The Role of Cyber-Physical-Social Systems in Smart Energy Future

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***Abstract*—Future energy systems (FESs) require greater interaction, integration, and cooperation between physical infrastructure, cyber technologies, and human participants from prosumers to communities and governments. Cyber-Physical-Social Systems (CPSSs) will be the enabling technology to ensure the efficiency, effectiveness, sustainability, security and safety of energy generation and use integrating human and social factors into consideration. In this paper, we will first present an overview of the challenges in CPSSs. We will then outline potential contributions that CPSSs can make to FESs, as well as the opportunities that FESs present to CPSSs.**

***Index Terms*—Cyber-physical systems, cyber-social systems, renewable energy, smart grid, human dynamics, generative AI, transformer, ChatGPT, information technology, holism, reductionism.**

I. Introduction

THE greatest discovery of electricity in the 19th Century has led to watershed changes in human history. Economic and societal changes require energy to drive; electric grids have been a backbone to carry energy in the form of electricity to help drive the changes. In recent years, the demands for clean energy and their efficient use have seen the emergence of Smart Grids (SGs) which integrate advanced technologies to make the grid and energy supply more reliable and secure. It incorporates the behaviors and actions of all the participants in the energy supply chain efficiently and effectively, supported by new technologies such as Cyber-Physical Systems (CPSs). The benefits and future challenges of using CPSs in SGs have been well documented in [1]. However, future energy requires making energy generation and use not only more efficient but also environmentally sustainable and socially responsible. This broader view has challenged the commonly thought future energy as just utilizing advanced technologies such as information and communication technologies (ICTs) and electronics to maintain an environmentally and economically sustainable energy system.

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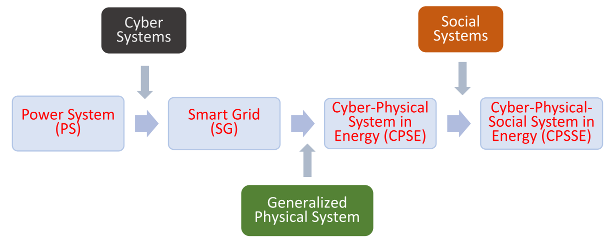

Fig. 1. The journey of electric power systems.

In [2], the journey of electric power systems was illustrated as shown in Fig. 1 where a Cyber-Physical-Social System (CPSS) in energy future was advocated. Cyber systems, namely ICTs, have significantly impacted how power systems operate, enabling information exchange and control much more timely and efficiently in the SGs. The next level is towards direct interaction and integration with industry and society to achieve great social and economic goals. Such a vision is very much required in the 21st Century for many reasons, such as limited available non-renewable energy sources on earth, pollution, and societal and environmental responsibilities. Apart from smarts such as advanced ICTs which are needed to ensure the uncertainties brought in by renewable energy sources (RESs) are under control to ensure uninterrupted energy supply, greater consideration of social, economic and environmental factors would see SGs to become CPSS in energy.

Almost any form of energy production and usage results in pollution and social costs usually hidden from the average users. More broadly, future energy encompasses a wide range of research and development issues such as standardization, policy framework and reform, operational technologies and systems, information and social technologies and systems [2]. Another factor which is often neglected is in the human or society dimensions where communities are more willing to proactively engage in energy generation and use processes and can even be receptable to certain degree of unreliability when needed in exchange for less environmental damages. Future energy must be dealt with in a holistic way across economic, environmental, and social perspectives.

In this article, we will first discuss the essence and key elements of CPSSs, exploring particularly the principles of holism and reductionism, two well-known philosophies, for complex problem solving in a scalable way. We further scrutinize the philosophical difference between Science, Technology, Engineering, and Mathematics (STEM), and Humanities, Arts, and

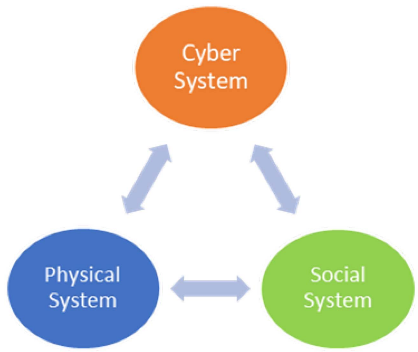

Fig. 2. Integration of cyber, physical and social systems.

Social Sciences (HASS) in dealing with complex problems of the world, emphasizing the importance of cross-disciplinary nature of skills required for CPSS studies. We will then examine how CPSSs can help the FES developments through demonstration of a few case studies, and what challenges FESs present to CPSSs and vice versa. Potential future perspectives of CPSSs for smart energy future are elaborated at the end. We advocate a just enough just in time principle for large scale complex problem solving, and elaborate the potential of the generative AI technologies such as Generative Pre-trained Transformers (GPTs) for CPSSs and FESs in automated discovery of human experiences and intelligence encapsulated in the Big Data, advocating a revival of the Knowledge-Based Systems (KBSs) to bridge between human intelligence and machine intelligence. We particularly emphasize the differences between STEM and HASS and promote a cross-disciplinary approach to engage both STEM and HASS researchers to work together to achieve common goals.

II. Cyber-Physical-Social Systems (CPSSs)

A. What is CPSS?

Cyber-Physical-Social Systems (CPSSs) are an emerging field where cyber-physical systems meet social systems. While CPSs refer to physical systems interconnected by and integrated by cyber-systems to deliver desirable outcomes, social systems are considered any complex system formed by human beings as a functioning society [3]. Integration of cyber, physical, social entities is critical to create a seamless, efficient and secure environment to achieve economic, social and environmental objectives [4], [5] (see Fig. 2). CPSS is poised to play an important role in the forthcoming Industry 5.0 in the next few decades, symbolizing harmonious collaboration between machine and humans/society. CPSS is arising from Industry 4.0 characterized by CPSs as complex, physically-aware engineered systems integrating cyber systems and the physical world to deliver efficiency and efficacy [6].

B. Challenges and Opportunities

CPSSs offer both challenges and opportunities as shown in [7], [8], [9], [10], [11], [12], [13], [14] where various aspects have been addressed. Some of them are described below. First, CPSSs are highly complex systems that integrate physical, cyber, and social components. This complexity can make it difficult to design, implement, and maintain these systems. This in turn begs new development in methodology for improved efficiency and productivity. Second, CPSSs are vulnerable to security and privacy breaches, which can compromise the safety and well-being of individuals and communities. For example, cyber-attacks such as inference attacks present the biggest challenges to confidentiality, integrity, reliability and authenticity; privacy is another major issue considering huge volumes of private data collected and processed [14]. There is another security issue in relation to physical systems which can be made secure by adopting AI technologies [15]. A holistic approach across cyber, physical and social components presents the opportunity to enhance safety and security by monitoring and responding to physical, cyber, and social threats in real-time. Third, CPSSs involve social and cultural factors, such as norms, values, and beliefs. These factors can raise ethical and legal issues related to data privacy, surveillance, and discrimination. A good example is a recently popular concept of smart cities [16]. Finally, CPSSs require collaboration between professionals from different disciplines, including engineering, computer science, social sciences, and humanities. This collaboration can be challenging due to differences in language, culture, and methodology, and in particular the 'divide' between the ways the two clusters of scientific endeavors, namely, STEM and HASS, see the world.

While both HASS and STEM disciplines require critical thinking, problem-solving, and analytical skills, and rely on empirical evidence and research to advance knowledge [17], HASS is concerned with the study of human behaviors, culture, language, history, and other social sciences. In contrast, STEM disciplines focus on scientific and technical subjects such as physics, chemistry, mathematics, computer science, and engineering. In addition, HASS disciplines often focus on qualitative research methods and tend to be more subjective, whereas STEM disciplines emphasize quantitative research methods and are more objective and empirical. Although HASS and STEM have some areas of overlap, they represent different methodological approaches. Despite their differences, both fields are essential for advancing human knowledge and understanding [ChatGPT, personal communication, April 20, 2023]. Studying CPSSs requires researchers from different fields to collaborate. For example, social scientists can work with engineers to study the impact of CPSS on society, while computer scientists can work with economists to analyze the economic impact of the technology. There are methodologies available to use for the integration. For instance, social science methods such as surveys and interviews can be integrated into STEM research to study the social and human aspects of CPSSs. Social scientists can conduct surveys to understand consumer attitudes towards smart grid and energy systems, while scientists and engineers can analyze technical data to understand the impact of the technologies on the power and energy systems. To narrow the gap between STEM and HASS, educational programs can be developed to train researchers and practitioners in both STEM and HASS fields to understand each other and work together on CPSS research projects.

There is another closely related topic, Cyber-physical-human systems (CPHSs), which integrate physical and cyber components, as well as human interactions, to create intelligent systems that can sense, act, and adapt to their environment [18]. These systems can be found in many applications, such as smart cities, transportation systems, manufacturing, healthcare, and more. They are designed to improve efficiency, safety, and overall performance by leveraging the power of advanced technologies such as Internet of Things (IoT), Artificial Intelligence (AI), and machine learning. For example, in the power grid, CPHSs can help detect and respond to power outages in real-time, reduce the impact of disruptions, and quickly restore service to affected areas. While CPSS and CPHS share the same root in human and social dynamics, the former focuses on community and societal responses and the latter on individual human's responses which are more suitable for studying personalized services and robotics.

C. CPSS: Holistic and Reductionist Viewpoints

Holism and reductionism are two approaches for studying complex systems. Holism holds the principle that the whole has priority over its parts with a focus on the emergent phenomena, while reductionism emphasizes that complex phenomena can be explained by scrutinizing individual parts. Integrating these two methodologies would bring out benefits for complex CPSSs at both micro and macro levels though information entropy preservation may be required during the integrated analysis and synthesis. For instance, to preserve the static and dynamic information of the whole system strictly, a unified platform (Sim-CPSS) can be used [19], which bridges the significant differences among different simulation environments with multi-domain, multi-time scale and multi-social behaviors. Space dimension and/or time complexity reduction may also be considered, for example, mapping high dimensional complete trajectory into a series of orthorhombic two-dimensional plane trajectories and quantifying the mechanism characteristics of each two-dimensional plane trajectory and then analyzing the mapping trajectory through piecewise parameter-fixed linearization process with sufficiently short evolution steps. Another application of whole-reductionism to power network operations can be found in [20].

It should be noted that holism and reductionism are predominantly STEM terms to describe two opposite ways of looking at the physical world. In HASS, their methodologies are categorized differently as shown in Fig. 3 in four paradigms [21] under two philosophical assumptions: ontology and epistemology. Ontology refers to assumptions about how we see the world, while epistemology refers to the assumptions about the best way to study the world [22]. Based on these assumptions, functionalism refers to the fact that the world is viewed as consisting mostly of social order (ontology) and hence seeks to study patterns of ordered events or behaviors using objective approach (epistemology). If social order is focused through the subjective interpretation of participants involved, this is called interpretivism. If one believes that the world consists of radical change and seeks to understand or enact change using

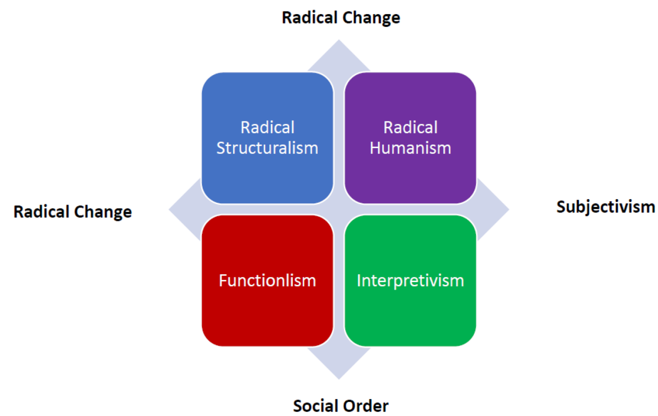

Fig. 3. Research methodology classification in HASS [21], [22].

an objectivist approach, then a radical structuralism paradigm is employed. If social change is understood subjectively, then a radical humanism paradigm is adopted. In this sense, holism and reductionism are closely related to functionalism where objectiveness and order (physics) reign supreme [21], [22].

III. Smart Energy Future With CPSSs

CPSSs can be used to support and enhance smart energy future. Apart from inheriting the benefits of CPSs for efficient and reliable power grids, in tasks such as real-time monitoring and control, demand response, renewable energy integration, and energy storage management [1], CPSSs can especially offer a 'co-design' environment to facilitate interactions and interplay between prosumers, policy-makers, communities, operators, CPS part of FESs, and HASS and STEM researchers and practitioners, to achieve greater social, economic, and environmental objectives collectively. As shown in Fig. 2, key to the success of CPSS is the interaction and interplay among their cyber-, physical-, and social- components. While recognizing CPSS in energy studies are embryonic at this point of time, still far from what CPSSs are capable of, in the following, a few case studies from our own works are offered to show the potential of using CPSSs to enhance FESs. We are particularly focused on exploring the relationships among the cyber-, physical-, and social- systems to see what kinds of benefits it can bring out and their potentials.

A. Interaction Between Cyber and Physical Systems to Support Social Demands

Consider a scenario where interaction between physical systems and cyber systems occurs while taking consideration of social factors (see Fig. 4).

For the communication network, the differentiated communication demands of users in the social system require it to have demand response ability. For the distribution network, the access of large-scale base station increases the difficulty for its operation and control.

Hence, it is desirable to realize the cooperative optimization of both the distribution network and the communication network by

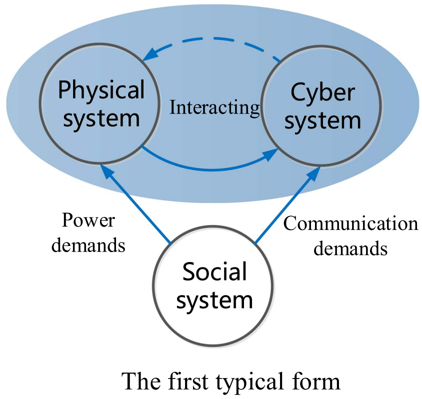

Fig. 4. Interaction between cyber and physical systems to support social demands.

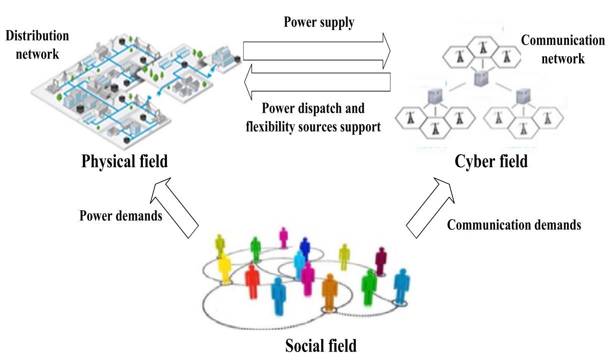

Fig. 5. Collaborative optimization of distribution and communication networks.

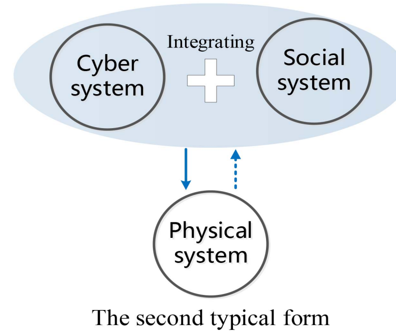

Fig. 6. Integration between cyber and social systems to support physical systems.

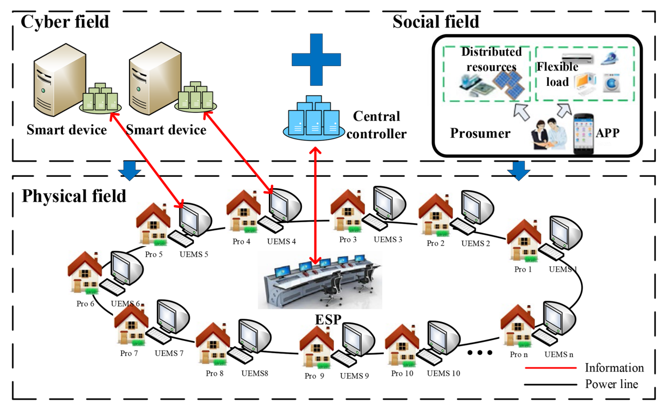

Fig. 7. Prosumers' energy management under CPSS.

designing a mechanism to meet the social needs. For example, to verify the effectiveness of cooperative optimization, two modes may be employed: one for the distribution network operator and the mobile network operator to optimize their objectives independently; the other deals with cooperative optimization of distribution network operator nd mobile network operator taking consideration of social factors. In the collaborative mode, the flexible sources of the distribution network include not only the neighboring grid support and backup, but also the power support from the mobile network. Therefore, the CPSS approach can provide a good solution to describe the complementary characteristics between users' personalized communication resource demands and energy demands (see Fig. 5). With the proactive support of the mobile network, the volatility of the net-load in the distribution network can be reduced substantially, as shown in [23].

B. Integration Between Cyber and Social Systems to Support Physical Systems

Another scenario is the integration between cyber and social systems to support the physical systems (see Fig. 6). A typical example is the development of energy management method via social data and load data fusion for prosumers in Fig. 7 [24].

For energy sharing between prosumers, their decision-making and outcomes are much affected by their social attributes. Both the load distribution data from cyber system and social attributes data from social system could be considered simultaneously. Under CPSS framework, to support prosumer's energy management of physical system, user load data are collected by smart meters and uploaded by user energy management system to the smart devices, and social survey can be implemented to obtain social attribute data including things such as white goods power, family member, ideal electricity saving behaviors, etc. The data from cyber systems represent the objective electricity consumption behaviors of prosumers, and data from social systems describe the subjective energy consumption preferences of prosumers. Integration of these two kinds of data can give rise to comprehensive understanding of the rationality and preference of prosumers' decision-making to improve the accuracy of energy management models.

Two cases of rational optimization and subjective optimization can be demonstrated to verify the performance of the proposed integration of social and load data for energy management. First, rational optimization is essentially a traditional profit-driven decision model under CPS, while the latter involves prosumers' social attributes and can be modelled from CPSS perspective. It can be shown that from the perspective of social attributes, optimal load strategies in a subjective scenario almost

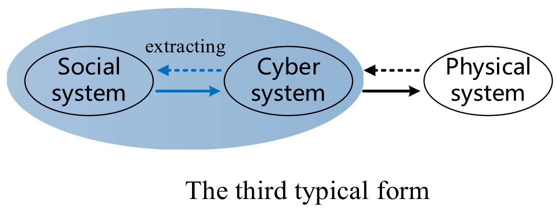

Fig. 8. Acquiring social information from cyber systems to support personalized energy services.

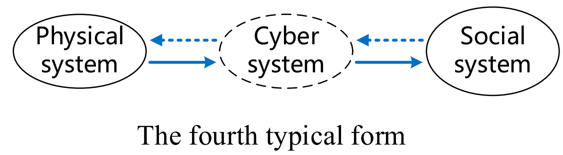

Fig. 10. Interaction between physical and social systems through cyber system.

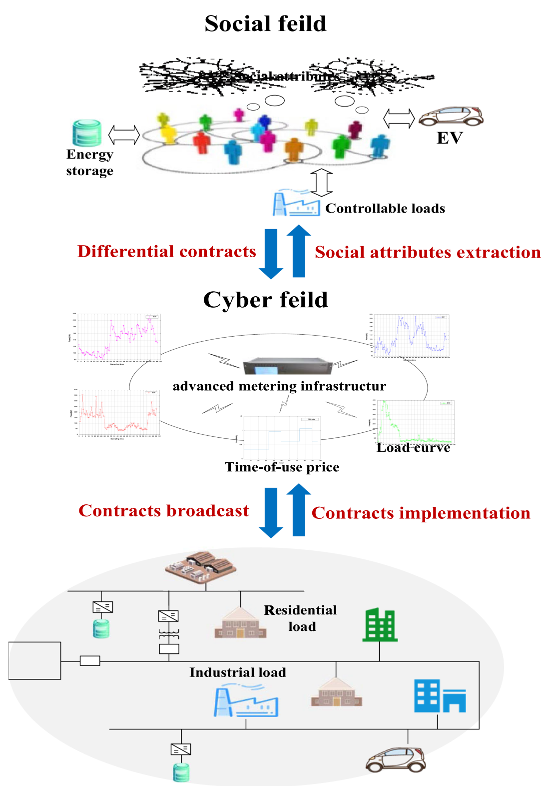

Fig. 9. Frequency regulation resource trading method for prosumers under CPSS.

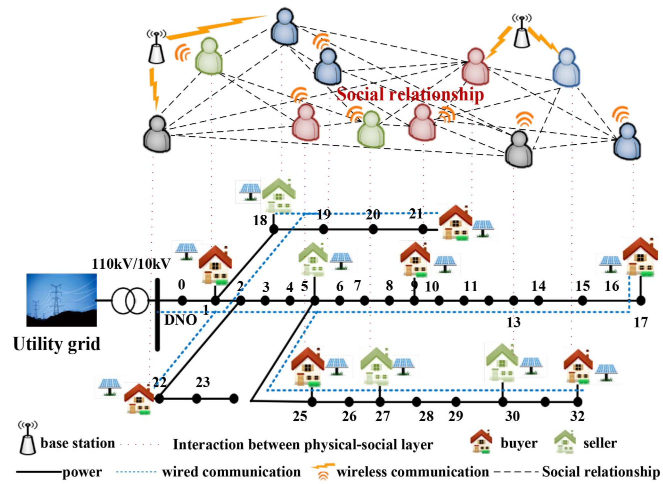

Fig. 11. CPSS for P2P energy sharing of prosumers.

follow the previous load pattern than rational prosumers, indicating the influence of social preferences on their load strategies, which further implies CPSS approach can take both rationality and preference of prosumers' decision-making into account and improve the accuracy of energy management models [24].

C. Acquiring Social Information From Cyber Systems to Support Personalized Energy Services of Physical Systems

There is a potential to acquire social information from cyber systems to support personalized energy services of physical systems as shown in Fig. 8. An example is the personalized frequency regulation resource trading contract design of aggregation service provider [25] as shown in Fig. 9. Electricity consumers can be considered a valuable frequency regulation resource. Personalized indicators can be extracted from the cyber system's information such as load curve and time-of-use electricity price to characterize and quantify social attributes and provide personalized frequency regulation resource trading services for physical system.

Based on the extracted personalized social field related indicators, a series of differential contract items including differential trading capacity and differential trading income can be designed by aggregation service provider and broadcast to prosumers through cyber network for selecting. Such comprehensive model has been shown to outperform others. It should be noted that considering the social attributes of users can better help virtual power plant aggregation service providers design incentive mechanisms for different types of users, formulate differentiated contracts, and effectively enhance the effectiveness of aggregators and users in participating in the frequency regulation auxiliary service market, as shown in Fig. 9.

D. Interaction of Physical and Social Systems Through Cyber Systems

An example would be the P2P energy sharing framework considering physical-social integrated preferences as shown in Fig. 10. In order to guarantee the safe and economic operations of the physical system, information can propagate and share through media in the social system, and cyber system acts as information carrier in the ubiquitous IOT network for complex information and knowledge contained in the physical and social systems as shown in Fig. 11.

[26] shows that considering both the physical knowledge and the prosumers' social reciprocity is superior to any other

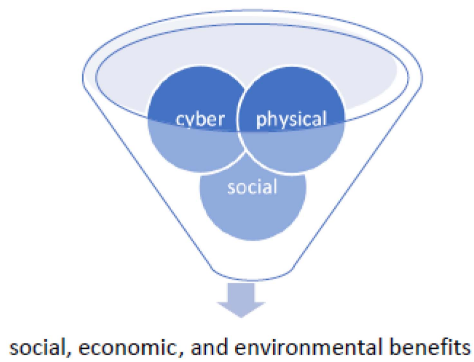

Fig. 12. Cooperation to deliver social, economic and environmental benefits.

schemes in terms of guaranteeing shared energy while stimulating cooperation effectively.

E. Integration of Cyber, Physical and Social Systems to Support Social and Economic Development

There is an increasing need of cooperation among the cyber-, physical-, and social- systems to bring out mutual benefits (see Fig. 12). There are two challenges: technological and sociological. Technological means there needs to be an effective interface between these three systems. Various approaches can be adopted to build the connection. For example, in Fig. 13, a specific simulation platform (Sim-CPSS) has been built to enable functioning of CPSS to deal with multi timescales, through an interface across multiple technology platforms [19].

This platform considers different time scales of various stages of operations in power systems and integrates them for overall system simulations, taking advantage of both the overall view of the holism and the mechanism view of the reductionism. It adopts 'events' rather time stamps to drive simulations and interaction and integration between system components of different time scales. It also uses blackboard mechanism as an information sharing platform to enable cross-field simulation, all interactive data involved in cross-field simulation is stored in a shared state "blackboard", and during the simulation process, different apps can only exchange data through the "blackboard". Furthermore, to enable cross-field multi-time scales simulation, Sim-CPSS provides support of multiple time scales data storage for "blackboard". However, such platform is limited to the thinking that both aspects of CPS and CPSS can be considered in a standardized format while in many cases, subjective judgements are not easy to conform to such way of thinking. Doing so would pose new questions of sensitivity to data and information transformation from STEM domain to HASS domain, and vice versa.

IV. Discussions and Conclusions

As shown above, key to the success of CPSSs for smart energy future are the smooth, deeply integrated interaction and interplay of the cyber-, physical-, social- systems in a timely fashion. In the future, it is expected that certain smart systems

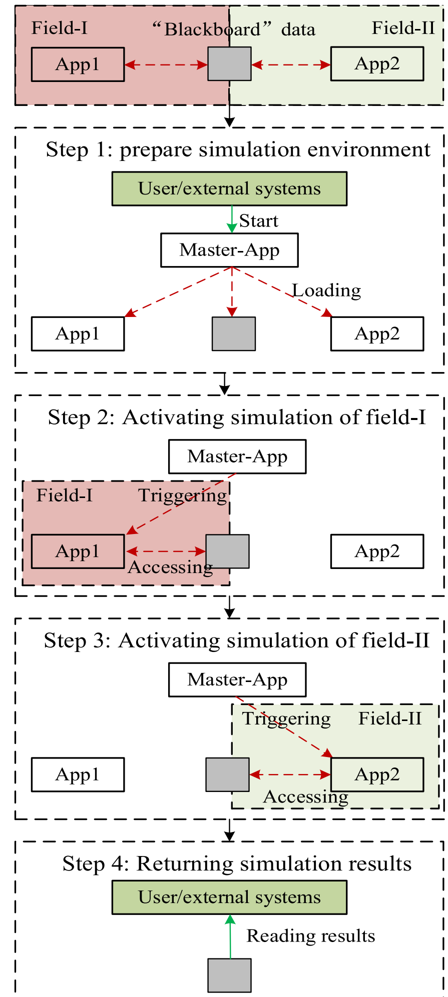

Fig. 13. Example simulation platform for CPSS.

such as energy ecosystem prognostic simulation tools will be developed to support policy developments, market regulation and grid operations, and deliver public goods in an integrated way. A few key challenges and opportunities are outlined below.

A. Dealing With Complexity: Scalability and Simplicity

Case studies in Section III are provided according to the ways the cyber, physical and social systems interact. Their limitations in space and time dimensions may be overcome by exploring their intrinsic relationships from both the holism and reductionism viewpoints in the future. For example, in the context of FESs, whether it is reasonable to directly reduce the CPSS dimensionality of integrated cyber, physical, social systems as a whole, or if these three systems can encapsulate the trajectories of whole CPSS without entropy decrease. Furthermore, how to integrate the holistic and reductionist approaches to study complex CPSSs is a challenge. There should be some compromise between how much micro and macro details are needed to understand the CPSS as a whole [27], utilizing them for improving reliability, resilience and restoration of FESs [28]. The celebrated Taylor expansion of mathematical functions gives a perfect inspiring example of relationship between accuracy and approximation, giving rise to a theoretical foundation for their balanced usage. This concept may be used to deal with large scale network CPSSs where network topology may be purposed simplified to give rise to a just enough solutions just in time. This just enough just in time philosophy will be particularly useful in dealing with those time-critical modelling, control and optimization tasks where just enough solutions, which may not even accurate but acceptable, are required just in time in order to meet the dynamic operational objectives. For example, future electricity dynamic pricing decisions may have to be made every five minutes which requires collection and processing of smart meter data across large scale distribution networks are accomplished well within five minutes.

B. Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) [29] is expected to play a very important role in CPSSs. In addition to those potential technological benefits brought to CPSs in terms of modelling, control and optimization capabilities in [1], the latest development of generative AI technologies such as Generative Pre-trained Transformers (GPTs) is presenting new opportunities to CPSSs, especially in bringing closer the relationship and information dealing between human intelligence and machine intelligence. One particular area which is experiencing revival is the KBSs (also known as Expert Systems) which was very popular in the 1980s and 1990s due to their ability to encapsulate expert knowledge and 'reason' like a human expert [29]. An outstanding problem is the resource-intensive knowledge acquisition which was done by human experts. This has hindered the development of KBSs in recent years. GPTs have presented a way to acquire such knowledge through machine learning [30]. ChatGPT is a good example [https://openai.com/blog/chatgpt], which is built based on the principle of large language modeling (i.e., predicting the next word based on the context of the previous words in a perceived coherent way. GPT as a transformer-based model can capture patterns, semantic relationships, and contextual information from the training data [31]. When huge legacy human knowledge data base is available, GPT technologies may help build a KBS to encapsulate human knowledge embedded in the data, hence overcoming the bottleneck problem of knowledge acquisition which was usually done by human engineers through interviewing and data analysis. However, the frontier of this research lies in finding a way to generate reliable, trustworthy KBS which can offer verifiable explanations, if needed, to support human decision-making. This requires extending the research beyond seeking 'attention' as the main mechanism.

C. Barries for Adopting CPSSs for Smart Energy Future

There are several barriers to the adoption and implementation of CPSS in Smart Energy, in addition to typical ones such as interoperability, security and privacy, data management, costs, and regulations. CPSS are highly complex systems that involve interactions between physical, cyber, and social component systems. This complexity can make it difficult for STEM and HASS professionals to work together effectively, as they may have different expertise and knowledge domains. CPSSs involve a wide range of disciplines, including engineering, computer science, social sciences, and humanities. Each discipline has its own language and terminology, which can create communication barriers and make it difficult for professionals from different disciplines to understand each other. STEM and HASS researchers and professionals often use different methodologies to analyze and interpret data. For example, STEM professionals may rely on mathematical models and simulations for analysis and synthesis [32], [33], [34], while HASS researchers and professionals may use qualitative research methods such as interviews and ethnography. CPSSs often involve social and cultural factors, such as norms, values, and beliefs. These factors can vary widely across different disciplines.

D. Human-Centred Design Philosophy and Approach

Human-centered design can be an approach that puts the prosumers, policy makers, operators, and any stakeholders involved, at the center of the design process. This will help bridge the gap between STEM and HASS by emphasizing the importance of understanding their needs, preferences, and behaviors, helping build a CPSS-based smart energy system which is more user-friendly, accessible, responsive, and culturally appropriate. For engagement, participatory design approach can be used to help STEM and HASS researchers and professionals work together to co-create CPSSs that are more inclusive and responsive to the needs of diverse communities [34]. Ethnography approach can also be adopted to help STEM better understand the social and cultural contexts in which CPSSs are used [35]. Collaborative platforms such as GitHub, GitLab, and Slack may be used to facilitate communication and collaboration between STEM and HASS by sharing code, data, and other resources [36].

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