Received: 2 December 2022 | Revised: 4 April 2023 | Accepted: 29 April 2023

Energy Conversion and Economics

DOI: 10.1049/enc2.12087

REVIEW

Computational social science in smart power systems: Reliability, resilience, and restoration

Jaber Valinejad[1] | **Lamine Mili**[2] | **Xinghuo Yu**[3] | **C. Natalie van der Wal**[4] | **Yijun Xu**[5]

[1] Data and System Science Lab, Harvard University, Cambridge, Massachusetts, USA

[2] Bradley Department of Electrical and Computer Engineering, Virginia Tech, Northern Virginia Center, Greater Washington D.C., Virginia, USA

[3] School of Engineering, RMIT University, Melbourne, Victoria, Australia

[4] University of Delft, Technology, Policy and Management, Department of Multi-Actor Systems, Delft, The Netherlands

[5] School of Electrical Engineering, Southeast University, Nanjing, China

Correspondence
Jaber Valinejad, Data and System Science Lab, Harvard University, Cambridge, Massachusetts, USA.
Email: JValinejad@mgh.harvard.edu

Abstract

Smart grids are typically modelled as cyber–physical power systems, with limited consideration given to the social aspects. Specifically, traditional power system studies tend to overlook the behaviour of stakeholders, such as end-users. However, the impact of end-users and their behaviour on power system operation and response to disturbances is significant, particularly with respect to demand response and distributed energy resources. Therefore, it is essential to plan and operate smart grids by taking into account both the technical and social aspects, given the crucial role of active and passive end-users, as well as the intermittency of renewable energy sources. In order to optimize system efficiency, reliability, and resilience, it is important to consider the level of cooperation, flexibility, and other social features of various stakeholders, including consumers, prosumers, and microgrids. This article aims to address the gaps and challenges associated with modelling social behaviour in power systems, as well as the human-centred approach for future development and validation of socio-technical power system models. As the cyber–physical–social system of energy emerges as an important topic, it is imperative to adopt a human-centred approach in this domain. Considering the significance of computational social science for power system applications, this article proposes a list of research topics that must be addressed to improve the reliability and resilience of power systems in terms of both operation and planning. Solving these problems could have far-reaching implications for power systems, energy markets, community usage, and energy strategies.

KEYWORDS

computational social science, energy, resilience, reliability, smart grids, social computing, social science, socio-technical systems

1 | INTRODUCTION

Humans contribute to all processes involved in electric generation, transmission, distribution, and consumption, from planning to operation and maintenance [1–3]. Both the end-users and the primary energy industry shape the smart grid operation's objectives significantly. A power grid can be considered a cyber–physical–social system in its essence [4]. In other words, social considerations must be taken into account on both the generation and end-user sides.

The social behaviour of prosumers (active end-users) influences the control and operation of the power system in real-time via demand responses and electric vehicle batteries. The cooperation and participation of end-users, whether passive or active, can contribute to their active involvement in the power system's ancillary services, such as voltage and frequency stability [5]. The functionality of primary energy industries, such as the coal industry and other organizations connected to the power system, is also influenced by social factors. Plus, human errors in the power industry influence maintenance, emergency dispatch operation, and rolling blackout [6, 7]. In addition, they may contribute to cascading failures leading to blackouts. Therefore, there is a need to analyze the power system's reliability and resilience by considering the social aspects.

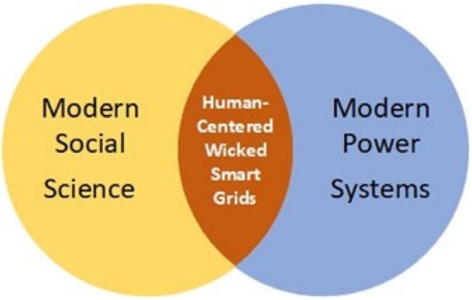

FIGURE 1 Modern power systems as cyber-physical–social system: a super-wicked problem.

To incorporate the social aspects into smart grids, we need to use modern social science and social computing [8, 9]. Taking into account social science, given that sociotactical problems are inherently wicked, the cyber–physical–social system in power engineering and energy infrastructure is a wicked problem requiring novel solutions [10, 11] (Figure 1).

2 | HUMAN-CENTRED APPROACH: BUILDING THE ARTIFICIAL SOCIETY TO MODEL THE SOCIAL BEHAVIOUR BASED ON SOCIAL SCIENCE AND NEUROSCIENCE THEORIES

The approach taken by power engineers, scholars, and researchers in addressing power system problems is fundamentally distinct from the methods employed by social scientists to tackle societal queries. While researchers in power systems strive to identify the most efficient solutions for power system operation and planning, achieving optimal solutions for social issues presents a significant challenge [12]. There is only a subjective definition of an optimal solution unless the optimization problem is cast using social science and psychological theories and social qualifications such as cooperation, flexibility, and experience to name a few. On the other hand, a power system as a cyber–physical system without considering the social aspect is a mostly tame or benign problem. Head et al. [12] defines tame problems as follows: “For any given tame problem, an exhaustive formulation can be stated containing all the information the problem-solver needs for understanding and solving the problem–provided he knows his “art,” of course. Current approaches proposed in the power systems have developed to deal with tame problems and are ill-equipped and insufficient to understand and deal with social issues and public policies considering multidisciplinary theories [13]. Social computing and social planning in power systems are ill-defined. Due to their subjectivity, incorporating social science into the power system optimization problems makes them a wicked problem because of their subjective nature. To incorporate computational social science and collective behaviour in power systems operation and planning, we propose to use generative computational social science. There is a need for modern social science and social computing to address the gap between cyber–physical and cyber–physical–social systems in power systems. Note that traditional social science relies on surveys, whereas contemporary social science relies more on social media and artificial intelligence (AI) tools such as natural language processing (NLP) [14]. Noted that NLP is a branch of artificial intelligence and linguistics that focuses on the interaction between computers and human languages. NLP involves the development of algorithms and models that can process, understand, and generate human language. NLP techniques are used in a wide range of applications such as language translation, sentiment analysis, speech recognition, chatbots, and text summarization. Plus, the term cyber refers to the interdependent network of information systems infrastructures, which includes the Internet, social media, telecommunications networks, computer systems, and embedded processors and controllers. In the literature, social scientists and researchers in computational social science advocate the use of an artificial society to model social systems' collective behaviour, the interaction between agents and human response [15–17]. The artificial society can be used for virtual experiments via agent-based modelling and simulations, which is an appropriate and promising method widely accepted by researchers addressing problems in sociology, complex systems, emergence, and evolutionary programming [18]. Artificial society and power systems, which are both network-structured, can be incorporated into each other to model the dependence between humans, computers, and the physical environment [19]. This incorporation allows us to model important interactions such as macro–micro social interaction, human–computer interaction, human–physical environment interaction, organization–physical environment interaction, and human–organization interaction. Consequently, analyzing and comprehending the collective behaviour of end-users in a human-centred power system can yield a better understanding of the cyber–physical–social system in power engineering, and lead to the derivation of new hypotheses that may not be practically testable in real-world scenarios. Through the utilization of an artificial society, planners can explore the impact of a diverse range of scenarios that may be prohibitively expensive or challenging to test solely through experiments or surveys. To enhance and reinforce the artificial society, the following factors should be considered:

1- There are various protocols, e.g. the overview, design concepts, details, and decision (known as ODD+D protocol) to standardize an artificial society.
2- Artificial society can leverage various social science and neuroscience theories, including broaden-and-build theory, Fredrickson theory [20], Barsade theory, bottom-up approach, and Damasio's Somatic Marker Hypothesis by using absorption [21] and amplification models.
3- Emotions are the foundation of psychological and social behaviours of the consumers and prosumers [22]. Indeed, the end-users' social behaviour and emotional status affect power system operation in various ways [13, 19]. For example, different types of emotions determine the end-users' satisfaction level. The consumers' satisfaction level and social behaviours, influence each other via the use of

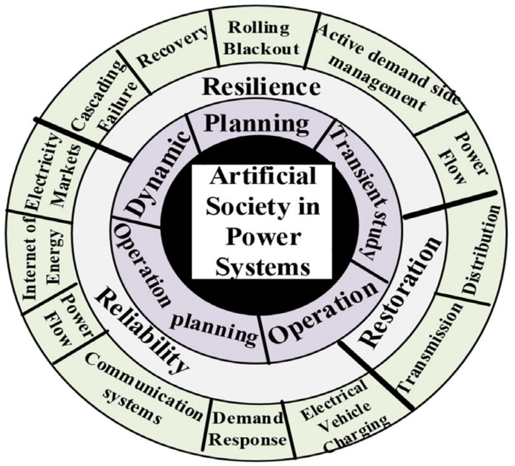

FIGURE 2 An overview of the research topics needed in computational social science for power system reliability, resilience, and restoration modelling using artificial society methodology.

social media platforms [23]. Emotions in the group can be expressed, received, or transferred in such a way as to affect the energy level of the group [24].

4- To account for consumers' and prosumers' levels of emotion, Barsade's and Fredrickson's theories are used by various researchers to model the impact of human behaviour on the emotion spread. The community's collective emotional level depends on the homogeneity and heterogeneity of each agent's emotional state and mood and their minimum, maximum, and mean level.

3 | THE OUTLINE OF THE PERCEIVED CYBER–PHYSICAL–SOCIAL SYSTEM IN A POWER SYSTEM FOR THE FUTURE: GAPS AND OBSTACLES

3.1 | Gaps

Nowadays, the exchange of information via the Internet between producers and consumers is gradually increasing so that the power industry is turning to an industrial Internet of Things industry. Because of the close interaction of producers and end-users in various applications of power systems, there is an inevitable demand to incorporate computational social science in power system operation and planning analysis from a reliability, resilience, and restoration perspective (Figure 2). Social aspects should be incorporated into power system analysis, planning, and control with different time scales as seen in the first circular layer of Figure 3. In addition, various operating and planning results are caused by the use of artificial society in the study of resilience, reliability, and restoration of the power system, as shown in the second circular layer. Reliability is enhanced by demand response, electrical vehicle charging, investment planning, communications systems, the Internet of energy, and electricity markets, to name a few. On the other hand, resilience covers cascading failure, recovery, rolling blackout, and active demand-side management, to name a few. Finally, computational social science should be modelled in the field of both distribution and transmission restoration. The use of social computing and artificial society in power systems in each of these analyses, but not limited to them, are as follows:

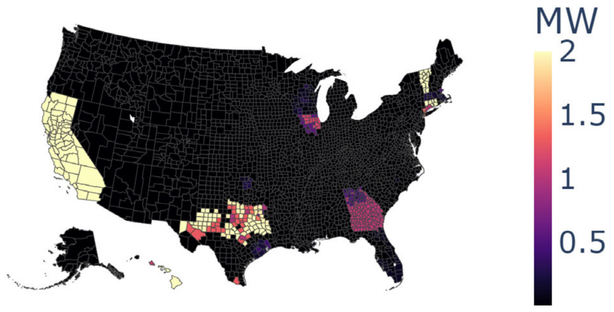

FIGURE 3 The US County-level storage capacity (MW).

3.1.1 | Reliability

The reliability of a system is defined as the probability that this system is able to retain, over a given time period, its intended function under given conditions when it is subject to internal or external failures [1]. Below are some of the ways in which social behaviour at both the generation and demand sides can affect the reliability of the power grid.

- Socio-technical power flow
- Investment in Mm and distributed energy resources (DERs)
- Socio-technical power system planning
- Cyber-physical–social demand response
- Transactive energy
- Socio-technical electricity markets
- Electrified transportation system with large penetration of electric vehicles
- Renewable energy
- Pandemic planning
- Socially intelligent voltage and frequency stability
- Socially intelligent economic dispatch and unit commitment

3.1.2 | Resilience

The resilience of a system to a class of unexpected extreme disturbances is defined as the ability of this system to (i) gracefully degrade its function by altering its structure in an agile way when it is subject to a set of disturbances of this class and (ii) quickly recover it once the disturbances have ceased with minimum losses[1]. Below are some of the ways in which social behaviour at both the generation and demand sides can affect the resilience of the power grid.

- Preparedness and prediction
- Socio-technical power flow

- Investment in microgrids (MGs) and distributed energy resources
- Socio-technical power system planning
- Socially intelligent rolling blackout and load shedding
- Electrified transportation system with large penetration of electric vehicles
- Pandemic planning
- Socially intelligent voltage and frequency stability
- Cascading failures
- Active demand side management
- Socially intelligent hierarchical distributed adaptive intelligent control
- Power system segmentation/islanding into weakly connected subsystems via high-voltage direct current (HVDC) electric power transmission

3.1.3 | Restoration

Power system restoration consists of phases, i.e. planning to restart and reintegration of the bulk power system, retaining critical sources of power (degraded level), and restoration after stabilizing at some degraded level [25]. Below are some of the ways in which social behaviour at both the generation and demand sides can affect the restoration of the power grid.

- Socio-technical distribution-level restoration
- Socio-technical transmission-level restoration
- Black start resources
- Damage assessment, repair, and reenergization

3.2 | Challenges and obstacles

Incorporating social computing in power system operation and planning brings new challenges, which are

1) Calibration and validation of social components are significant challenges for social science modelling in power systems. New methods and techniques for calibrating and validating the model are required. This article will discuss how to calibrate and validate the cyber–physical–social model used in power engineering.
2) Power engineers are unfamiliar with theories from social science, neuroscience, social psychology, and cyberpsychology that can be used to model socially intelligent frameworks in power systems. Hence, they are unable to verify cyber–physical–social models due to a lack of knowledge in computational social science.
3) Social behaviours are inherently uncertain. As a result, incorporating computational social science into the power system increases the model's degree of uncertainty. Hence, appropriate stochastic models are required. Note that this does not imply that we increase the degree of uncertainty associated with the results. Indeed, when we disregard social science, we ignore the social dimension of the power system, producing results that are far from reality [13, 19, 26].
4) Assessing social and psychological behaviour can be a challenging undertaking. Traditionally, surveys have been widely utilized as a means of measuring social behaviour. However, this approach can be both costly and time-consuming. Furthermore, the reliability of the results may be compromised due to the limited sample size. Consequently, there is a pressing need for innovative forms of social sensing to accurately quantify social behaviour, particularly in the context of modelling the cyber–physical–social paradigm in power systems.
5) The social component of the cyber–physical–social system lacks an exhaustive list of possible solutions. As a result, it can be described in a variety of ways. Social behaviours are qualitative rather than quantitative. It is necessary to establish an appropriate and quantifiable scale for social behaviour in order to incorporate it into the cyber–physical mathematical model.
6) To address cyber–physical–social system problems, a social stopping rule must be defined. Different utilities and power industries may prioritize social objectives at different levels. Additionally, we must define appropriate social constraints and objectives for each application of social science in power systems.
7) Solving a cyber–physical–social system optimization problem that encompasses social, cyber, and physical issues can be complex and time-consuming. Due to the highly nonlinear and uncertain nature of social computing, it exacerbates the challenges inherent in the cyber–physical–social system. The relationship between social behaviours is nonlinear. We cannot say, for example, that there is a linear relationship between satisfaction and energy consumption. As another illustration, we cannot assert that there is a linear relationship between the level of satisfaction and cooperation. We require novel methods and strategies for dealing with socially intelligent models embedded in power systems.

4 | HUMAN-CENTRED APPROACH IN THE CYBER–PHYSICAL–SOCIAL SYSTEM OF POWER SYSTEMS FOR FUTURE DEVELOPMENTS

In this section, we elaborate on research topics needed in computational social science for power system reliability, resilience, and restoration, for future developments. For each research topic, we explain why we need social science, the psychological behaviour of stakeholders, and, therefore, an artificial society.

4.1 | Socio-technical power flow

The availability of electricity affects both the mental well-being and physical well-being of consumers, prosumers, and the community as a whole [27]. When a disaster strikes, part of the power system may be disconnected or damaged, resulting in the shedding of generation and load. Evidently, this shedding should be achieved by minimizing its impact on social well-being and community resilience subject to power flow constraints [13]. To model a socially intelligent power flow, the social behaviours of end users, primary energy companies, and secondary energy providers must be incorporated. Willingness, consensus, convenience, satisfaction, cooperation, confidence, reliability, adaptability, experience, and empathy are just a few of the social behaviours. The primary social-related objective functions for power system operation that can be considered are well-being, social welfare, equality and fairness, trust, and community capital.

4.2 | Investment in microgrids and distributed energy resources

The investment in microgrids and distributed energy resources play a key role in social, economic, and infrastructure reliability, and resilience. Annual global battery storage installations by residential, commercial, and industrial consumers are increased from 100 MW in 2017 to 10 GW in 2021. Storage capacity at the county level in the United States is depicted in Figure 3. Numerous counties have numerous electric energy storage systems, which affect the power systems' reliability, efficiency, and resilience. A significant portion of the storage ownership is held by end users. Given the diverse range of social behaviours and characteristics among this population, their impact on the reliability and resilience of power systems may differ depending on the region. Consequently, it is imperative to take into account their social behaviour when conducting studies on power systems. Furthermore, in addition to the technical and economic dimensions of this investment, which have been previously discussed in the literature, investment in microgrids should also take into consideration factors such as social well-being and community resilience.

4.3 | Socially intelligent transactive energy

Another application of computational social science in power systems is transactive energy, where stakeholders such as wholesale and retail sellers, prosumers, and buyers of energy services interact with one another by leveraging the concept of interoperability and using the value signals. The modelling of the decision-making of the latter relies heavily on the modelling of their social behaviour. The United States' electricity system is moving toward a future full of DERs located everywhere and in all shapes and sizes, raising the value of utility-customer relations. The energy flexibility platform and interface, GridWise Olympic Peninsula Project, and the Pacific Northwest Demonstration Project as examples of using transactive energy show the importance of engagement and cooperation of costumers in the double auction market [28].

4.4 | Socio-technical electricity markets

The power market, similar to any other market, should consider the psychological aspects of the investors, such as trust and satisfaction [29]. In turn, the culture of each community can influence these psychological aspects [30]. The winner of this electric market is the stakeholder who takes the consumers and their social behaviour into account [31]. During a disaster, it may become even more important to consider social issues when setting prices. During and after a disaster, due to the scarcity of electric energy, its price should be set up in a fair manner, not by the electric market; see for example the ice storm in Texas in February 2021 where the price of electricity skyrocketed [32]. To model a socio-technical electricity market, the social behaviours of end users, retailers, generation companies (GENCOSs), transmission companies (TRANSCOs), and distributed generators' owners must be incorporated. Price-information-seeking, energy-information-seeking, confidence, learning, privacy, risk perception, collaboration, and experience are just a few of the social behaviours. The primary social-related objective functions that can be considered are community resilience, social welfare, equality and fairness, trust, and community capital.

4.5 | Electrified transportation system with large penetration of electric vehicles

Nowadays, electric vehicles are widely used all over the world because of their reduced greenhouse emissions [33]. With an optimal planning of electric vehicles, it is possible to improve the voltage profile and frequency stability of the grid while the power quality of the grid is maintained in the allowed range according to IEEE 519-2014 standard [34–36]. Considering the growth of electric energy consumption and different types of electrical loads, the demand for a reliable and efficient converter that can transfer electric power from different types of sources to different kinds of loads have risen [37–39]. Long charging time may make an electric vehicle's owner anxious. The limited distance to drive per charge can increase the owner's concern [40]. By driving until discharging the electric vehicle battery following the vehicle-to-grid program, the owner may face problems to reach a destination. Furthermore, when using a blockchain for electric vehicles, the owners may be anxious about their privacy and information [41]. This anxiety and concern regarding the charging, discharging, and privacy affect the owner's actions and decision to experience a large variability [42]. An effective way to address this problem is to enhance the active demand side management to participate in the vehicle-to-grid program. The participation of the owner also depends on the level of cooperation, flexibility, and trust in the aggregator.

4.6 | Renewable energy

The electric generation of renewable energy units, such as wind turbines and photovoltaic units, experience random intermittences [43, 44]. This makes their productions highly uncertain and difficult to predict. Figure 4 shows the US county-level average number of distribution generators. As we can see, renewable energy has a high penetration level in the power grid these days. Due to the high rate of distributed generator

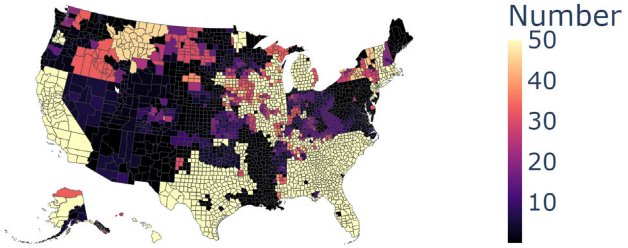

FIGURE 4 The US County-level average number of distribution generators.

insertion, the level of generation uncertainty increases, posing a challenge for power system operators. For instance, during the Texas blackout, some wind turbines became frozen, as forecasters were unable to account for these uncertainties [45]. Thus. active end-users' appropriate social behaviour, e.g. a high level of adaptability, empathy, and cooperation, can assist power system stakeholders in addressing the challenges posed by this type of uncertainty. Consequently, the frequency of the power system may increase as a result of increased consumer cooperation. Moreover, the participation of owners of distributed generators in supporting critical loads during a disaster is contingent on their level of cooperation.

4.7 | Socio-technical power system planning

Planners of power systems can influence community resilience, social welfare, equality, fairness, and community capital through their decisions on the investment in new generating units, transmission lines, and charging stations for electric vehicles [26]. In the socio-technical power system planning, social features of various stakeholders, e.g. prosumers, consumers, electrical vehicle owners, DERs, retailers, utilities, GENCOs, TRANSCOs, distribution companies (DISCOs), MG, load serving entities, aggregator, independent system operators (ISOs), regional transmission organizations, coal industry, natural gas industry, and critical infrastructures can be considered by planners. These social features can include emission-information-seeking behaviour, reliability, confidence, learning, cooperation, privacy, institutional efficiency, risk perception, emotion, flexibility, collaboration, and experience, to name a few.

4.8 | Economic dispatch and unit commitment

Figures 5 and 6 show the US county-level photovoltaic and wind capacity, respectively. As we can see, the photovoltaic and wind turbine capacity in the US power grid is quite high. Thus, a collaboration between owners of photovoltaic and wind turbines and power system operators can contribute to the reliability, sustainability, and efficiency of the power system. In addition, active end-users can supply some parts of the electricity to the load as part of the grid's real-time operation. Hence, the prosumers' high level of cooperation and flexibility can increase the economic dispatch and unit commitment efficiency if it is properly modelled.

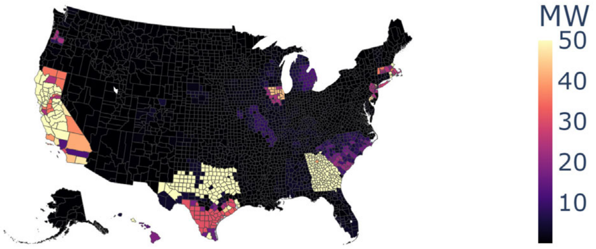

FIGURE 5 The US County-level photovoltaic capacity (MW).

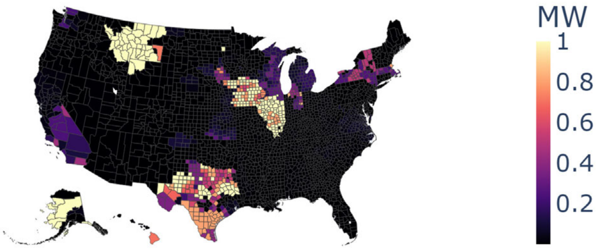

FIGURE 6 The US County-level wind capacity (MW).

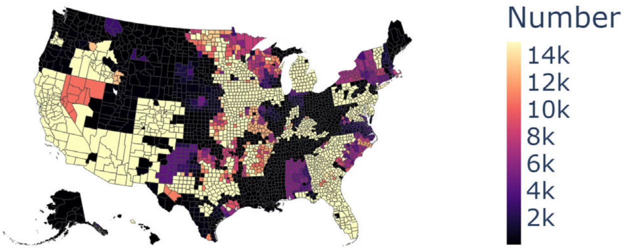

FIGURE 7 The US County-level average number of customers enrolled in demand response.

4.9 | Socio-technical demand response

Figures 7 and 8 show the US county-level number of customers enrolled in demand response and resulted from average energy savings (MWh). These figures emphasize three points: 1- This figure demonstrates the widespread participation of

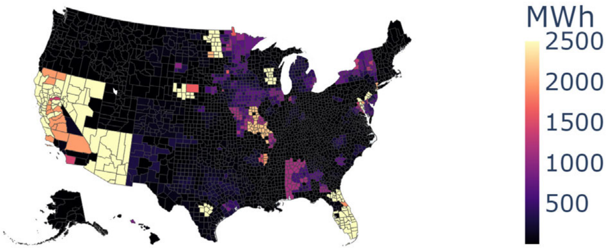

FIGURE 8 The US County-level average energy savings by demand response (MWh).

consumers in demand response. Thus, end users exert a significant influence on the operational power balance through their social behaviour [19, 46]. 2- Consumer participation varies by county. This implies that each of these counties, with its unique social characteristics, has its own set of social needs. 3- Demand response can result in a variety of benefits, including profit. We can speculate on why one U.S. state is able to conserve more energy than others. The benefits may be related to the psychological behaviour of consumers. The study of demand response in the literature is limited to the economic [47] and sustainability [48] aspects. Despite its significant importance, many demand response models tend to overlook the social science aspect. The level of participation in demand response scheduling is intricately linked to various social factors such as flexibility, cooperation, empathy, emotional status, and habits within the community. Therefore, it is crucial to account for these social elements when developing demand response models, which involves striking a balance between multiple objective functions, such as social well-being, sustainability, and cost, among others.

4.10 | Cascading failures

Cascading failures in power systems, e.g. the blackout that the USA and Italy experienced in 2003, can induce failures in other critical infrastructures such as transportation, water supply, health care systems, financial services, and communication systems [49]. The utilities and end-users' role is to take appropriate actions to minimize the economic losses that may result, which is dependent on human activity and mental states, habits, and culture. For example, if a blackout occurs, microgrids can provide electricity to critical loads such as hospitals, gas stations, police stations, and data centres, to name a few. Overloading is one of the triggers for a cascading failure in power systems, leading to equipment outages and blackouts [50]. It turns out that active demand side management can mitigate this risk. Furthermore, the detrimental consequences of electric power outages on a community can be alleviated via enhancing the level of cooperation, flexibility, and empathy. If power outages occur, we must put critical loads as a priority to supply to enhance community resilience. The prosumers within the community can share their electricity with vulnerable people, e.g. the elderly and handicapped and sick people, as a priority. Besides, the consumers within the community can reduce their loads.

4.11 | Socially intelligent rolling blackout and load shedding

Rolling blackouts affect the power system end-users. For economic and political reasons, blackouts will be concentrated in poor areas and least felt in rich areas [51]. To reduce community vulnerability and increase power system resilience, rolling blackouts should be carried out fairly. The levels of cooperation and flexibility of the end-users can help the utilities to enhance both the infrastructure and the community resilience. These levels are influenced by the levels of satisfaction, trust, experience, risk perception, willingness, collaboration, and learning of the end-users, to name a few. To model socially intelligent rolling blackout and load shedding, it is necessary to integrate computational social science into conventional cyber–physical power systems through the use of social and cyber-psychological science and theories, as well as social sensing.

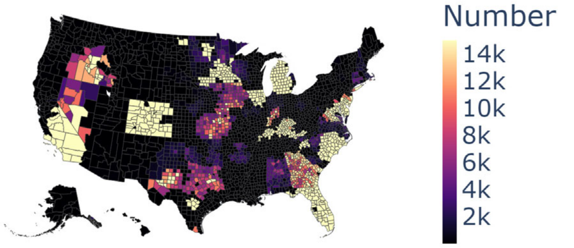

FIGURE 9 The US County-level average number of customers with direct load control.

4.12 | Recovery to a Specific Disaster

A line, a tower, a transformer, and a substation have different times to repair, typically from small to large. Past experience and the level of cooperation and flexibility and the level of satisfaction of the utility workforce, as well as the level of information and resources available to them, may have an impact to estimate the times to repair. Pre-event prevention and mitigation of the impact of the hurricane on the power system and the emergency services are event modifiers between the event and post-event time period. We propose to leverage an artificial society to model workforce behaviour that influences power system vulnerability. The 2021 Texas winter storm made more than 4.5 million homes, businesses, and event critical loads lose electricity [52]. Furthermore, the market-oriented system in the Energy Reliability Council of Texas (ERCOT) electrical grid results in bills of up to \$ 17,000 for less than 1 month of service. The power outage, high electricity prices, and difficulty in recovering from the Texas storm crisis result from a lack of community capital, such as cooperation and empathy, and adequate winterization of power infrastructure. These factors made the Texas storm crisis one of the most expensive disasters in history, with an estimated cost loss of \$ 195 billion. We can improve the recovery process and reduce repair times by increasing the experience and knowledge of the utility workforce through continuous learning, increased cooperation, and increased adaptability of related stakeholders.

4.13 | Active demand side management and direct load control

Figure 9 shows the US county-level average number of customers with direct load control. Loads that are large enough and can be controlled quickly can be used to control and improve grid frequency regulation [53, 54]. Frequency regulation is of high importance to power system stability. Active consumers in smart grids can play a significant role in providing ancillary services for power system transient stability. Although frequency regulation is important in normal power system operation, it is more crucial and challenging during a disaster [55]. The consumers who receive signals from smart meters can decrease the risk of electricity outage by participating in active demand side management. They can turn off unnecessary electric devices for a few hours as soon as they receive a signal about the disaster from the emergency services or utilities. The participation of consumers in active demand side management to provide ancillary services for frequency regulation is entwined with their social behaviour.

4.14 | Impact of an epidemic on power system operation

An epidemic, e.g. COVID-19 induces a decrease in industrial and commercial loads and a possible increase in residential loads [56]. It may produce an increase in the harmonic voltage levels at specific frequencies. This in turn increases the vulnerability of the power system to voltage and frequency instabilities. The cooperation and flexibility of the end-users who are willing to engage in the demand response program are essential to enhance power system stability margins in real-time.

4.15 | Pandemic planning

An infectious outbreak such as pandemic influenza impacts the primary energy and, in turn, the electric supply chain. Consequently, it affects electric generation and decreases the resiliency of the power system. In fact, a pandemic makes a disconnection between the fuel supply chain (the primary energy) and the electric sector (the secondary energy) [57]. Hence, the normal operation of the bulk power system is disturbed. This is the reason why studying the impact of the pandemic on electric power systems is emphasized by European electricity, gas, and oil coordination groups, and selected US Federal agencies such as Health and Human Services (HHS), Department of Homeland Security (DHS), Department of Energy (DOE), Department of Transportation (DOT), and Department of the Interior (DOI). The outbreak of influenza or other infectious diseases, e.g. coronavirus or the 2003 outbreak of SARS, can negatively influence power systems from coal supply chin to fuel transportation to electricity production.

4.16 | Environmental protective policies and regulations

To improve environmental conservation programs, end users may be incentivized to invest in distributed energy resources. As one course of action, consumers can shift their load to the hour that environmentally friendly energy sources, e.g. wind turbines, and solar thermal panels, generate electricity. These consumers' motivations are to reduce air emissions and water pollution, which are critical issues in the use of conventional energy, in order to protect the environment.

4.17 | Restoration

Restoration of a power system following a blackout induced by various extreme events is a complex process. It consists of phases, i.e. planning to restart and reintegration of the bulk power system, retaining critical sources of power (degraded level), and restoration after stabilizing at some degraded level. The level of experience, knowledge, learning rate, the cooperation of the workforce, experts, and operators influence the quality of restoration.

5 | HUMAN-CENTRED FEATURES IN THE CYBER–PHYSICAL–SOCIAL SYSTEMS OF POWER SYSTEMS

The Internet of Things, big data and cloud computing, complex networks, blockchain, instant data and edge computing, artificial intelligence, and power system supervisory control and data acquisition (SCADA) are typical cyber–physical systems and technologies [58]. However, a power system today is a cyber–physical–social system where the social system refers to stakeholders' social behaviours, which affect the way the power system operates. These stakeholders' social behaviour has a significant impact on the efficiency, reliability, and resilience of a power system [26]. We extend these features to power systems stakeholders. We classify the social elements in different manners. Figures 10 shows the classification of social features in cyber–physical–social system in power engineering. The classification of social traits can be target-based, time-based, or stakeholder-based. In the target-based classification, social features are categorized into resiliency-based, sustainability-based, economic-based, efficiency-based, stability margin-based, and reliability-based characteristics. In the time-based classification, social components are categorized into planning-based, operational planning-based, real-time operation-based, and real-time, dynamics, and transients-based characteristics. In the stakeholder-based classification, social features are categorized into end-users-based, primary energy provider-based, secondary energy provider-based, and other organizations-based behaviours.

Table 1 shows the stakeholder-based classification of the social features. Each of these stakeholders, humans, organizations, and societies, is defined by their specific social characteristics. In addition, Tables 2 and 3 show the target-based and time-based classification of the social features, respectively.

The social behaviour of the end-users is individual-based. When they are highly satisfied, the end-users, such as prosumers and electric vehicle owners, increase their level of flexibility, cooperation, and trust in secondary energy providers such as electric utilities or retailers. Consequently, they are more willing to participate in demand response, active demand side management, and vehicle-to-grid programs, to name a few.

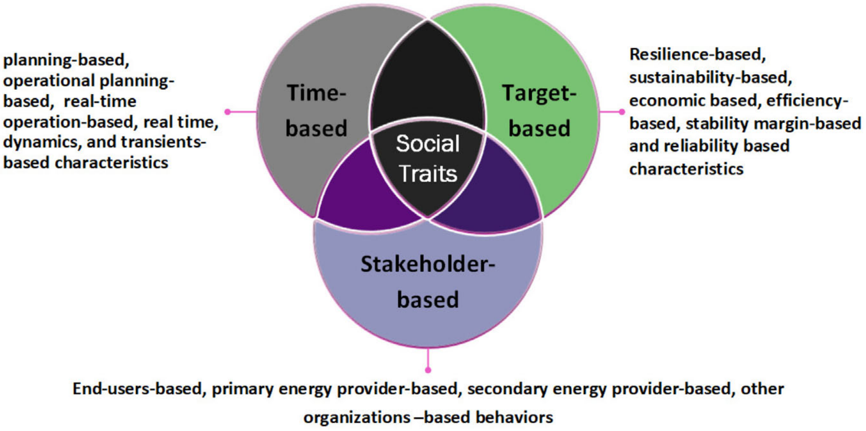

FIGURE 10 Classification of social features in super-wicked cyber-physical-social system in power engineering.

TABLE 1 The stakeholder-based classification of the social features for power system operation and planning.

Stakeholders	Sub-stakeholders	Social Features
End users	Prosumers, consumers, electrical vehicle owners, (active, passive end users), critical loads	Willingness, convenient, emotion, fear, satisfaction, empathy, risk perception, price-Information-seeking, social wale fare, comfort, collaboration, experience, motivation, learning, flexibility, bias, cooperation, belief, mass media diffusion, mental health, physical health
Secondary energy providers	Retailers, utilities, GENCOs, TRANSCOs, DISCOs, MGs, load serving entities, aggregators, ISOs, Regional transmission organizations (RTO), DERs	Price-Information-seeking, energy-information-seeking, reliability, confidence, learning, cooperation, privacy, work efficiency, risk perception, emotion, fear, collaboration, experience, mental health, physical health
Primary energy companies	Coal industry, natural gas industry, hydro, biofuels and waste, oil	Price-information-seeking, fuel-information-seeking, reliability, confidence, learning, cooperation, work efficiency, risk perception, emotion, collaboration, experience, mental health, physical health
Other entities	City councils, edge computing service provider (ESP)	Emission-information-seeking, reliability, confidence, learning, cooperation, privacy, work efficiency, risk perception, emotion, flexibility, collaboration, experience

Furthermore, if the consumers and the prosumers exhibit a high level of empathy and collaboration, they may be willing to enhance the power system's efficiency, reliability, and resiliency. On the other hand, how the end-users think affects their decision-making related to the power system operation. Their decision-making is also affected by their experience and their learning behaviour [59]. In addition, the secondary energy providers can increase the motivation of the end-users to contribute to better efficiency of the demand response.

During a disaster, when the end-users experience fear and a shortage of electricity, they perceive risk. This risk, in turn, increases their level of cooperation [23]. Hence, they are more prone to participate in an active demand side management program and share electricity with their neighbours who have experienced an outage. In addition to the quality of service, social diffusion through the social media platforms affects their satisfaction level. Social diffusion means that an end-user's emotion affects the feeling of others about power system services. The social behaviour of secondary energy providers, primary energy companies, and other entities is organizational-based. The social behaviours of each stakeholder can affect its service quality and decisions that are very important to the performance, reliability, and resilience of power systems.

6 | CALIBRATION AND VALIDATION OF THE CYBER–PHYSICAL–SOCIAL MODEL IN POWER ENGINEERING

The preceding sections have underscored the importance of taking social factors into account when conducting studies and analyses of power systems. In order to achieve this objective, it is imperative to develop mathematical cyber–physical models for each application that has been discussed, namely reliability, resilience, and restoration, utilizing the tools and techniques of social computing. Figure 11 presents the process of validation of cyber-physical–social system in power engineering. While the cyber and physical components of the power system can be effectively modelled, as previously noted, the social component poses unique modelling challenges that must be addressed. Regarding the cyber and physical components, they are provided with a large number of sensors that can be used

TABLE 2 The target-based classification of the social features for power system operation and planning.

Power system objectives	Social features
Resiliency enhancement	Emotion, fear, satisfaction, empathy, risk perception, flexibility, experience, learning behaviour, bias, mass media information diffusion
Sustainability enhancement	Willingness, convenience, comfort, motivation, mass media information diffusion
Economic enhancement	Price-information-seeking behaviour, energy-information-seeking behavior, consensus
Efficiency enhancement	Social welfare, consensus, well-being
Stability margin enhancement	Collaboration, flexibility, cooperation
Reliability enhancement	Confidence, belief, collaboration, flexibility, cooperation

TABLE 3 The time-based classification of the social features for power system operation and planning.

Power system objectives	Social features
Planning	Social welfare, well-being, satisfaction, mass media diffusion, learning behaviour, comfort, motivation
Operational planning	Price-information-seeking, energy-information-seeking, mass media diffusion, satisfaction, learning behaviour, comfort, motivation
Real-time operation	Willingness, satisfaction, price-information-seeking, energy-information-seeking, mass media diffusion, flexibility, risk perception, experience, collaboration, cooperation, confidence, bias, empathy
Real-time, dynamics, and transients	Willingness, convenience, emotion, fear, satisfaction, mass media diffusion, flexibility, risk perception, experience, collaboration, cooperation, reliability, belief, confidence, bias, empathy

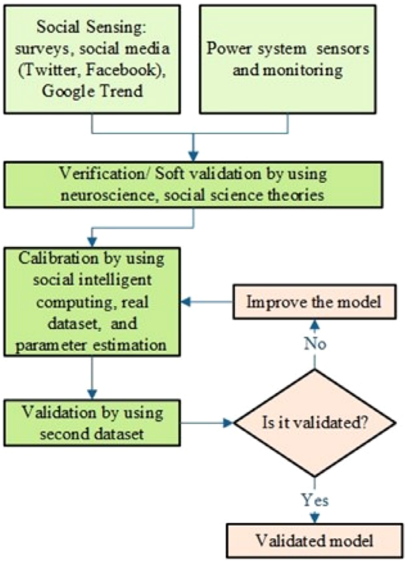

FIGURE 11 The process of validation of cyber-physical–social system in power engineering.

to calibrate and validate the associated models. As for the social component, traditional social science has relied on surveys to measure social behaviour. However, today new tools can be utilized, including natural language processing, machine learning algorithms, computer-text analysis tools, and social media, to name a few. For instance, prosumers', consumers', and organizations' social behaviour can be quantified by utilizing social media platforms such as Twitter and Facebook and social sensing tools and performing sentiment analysis. Social scientists or psychologists in the modern era can unveil social patterns through an analysis of the text's language [14]. The language that people utilize reveals their psychological state [60]. For instance, when individuals use the first plural pronouns more frequently in their speech, this demonstrates a high level of cooperation and cohesion among them [14, 61]. Additionally, GoogleTrend can be utilized to detect social and psychological patterns. Obviously, these novel social sensing technologies generate a wealth of data for social model calibration and validation. Figure 12 indicates the process of validation of the cyber–physical–social system in power engineering. When social computing is employed, the social model is calibrated using social datasets, which are gathered via appropriate social sensing techniques, such as social media. In particular, when studying resilience, social-related datasets can be collected for a specific event by analyzing social data gathered from Twitter. Then, the parameters of the social model are estimated. Finally, the model is validated by comparing the predicted data against the social data collected from another event. Model validation is an integral part of the social computing model since it allows us to discover new social features not accounted for in the model if the predictions are far off.

7 | CONCLUSION

In this article, we have highlighted the need to account for the cyber–physical–social dependence in power engineering in order to model and optimize the efficiency, resilience, sustainability, reliability, stability, and economic aspect of the power infrastructure and the associated social community. To meet this requirement, we utilize social computing to model the social behaviour of prosumers, consumers, utilities, and other stakeholders. We have provided a comprehensive list of research topics needed in computational social science for various power system operation and planning activities. We believe that our approach represents a paradigm shift in that it integrates power systems and social computing. Each of the applications stated needs a significant research effort to mature. Integrating social computing into the power system planning and operation process allows us to derive new hypotheses and test different scenarios that will be validated using real data gathered from various social media tools, like Twitter and Facebook. By leveraging natural language processing, machine learning algorithms, and text mining tools, these social sensing tools enable us to identify linguistic and psychological patterns. This compels us to assess the social behaviour of consumers and other stakeholders. Validating the model, which is a necessary component of social computing models, enables us to learn from real-world data.

AUTHOR CONTRIBUTIONS

Jaber Valinejad: Conceptualization, writing - review and editing. Lamine Mili: Funding acquisition, investigation, supervision, writing - review and editing. Xinghuo Yu: Investigation, supervision, writing - review and editing. Natalie van der Wal: Formal analysis, methodology, writing - review and editing. Yijun Xu: Conceptualization, investigation, visualization, writing - review and editing.

CONFLICT OF INTEREST

We confirm that my co-authors and I have no conflict of interest to disclose.

FUNDING INFORMATION

We confirm that my co-authors and I have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study

ORCID

Jaber Valinejad https://orcid.org/0000-0003-3619-1606

REFERENCES

1. Mili, L., Triantis, K., Greer, A.: Integrating community resilience in power system planning. In: Power Engineering: Advances and Challenges Part B: Electrical Power, pp. 192–211. CRC Press, Boca Raton, FL (2018)
2. Zhang, J.J., Wang, F.Y., Wang, X., Xiong, G., Zhu, F., Lv, Y., et al.: Cyber–physical–social systems: the state of the art and perspectives. IEEE Trans. Comput. Social Syst. 5(3), 829–840 (2018)
3. Zhang, J.J., Gao, D.W., Zhang, Y., Wang, X., Zhao, X., Duan, D., et al.: Social energy: mining energy from the society. IEEE/CAA J. Autom. Sin. 4(3), 466–482 (2017)
4. Xue, Y., Yu, X.: Beyond smart grid-cyber–physical–social system in energy future [point of view]. Proc. IEEE 105(12), 2290–2292 (2017)
5. Sevdari, K., Calearo, L., Andersen, P.B., Marinelli, M.: Ancillary services and electric vehicles: an overview from charging clusters and chargers technology perspectives. Renewable Sustainable Energy Rev. 167, 112666 (2022)
6. Bao, Y., Guo, J., Tang, J., Li, Z., Pang, S., Guo, C.: Analysis of power system operation reliability incorporating human errors. In: 2014 17th International Conference on Electrical Machines and Systems (ICEMS), pp. 1052–1056. IEEE, Piscataway, NJ (2014)
7. Bompard, E., Huang, T., Wu, Y., Cremenescu, M.: Classification and trend analysis of threats origins to the security of power systems. Int. J. Electr. Power Energy Syst. 50, 50–64 (2013)
8. Heyck, H.: Age of System: Understanding the Development of Modern Social Science, JHU Press, Baltimore, MD (2015)
9. Zwilling, M.: Big data challenges in social sciences: an NLP analysis. J. Comput. Inf. Syst. 63(3), 537–554 (2022)
10. Head, B.W., Alford, J.: Wicked problems: implications for public policy and management. Adm. Soc. 47(6), 711–739 (2015)
11. Levin, K., Cashore, B., Bernstein, S., Auld, G.: Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. Policy Sci. 45, 123–152 (2012)
12. Rittel, H.W., Webber, M.M.: Dilemmas in a general theory of planning. Policy Sci. 4(2), 155–169 (1973)
13. Valinejad, J., Mili, L.: Community resilience optimization subject to power flow constraints in cyber–physical–social systems. IEEE Syst. J. 1–12 (2022). https://doi.org/10.1109/JSYST.2022.3210075
14. Tausczik, Y.R., Pennebaker, J.W.: The psychological meaning of words: Liwc and computerized text analysis methods. J. Lang. Soc. Psychol. 29(1), 24–54 (2010)
15. Ye, P., Wang, S., Wang, F.Y.: A general cognitive architecture for agent-based modeling in artificial societies. IEEE Trans. Comput. Soc. Syst. 5(1), 176–185 (2017)
16. Davidsson, P.: Agent based social simulation: a computer science view. J. Artif. Soc. Soc. Simul. 5(1), 1 (2002)
17. Valinejad, J., Mili, L., Van.Der.Wal, C.N.: Multi-agent based stochastic dynamical model to measure community resilience. J. Soc. Comput. 3(3), 262–286 (2022)
18. Ye, P., Wang, S., Wang, F.Y.: A general cognitive architecture for agent-based modeling in artificial societies. IEEE Trans. Comput. Social Syst. 5(1), 176–185 (2017)
19. Valinejad, J., Mili, L., van der Wal, C.N., Xu, Y.: Environomic-based social demand response in cyber–physical–social power systems. IEEE Trans. Circuits Syst. II Express Briefs 69(3), 1302–1306 (2021)
20. Fredrickson, B.L., Joiner, T.: Positive emotions trigger upward spirals toward emotional well-being. Psychol. Sci. 13(2), 172–175 (2002)
21. Bosse, T., Duell, R., Memon, Z.A., Treur, J., Van Der Wal, C.N.: Multi-agent model for mutual absorption of emotions. Paper presented at the 23rd european conference on modelling and simulation, 9–12 June 2009
22. Erol, B.A., Majumdar, A., Benavidez, P., Rad, P., Choo, K.K.R., Jamshidi, M.: Toward artificial emotional intelligence for cooperative social human–machine interaction. IEEE Trans. Comput. Social Syst. 7(1), 234–246 (2019)
23. Gao, C., Liu, J.: Network-based modeling for characterizing human collective behaviors during extreme events. IEEE Trans. Syst. Man Cybern. Syst. 47(1), 171–183 (2017)
24. Hoogendoorn, M., Treur, J., van der Wal, C.N., van Wisen, A.: An agent-based model for the interplay of information and emotion in social diffusion. In: Proceedings of the 10th IEEE/WIC/ACM International Conference on Intelligent Agent Technology, IAT'10, pp. 439–444. IEEE, Piscataway, NJ (2010)
25. Liu, Y., Fan, R., Terzija, V.: Power system restoration: a literature review from 2006 to 2016. J. Mod. Power Syst. Clean Energy 4(3), 332–341 (2016)
26. Valinejad, J.: Measuring and Enhancing the Resilience of Interdependent Power Systems, Emergency Services, and Social Communities. Virginia Tech, Blacksburg, VA (2022)
27. Critchley, R., Gilbertson, J., Grimsley, M., Green, G., Group, W.F.S., et al.: Living in cold homes after heating improvements: evidence from warm-front, England's home energy efficiency scheme. Appl. Energy 84(2), 147–158 (2007)
28. Hammerstrom, D.J., Ambrosio, R., Carlon, T.A., DeSteese, J.G., Horst, G.R., Kajfasz, R., et al.: Pacific Northwest Gridwise Testbed Demonstration Projects; Part I. Olympic Peninsula Project. Pacific Northwest National Laboratory, Richland, WA (2008)
29. Yang, Q., Wang, H.: Blockchain-empowered socially optimal transactive energy system: framework and implementation. IEEE Trans. Ind. Inf. 17(5), 3122–3132 (2020)
30. Hobman, E.V., Frederiks, E.R., Stenner, K., Meikle, S.: Uptake and usage of cost-reflective electricity pricing: insights from psychology and behavioural economics. Renewable Sustainable Energy Rev. 57, 455–467 (2016)

31. Ba, S., Pavlou, P.A.: Evidence of the effect of trust building technology in electronic markets: price premiums and buyer behavior. MIS Q. 243–268 (2002)
32. Clack, C.T., Choukulkar, A., Coté, B., McKee, S.A.: ERCOT winter storm Uri blackout analysis. https://www.vibrantcleanenergy.com/wp-content/uploads/2021/03/VCE-ERCOT-StormUri.pdf (2021). Accessed February 2021
33. Kazemtarghi, A., Dey, S., Mallik, A., Johnson, N.G.: Asymmetric half-frequency modulation in dab to optimize the conduction and switching losses in ev charging applications. IEEE Trans. Transp. Electrif. 1–1 (2023). https://doi.org/10.1109/TTE.2023.3234198
34. Kazemtarghi, A., Dey, S., Mallik, A.: Optimal utilization of bidirectional evs for grid frequency support in power systems. IEEE Trans. Power Delivery 38(2), 998–1010 (2023)
35. Norouzi, S., Ghoreishy, H., Ale.Ahmad, A., Tahami, F.: A new variable frequency zero voltage switching control method for boost converter operating in boundary conduction mode. Int. J. Eng. 33(11), 2222–2232 (2020)
36. Kazemtarghi, A., Chandwani, A., Ishraq, N., Mallik, A.: Active compensation-based harmonic reduction technique to mitigate power quality impacts of EV charging systems. IEEE Trans. Transp. Electrif. 9(1), 1629–1640 (2022)
37. Salehi, M., Khodabandeh, M., Amirabadi, M.: Zeta-based AC-link universal converter. In: 2022 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1–7. IEEE, Piscataway, NJ (2022)
38. Noruzi, S., Ghoreishy, H., Ahmad, A.A., Tahami, F., Ahmadiahangar, R., Rosin, A.: Variable frequency control method of boost converter operating in boundary conduction mode. In: 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), pp. 1–6. IEEE, Piscataway, NJ (2020)
39. Salehi, M., Amirabadi, M.: A soft-switching zeta-based ac-link universal converter. Paper presented at 2023 IEEE applied power electronics conference and exposition (APEC), Orlando, FL, 19–23 March 2023
40. Seebauer, S.: The psychology of rebound effects: explaining energy efficiency rebound behaviours with electric vehicles and building insulation in austria. Energy Res. Soc. Sci. 46, 311–320 (2018)
41. Knirsch, F., Unterweger, A., Engel, D.: Privacy-preserving blockchain-based electric vehicle charging with dynamic tariff decisions. Comput. Sci. - Res. Dev. 33, 71–79 (2018)
42. Axsen, J., Orlebar, C., Skippon, S.: Social influence and consumer preference formation for pro-environmental technology: the case of a UK workplace electric-vehicle study. Ecol. Econ. 95, 96–107 (2013)
43. Salehi, M., Shahabadini, M., Iman.Eini, H., Liserre, M.: Predictive control of grid-connected modified-CHB with reserve batteries in photovoltaic application under asymmetric operating condition. IEEE Trans. Ind. Electron. 69(9), 9019–9028 (2021)
44. Notash, F.Y., Zahedi, N., Hosseini, S.H.: A multi-level input soft switching fly-back converter performance in a stand-alone WECS powering a predictive current controlled PMSM. In: 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC), pp. 157–162. IEEE, Piscataway, NJ (2018)
45. Gao, L., Hu, H.: Wind turbine icing characteristics and icing-induced power losses to utility-scale wind turbines. Proc. Natl. Acad. Sci. U. S. A. 118(42), e2111461118 (2021)
46. Nematkhah, F., Bahrami, S., Aminifar, F., Catalão, J.P.S.: Exploiting the potentials of HVAC systems in transactive energy markets. IEEE Trans. Smart Grid 12(5), 4039–4048 (2021)
47. Ye, M., Hu, G.: Game design and analysis for price-based demand response: an aggregate game approach. IEEE Trans. Cybern. 47(3), 720–730 (2016)
48. Lokeshgupta, B., Sivasubramani, S.: Multi-objective dynamic economic and emission dispatch with demand side management. Int. J. Electr. Power Energy Syst. 97, 334–343 (2018)
49. Dobson, I., Carreras, B.A., Newman, D.E.: A loading-dependent model of probabilistic cascading failure. Probab. Eng. Inf. Sci. 19(1), 15–32 (2005)
50. Mirzapour, O., Mohammadi, F., Sahraei Ardakani, M.: Multidimensional scenario selection for power systems with line and generation outages. In: 2022 North American Power Symposium (NAPS), pp. 1–5. IEEE, Piscataway, NJ (2022)
51. Aidoo, K., Briggs, R.C.: Underpowered: Rolling blackouts in africa disproportionately hurt the poor. Afr. Stud. Rev. 62(3), 112–131 (2019)
52. Kyne, D.: Winter storm URI 2021: a litmus test for extreme event resiliency. J. Extreme Events 2023, 2250004 (2023)
53. Anderson, B., Reilly, J., Krishnan, V.: Load control for frequency response-a literature review. https://www.osti.gov/biblio/1846936 (2022). Accessed 1 Februry 2022
54. Norouzi, S., Ghoreishy, H., Ahmad, A.A., Tahami, F.: Stability analysis of variable frequency control method of soft switching for boost converter with wide bandgap semiconductors. In: 2023 14th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), pp. 1–7. IEEE, Piscataway, NJ (2023)
55. Bevrani, H.: Robust Power System Frequency Control. Vol. 4, Springer, Cham (2014)
56. Elavarasan, R.M., Shafiullah, G., Raju, K., Mudgal, V., Arif, M.T., Jamal, T., et al.: COVID-19: impact analysis and recommendations for power sector operation. Appl. Energy 279, 115739 (2020)
57. Zhong, H., Tan, Z., He, Y., Xie, L., Kang, C.: Implications of COVID-19 for the electricity industry: a comprehensive review. CSEE J. Power Energy Syst 6(3), 489–495 (2020)
58. Hasan, M.K., Alkhalifah, A., Islam, S., Babiker, N.B., Habib, A.A., Aman, A.H.M., et al.: Blockchain technology on smart grid, energy trading, and big data: security issues, challenges, and recommendations. Wireless Commun. Mobile Comput. 2022, 1–26 (2022)
59. Schreiner, D.C., Yalcinbas, E.A., Gremel, C.M.: A push for examining subjective experience in value-based decision-making. Curr. Opin. Behav. Sci. 41, 45–49 (2021)
60. Boyd, R.L., Schwartz, H.A.: Natural language analysis and the psychology of verbal behavior: the past, present, and future states of the field. J. Lang. Soc. Psychol. 40(1), 21–41 (2021)
61. Simmons, R.A., Gordon, P.C., Chambless, D.L.: Pronouns in marital interaction: What do you and I say about marital health? Psychol. Sci. 16(12), 932–936 (2005)

How to cite this article: Valinejad, J., Mili, L., Yu, X., van der Wal, C.N., Xu, Y.: Computational social science in smart power systems: Reliability, resilience, and restoration. Energy Convers. Econ. 1–12 (2023). https://doi.org/10.1049/enc2.12087