al., 2018; Kaur et al., 2019; Qureshi et al., 2020), Smart Grid (Qureshi et al., 2020; Feng and Liao, 2020) and Industrial Internet of things (Zhang et al., 2018b; Cheng et al., 2020) also provides intelligent sensing capabilities and secure transmission network towards effecting consumer-oriented DT framework.

Data and metadata analysis: Data in its raw form is neither useful for recommendation system nor for energy forecast, it is therefore important to understand key variables associated with energy forecast and recommendation. It will be required to commit efforts into data preprocessing in order to extract important features such as social behavior, temperature, demographic information, geographical information, etc. The following describes methods for obtaining key features associated with energy consumers.

Data Gathering and Insights: Data collected form smart meters, weather station and historic consumption are utilized for the development of parameters required for the DT implementation and simulation (Karanjkar et al., 2018). Consumer associated data are collected, measured, processed and analyzed to develop customized and optimal energy strategies (Castelli et al., 2019). Online social media networks are used to obtain consumption data within a social group used by individual DT. This source of information promotes inclusiveness and allows for every consumer within a social group to be carried along.

Large amount of heterogeneous consumption data describing various energy phenomenon are intuitively useful in modeling machine learning based analytic tools. This heterogeneous data obtained from real-world scenarios represents a valuable and precious ingredient, useful in performing services that are deemed complex. The application of AI helps to provide useful insight into this data for automated decision making ability.

Feature engineering: Data cannot be utilized either for recommendation or energy forecast in a raw form, understanding of the key variables influencing energy forecast is therefore necessary. Efforts can be committed into the understanding of the salient features that can influence energy consumption. These include procedures involving preparation of high dimensionality data for data mining operations. In this study, analysis of key categories of features/variables for rating consumers is discussed (Zhang et al., 2018a). Such data includes forecast and key historical energy data comprising of hourly electric demand data obtained from utility, social media features, residential features along with policy related features, weather data including outdoor dry bulb, outdoor relative humidity, outdoor air density, ground temperature, zonal total internal heat gain and building data such as lighting, energy consumption and number of occupants, to mention but few. Additional features such as energy profiles for weekdays, weekends, holiday situations, temperature, time (Spichakova et al., 2019) and demographic information of consumers which includes age, family size and historic consumption data were also taken into consideration. These features are considered as factors influencing the energy dynamics of consumers. Table 1 summarizes the review of related works on DT.

Review energy forecasting: Energy forecasting can be broadly classified into the following three main categories short-, medium- and long-term load forecasting. Short-term load forecasting allows energy consumption to be determined for a period ranging from 1 h to 1 week ahead (Ahmad et al., 2018; Jiao et al., 2018; Bouktif et al., 2019) while medium-term load forecasting normally last for a period between 2 weeks and three years with the main intent of planning, maintaining and dispatching load *ex ante* (Essallah and Khedher, 2019; Spichakova et al., 2019). Long-term load forecasting is important ingredient in the efforts aimed

Table 1
Related works on digital twins.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type
Brosinsky et al. (2018)	Dynamic digital mirror	Energy management system (EMS)	Proposed platform operates faster than SCADA	Difficulties in obtaining detailed modeling of the power system	Control centers for power systems
Andryushkevich et al. (2019)	Ontological modeling language	Hybrid renewable energy system	Provide means for updating DT in the energy sector	Lack of tools for automating data synchronization	Energy prosumer
Francisco et al. (2020)	Regression	University campus power supply	Examines temporal dimension for bench marking energy	Difficulties in determining level of agreement for building efficiency	Campus
Zhou et al. (2019)	Online analysis digital twin	EMS system for power grid	Fast complete online analysis using data-driven large scale model	Sub-second delay exists	Dispatching control centers

at achieving desired understanding of future energy demand allowing a long term view into the consumption of electricity towards the development, planning and drafting efficient policies of national economies (Silva et al., 2018; Chen et al., 2019).

A robust load forecasting model spanning different time horizon is crucial for effective operation of the power system (Fallah et al., 2018; Sangrody et al., 2018) and has been identified to play significant role in optimizing the practical operation of DT (Xie et al., 2019). Early research into energy load prediction have been focused on regression analysis while a combination of multiple meta heuristic techniques such as genetic support vector machine (SVM) and Firefly algorithm neural network have also proven to be effective (Fallah et al., 2018). Work Xie et al. (2019) proposed a demand forecasting model for DT application in power grid using Deep neural network (DNN) based ordinary differential equation. Study outcomes from a short-term residential load demand forecast indicated an appreciable level of accuracy for vast array of prediction applications especially in future energy consumption forecast, and market price for grid economic optimization. Work Damiani et al. (2019) presented a DT implementation of a short-term electricity price forecasting model for electricity cost optimization in logistic centers using autoregression model. The authors identified electricity price as major performance indicator in the operation of logistic centers with high energy demand. Based on this information, they presented an innovative and synergic power consumption inner tool for best price predictive analysis. Work Kychkin and Nikolaev (2020) proposed DT enabled IoT-based ventilation control for energy saving in mining operation. The DT implementations incorporates an online short-term load forecasting of energy consumption using integrated linear auto regression, linear regression, and multilayer perceptron predictive models. Study outcomes revealed that forecast was useful in optimizing mine air regulation algorithm and energy. Work O'Dwyer et al. (2020) proposed an integrated DT and energy management tool for achieving coordination in multi-vector smart energy system. The proposed tool is underpinned by forecasting, optimization and coordination service subsystems implemented using Artificial neural network (ANN), gradient boosting and k-means clustering algorithms for about 97% curtailment of high system constraint violation. On the other hand, work Nwauka et al. (2018) argued on application of Industry 4.0 for the integration of distributed energy resources applications based on the exploration of basic operational and technical requirements of virtual power plants. The proposed intelligent management framework carried out scheduling optimization using real-time day-ahead forecast of load, electricity spot prices, and generation profile. Table 2 describes an overview of energy forecast application to DT.

3.2. Digital twin for consumer energy services

The consumer ES described in this section focuses on the use of DT technology (O'Dwyer et al., 2020; Kabugo et al., 2020; Teng et al., 2021) for post generation associated services employed for consumer end demand management, service reliability and convenience geared towards energy efficiency. Based on this, relevant services associated with energy efficiency can be provided to consumers which could belong to the following categories (Tao et al., 2017; Bakhtadze et al., 2019; Tao et al., 2019):

- Energy consumption analysis and forecast associated services (Kabugo et al., 2020): The result of high achievable precision between the virtual and physical world which allows for the projection of energy consumption on various scale such as on daily, weekly or monthly basis. In addition, the future consumption of energy can also be estimated allowing for potential discovery of better energy behaviors and choices.
- Energy management services based on behavioral analysis (Li et al., 2020; Xiang et al., 2020): Users are analyzed based on their energy consumption habits using DT real-time monitoring services allowing for the correction of poor energy behavior and lifestyle for consumers in real-time. This can be achieved by simply analyzing the consumption habits for computing life actions associated with energy behaviors in the one hand and helping utilities manage and effectively hands off DSM using DT energy services while giving them the ability to improve on quality of service on the other hand.
- Provision of intelligent service update and optimization (Min et al., 2019): DT allows for the generation of consumer habits based on their different and independent patterns of energy use. Holding the opportunity for the real-time correction of consumer poor energy habits. This majorly is as result of analysis of specific user consumption habit and checking whether they are within the healthy consumption band.

4. Recommendation features/tips

In this section, we present recommendation system as a major component in the IES framework (Fig. 1) described earlier in Section 2.

The key element of a recommender system is its ability to understand the preferences of an active user simply by analyzing the user and/or other user's behavior (Lu et al., 2019; Ayres et al., 2018; Hafshejani et al., 2018). This domain of study evolved in the

Table 2
Related work on energy forecasting for digital twins.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type
Xie et al. (2019)	DNN, Ordinary differential equation	Smart grid	Balance and stable forecast performance for volatile electricity load	High uncertainty in data attributes	Residential consumers and utilities
Damiani et al. (2019)	Autoregression model	Maritime infrastructure	Reduces high initial energy demand for planning stage of logistic center	Difficulties in eliminating periodic components of series due to periodic delays	Commercial sector: Maritime
Kychkin and Nikolaev (2020)	Linear autoregression, Linear regression, Naïve model, & Multi-layer perceptron	Cyber–physical system for mining sector	Proposed model guarantees energy efficiency	–	Industrial sector: Mining
O'Dwyer et al. (2020)	ANN, K-means, gradient boosting, random forest	Smart energy management system	Optimal operation decision provision via day ahead forecasting and curtails high system violation by 97%	Lack of extensive energy forecasting	Residential consumers and utilities
Nwauka et al. (2018)	Predictive analytics model	Virtual power plants	Hybrid model produces better coefficient estimation	Policies, institutional, regulatory barriers to deployment	Utility

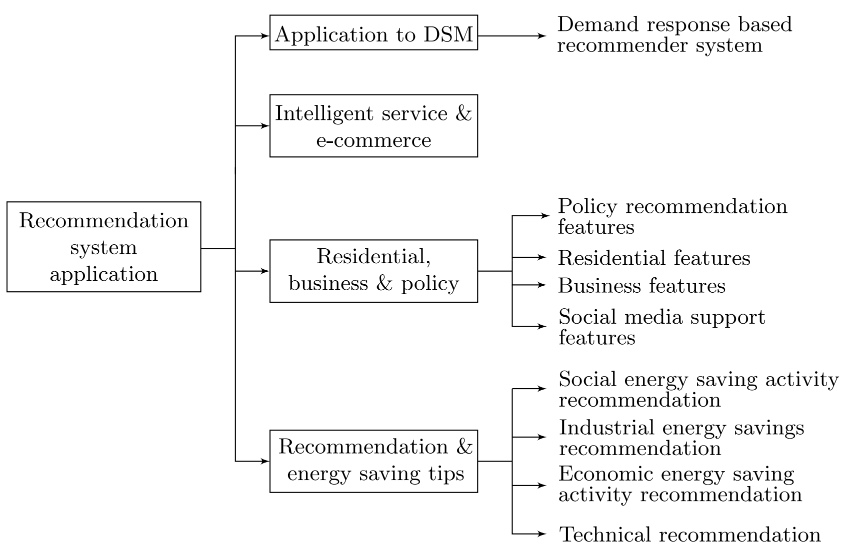

Fig. 3. Recommendation system application.

mid-1990s, when, researchers were interested in the application of rating structure (Lu et al., 2019; Adomavicius and Tuzhilin, 2005). E-commerce and web services were the first to utilize recommendation systems. This was soon followed by social network and service selection (Mezni and Abdeljaoued, 2018). Recommendation systems have been mainly researched based on the following approaches: collaborative filtering and content/knowledge based with associated merit and demerits (Karbhari et al., 2017). Collaborative filtering methods generate recommendations for an item based on similarities existing between users' history (Lu et al., 2019; Tarus et al., 2017), content based methods generate recommendations for an item based on similarities existing between item description and user history (Lu et al., 2019) (see Table 5), the knowledge-based approach generates recommendations based on the domain knowledge about how the product meets users' needs (Tarus et al., 2017) (see Table 3).

In a previous study, an approach incorporating intelligent recommendation system for innovative service design based on user behavior change has been examined (Trappey et al., 2013). To further extend the application of IES using recommendation system, we present recommendation system as a major component in the IES framework (Fig. 1) described earlier in Section 2.

Recommendation system for energy applications: This section examines the four major categories for providing recommendation tips to energy consumers, namely: business and industries, residential, and policy categories. Recommendation systems area of applications in our context describes the case studies and the area of application especially within the energy domain as depicted in Fig. 3. The section further elaborates on the following application areas for recommendation provision:

(a) Application to DSM
(b) Application to intelligent services and e-commerce

(c) Application to consumer behavior
(d) Residential, industrial, business and policy
(e) Social, technical and economical

4.1. Application to energy management and intelligent services

(a) Application to DSM: There are numerous electricity plans available to consumers to take advantage of which often introduces confusion on which is the most suitable service for individual energy consumers to adopt in managing their energy supply subject to lifestyle (Ros et al., 2018). This section describes various aspects of recommender system in relation to energy.

Demand response based recommender system: A vast amount of efforts have been committed to studying technological approach for reducing electricity demand by switching from peak to off-peak. In doing this, platforms that monitor and control household energy consumption and systems that provide energy efficiency by encouraging behavioral changes for energy efficiency are required (Alsalemi et al., 2019; Jabir et al., 2018a). DSM is a major area of interest for smart grid (Teh et al., 2018; Metwaly and Teh, 2020; Jabir et al., 2018b), with demand side Personalized recommendations system (PRS) leading the way in inferring residential user's needs and interests on their energy saving appliances (Luo et al., 2017). There is a vast amount of research work carried out on Demand response (DR) based recommender systems (Behl et al., 2016; Luo et al., 2017). The work of Behl et al. (2016) presented a data driven approach to a recommender system for DSM. They employed the use of regression tree algorithm alongside open source MATLAB based DR-Adviser for the control of commercial building and providing suitable recommendations to residents. The study presented by Luo et al. (2017), attempts to integrate demand side based PRS and service computing paradigm. Authors revealed that residential user potential interest and demand for energy conservation is been inferred using PRS approach for service recommendation. Demand side PRS comes in various format, such as retail plan for electricity, suggestions or recommendation on energy consumption (Luo et al., 2020), or appliances optimized for saving. Another approach to achieving this is to apply a Non-intrusive appliance load monitoring (NILM) technique to disaggregate the smart meter data from the utilization profile of end user home appliances and compare appliance similarities measure using generalized particle filtering (Luo et al., 2017). The goal of this service is to ensure consumer satisfaction by simply stimulating or encouraging them to acquire energy saving appliances, so as to reduce the cost of energy consumption for users. Table 3 describes related works on demand side recommender system.

(b) Application of recommendation system to intelligent services and e-commerce: Intelligent energy management services based on actionable recommendation and analytics have been seen to give consumers the motivation for energy conservation, and identify problems in their energy behaviors (Shin and Hwang, 2012). By suggesting information about suitable products to consumers, recommender systems have emerged as the cornerstone of e-commerce platforms that provide services associated with competition (Li et al., 2016; Mahmood et al., 2015). One of the major advantages of intelligent techniques in home energy management is the ability to aid reduction in power consumption and support DSM (Ayres et al., 2018). Work Ayres et al. (2018) developed a novel intelligent architecture for energy conservation in homes based on recommended suggestions aimed at improving energy efficiency and reducing Cost of energy (CE). Within this context (Zamil et al., 2018) used intelligent solutions based on mobile multimedia technologies to determine the activities of residents in a household.

Intelligent services targeted towards energy management could require some level of adjustments from home appliances to cater for energy conservation (Ayres et al., 2018). Within this context, several reviews have been presented. Work Romero et al. (2018) presented a DR framework for the integration of intelligent EMS for enabling reduction in the CE and holistic optimization of DR in homes. A study of consumer engagement based on consumer experience obtained from energy efficiency is presented in Kompos et al. (2019). The authors presented a realistic and innovation solution geared towards the delivery of consumer-oriented and behavioral transforming platform developed using economic building with affordable sensors. In addition, consumer-centric intelligent control features alongside HVAC supportive control was used to conserve energy. Work Marinakis et al. (2020) presented a smart ES based intelligent energy management using big data technologies for the development and exploration of smart ES while incorporating a decision support system which allows convenient information gathering for generating recommendations. Table 4 provides a summary of related works on intelligent ES and e-commerce, while Table 5 summarizes recent works on application of recommender systems.

4.2. Application to consumer behavior modeling

(c) Application to consumer behavioral reflective attributes: The behavior of consumers has been described as soft characteristic which proves difficulties in measuring objectively in a similar way as energy consumption (Zehnder et al., 2015). Note that not all consumer behaviors result into energy conservation. It is therefore important to identify relevant behavioral patterns that result into energy savings (Zehnder et al., 2015). Important patterns must result into at least an action which results into energy savings and comprises of normal events. The main task in this situation is for recommender system to identify moments where consumers forget to follow a regular pattern and suggest actions that lead to energy reduction. Traditional approach to obtaining human behavior is via the use of price response reproduction in relation to using discrete choice model for capturing technology adoption and constant elasticity of substitution (Venturini et al., 2018). As indicated in Kashani and Ozturk (2017), two third of energy consumption in residents are associated with human behavior. Work Zhang et al. (2019) examined the role of behavior in the uptake of energy efficiency by monitoring their energy consumption pattern and providing suitable recommendations. A better understating of behavioral, social and cultural factors associated with energy efficiency is therefore required (Kashani and Ozturk, 2017). The value associated with mining consumer behavioral pattern from power system data is increasing and its usefulness for operation in power system is eminent (Xu et al., 2017). According to the literature, the authors in Xu et al. (2017) presented a complementary analysis of energy consumer electricity behavior using k-means algorithms with outcomes showing potential for energy consumption optimization. Work Galperova and Galperov (2018) reported that modeling the behavior of consumer is required for the assessment of electricity systems' mode of operation while modeling consumer active behavior using agent-based technique indicating their role in the smart grid concept allowing for a feedback connection between the grid and consumers. Work Alsalemi et al. (2019) presented a survey on recommender system and change in habitual behavior for energy conservation based on reviewed literature that aims at understanding energy consumers' behaviors with intention of changing it based on recommended energy saving tips. They further developed the theory of "habit-loop" and "micro-moment" to determine the moment when recommendation is optimal, and reward is effective for effecting gradual energy change among consumers.

Table 3
Related works on demand side recommender system.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type
Romero et al. (2018)	OpenADR model	EMS-equipped smart homes	Human-centric demand management approach	EMS and Smart home devices are not interoperable	Residential and tertiary energy consumers
Luo et al. (2016)	NILM	NILM: Smart grid	Investigates application of recommendations to smart grid DSM	Computational cost, data sparsity & cold start problems	E-commerce & electricity retail
Behl et al. (2016)	Regression tree	Large scale energy systems	Recorded 92.8–98.9% accuracy saving up to 380 kW load	Complication in defining partition line/region	Commercial building
Luo et al. (2017)	SVM & Particle swarm optimization	NILM: Electrical appliance	PRS achieved a high level of recommendation accuracy up to 97.0%	Lack of representative data for laundry dryer lowers recommendation accuracy	Smart grid residential consumer

Table 4
Related work on intelligent services and e-commerce.

Ref.	Methodology	Knowledge Gap	Platform	Benefits	Drawbacks	User type
Li et al. (2018a)	Bayesian updating	Effect of recommender systems on manufacturer	Electronic market place, channel structure for retailer and manufacturer	Additional sales	Consumers get benefits at the expense of retailer and manufacturers	Manufacturers, retailers and consumers
Gupta et al. (2018)	Questionnaire surveys, community events & house monitoring	Illustrative Study	households, Decorum model management	Provides residents experience based on visual energy feedback provision	Small number of participants	House holders
Hussain et al. (2018)	Multi objective genetic algorithm, Pareto optimization	Improvement of performance parameters	HEMS	Proposed algorithm allows selection of optimal size dispatch generators	Long computational time	Energy consumers
Cacciatore et al. (2017)	Heuristics, occupancy and distributed control strategy	Achieve coordination for individual lamp dimming	Custom-built simulator	Cost reduction of street lighting	Current implementation does not account for users passing close to the lamp	Pedestrians
Kolloch and Dellermann (2018)	Actor network theory	Applicability of controversy method to other innovation	HEMS	Contributes to management aspect of digital innovation	limits innovation by setting predefined goals for decentralizing energy supply	Consumers

Table 5
Related works on recommender systems.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type
Primo et al. (2012)	Collaborative filtering, content based and Hybrid	Semantic web	Application of data and object properties as a solution to educational recommender system	The platform is unable to integrate different web services to obtain a single learning application	Educational environments
Sellami et al. (2013)	Content based, collaborative filtering and semantic-social algorithms	Semantic web and social network technology	Semantic recommender system performs better	Smaller number of connected users can reduce precision	Social network users

4.3. Residential, business and policy

This section examines the legal, regulatory regimens, and policies available across the globe and further provides directions for policy makers responsible for the deployment of IES. The section further examines an overview of business and residential features supporting effective uptake of IES as summarized in Table 6.

(a) Policy recommendations features for saving energy: Policy can be described as a dynamic process associated with the sum of actions, regulations, laws and other related factors that influence energy conservation among energy consumer. Policy recommendations stand as a well research category for energy conservation (Alsalemi et al., 2019). Most countries are coming up with regulations and promulgating laws that support energy conservation. The European Union has introduced policies encouraging member states to adopt measures targeting energy conservation (Xu et al., 2017). In a similar move, the US has designated federal agencies for overseeing the conservation of

Table 6
Related works on feature engineering: Business, residential and policy.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type	Feature
Nilashi et al. (2019)	Multi criteria collaborative filtering	Eco friendly hotel	Prediction scalability is able to handle large amount of user ratings	Effectiveness of proposed ANFIS requires further investigation	Consumers	Residential
Johansson and Thollander (2018)	Questionnaire & semi structure interviews	EMS	Efficient energy management	Proposed standard cater for long-term strategies	Industry, energy managers	Business & Policy
Hoicka and Parker (2017)	Interviews	EnerGuide for Houses and ecoEnergy programs	Results indicated positive response to complex retrofit model of residents	Lack of information on cost as a barrier to retrofitting actions	Homeowners	Residential

energy based on the United States National Energy Saving Policy Act of 1988 as amended. New Zealand energy strategy 2011–2021 specifies efficient use of energy as a major point in her four area of interest in the strategic drive towards energy conservation. Following this trend, a number of policy recommendations have been introduced by the Chinese government to promote energy efficiency and reduce GHG (Zhou et al., 2019). Work Zhou et al. (2019) reported that air pollution related to energy consumption is a major driver for policy reforms in the energy sector. Work Morton et al. (2018) presented Green Deal, a UK's Department of Energy and Climate Change initiative targeted towards energy efficiency policy for domestic energy and was implemented based on the following stages: Assessment of green deal using energy efficiency audit of appliances, recommendations provision based on cost effective energy options, and selection of green deal plan to mention but few. A similar measure is the information policies based on energy benchmarking and labeling (EU Energy Label and US lighting label) towards addressing information barrier by implementing ENERGY STAR across a number of EU member states and the US. Additionally, building codes and appliance standards are identified as important regulatory policy measures targeting energy conservation. Similarly, policy targeting consumer-oriented efficiency recommendations based on DT can encourage consumer to take up energy efficiency measures.

(b) Residential features: Energy efficiency in residential apartment is majorly associated with appliances and lighting, ventilation, heating, refrigeration and cooling (Moglia et al., 2018). Residential buildings currently account for roughly 40% energy consumption standing as the substantial consumption sector within the EU (Kompos et al., 2019) and measures required to obtain necessary features for accurate determination of residential energy consumption are required. In the same vein, energy waste in the residential sector is high due to a number of contributing factors. A major factor is low penetration of technologies that enable efficiency in the use of energy among consumers. Another is difficulty in quantifying and modeling the level of user comfort due to disparity among individual users making the deployment of automated building energy management units challenging (Shaikh et al., 2014). Having said these, the most important factor resulting in the misuse of energy in buildings is the issue of users careless behavior towards energy conservation. Researchers are identifying interesting approaches and features associated with recommendations based on the optimization of residential energy consumption. For example, real-time monitoring of residential energy consumption can contribute about 40% efficiency on the energy consumed in buildings (Kamilaris et al., 2014). Work Óscar García et al. (2017) presented an integrated approach using social computing and context aware platform for encouraging energy conservation among residents. Work Moglia et al. (2018) proposed adoption of resident energy efficiency using agent based model. In their work, recommendations for obtaining efficient energy products were provided to households using information agent. Work Hoicka and Parker (2017) proposed approaches for improving energy efficiency in homes using retrofit recommendations. They consider residential facilities as a system and indicated the potential for saving 50% to 80% energy if the specified retrofit stages are followed. They further identify high performance envelope such as wall insulation (make and model), and weather data as important retrofit feature for energy optimization (Hoicka and Parker, 2017).

(c) Business features: In recent years, the e-commerce industries have found wide use for recommendation system in the provision of personalized marketing experience to consumers (Guo et al., 2018). This aspect intends to provide information about relevant features associated with energy conservation in the business sector. Features falling into this category utilize data relating to businesses which could include nature of equipment, level of income, devices or machine that are deployed for production. Recommendations are generated using consumption profiles and consumers' action which can be in the form of heat produced by electric drives. The hospitality business is one out of many that has in recent times been responding to customers' sensitivity to the call for eco-friendly environment (Gupta et al., 2019). These calls have often resulted in hospitality businesses adopting energy saving and carbon reduction measures as part of their corporate social responsibilities (Lee and Brusilovsky, 2018; Nilashi et al., 2019). Work Nilashi et al. (2019) presented a multi criteria collaborative filtering technique for recommendation system based on preference learning of energy saving hotels. In their approach, preference on energy saving facility was predicted using Adaptive neuro-fuzzy inference system (ANFIS), while membership function of fuzzy logic was learned using ANN. A research was presented on e-commerce recommendation system for sustainable e-business using multi-source fusion of information (Guo et al., 2018). The author in Guo et al. (2018) employed the use of multi-source information to determine consumers preference for e-business recommendation system prescribing that an e-commerce recommender system should integrate features such as consumer location and historic behavior information (Guo et al., 2018). Work DixonoMara and Ryan (2018) examines the key motivation for introducing measures of efficiency in energy dependent sectors such as food retail sector. Paper Trianni et al. (2013) further identified features responsible for energy efficiency among different categories of consumers which includes business characteristics, operating environments, attitudes and reaction towards policies targeting energy efficiency. Similarly, International Energy Agency (2015) reported that developers of businesses can elect to pay attention to features representing the subset of an Small to medium-sized enterprise (SME), some of these include: the region of operation, size of the company, supply chain and the business sector.

These features are potential contributors to energy efficiency in SMEs. Other less tangible factors such as competition, disruption avoidance, consumer experience, and ambiance have also been identified (DECC (UK Department of Energy and Climate Change), 2014).

(d) Industrial energy-saving recommendation: For a low carbon economy to thrive, there is need for improvements in energy efficiency as 33% of the world energy consumption is a direct result of industrial activities. Improving energy efficiency at the industrial scale does not only have immense effect on the environment, but also lead to reduction of CE and the amount of GHG emitted while enhancing the competitiveness of the industry (Johansson and Thollander, 2018). By reducing the profile of a company's energy consumption, there is huge potential for improving profitability. Contrary to this, companies often fall short of adopting the several energy efficiency measures available, known as gap in energy efficiency (Jaffe and Stavins, 1994; Martin et al., 2012). Previous research works in this direction indicated great potentials for efficiency improvements in industrial energy consumption. A study on the driving forces and barriers associated with the uptake of energy efficiency in the industrial sectors and recommendations for energy management within homes has been presented (Johansson and Thollander, 2018). Work Trivedi and Bhatt (2018) provides a review on the application of energy conservation measures to the manufacturing industry. They reported that energy conservation is important as there are measures that enable conservation across manufacturing units. They further discussed technological measures that ensure energy conservation which resulted into recommendations of some actions that proposes to optimize energy in food, bread and metal industries. In a similar work presented by Arya et al. (2016) energy audit on aluminum industry was carried out by observing real-time, online and offline data resulting into 5 type of valuable recommendations for loads associated with: motors, lighting, fans and compressor. They further reported daily savings of 12 kWh by following recommendations applied to lighting load. Work Tan et al. (2019) reported on the implementation of energy substitution policy on industrial scale. They described 20 types of technologies aiding energy saving and emission reduction models which is further subdivided into 4 categories including electricity-, energy-, and coal-saving as well as the linkage technologies based on the energy saving effect of the itemized varieties of energy.

4.4. Social, economic and technical recommendations/tips

Consumer education is a conventional strategy for behavioral change on the execution of certain tasks. The behavioral control perception and the sense of consumer responsibility can be strengthened by providing them concrete and actionable suggestion. The provision of recommendations to consumers helps them to form the habit of energy conservation (Gölz and Hahnel, 2016; Koroleva et al., 2019). This section describes a number of recommendations/tips in the following categories: social, technical and economical recommendations.

(a) Social energy-saving activity recommendation: The concept of social computing encourages collaboration between machines and humans in providing solution to social problems based on the utilization of innovative socio-technical approach. This technique has evolved to become strong following the identification of agent's virtual organizations as a major powerful tool supporting social computing. By application, social machines are result of social computing producing entities that support social and technical management practices. An instance of such entities are social media platforms which include Facebook, Twitter, Instagram to mention but few. Social interaction resulting from the introduction of competition among consumers has proven to be useful tool in encouraging consumers to reduce energy consumption and further accelerate the change in behavior that favors energy conservation (Óscar García et al., 2017). In the same vein, social power gaming approach to conserving energy based on social interaction using real-time representation of cost, energy usage and data analytics has been examined (De Luca and Castri, 2014). This approach illustrates a friendly technique to achieve energy conservation using tools supporting energy visualization. In addition, social competition and feedback reward have been identified as viable measure for encouraging consumers to adopt energy conservation. This often appears in the form of collaboration, energy community or social competition (AlSkaif et al., 2018; Li et al., 2018b) allowing residential consumers to compare their energy consumption/energy performance to those of neighbors with identical household. To this end social computing paradigm can be implemented to develop a social system that allows collaboration between machine and human to resolve social related challenges using AI (Shadbolt, 2013). A number of social factors can be associated with acceptance of recommendations, thus advice or recommendation given by social peers or people belonging to trusted group are likely accepted (Starke et al., 2017). Work Luo et al. (2019) introduced an electricity retail plan recommender system for end consumer based on social information filtering techniques. Work Moglia et al. (2018) examined social network influence in the adoption of energy efficiency using agent based model for recommendation provision. Paper (Lee and Brusilovsky, 2018) presented a social link oriented recommender system that provides insight on related items. Work Óscar García et al. (2017) presented an integrated framework using social computing and context aware platform for encouraging energy conservation among residents. A concise summary of related review on social, technical and economic recommendations has been presented in Table 7.

(b) Economical energy-saving activity recommendation: The key role of implementing energy saving strategies lies directly on economic entities (Popkova et al., 2018). This therefore necessitates the need for economic entities to be interested in the process and results of energy conservation. According to UNEP (2011) annual report, for an economy to be green, it must display efficiency and fairness in terms of resources optimization, encourage social inclusiveness and must be low carbon based. Furthermore, the authors iterated on the importance of self motivation of economic entities in the developments of energy saving strategies. Issues associated with motivations for energy conservation for business consumers were discussed in Park and Kwon (2017). Work Popkova et al. (2018) reported on the approach for interpreting the importance of energy savings for the economic entities within the cooperate energy market using regression correlation analysis. The first considerations were given to self-motivation based on consumer or entities internal environment allowing organizations (entities) to identify energy saving opportunities using internal motivations and carrying out such implementations to facilitate energy efficiency. They identified the following requirements as necessary for achieving self motivation for energy saving (Park and Kwon, 2017):

- Provision of the logic and nature of the motivation process required for saving energy by the economic entity.
- Recognition of key variable required for energy saving motivation by economic entities.

Work (Campisi et al., 2018) presented on the economic viability of improving street lighting energy efficiency for residents of Rome. They discussed the economic implications of adopting LED luminaries technology and also computed the potential cost and quantity of energy it could save. Work Tetiana et al.

Table 7
Related works on social, technical and economical recommendations.

Ref.	Methodology	Platform	Benefits	Drawbacks	User type	Category
Óscar García et al. (2017)	Web monitor of the power application interface	–	Increased awareness about efficient use of energy based on social actions	Energy optimization was not maintained after the experiment was concluded	Public buildings	Soc
Koroleva et al. (2019)	Gamification approach, baseline and assessment questionnaires	Mobile app, Google fireball messaging service	Stability in energy consumption irrespective of exogenous factors	Short duration of study (4 months) may result into consumers relapse	Electricity consumers	Soc/Tech

(2018) developed an innovative model for replicating the economic behavior of agents associated with energy conservation. The authors developed a management system for introducing and analyzing energy conservation technologies. An approach based on the principle of economic efficiency was used to implement agent energy-conservation behavior model. Work (Hilorme et al., 2019) presented a model for forecasting entrepreneurship energy savings and further developed energy saving technologies for the identification of potential area for aggressive activities in the energy markets. By analyzing the developed energy saving models, conclusion was arrived at based on obtained economic efficiency. From economic point of view, Meshcheryakova et al. (2018) presented an article on the industrial facilities' energy efficiency and its role in societal development. The authors identified energy balance for a given production type and cost of production structure as a major indicator for the CE. They further provided recommendations targeted towards reduction in CE.

(c) Technical recommendations is a crucial part of measures geared towards improving energy efficiency. From the technical perspective of energy conservation, provision of stimulants and regulation towards utilization of the best available and efficient technologies and better energy auditing schemes to advance the cause of energy conservation is required (Alekseev et al., 2019). Recent research has also shown that consumer behavior is important factor for achieving efficient household energy conservation and technical intervention has been identified as a major enabler for achieving such efficiency in energy consumption (Alsalemi et al., 2019). Works that build on the use of technology for changing the behaviors of consumers in relation to energy conservation have been presented (Gaglia et al., 2019; Koroleva et al., 2019; Lester, 2015). Paper Gaglia et al. (2019) presented a technical and energy characteristics of residential energy consumption with the potential for energy conservation and emission reduction in non-insulated building. Their estimation of the percentage of various space heating for residential building type was obtained based on heating degree hour while potentials for energy conservation or estimation of occupancy behavior was determined using actual specific energy consumption. Furthermore, findings on considerations for the development of technological solutions to energy conservation problems have been limited in supply, and alternative approaches have employed theoretical models. None of the available approaches have been able to obtain a real-life validation of behavioral change favoring energy conservation or provide suitable recommendation in such manner for various categories of users. Similarly, the consumption of energy should be seen beyond individual decision but rather as an integration of technologies, social norms and infrastructures making it a social technical process. New directions are based on the use of machine learning models which categorize consumers by appropriately mapping them for personalized recommendation. An approach that integrates interactive visualization of consumption, attention triggers, recommendations for energy savings, smart meter data and gamification for socio-technical and behavioral changes for energy conservation measures was proposed by Koroleva et al. (2019).

5. Result analysis and discussion

This section gives an evaluation result of content analysis for summarized literature prevalent in the domain of discuss. In addition, the relevance of the selected papers was based on the subject of "innovation" and "energy services" (see Table 8) from selected databases. The relevance of selected documents was determined using keywords, citation index, and specific search categories in order to limit the wide scope of available literature. Owing to the heterogeneous and complex nature of IES, in all two major databases (IEEE Xplore and Scopus scientific library) were considered in this section and attention was given to categories such as "conferences" and "journals" with all presenting a point of view and unique contributions to the concept of IES. To better place the context (innovation, energy and services) and scope (IEEE Xplore and Scopus scientific library databases) to which this study is being conducted, we observed studies over a period of ten years starting from the year 2010 to 2019.

Energy services are categorized based on the nature of similarities or closeness. There is potential ambiguity in classifications as some services cuts across two or more categories. Services associated with water heating, space heating, cooling, lighting and cooking have been seen to be among the most occurring instance of energy services. Among the selected set of databases, key search words (Table 8) were used as query term to obtain the frequency of occurrences of the selected terms.

Fig. 4 is a pictorial depiction of results obtained from an objective evaluation of IES literature based on search result from IEEE Xplore and Scopus databases. It breaks down the frequency of occurrence of IES over the period between 2010 and 2019 by publication. It can be observed especially starting from the year 2013 to 2019 that IES enjoyed an upward trend across the two observed databases indicating about 83% increase in its adoption a result indicative of the general S-curve pattern of innovation services. In addition, the adoption of these services peaked in 2012 as observed across the two databases. This increasing trend can be associated with a number of factors which in most cases are social or economic factors and the possible adoption of innovations as a recovery mechanism from the 2008 global financial crisis. Such innovations are in the area of integration and improvements in performance of renewable energy sources (PV photovoltaic), integration of intelligent management of electrical network and increase in R&D spending on energy by the private sector. Such indication is the increase in private energy sector R&D spending which rose from 10.1 billion dollar in 2003 to about \$21.6 billion in 2012 (Rhodes et al., 2014). There is also evidence that innovative activities and spending declined towards 2011 from 26.7% to about 10.8% during the period of crisis (OECD, 2012). Between year 2012 and 2013, content analysis revealed about 80% reduction in reporting IES. Across both databases, the situation analysis starting from 2013, indicated an upward trend in the adoption of IES.

Fig. 5 depicts the trend in yearly publications for IES contributing technologies. We used this trend to describe the historical

Table 8
Search keywords.

IES	DT	Recommendations	Behavioral attributes
“innovation” AND “energy services”	“energy services” AND “digital twins”	“energy services” AND “recommendation”	“energy services” AND “consumer behavior”

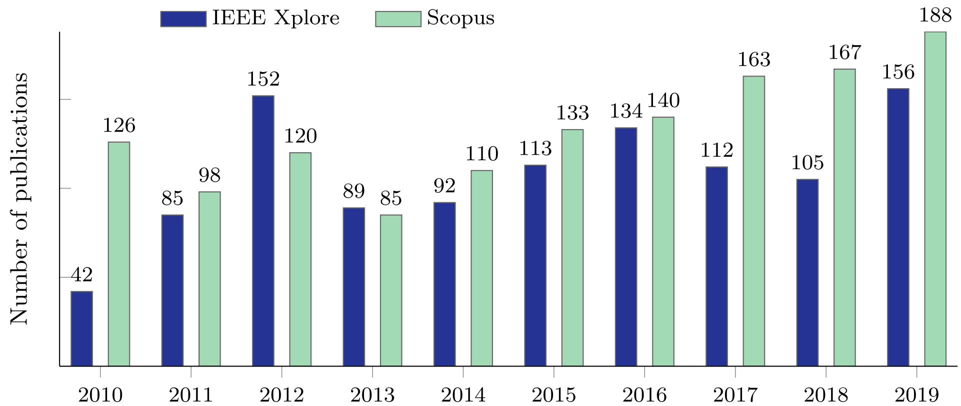

Fig. 4. Yearly number of publications in the period from 2010 to 2019 for IES from IEEE Xplore and Scopus database.

relationships between IES and individual contributing technologies. Trend indicates that behavioral reflective attributes closely follow recommendation tools, leaving DT with the least traction. This trends corroborates the possibilities of combining these closely related technologies. The slow traction recorded by DT publications can particularly be attributed to late introduction in the 2000s (Grieves, 2015), which however peaked in 2018. This dramatic increase in 2018 supports the conclusion that DT is one of top 10 technological trends in 2018 (Khajavi et al., 2019). Moreover, we visualize the percentage share of contributing technologies to IES (Fig. 5). A more significant increase was recorded by recommendation amounting to 53% which is closely followed by 45.3% recorded by behavioral attributes in the period between 2010 and 2019. This trend is plausible revelation that recommendation incentivized by extrinsic rewards is capable of stimulating pro-energy behaviors. To support this claim, a 0.911 correlation coefficient further corroborates a strong positive relationship.

When viewed through the lens of innovative studies, these trends can be seen to follow a classical path based on historical pattern of transition in technology where traditional notion of technology is threatened by advancement in innovation. Such advancements can be in the form of the introduction of smart meter technology, innovative contract offers, increase share of renewable energy, new business models based on peer to peer networking and informed customer participation in the energy market. An upward trend recorded from 2014 can be seen as positive sign of investments in R&D towards innovation in the energy sector which has been on the increase. Since 2015 a provision for an additional $4billion has been made available to about 40 initiated partnership in innovation and international research. These efforts are further reflected by the global measures by intergovernmental innovation initiative towards up scaling commitment for R&D investment into clean energy R&D between 2015–2020 (OECD, 2018).

It is worthy of note that overall outcome of the analysis indicated increase in the adoption of IES, subject to academic literature. However, occasional disagreement subject to the optimal approach to developing IES occurs in the energy industry (Greco et al., 2017; OECD, 2018). A way of viewing this is the long lead time existing between the research and development stage resulting in long payback periods experienced by private investors. In order to mitigate such effect, focused attention will be required from public sector to abate this effect with efforts in ensuring sustainable development in innovative solutions in the energy sector and provision of long term funding opportunities. This double prong approach will help cushion funding innovation while alleviating the effect of developmental gap and associated risks.

Challenges of proposed IES model: In spite the immense benefits associated with IES, there are often cases where effective adoption of these services by consumers are met with certain barriers or degree of failure. This can be subject to financial feasibility related concerns or lack of sufficient support from the government in the form of allocation for the IES uptake. Such could be as result of non-availability of energy audit report and necessary recommendation for improving energy efficiency based on adoption of IES. Again, in situations where necessary recommendations obtained from energy audit exist, advice given may have been considered as symbolic and never implemented. In some cases, local authorities set high targets which are often not practically feasible but majorly founded on political grounds of achieving their climate goals or gaining international political attention. Moreover, local authorities tend to lose focus on their initiating and refurbishing role towards implementation of IES, hence losing track or eventually detaching from successful implementation of such IES ambitions.

In other cases, deadlock often occurs resulting from poor experience with previous or similar IES projects, resulting to significant impact in the adoption of new or similar services by consumers. Behavioral barriers (Kowalska-Pyzalska, 2018) have also been suggested and can be attributed to bounded rationality such as lack of information, limitation in information processing capability, laziness or risk aversion preventing guaranteed rational behavior of consumers towards IES adoption as optimal choice. Integration of IES in some cases results into additional investments in infrastructure leading to increase in rent and are therefore considered as non profitable investment in the short term. Consumers are often weary of adopting IES even when the associated benefits are obviously presented to them, due to fears relating to potential teething problems normally associated with new technologies.

6. Conclusion

In this study, we presented a concept of IES based recommender system for personalized and smart advice provision based

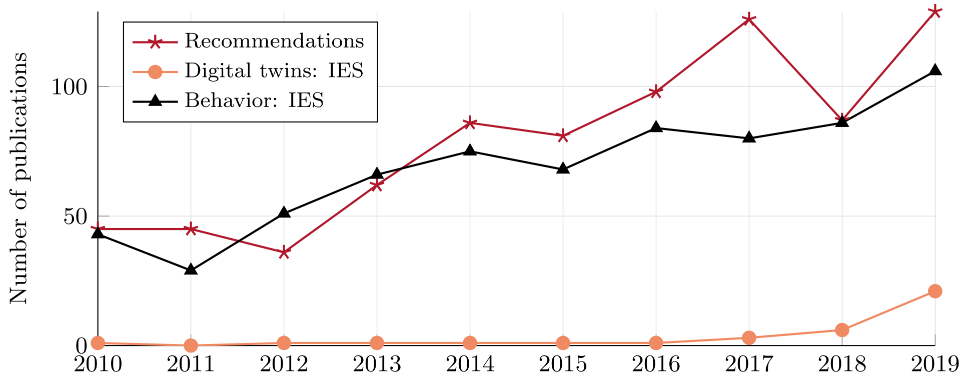

Fig. 5. Visualization of yearly number of publications for IES contributing technologies in the period 2010–2019 from IEEE Xplore and Scopus databases.

on holistic state-of-the-art review and content analysis of previous approaches. Our main contribution is to emphasize the role of consumers as major actor in the effort geared towards energy conservation by adopting innovative solutions provided by recent advances in recommender system and DT technology. The architecture of the proposed IES framework has been described in this study. The proposed platform provides energy saving options while alleviating the need to significantly alter consumers lifestyle. We observed two major trends in research. First, a comprehensive content analysis revealed an upward trend in the adoption of IES. This outcome supports the objectives of the study, indicating about 83% increase in its adoption. The second is the group of IES contributing technologies, content analysis revealed an upward trend recorded by recommendation studies produces identical outcome for behavioral attributes literature. This result further strengthens arguments that recommendation provision affects energy behavior. These research trends in our opinion are largely due to increase awareness, R&D investments, or various incentivized adoption of IES based DSM tools motivated by economic, social influence or psychological factors as suggested by literature.

Although the core investigation of the study is focused on the understanding of IES based on state-of-the-art review and content analysis of previous/antecedent approaches, one noticeable advantage is its applicability as stimulant or supporting information towards investments into consumer-oriented programs targeting energy efficiency. We acknowledge possible limitations relating to adoption barriers including teething problems identified with new or emerging technologies, behavioral barriers or poor experience with previous IES.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work of A. E. Onile and E. Petlenkov was partly supported by the Estonian Research Council grant PRG658. The work of A. E. Onile in the project "ICT program" was supported by the European Union, Estonia through European Social Fund. R. Machlev and Y. Levron were partly supported by Israel Science Foundation grant No. 1227/18.

References

ABB, 2020. Review digital twins and simulations. [Online] Available https://search.abb.com/library/Download.aspx?DocumentID=9AKK107492A3437&LanguageCode=en&DocumentPartId=&Action=Launch. (Accessed 11 May 2020).

Abbar, S., Boumaiza, A., Mohandes, N., Sanfilippo, A., 2018. Modeling innovation diffusion for renewable energy technologies in city neighborhoods. In: 2018 9th International Renewable Energy Congress. IREC. IEEE, pp. 1–6. http://dx.doi.org/10.1109/irec.2018.8362523.

Abrahamson, E., Rosenkopf, L., 1997. Social network effects on the extent of innovation diffusion: A computer simulation. Organ. Sci. 8, 289–309. http://dx.doi.org/10.1287/orsc.8.3.289.

Adomavicius, G., Tuzhilin, A., 2005. Toward the next generation of recommender systems: A survey of the state-of-the-art and possible extensions. IEEE Trans. Knowl. Data Eng. 17 (6), 734–749. http://dx.doi.org/10.1109/tkde.2005.99.

Aguilar, J., Valdiviezo-Díaz, P., Riofrio, G., 2017. A general framework for intelligent recommender systems. Appl. Comput. Inform. 13 (2), 147–160. http://dx.doi.org/10.1016/j.aci.2016.08.002.

Ahmad, T., Rana, M.R.R., Akbar, M.A., Nawaz, A., 2018. A scalable feature extraction technique for social media analysis. [Online] Available https://www.iea.org/topics/covid-19. (Accessed 09 October 2020).

Alekseev, A.N., Lobova, S.V., Bogoviz, A.V., Ragulina, Y.V., 2019. A critical review of Russia's energy efficiency policies in the construction and housing sector. Int. J. Energy Econ. Policy 9 (4), 166–172. http://dx.doi.org/10.32479/ijeep.7608.

Alsalemi, A., Sardianos, C., Bensaali, F., Varlamis, I., Amira, A., Dimitrakopoulos, G., 2019. The role of micro-moments: A survey of habitual behavior change and recommender systems for energy saving. IEEE Syst. J. 13, 3376–3387. http://dx.doi.org/10.1109/jsyst.2019.2899832.

AlSkaif, T., Lampropoulos, I., van den Broek, M., van Sark, W., 2018. Gamification-based framework for engagement of residential customers in energy applications. Energy Res. Soc. Sci. 44, 187–195. http://dx.doi.org/10.1016/j.erss.2018.04.043.

Andryushkevich, S.K., Kovalyov, S.P., Nefedov, E., 2019. 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. http://dx.doi.org/10.1109/indin41052.2019.8972267.

Arya, A., Jyoti, Arunachalam, P., Bhuvaneswari, N., Kumar, A., Ramesh, L., Ganesan, V., Egbert, H., 2016. Review on industrial audit and energy saving recommendation in aluminium industry. In: 2016 International Conference on Control, Instrumentation, Communication and Computational Technologies. ICCICCT. IEEE, http://dx.doi.org/10.1109/iccicct.2016.7988054.

Autant-Bernard, C., Chalaye, S., Manca, F., Moreno, R., Suriñach, J., 2010. Measuring the adoption of innovation. A typology of EU countries based on the innovation survey. Innov.: Eur. J. Soc. Sci. Res. 23 (3), 199–222. http://dx.doi.org/10.1080/13511610.2010.547739.

Ayres, R.M.J., de Souza, A.N., Gastaldello, D.S., do Amaral, L.M.H., Ikeshoji, M.A., Santana, G.V., 2018. A new intelligent system architecture for energy saving in smart homes. In: 2018 13th IEEE International Conference on Industry Applications. INDUSCON. IEEE, http://dx.doi.org/10.1109/induscon.2018.8627300.

Bak, C., 2017. Generating growth from innovation for the low-carbon economy exploring safeguards in finance and regulation. http://dx.doi.org/10.1163/9789004322714_cclc_2017-0136-002, [Online] Available https://www.cigionline.org/sites/default/files/documents/Paperno.117_WEB.pdf. (Accessed 20 November 2020).

Bakhtadze, N., Pavlov, B., Pyatetsky, V., Suleykin, A., 2019. Digital energy ecosystems. IFAC-PapersOnLine 52 (13), 30–35. http://dx.doi.org/10.1016/j.ifacol.2019.11.088.

Baptista, R., Swann, P., 1998. Do firms in clusters innovate more? Res. Policy 27 (5), 525–540. http://dx.doi.org/10.1016/s0048-7333(98)00065-1.

Batchelor, S., Brown, E., Scott, N., Leary, J., 2019. Two birds, one stone—reframing cooking energy policies in Africa and Asia. Energies 12, http://dx.doi.org/10.3390/en12091591.

Batchelor, S., Leary, J., Leach, M.A., Brown, E., 2018. eCook global market assessment where will the transition take place first? Unpublished. http://dx.doi.org/10.13140/RG.2.2.22612.30082.

Behl, M., Smarra, F., Mangharam, R., 2016. DR-advisor: A data-driven demand response recommender system. Appl. Energy 170, 30–46. http://dx.doi.org/10.1016/j.apenergy.2016.02.090.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ. Innov. Societ. Transit. 16, 51–64. http://dx.doi.org/10.1016/j.eist.2015.07.003.

Bigoloni, M., Filipponi, S., 2017. Monet: An innovative system to manage energy services. Energy Procedia 111, 846–855. http://dx.doi.org/10.1016/j.egypro.2017.03.247.

Borup, M., Klitkou, A., Andersen, M., Hain, D., Lindgaard Christensen, J., Rennings, K., 2013. Indicators of Energy Innovation Systems and Their Dynamics. A Review of Current Practice and Research in the Field: Radar Report. EIS, [Online] Available https://orbit.dtu.dk/files/71114009/Indicators_of_energy_innovation.pdf. (Accessed 06 May 2020).

Bouktif, S., Fiaz, A., Ouni, A., Serhani, M.A., 2019. Single and multi-sequence deep learning models for short and medium term electric load forecasting. Energies 12 (1), 149. http://dx.doi.org/10.3390/en12010149.

Bridge, G., Bouzarovski, S., Bradshaw, M., Eyre, N., 2013. Geographies of energy transition: Space, place and the low-carbon economy. Energy Policy 53, 331–340. http://dx.doi.org/10.1016/j.enpol.2012.10.066.

Brosinsky, C., Westermann, D., Krebs, R., 2018. Recent and prospective developments in power system control centers: Adapting the digital twin technology for application in power system control centers. In: 2018 IEEE International Energy Conference. ENERGYCON. pp. 1–6. http://dx.doi.org/10.1109/energycon.2018.8398846.

Brown, E., Leary, J., Davies, G., Batchelor, S., Scott, N., 2017. Ecook: What behavioural challenges await this potentially transformative concept? Sustain. Energy Technol. Assess. 22, 106–115. http://dx.doi.org/10.1016/j.seta.2017.02.021.

Brown, E., Sumanik-Leary, J., 2016. A Review of the Behavioural Change Challenges Facing a Proposed Solar and Battery Electric Cooking Concept. Tech. Rep., Evidence on Demand, http://dx.doi.org/10.12774/eod_cr.browneetal.

Cacciatore, G., Fiandrino, C., Kliazovich, D., Granelli, F., Bouvry, P., 2017. Cost analysis of smart lighting solutions for smart cities. In: 2017 IEEE International Conference on Communications. ICC. IEEE, http://dx.doi.org/10.1109/icc.2017.7996886.

Campisi, D., Gitto, S., Morea, D., 2018. Economic feasibility of energy efficiency improvements in street lighting systems in Rome. J. Cleaner Prod. 175, 190–198. http://dx.doi.org/10.1016/j.jclepro.2017.12.063.

Castelli, G., Tognola, G., Campana, E.F., Cesta, A., Diez, M., Padula, M., Ravazzani, P., Rinaldi, G., Savazzi, S., Spagnuolo, M., Strambini, L., 2019. Urban intelligence: A modular, fully integrated, and evolving model for cities digital twinning. In: 2019 IEEE 16th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT and AI. HONET-ICT. http://dx.doi.org/10.1109/honet.2019.8907962.

Chalvatzis, K.J., Rubel, K., 2015. Electricity portfolio innovation for energy security: The case of carbon constrained China. Technol. Forecast. Soc. Change 100, 267–276.

Chen, R., hua Rao, Z., ming Liao, S., 2019. Hybrid LEAP modeling method for long-term energy demand forecasting of regions with limited statistical data. J. Central South Univ. 26 (8), 2136–2148. http://dx.doi.org/10.1007/s11771-019-4161-0.

Cheng, J., Zhang, H., Tao, F., Juang, C.-F., 2020. DT-Ii: Digital twin enhanced industrial internet reference framework towards smart manufacturing. Robot. Comput.-Integr. Manuf. 62, 101881. http://dx.doi.org/10.1016/j.rcim.2019.101881.

Clausen, J., Fichter, K., 2019. The diffusion of environmental product and service innovations: Driving and inhibiting factors. Environ. Innov. Societ. Transit. 31, 64–95. http://dx.doi.org/10.1016/j.eist.2019.01.003.

Cooke, P., 2001. Regional innovation systems, clusters, and the knowledge economy. Ind. Corp. Change 10 (4), 945–974. http://dx.doi.org/10.1093/icc/10.4.945.

Damiani, L., Revetria, R., Morra, E., 2019. A digital twin for supporting energy management in complex maritime terminals. In: The International Maritime Transport and Logistics Conference.

De Luca, V., Castri, R., 2014. The social power game: A smart application for sharing energy-saving behaviours in the city. In: Proceedings of the AVI 2014 International Working Conference on Advanced Visual Interfaces. [Online] Available https://repository.supsi.ch/4670/. (Accessed 06 October 2020).

DECC (UK Department of Energy and Climate Change), 2014. Research to assess the barriers and drivers to energy efficiency in small and medium sized enterprises. [Online] Available https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/392908/Barriers_to_Energy_Efficiency_FINAL_2014-12-10.pdf. (Accessed 06 October 2020).

Delzendeh, E., Wu, S., Lee, A., Zhou, Y., 2017. The impact of occupants' behaviours on building energy analysis: A research review. Renew. Sustain. Energy Rev. 80, 1061–1071. http://dx.doi.org/10.1016/j.rser.2017.05.264.

DixonoMara, C., Ryan, L., 2018. Energy efficiency in the food retail sector: Barriers, drivers and acceptable policies. Energy Effic. 11, 445–464. http://dx.doi.org/10.1007/s12053-017-9577-5.

Essallah, S., Khedher, A., 2019. A comparative study of long-term load forecasting techniques applied to Tunisian grid case. Electr. Eng. 101 (4), 1235–1247. http://dx.doi.org/10.1007/s00202-019-00859-w.

European Union, 2018. Workshop on open marketplaces to spur innovative energy services jointly organized between DG ener and DG connect and the alliance AIOTI. [Online] Available https://aioti.eu/wp-content/uploads/2018/10/tor-eu-workshop-on-energy-marketplaces-18_10_18draft.pdf. (Accessed 20 November 2020).

Fallah, S., Deo, R., Shojafar, M., Conti, M., Shamshirband, S., 2018. Computational intelligence approaches for energy load forecasting in smart energy management grids: State of the art, future challenges, and research directions. Energies 11 (3), 596. http://dx.doi.org/10.3390/en11030596.

Fell, M.J., 2017. Energy services: A conceptual review. Energy Res. Soc. Sci. 27, 129–140. http://dx.doi.org/10.1016/j.erss.2017.02.010.

Feng, C., Liao, X., 2020. An overview of "Energy + Internet" in China. J. Cleaner Prod. 258, 120630. http://dx.doi.org/10.1016/j.jclepro.2020.120630.

Figueroa, A., de Molière, L., Pegels, A., Never, B., Kutzner, F., 2019. Show me (more than) the money! Assessing the social and psychological dimensions to energy efficient lighting in Kenya. Energy Res. Soc. Sci. 47, 224–232. http://dx.doi.org/10.1016/j.erss.2018.10.002.

Foxon, T.J., 2013. Transition pathways for a UK low carbon electricity future. Energy Policy 52, 10–24. http://dx.doi.org/10.1016/j.enpol.2012.04.001.

Francisco, A., Mohammadi, N., Taylor, J.E., 2020. Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking. J. Manage. Eng. 36, 04019045. http://dx.doi.org/10.1061/(asce)me.1943-5479.0000741.

Fujimori, S., Kainuma, M., Masui, T., Hasegawa, T., Dai, H., 2014. The effectiveness of energy service demand reduction: A scenario analysis of global climate change mitigation. Energy Policy 75, 379–391. http://dx.doi.org/10.1016/j.enpol.2014.09.015.

Fuller, A., Fan, Z., Day, C., Barlow, C., 2020. Digital twin: Enabling technologies, challenges and open research. IEEE Access 8, 108952–108971. http://dx.doi.org/10.1109/access.2020.2998358.

Gaglia, A.G., Dialynas, E.N., Argiriou, A.A., Kostopoulou, E., Tsiamitros, D., Stimoniaris, D., Laskos, K.M., 2019. Energy performance of European residential buildings: Energy use, technical and environmental characteristics of the Greek residential sector – energy conservation and CO2 reduction. Energy Build. 183, 86–104. http://dx.doi.org/10.1016/j.enbuild.2018.10.042.

Galperova, E., Galperov, V., 2018. Modeling the active consumer behavior based on the agent approach. In: Russian-Pacific Conference on Computer Technology and Applications. pp. 1–4. http://dx.doi.org/10.1109/RPC.2018.8482157.

Óscar García, Alonso, R., Prieto, J., Corchado, J., 2017. Energy efficiency in public buildings through context-aware social computing. Sensors 17, 826. http://dx.doi.org/10.3390/s17040826.

Gaspari, M., Lorenzoni, A., Frías, P., Reneses, J., 2017. Integrated energy services for the industrial sector: An innovative model for sustainable electricity supply. Util. Policy 45, 118–127. http://dx.doi.org/10.1016/j.jup.2017.03.002.

Geels, F.W., Sovacool, B.K., Schwanen, T., Sorrell, S., 2017. Sociotechnical transitions for deep decarbonization. Science 357, 1242–1244. http://dx.doi.org/10.1126/science.aao3760.

Gölz, S., Hahnel, U.J.J., 2016. What motivates people to use energy feedback systems? A multiple goal approach to predict long-term usage behaviour in daily life. Energy Res. Soc. Sci. 21, 155–166. http://dx.doi.org/10.1016/j.erss.2016.07.006.

Greco, M., Locatelli, G., Lisi, S., 2017. Open innovation in the power & energy sector: Bringing together government policies, companies' interests, and academic essence. Energy Policy 104, 316–324. http://dx.doi.org/10.1016/j.enpol.2017.01.049.

Grieves, M., 2015. Digital twin: Manufacturing excellence through virtual factory replication.

Grübler, A., Wilson, C., 2013. Energy Technology Innovation. Cambridge University Press, http://dx.doi.org/10.1017/cbo9781139150880.

Guo, Z., Zhou, K., Zhang, C., Lu, X., Chen, W., Yang, S., 2018. Residential electricity consumption behavior: Influencing factors, related theories and intervention strategies. Renew. Sustain. Energy Rev. 81, 399–412. http://dx.doi.org/10.1016/j.rser.2017.07.046.

Gupta, R., Barnfield, L., Gregg, M., 2018. Exploring innovative community and household energy feedback approaches. Build. Res. Inf. 46 (3), 284–299.

Gupta, A., Dash, S., Mishra, A., 2019. All that glitters is not green: Creating trustworthy ecofriendly services at green hotels. Tour. Manag. 70, 155–169. http://dx.doi.org/10.1016/j.tourman.2018.08.015.

Haas, R., Nakicenovic, N., Ajanovic, A., Faber, T., Kranzl, L., Müller, A., Resch, G., 2008. Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy 36 (11), 4012–4021. http://dx.doi.org/10.1016/j.enpol.2008.06.028.

Hafshejani, Z.Y., Kaedi, M., Fatemi, A., 2018. Improving sparsity and new user problems in collaborative filtering by clustering the personality factors. Electron. Commerce Res. 18 (4), 813–836. http://dx.doi.org/10.1007/s10660-018-9287-x.

Havard, V., Jeanne, B., Lacomblez, M., Baudry, D., 2019. Digital twin and virtual reality: A co-simulation environment for design and assessment of industrial workstations. Prod. Manuf. Res. 7 (1), 472–489. http://dx.doi.org/10.1080/21693277.2019.1660283.

Hewitt, R.J., Bradley, N., Compagnucci, A.B., Barlagne, C., Ceglarz, A., Cremades, R., McKeen, M., Otto, I.M., Slee, B., 2019. Social innovation in community energy in europe: A review of the evidence. Front. Energy Res. 7, http://dx.doi.org/10.3389/fenrg.2019.00031.

Hills, J.M., Michalena, E., Chalvatzis, K.J., 2018. Innovative technology in the Pacific: Building resilience for vulnerable communities. Technol. Forecast. Soc. Change 129, 16–26.

Hilorme, O., Zamazii, T., Judina, O., 2019. Formation of risk mitigating strategies for the implementation of projects of energy saving technologies. [Online] Available https://www.abacademies.org/articles. (Accessed 06 May 2020).

Hoicka, C.E., Parker, P., 2017. Assessing the adoption of the house as a system approach to residential energy efficiency programs. Energy Effic. 11 (2), 295–313. http://dx.doi.org/10.1007/s12053-017-9564-x.

Honeywell, 2019. Honeywell Forge APM – Asset performance management. [Online] Available https://www.honeywellprocess.com/en-US/online_campaigns/asset_performance_insight/Documents/PINForgeAPMR1.pdf. (Accessed 11 May 2020).

Hong, B., Zhang, W., Zhou, Y., Chen, J., Xiang, Y., Mu, Y., 2018. Energy-internet-oriented microgrid energy management system architecture and its application in China. Appl. Energy 228, 2153–2164. http://dx.doi.org/10.1016/j.apenergy.2018.07.081.

Hussain, B., Hasan, Q.U., Javaid, N., Guizani, M., Almogren, A., Alamri, A., 2018. An innovative heuristic algorithm for IoT-enabled smart homes for developing countries. IEEE Access 6, 15550–15575. http://dx.doi.org/10.1109/access.2018.2809778.

Hyysalo, S., Johnson, M., Juntunen, J.K., 2017. The diffusion of consumer innovation in sustainable energy technologies. J. Cleaner Prod. 162, S70–S82. http://dx.doi.org/10.1016/j.jclepro.2016.09.045.

IEA, 2013. IEA DSM Task 16: Competitive energy services (energy contracting, ESCO services). [Online] Available http://www.ieadsm.org, (Accessed 20 April 2020).

International Energy Agency, 2015. Accelerating energy efficiency in small and medium-sized enterprises. [Online] Available https://www.iea.org/publications/. (Accessed 06 October 2020).

Irizar-Arrieta, A., Gómez-Carmona, O., Bilbao-Jayo, A., Casado-Mansilla, D., Lopez-De-Ipina, D., Almeida, A., 2020. Addressing behavioural technologies through the human factor: A review. IEEE Access 8, 52306–52322.

Jabbour, C.J.C., Neto, A.S., Gobbo, J.A., de Souza Ribeiro, M., de Sousa Jabbour, A.B.L., 2015. Eco-innovations in more sustainable supply chains for a low-carbon economy: A multiple case study of human critical success factors in Brazilian leading companies. Int. J. Prod. Econ. 164, 245–257. http://dx.doi.org/10.1016/j.ijpe.2014.11.015.

Jabir, H., Teh, J., Ishak, D., Abunima, H., 2018a. Impacts of demand-side management on electrical power systems: A review. Energies 11 (5), 1050. http://dx.doi.org/10.3390/en11051050.

Jabir, H.J., Teh, J., Ishak, D., Abunima, H., 2018b. Impact of demand-side management on the reliability of generation systems. Energies 11 (8), 2155. http://dx.doi.org/10.3390/en11082155.

Jaffe, A.B., Stavins, R.N., 1994. The energy-efficiency gap what does it mean? Energy Policy 22, 804–810. http://dx.doi.org/10.1016/0301-4215(94)90138-4.

Jiao, R., Zhang, T., Jiang, Y., He, H., 2018. Short-term non-residential load forecasting based on multiple sequences LSTM recurrent neural network. IEEE Access 6, 59438–59448. http://dx.doi.org/10.1109/access.2018.2873712.

Johansson, M.T., Thollander, P., 2018. A review of barriers to and driving forces for improved energy efficiency in Swedish industry– Recommendations for successful in-house energy management. Renew. Sustain. Energy Rev. 82, 618–628. http://dx.doi.org/10.1016/j.rser.2017.09.052.

Kabugo, J.C., Jämsä-Jounela, S.-L., Schiemann, R., Binder, C., 2020. Industry 4.0 based process data analytics platform: A waste-to-energy plant case study. Int. J. Electr. Power Energy Syst. 115, 105508. http://dx.doi.org/10.1016/j.ijepes.2019.105508.

Kahma, N., Matschoss, K., 2017. The rejection of innovations? Rethinking technology diffusion and the non-use of smart energy services in Finland. Energy Res. Soc. Sci. 34, 27–36. http://dx.doi.org/10.1016/j.erss.2017.05.024.

Kalt, G., Wiedenhofer, D., Görg, C., Haberl, H., 2019. Conceptualizing energy services: A review of energy and well-being along the energy service cascade. Energy Res. Soc. Sci. 53, 47–58. http://dx.doi.org/10.1016/j.erss.2019.02.026.

Kamilaris, A., Kalluri, B., Kondepudi, S., Wai, T.K., 2014. A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings. Renew. Sustain. Energy Rev. 34, 536–550. http://dx.doi.org/10.1016/j.rser.2014.03.037.

Karanja, A., Mburu, F., Gasparatos, A., 2019. A multi-stakeholder perception analysis about the adoption, impacts and priority areas in the Kenyan clean cooking sector. Sustain. Sci. 15 (1), 333–351. http://dx.doi.org/10.1007/s11625-019-00742-4.

Karanjkar, N., Joglekar, A., Mohanty, S., Prabhu, V., Raghunath, D., Sundaresan, R., 2018. Digital twin for energy optimization in an SMT-PCB assembly line. http://dx.doi.org/10.1109/iotais.2018.8600830.

Karbhari, N., Deshmukh, A., Shinde, V.D., 2017. Recommendation system using content filtering: A case study for college campus placement. In: 2017 International Conference on Energy, Communication, Data Analytics and Soft Computing. ICECDS. IEEE, http://dx.doi.org/10.1109/icecds.2017.8389579.

Kashani, A., Ozturk, Y., 2017. Residential energy consumer behavior modification via gamification. In: 2017 IEEE 6th International Conference on Renewable Energy Research and Applications. ICRERA. IEEE, http://dx.doi.org/10.1109/icrera.2017.8191247.

Kaur, E., Sharma, S., Verma, A., Singh, M., 2019. An energy management and recommender system for lighting control in internet-of-energy enabled buildings. IFAC-PapersOnLine 52 (4), 288–293. http://dx.doi.org/10.1016/j.ifacol.2019.08.213.

Kaygusuz, K., 2011. Energy services and energy poverty for sustainable rural development. Renew. Sustain. Energy Rev. 15 (2), 936–947. http://dx.doi.org/10.1016/j.rser.2010.11.003.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., Holmstrom, J., 2019. Digital twin: Vision, benefits, boundaries, and creation for buildings. IEEE Access 7, 147406–147419. http://dx.doi.org/10.1109/access.2019.2946515.

King, D., 2017. Global clean energy in 2017. Science 355 (6321), 111. http://dx.doi.org/10.1126/science.aam7088.

Kolloch, M., Dellermann, D., 2018. Digital innovation in the energy industry: The impact of controversies on the evolution of innovation ecosystems. Technol. Forecast. Soc. Change 136, 254–264. http://dx.doi.org/10.1016/j.techfore.2017.03.033.

Kompos, K., Launonen, H., Navarro, E.M.M., Sohre, A., Schubert, I., Zacharis, E., 2019. Transforming energy efficiency into an entirely new customer experience—An effective way to engage consumers—The utilitee project concept. Proceedings 20, 21. http://dx.doi.org/10.3390/proceedings2019020021.

Koroleva, K., Melenhorst, M., Novak, J., Gonzalez, S.L.H., Fraternali, P., Rizzoli, A.E., 2019. Designing an integrated socio-technical behaviour change system for energy saving. In: Proceedings of the 8th DACH+ Conference on Energy Informatics, vol. 2, http://dx.doi.org/10.1186/s42162-019-0088-9.

Kotilainen, K., Mäkinen, S.J., Järvetausta, P., Antti, R., Markkula, J., 2016. The role of residential prosumers initiating the energy innovation ecosystem to future flexible energy system. In: International Conference on the European Energy Market. EEM. IEEE, pp. 1–5.

Kowalska-Pyzalska, A., 2018. What makes consumers adopt to innovative energy services in the energy market? A review of incentives and barriers. Renew. Sustain. Energy Rev. 82, 3570–3581. http://dx.doi.org/10.1016/j.rser.2017.10.103.

Kychkin, A., Nikolaev, A., 2020. IoT-based mine ventilation control system architecture with digital twin. In: 2020 International Conference on Industrial Engineering, Applications and Manufacturing. ICIEAM. IEEE, http://dx.doi.org/10.1109/icieam48468.2020.9111995.

Lee, D., Brusilovsky, P., 2018. Recommendations based on social links. In: Social Information Access. Springer International Publishing, pp. 391–440. http://dx.doi.org/10.1007/978-3-319-90092-6_11.

Lester, P., 2015. Future home tech: 8 energy-saving solutions on the horizon. [Online] Available https://www.energy.gov/. (Accessed 06 October 2020).

Li, L., Chen, J., Raghunathan, S., 2018a. Recommender system rethink: Implications for an electronic marketplace with competing manufacturers. Inf. Syst. Res. 29 (4), 1003–1023. http://dx.doi.org/10.1287/isre.2017.0765.

Li, X., Ge, Y., Mao, X., Xue, W., Xu, N., 2018b. Improved energy structure prediction model based on energy demand forecast. In: 2018 2nd IEEE Conference on Energy Internet and Energy System Integration. EI2. IEEE, http://dx.doi.org/10.1109/ei2.2018.8582170.

Li, W., Rentemeister, M., Badeda, J., Jöst, D., Schulte, D., Sauer, D.U., 2020. Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation. J. Energy Storage 30, 101557. http://dx.doi.org/10.1016/j.est.2020.101557.

Li, X., Zhao, X., Wang, J., 2016. The innovation research of low carbon building energy. In: 2016 Chinese Control and Decision Conference. CCDC. IEEE, pp. 6150–6152.

Lu, Y., Peng, T., Xu, X., 2019. Energy-efficient cyber-physical production network: Architecture and technologies. Comput. Ind. Eng. 129, 56–66. http://dx.doi.org/10.1016/j.cie.2019.01.025.

Luo, F., Ranzi, G., Kong, W., Dong, Z.Y., Wang, S., Zhao, J., 2017. Non-intrusive energy saving appliance recommender system for smart grid residential users. IET Gener. Transm. Distrib. 11 (7), 1786–1793. http://dx.doi.org/10.1049/iet-gtd.2016.1615.

Luo, F., Ranzi, G., Kong, W., Liang, G., Dong, Z.Y., 2020. A personalized residential energy usage recommendation system based on load monitoring and collaborative filtering. IEEE Trans. Ind. Inform. 1. http://dx.doi.org/10.1109/tii.2020.2983212.

Luo, F., Ranzi, G., Wang, X., Dong, Z.Y., 2016. Service recommendation in smart grid: Vision, technologies, and applications. In: 2016 9th International Conference on Service Science. ICSS. IEEE, http://dx.doi.org/10.1109/icss.2016.12.

Luo, F., Ranzi, G., Wang, X., Dong, Z.Y., 2019. Social information filtering-based electricity retail plan recommender system for smart grid end users. IEEE Trans. Smart Grid 10, 95–104. http://dx.doi.org/10.1109/tsg.2017.2732346.

Ma, L., 2019. An economic model for geothermal energy consumption based on industrial innovation and structural upgrading. Int. J. Heat Technol. 37 (3), 787–791. http://dx.doi.org/10.18280/ijht.370315.

Ma, Z., Ren, H., Lin, W., 2019. A review of heating, ventilation and air conditioning technologies and innovations used in solar-powered net zero energy solar decathlon houses. J. Cleaner Prod. 240, 118158. http://dx.doi.org/10.1016/j.jclepro.2019.118158.

Mahmood, A., Ahmad, A., Javed, H., Mehmood, Z., Khan, Z., Qasim, U., Javaid, N., 2015. A survey of 'user comfort' in home energy management systems in smart grid. In: 2015 IEEE 29th International Conference on Advanced Information Networking and Applications Workshops. IEEE, http://dx.doi.org/10.1109/waina.2015.124.

Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N., 2010. Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors. J. Ind. Ecol. 14 (5), 770–790.

Marinakis, V., Doukas, H., Tsapelas, J., Mouzakitis, S., Sicilia, Á., Madrazo, L., Sgouridis, S., 2020. From big data to smart energy services: An application for intelligent energy management. Future Gener. Comput. Syst. 110, 572–586. http://dx.doi.org/10.1016/j.future.2018.04.062.

Martin, R., Muûls, M., de Preux, L.B., Wagner, U.J., 2012. Anatomy of a paradox: Management practices, organizational structure and energy efficiency. J. Environ. Econ. Manage. 63 (2), 208–223. http://dx.doi.org/10.1016/j.jeem.2011.08.003.

Meshcheryakova, T., Tkacheva, E., Kabanova, D., 2018. Energy efficiency of industrial facilities as a factor of sustainable development of the country's economy. In: Mottaeva, A., Melović, B. (Eds.), In: MATEC Web of Conferences, vol. 193, EDP Sciences, p. 03004. http://dx.doi.org/10.1051/matecconf/201819303004.

Metwaly, M.K., Teh, J., 2020. Probabilistic peak demand matching by battery energy storage alongside dynamic thermal ratings and demand response for enhanced network reliability. IEEE Access 8, 181547–181559. http://dx.doi.org/10.1109/access.2020.3024846.

Mezni, H., Abdeljaoued, T., 2018. A cloud services recommendation system based on fuzzy formal concept analysis. Data Knowl. Eng. 116, 100–123. http://dx.doi.org/10.1016/j.datak.2018.05.008.

Min, Q., Lu, Y., Liu, Z., Su, C., Wang, B., 2019. Machine learning based digital twin framework for production optimization in petrochemical industry. Int. J. Inf. Manage. 49, 502–519. http://dx.doi.org/10.1016/j.ijinfomgt.2019.05.020.

Miremadi, I., Saboohi, Y., Jacobsson, S., 2018. Assessing the performance of energy innovation systems: Towards an established set of indicators. Energy Res. Soc. Sci. 40, 159–176. http://dx.doi.org/10.1016/j.erss.2018.01.002.

Moglia, M., Podkalicka, A., McGregor, J., 2018. An agent-based model of residential energy efficiency adoption. J. Artif. Soc. Soc. Simul. 21 (3), http://dx.doi.org/10.18564/jasss.3729.

Morley, J., 2018. Rethinking energy services: The concept of 'meta-service' and implications for demand reduction and servicizing policy. Energy Policy 122, 563–569. http://dx.doi.org/10.1016/j.enpol.2018.07.056.

Morton, C., Wilson, C., Anable, J., 2018. The diffusion of domestic energy efficiency policies: A spatial perspective. Energy Policy 114, 77–88. http://dx.doi.org/10.1016/j.enpol.2017.11.057.

Mourtzis, D., Boli, N., Alexopoulos, K., Różycki, D., 2018. A framework of energy services: From traditional contracts to product-service system (PSS). Procedia CIRP 69, 746–751. http://dx.doi.org/10.1016/j.procir.2017.11.118.

Mrazovac, B., Bjelica, M.Z., Teslic, N., Papp, I., Temerinac, M., 2012. Consumer-oriented smart grid for energy efficiency. In: VDE Kongress.

Murthy, A., Han, D., Jiang, D., Oliveira, T., 2015. Lighting-enabled smart city applications and ecosystems based on the IoT. In: 2015 IEEE 2nd World Forum on Internet of Things. WF-IoT. IEEE, pp. 757–763. http://dx.doi.org/10.1109/wf-iot.2015.7389149.

Nilashi, M., Ahani, A., Esfahani, M.D., Yadegaridehkordi, E., Samad, S., Ibrahim, O., Sharef, N.M., Akbari, E., 2019. Preference learning for eco-friendly hotels recommendation: A multi-criteria collaborative filtering approach. J. Cleaner Prod. 215, 767–783. http://dx.doi.org/10.1016/j.jclepro.2019.01.012.

Nwauka, O., Telukdarie, A., Enslin, J., 2018. Virtual power plant basic requirements for integration of distributed energy resources driven by industry 4.0. IEOM 511–523.

O'Dwyer, E., Pan, I., Charlesworth, R., Butler, S., Shah, N., 2020. Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems. Sustainable Cities Soc. 62, 102412. http://dx.doi.org/10.1016/j.scs.2020.102412.

OECD, 2012. Innovation in the crisis and beyond. [Online] Available https://www.oecd.org/. (Accessed 04 April 2020).

OECD, 2018. Round table on sustainable development: Accelerating the development and diffusion of low-emissions innovations. [Online] Available http://www.oecd.org/sd-roundtable/. (Accessed 20 April 2020).

Onile, A.E., Belikov, J., Levron, Y., 2020. Innovative energy services for behavioral reflective attributes and intelligent recommender system. In: 2020 IEEE PES Innovative Smart Grid Technologies Europe. ISGT-Europe. IEEE.

Pandharipande, A., Payyadakath, S., Violatto, G., Thijssen, P., 2019. Energy data services with connected street lighting. In: 2019 IEEE 5th World Forum on Internet of Things. WF-IoT. pp. 778–782. http://dx.doi.org/10.1109/wf-iot.2019.8767337.

Park, E., Kwon, S.J., 2017. What motivations drive sustainable energy-saving behavior?: An examination in South Korea. Renew. Sustain. Energy Rev. 79, 494–502. http://dx.doi.org/10.1016/j.rser.2017.05.150.

Paukstadt, U., Gollhardt, T., Blarr, M., Chasin, F., Becker, J., 2019. A taxonomy of consumer-oriented smart energy business models. In: ECIS.

PEAKapp, 2017. Personal energy administration kiosk application: An ICT-ecosystem for energy savings through behavioural change, flexible tariffs and fun. [Online] Available http://www.peakapp.eu/projectoverview/. (Accessed 09 October 2020).

Plepys, A., Heiskanen, E., Mont, O., 2015. European policy approaches to promote servicizing. J. Cleaner Prod. 97, 117–123. http://dx.doi.org/10.1016/j.jclepro.2014.04.029.

Polzin, F., 2017. Mobilizing private finance for low-carbon innovation – A systematic review of barriers and solutions. Renew. Sustain. Energy Rev. 77, 525–535. http://dx.doi.org/10.1016/j.rser.2017.04.007.

Polzin, F., von Flotow, P., Nolden, C., 2016. Modes of governance for municipal energy efficiency services – the case of LED street lighting in Germany. J. Cleaner Prod. 139, 133–145. http://dx.doi.org/10.1016/j.jclepro.2016.07.100.

Popkova, E.G., Inshakov, O.V., Bogoviz, A.V., 2018. Motivation of energy saving within the corporate market responsibility of economic entities. In: Lecture Notes in Networks and Systems. Springer International Publishing, pp. 95–105. http://dx.doi.org/10.1007/978-3-319-90966-0_7.

Primo, T.T., Vicari, R.M., Bernardi, K.S., 2012. User profiles and learning objects as ontology individuals to allow reasoning and interoperability in recommender systems. In: Proceedings of the 2012 IEEE Global Engineering Education Conference. EDUCON. IEEE, pp. 1–9.

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., Nee, A., 2019. Enabling technologies and tools for digital twin. J. Manuf. Syst. http://dx.doi.org/10.1016/j.jmsy.2019.10.001.

Qureshi, K.N., Hussain, R., Jeon, G., 2020. A distributed software defined networking model to improve the scalability and quality of services for flexible green energy internet for smart grid systems. Comput. Electr. Eng. 84, 106634. http://dx.doi.org/10.1016/j.compeleceng.2020.106634.

Rasheed, A., San, O., Kvamsdal, T., 2020. Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access 8, 21980–22012. http://dx.doi.org/10.1109/access.2020.2970143.

Rhodes, A., Skea, J., Hannon, M., 2014. The global surge in energy innovation. Energies 7 (9), 5601–5623. http://dx.doi.org/10.3390/en7095601.

Rinkinen, J.S.E., Torriti, J., 2019. Energy fables: Challenging ideas in the energy sector. [Online] Available https://www.buildingsandcities.org/insights/reviews/energy-fables-challenging-ideas-energy-sector.html. (Accessed 06 May 2020).

Romero, A., Agustin, P.D., Tsitsanis, T., 2018. Integration of real-intelligence in energy management systems to enable holistic demand response optimization in buildings and districts. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe). IEEE, http://dx.doi.org/10.1109/eeeic.2018.8494522.

Ros, A.J., et al., 2018. International experiences in retail electricity markets. [Online] Available https://brattlefiles.blob.core.windows.net/. (Accessed 05 May 2020).

Rudskaia, I., Rodionov, D., 2018. The concept of total innovation management as a mechanism to enhance the competitiveness of the national innovation system. In: International Conference on Internet and E-Business. pp. 246–251.

Ruohomaki, T., Airaksinen, E., Huuska, P., Kesaniemi, O., Martikka, M., Suomisto, J., 2018. Smart city platform enabling digital twin. In: 2018 International Conference on Intelligent Systems. IS. IEEE, http://dx.doi.org/10.1109/is.2018.8710517.

Sangrody, H., Zhou, N., Tutun, S., Khorramdel, B., Motalleb, M., Sarailoo, M., 2018. Long term forecasting using machine learning methods. In: 2018 IEEE Power and Energy Conference At Illinois. PECI. IEEE, http://dx.doi.org/10.1109/peci.2018.8334980.

Sellami, K., Kassa, R., Dris, D., Tiako, P.F., 2013. Taking advantage of semantic-social information in recommendation systems. In: 2013 3rd International Symposium ISKO-Maghreb. IEEE, pp. 1–9.

Selvakkumaran, S., Ahlgren, E.O., 2020. Impacts of social innovation on local energy transitions: Diffusion of solar PV and alternative fuel vehicles in Sweden. Glob. Transit. 2, 98–115. http://dx.doi.org/10.1016/j.glt.2020.06.004.

Shadbolt, N., 2013. Knowledge acquisition and the rise of social machines. Int. J. Hum.-Comput. Stud. 71 (2), 200–205. http://dx.doi.org/10.1016/j.ijhcs.2012.10.008.

Shaikh, P.H., Nor, N.B.M., Nallagownden, P., Elamvazuthi, I., Ibrahim, T., 2014. A review on optimized control systems for building energy and comfort management of smart sustainable buildings. Renew. Sustain. Energy Rev. 34, 409–429. http://dx.doi.org/10.1016/j.rser.2014.03.027.

Sharif, N., 2006. Emergence and development of the national innovation systems concept. Res. Policy 35 (5), 745–766. http://dx.doi.org/10.1016/j.respol.2006.04.001.

Shea, R.P., Kissock, K., Selvacanabady, A., 2019. Reducing university air handling unit energy usage through controls-based energy efficiency measures. Energy Build. 194, 105–112. http://dx.doi.org/10.1016/j.enbuild.2019.04.020.

Shin, J.-H., Hwang, J., 2012. Intelligent energy information service based on a multi-home environment. Procedia Comput. Sci. 10, 197–204. http://dx.doi.org/10.1016/j.procs.2012.06.028.

Silva, F.L., Souza, R.C., Oliveira, F.L.C., Lourenco, P.M., Calili, R.F., 2018. A bottom-up methodology for long term electricity consumption forecasting of an industrial sector - Application to pulp and paper sector in Brazil. Energy 144, 1107–1118. http://dx.doi.org/10.1016/j.energy.2017.12.078.

SOCIALENERGY, 2017. A gaming and social network platform for evolving energy markets' operation and educating virtual energy communities. [Online] Available http://socialenergy-project.eu/. (Accessed 10 October 2020).

Spichakova, M., Belikov, J., Nõu, K., Petlenkov, E., 2019. Feature engineering for short-term forecast of energy consumption. In: 2019 IEEE PES Innovative Smart Grid Technologies Europe. ISGT-Europe. pp. 1–5. http://dx.doi.org/10.1109/isgteurope.2019.8905698.

Stark, R., Kind, S., Neumeyer, S., 2017. Innovations in digital modelling for next generation manufacturing system design. CIRP Ann. 66 (1), 169–172. http://dx.doi.org/10.1016/j.cirp.2017.04.045.

Starke, A., Willemsen, M., Snijders, C., 2017. Effective user interface designs to increase energy-efficient behavior in a rasch-based energy recommender system. In: Proceedings of the Eleventh ACM Conference on Recommender Systems. ACM, http://dx.doi.org/10.1145/3109859.3109902.

Strydom, A., Musango, J.K., Currie, P.K., 2020. Connecting energy services, carriers and flows: Rethinking household energy metabolism in Cape Town, South Africa. Energy Res. Soc. Sci. 60, 101313. http://dx.doi.org/10.1016/j.erss.2019.101313.

Tan, X., Li, H., Guo, J., Gu, B., Zeng, Y., 2019. Energy-saving and emission-reduction technology selection and CO2 emission reduction potential of China's iron and steel industry under energy substitution policy. J. Cleaner Prod. 222, 823–834. http://dx.doi.org/10.1016/j.jclepro.2019.03.133.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F., 2017. Digital twin-driven product design, manufacturing and service with big data. Int. J. Adv. Manuf. Technol. 94 (9–12), 3563–3576. http://dx.doi.org/10.1007/s00170-017-0233-1.

Tao, F., Zhang, M., Nee, A., 2019. Digital twin and services. In: Digital Twin Driven Smart Manufacturing. Elsevier, pp. 203–217. http://dx.doi.org/10.1016/b978-0-12-817630-6.00010-2.

Tarus, J.K., Niu, Z., Mustafa, G., 2017. Knowledge-based recommendation: A review of ontology-based recommender systems for e-learning. Artif. Intell. Rev. 50 (1), 21–48. http://dx.doi.org/10.1007/s10462-017-9539-5.

Teh, J., Ooi, C., Cheng, Y.-H., Zainuri, M.A.M., Lai, C.-M., 2018. Composite reliability evaluation of load demand side management and dynamic thermal rating systems. Energies 11 (2), 466. http://dx.doi.org/10.3390/en11020466.

Teng, S.Y., Touš, M., Leong, W.D., How, B.S., Lam, H.L., Máša, V., 2021. Recent advances on industrial data-driven energy savings: Digital twins and infrastructures. Renew. Sustain. Energy Rev. 135, 110208. http://dx.doi.org/10.1016/j.rser.2020.110208.

Tetiana, H., Inna, N., Walery, O.-K., Olga, G., Svetlana, D., 2018. Innovative model of economic behavior of agents in the sphere of energy conservation. Acad. Entrepreneurship J. 24 (3), 1–7, [Online] Available https://www.abacademies.org/, (Accessed 06 October 2020).

Trappey, A.J., Trappey, C.V., Wu, C.-Y., Fan, C.Y., Lin, Y.-L., 2013. Intelligent patent recommendation system for innovative design collaboration. J. Netw. Comput. Appl. 36 (6), 1441–1450. http://dx.doi.org/10.1016/j.jnca.2013.02.035.

Trianni, A., Cagno, E., Worrell, E., Pugliese, G., 2013. Empirical investigation of energy efficiency barriers in Italian manufacturing SMEs. Energy 49, 444–458. http://dx.doi.org/10.1016/j.energy.2012.10.012.

Trivedi, V., Bhatt, N., 2018. A review on energy conservation in manufacturing industry. In: 2018 International Conference on Current Trends Towards Converging Technologies. ICCTCT. IEEE, http://dx.doi.org/10.1109/icctct.2018.8551031.

Uhlemann, T.H.-J., Lehmann, C., Steinhilper, R., 2017. The digital twin: Realizing the cyber-physical production system for industry 4.0. Procedia CIRP 61, 335–340. http://dx.doi.org/10.1016/j.procir.2016.11.152.

UN United Nations Sustainable Development Goals, 2018. About the sustainable development goals. [Online] Available https://www.un.org/sustainabledevelopment/sustainable-development-goals/. (Accessed 10 October 2020).

UNEP, 2011. Towards a green economy: Pathways to sustainable development and poverty eradication. [Online] Available https://www.unep.org/greeneconomy. (Accessed 06 October 2020).

Vaidyanathan, G., Sankaranarayanan, R., Yap, N.T., 2019. Bridging the chasm – Diffusion of energy innovations in poor infrastructure starved communities. Renew. Sustain. Energy Rev. 99, 243–255. http://dx.doi.org/10.1016/j.rser.2018.09.041.

Vargo, S.L., Akaka, M.A., Wieland, H., 2020. Rethinking the process of diffusion in innovation: A service-ecosystems and institutional perspective. J. Bus. Res. 116, 526–534. http://dx.doi.org/10.1016/j.jbusres.2020.01.038.

Venturini, G., Tattini, J., Mulholland, E., Gallachóir, B.Ó., 2018. Improvements in the representation of behavior in integrated energy and transport models. Int. J. Sustain. Transp. 13 (4), 294–313. http://dx.doi.org/10.1080/15568318.2018.1466220.

WHO, 2018. Burden of disease from household air pollution for 2016 V3 April 2018. [Online] Available https://www.who.int/airpollution/data/HAP_BoD_results_May2018_final.pdf. (Accessed 10 October 2020).

Willis, R., Webb, M., Wilsdon, J., 2007. The Disrupters: Lessons for Low-Carbon Innovation from the New Wave of Environmental Pioneers. Reports and Working Papers (Project Report), Nesta, http://dx.doi.org/10.13140/RG.2.1.3013.9128.

Wilson, C., Tyfield, D., 2018. Critical perspectives on disruptive innovation and energy transformation. Energy Res. Soc. Sci. 37, 211–215. http://dx.doi.org/10.1016/j.erss.2017.10.032.

Wittmayer, J.M., de Geus, T., Pel, B., Avelino, F., Hielscher, S., Hoppe, T., Mühlemeier, S., Stasik, A., Oxenaar, S., Rogge, K.S., Visser, V., Marín-González, E., Ooms, M., Buitelaar, S., Foulds, C., Petrick, K., Klarwein, S., Krupnik, S., de Vries, G., Wagner, A., Härtwig, A., 2020. Beyond instrumentalism: Broadening the understanding of social innovation in socio-technical energy systems. Energy Res. Soc. Sci. 70, 101689. http://dx.doi.org/10.1016/j.erss.2020.101689.

Xiang, F., yuan Huang, Y., Zhang, Z., Zuo, Y., 2020. Digital twin driven energy-aware green design. In: Digital Twin Driven Smart Design. Elsevier, pp. 165–184. http://dx.doi.org/10.1016/b978-0-12-818918-4.00006-3.

Xie, X., Parlikad, A.K., Puri, R.S., 2019. A neural ordinary differential equations based approach for demand forecasting within power grid digital twins. In: 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids. SmartGridComm. IEEE, http://dx.doi.org/10.1109/smartgridcomm.2019.8909789.

Xu, T., Zhu, C., Shi, L., Gao, L., Zhang, M., 2017. Evaluating energy efficiency of public institutions in China. Resour. Conserv. Recy. 125, 17–24. http://dx.doi.org/10.1016/j.resconrec.2017.05.008.

Yan, K., Xu, W., Yao, B., Zhou, Z., Pham, D.T., 2018. Digital twin-based energy modeling of industrial robots. In: Communications in Computer and Information Science. Springer Singapore, pp. 333–348. http://dx.doi.org/10.1007/978-981-13-2853-4_26.

Yang, F., Cheng, Y., Yao, X., 2019. Influencing factors of energy technical innovation in China: Evidence from fossil energy and renewable energy. J. Cleaner Prod. 232, 57–66. http://dx.doi.org/10.1016/j.jclepro.2019.05.270.

Zamil, M.G.A., Rawashdeh, M., Samarah, S., Hossain, M.S., Alnusair, A., Rahman, S.M.M., 2018. An annotation technique for in-home smart monitoring environments. IEEE Access 6, 1471–1479. http://dx.doi.org/10.1109/access.2017.2779158.

Zehnder, M., Wache, H., Witschel, H.-F., Zanatta, D., Rodriguez, M., 2015. Energy saving in smart homes based on consumer behavior: A case study. In: 2015 IEEE First International Smart Cities Conference ISC2. IEEE, pp. 1–6.

Zhang, C., Cao, L., Romagnoli, A., 2018a. On the feature engineering of building energy data mining. Sustainable Cities Soc. 39, 508–518. http://dx.doi.org/10.1016/j.scs.2018.02.016.

Zhang, D., Chan, C.C., Zhou, G.Y., 2018b. Enabling industrial internet of things (iIoT) towards an emerging smart energy system. Glob. Energy Interconnect. 1 (1), 39–47. http://dx.doi.org/10.14171/j.2096-5117.gei.2018.01.005, http://www.sciencedirect.com/science/article/pii/S2096511718300057.

Zhang, Y., Meng, K., Kong, W., Dong, Z.Y., 2019. Collaborative filtering-based electricity plan recommender system. IEEE Trans. Ind. Inform. 15 (3), 1393–1404. http://dx.doi.org/10.1109/tii.2018.2856842.

Zhou, M., Yan, J., Feng, D., 2019. Digital twin framework and its application to power grid online analysis. CSEE J. Power Energy Syst. 5 (3), 391–398.