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Interdisciplinary Vision of the Digitalized Future Energy Systems

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ABSTRACT Global energy systems are transforming from fossil fuels to renewables, but the conventional electricity systems are so fragile that could lead to negative consequences such as soaring prices, rolling blackouts, security issues and delays to emission reductions. Confronting to these issues, electricity systems of the future will be vastly changed, dominated by new technologies and business models, increasingly digital and highly complex. Such transformation will be enabled by means to efficiently, stably and affordably distribute electrical power from many sources and storage points. Market design, policy, regulations, legislations, cyber security and politics are barely keeping up with advances in technologies, and energy technology choices have multi-generational implications for people and economies. These issues are global and to find a solution requires true systems thinking, informed by cutting-edge research. This paper envisages interdisciplinary digitalized future energy systems for emission reductions and proposes a 6-theme template to shape the future energy system. The six research themes have been designed such that the ''whole is greater than the sum of the parts''. Each theme is informed by the others and the inter-linking of the six themes' inputs and outputs will drive the outcomes and impacts of future energy systems.

INDEX TERMS Cyber-physical system, energy storage, future energy system, grid digitalization, interdisciplinarity.

I. INTRODUCTION

THE world is now in the throes of an energy transformation, driven by the transition need from fossil fuels to sustainable energy. For example, 10% of eastern Australia's traditional generation has closed since 2012, and more than half of the existing 24 coal fire power plants will soon be older than 40 years, which will accelerate the decommissioning process [1]. By 2050, Australian consumers will control more than 25% of electricity system investment decisions and generate more than 35% of all electricity.

As this transition has already commenced, electricity would be the primary energy carrier, but the existing electricity systems are so fragile that could lead to negative consequences. For instance, the 28 Sep. 2016 state-wide blackout in South Australian, where 51% electricity demand supplied by wind power prior to the event, clearly illustrated the catastrophic impact of uncertainties from renewable energy [2]. The 23 Dec. 2015 cyber-attack on Ukrainian regional electric distribution network resulted in power outages that affected approximately 225,000 customers for several hours, which manifests the vulnerability of cyber-physical electricity system [3]. In 2021, the severe winter storm resulted in Texas power crisis with blackouts across more than 75% of the state and the incurred damages were as high as $195 billion [4]. Other consequences include soaring prices and delays to emission reductions. These issues are global, and solutions could benefit Organisation for Economic Co-operation and Development (OECD) and developing nations, particularly the 1.3 billion people currently living without access to electricity.

In the past, massive economy of scale ensured that electricity was affordable, and simple system design ensured that electricity was reliable. However, sustainability was not prioritized in the traditional system. The energy systems of the future will be vastly different from the past. The transformation of global energy systems from fossil fuels to renewables will be enabled by a means to efficiently, stably and affordably distributed electrical power from many sources and storage points to houses, factories, buildings and transport systems. The future electricity systems are expected to be dominated by new technologies and business models, increasingly digital and highly complex, mainly from the following aspects:

1) increasingly variable as the penetration of renewables rises;
2) increasingly distributed as homes and businesses adopt new technologies;
3) increasingly electrified as electric vehicles become popular; and
4) increasingly fused with a variety of interdisciplinary sectors such as social, political, economic, and regulatory areas.

To address the above trends, true systematic thinking is required. The success in energy transition requires revolutions on the technical side as well as on other aspects engaging stakeholders. The existing engineering-based research (e.g. [5]–[7]) on future energy systems mainly focuses on providing the technical solutions, which could devalue the impact of interdisciplinary factors from social and legal aspects. In the meantime, pure social/legal research (e.g. [8]–[10]) may lack the fundamental understanding of the inherent constraints in engineering problems. In this situation, there is a research gap in investigating the multiple disciplines involved in energy system development, which will be the focus in this paper.

To fill this gap, informed by the cutting-edge technologies and research, we envisage the interdisciplinary prospective of digitalized future energy systems (DFES) to future-proof global electricity systems, ensuring secure, reliable, affordable, sustainable electricity for economic advancement. The success of the future energy system hinges in six key aspects:

1) Being able to store energy and, by doing so, smoothen the intermittency of renewable energy, balance out supply and demand, use excessive renewable energy and connect primary and secondary energy sources.
2) Being able to manage a very large fleet of electric vehicles (EV) including hybrid, battery and next generation fuel cell EVs, which join up the silo between energy and transport so that the grid can cope with, and so that both transport and energy infrastructure are built efficiently for the second largest emission sector – transportation sector.
3) Creating robust physical interconnections across the grid to cope with the closure of coal-fired power stations, and to accommodate high penetration of intermittent renewable energy and distributed energy resources (DER), while maintaining system security and reliability.
4) Designing open yet secure cyber infrastructure for intelligent energy monitoring, control, trading, and stakeholder engagement, so as to manage cyber security and disaster risk.
5) Building a socio-political-economic framework that supports system complexity, renewable uptake and consumer/prosumer choices.
6) Investigating the driving role of policy and regulations for energy sustainability and security in future energy systems.

The above six aspects cover interdisciplinary considerations and they are naturally interrelated. For instance, market design, policy, regulations, legal processes and politics should keep up with advances in technology, and energy technology choices have multi-generational implications for people and economies. In this paper, the six aspects are summarized into six research themes, from which we propose an interdisciplinary DFES template in the sense that "the whole is greater than the sum of the parts" to shape the future development of digitalized energy systems. This template is expected to provide a benchmark reference for energy system research and development.

The remaining of this paper is constructed as follows: Section II provides an overview of DFES and elaborates the proposed DFES template; Section III-VIII presents the topics in each research theme; Section IX suggests potential interdisciplinary research opportunities and methods; and Section X concludes the paper.

II. OVERVIEW OF DFES

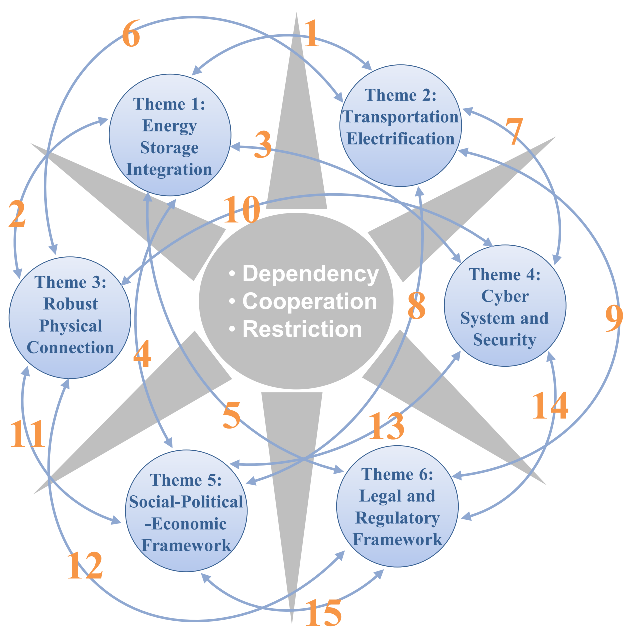
A. THE ENERGY SYSTEM TRANSITION

In the past, the electricity was delivered through one-way flow where the electricity is generated from a few large, stable power stations, transmitted/distributed to the customers through an analogue grid, and only few market participants are involved.

In recent years, many countries have announced their long-term renewable targets for the future energy systems to overcome the current climate challenges. For example, US has announced the American target of achieving 50% of clean power generation by 2025 [11]; some even more ambitious goals such as the global 100% clean and renewable roadmap [12]. To incorporate the ambitious renewable targets and the global sustainability trend, the conventional energy systems must undergo dramatic transformations and upgrades.

Future energy system aims to maximize the harvest from renewable sources, such as solar, wind, wave, and biomass. In the meantime, despite its potential risks, nuclear energy has also been used as clean energy in some countries, such as France and Ukraine. Due to the natural resource scarcity and the high cost of other renewable energy sources (RES), the share of nuclear power would not be reduced in the short term [13]. In this situation, technological reinforcement in nuclear safety and waste disposal are also important in future energy transition.

Renewable energy system requires efficient accommodation of renewable energy to meet the load-side demand. For these purposes, digitalized energy systems are designed to enable two-way electricity flow. The electricity power is generated from many new distributed and variable sources in both generation and distribution systems. Energy storages are widely deployed to accommodate the variation of renewables.



Interaction Scenarios and Classification (D – Dependency, C – Cooperation, R – Restriction):

1. Theme 1&2
- battery energy storage serves as the energy source to drive EVs (D)
- EVs act as mobile energy storage in power network (D)

2. Theme 1&3
- energy storage improves physical system robustness (D)
- P2G technologies connect power and gas networks (C)

3. Theme 1&4
- cyber system enables energy storage integration and control (D)

4. Theme 1&5
- policies support and constrain energy storage integration (C, R)
- energy storage participates in energy market (D)

5. Theme 1&6
- comply with regulations for energy storage (R)
- regulations are based on the working principle of energy storage technologies (D)

6. Theme 2&3
- EVs are improves physical system robustness (D)
- V2G technology connects energy and transport systems (C)

7. Theme 2&4
- cyber system enables EV integration and control (D)

8. Theme 2&5
- policies support and constrain wide use of EV (C, R)
- EVs participates in power market (D)

9. Theme 2&6
- comply with regulations for EVs (R)
- regulations are based on the working principle of EVs (D)

10. Theme 3&4
- incorporate to build CPS (C)

11. Theme 3&5
- policies are the basis for physical connections (D)
- trade-off of economy and robustness in system planning (R)

12. Theme 3&6
- regulations support physical system robustness (C)
- regulations are based on the laws of physics (D)

13. Theme 4&5
- policies support and constrain cyber system development (C, R)
- cyber system improves energy market efficiency (C)

14. Theme 4&6
- comply with regulations for cyber security (R)
- regulations are based on the working principle of cyber technologies (D)

15. Theme 5&6
- regulations are based on the social and economic needs (D)

FIGURE 1. The interdisciplinary DFES template and interaction scenarios.

The electricity is transmitted and distributed through a deeply digitalized network with consumers, prosumers, aggregators and many other new players acting as market participants.

B. PROPOSED DFES TEMPLATE

To emphasize how digitalization could benefit and constrain the energy system development, the DFES is presented under an interdisciplinary template where six key research themes are raised in a sense that "the whole is greater than the sum of the parts". The six key research themes are:

Theme 1 (Energy Storage Integration): Energy storage is essential to the energy transition. Integrating energy storage solutions will help to solve many issues related to the intermittency of RESs and create links between electricity and other energy networks.

Theme 2 (Transportation Electrification): Electrification of transportation is the next major transition towards emission reduction, and the electricity grid needs to cope with the integration of a very large fleet of EVs without impacting the reliability of electricity supply, if not enhancing the efficiency and resilience with advanced EV charging strategies.

Theme 3 (Robust Physical Connection): The laws of physics require electricity supply and demand to be balanced at all times, at all locations of the grid. Robust physical infrastructure is needed across the grid to facilitate the adaptive closure of coal-fired power stations, and to allow the vast integration of intermittent RESs and DERs without compromising system reliability.

Theme 4 (Cyber Systems and Security): Robust cyber infrastructure is to create open yet secure cyber connections across the electricity systems, which involves advanced information and telecommunication technologies, sophisticated software, data analytics and artificial intelligence to design the cyber architecture of a real-time energy system. This could enable supply, storage and demand to be orchestrated to act in unison, for the benefit of grid affordability and stability, and could counteract the intermittency sources.

Theme 5 (Social-Political-Economic Framework): Along with the advancement of digital technologies in Theme 1-4, factors from other disciplines can pose cross-disciplinary challenges to the digitalization of future energy systems. The potential constraints include the unsupportive policies, lack of technology standards, inappropriate electricity market and tariff design, social privacy concerns, etc. There is a pressing need to develop new socio-political-economic framework to deal with these issues.

Theme 6 (Legal-Regulatory Framework): The deployment of digital technologies can be hindered by the legal infrastructure and the outdated regulation. The lack of a clear legal structure limits the exploration and exploitation of customer and DER data. The outdated regulation tends to offer more benefits in network infrastructure investment rather than the potentially cost-effective alternatives in grid digitalization. The legal and regulatory environment is complex, and the reform in these areas is practically regional (e.g. specific to different countries) and time-consuming. However, the potential implications of such reform are global, which calls for a more efficient legal-regulatory framework to support, accelerate and sustain the energy transition.

As indicated by the arrows in Fig. 1, each research theme in the template is informed by the others and the interlinking of the six research themes will drive the outcomes and impact of the entire system. We categorize their interactions into three dimensions, namely dependency, cooperation, and restriction:

TABLE 1. Summary of cutting-edge energy storage technologies.

Technology	Pros	Cons	Applications	References
P2G/P2L	- High energy efficiency - Large capacity - Low transportation cost	- High investment cost	- accommodate surplus renewable energy - voltage regulation - Synergy with gas/heat networks	[14]-[17]
Hydrogen	- High energy density - High energy efficiency - Large capacity - Low operation/maintenance costs - Light weight - Remote installation	Implementation challenges: - Low temperature - Safety risks - High storage costs - Power management	- accommodate surplus renewable energy -Large-scale long-term energy carrier	[18]-[22]
Supercapacitor	- Long cycling time - High cycle efficiency	- High self-discharge rate - High capital cost - Safety risks	-Short-term energy storage - Uninterruptible power supply - Size and cost reduction for power electronics devices - Intermittency mitigation - Complement slow-response energy storage - Energy buffer	[23]-[25]
Compressed air	- Fast construction time - Low investment costs - Long service life - Small geographic restrictions - High reliability	- Demand on underground geology	- Large-scale energy storage - Accommodate excess renewable energy - Combined cooling, heating, and power system	[26]-[31]
Virtual energy storage	Fast response High ramping rate Flexible Low capital cost	- Market risks - Difficulties in coordinating heterogeneous resources	- Energy management - Enhance power quality - Enhance distribution network resilience - Ancillary services	[26], [32]

- Dependency: The dependency means that the research in one theme can have impact on the technology development in other themes, which will influence the revolution of the entire system. For example, the transport electrification in Theme 2 highly depends on the energy storage technologies in Theme 1 as battery storage serves as the prerequisite for transport electrification. The making of policy in Theme 5 and the enacting of regulation in Theme 6 are based on the knowledge of physical laws from the other technical themes.
- Cooperation: For multiple themes with a common goal, cooperation means more benefits could be gained through sharing and mutual assistance. For instance, the energy storage techniques in Theme 1 are integrated into the robust physical network in Theme 3 to achieve the multi-energy system. The physical infrastructure in Theme 3 and cyber infrastructure in Theme 4 are incorporated to establish a cyber-physical system (CPS).
- Restriction: The restriction means that research and development in one theme limits and/or constrains the actions in another theme. Some examples are the restrictions from energy policy (Theme 5) and regulations (Theme 6) on technology developments in other themes. If the existing restrictions are well coordinated a common goal, such as achieving a safe and efficient energy transition and meeting renewable targets, such interactions would be mostly positive and valuable from an integral view.

In the DFES context, the 6 research themes are integrated and the above 3 dimensions broadly exist in the interactions among the themes. An efficient and resource-saving energy transition requires an overall DFES planning with full coverage of all 6 themes and coordinating their interactions. Specifically, compared to infrastructuring for each theme separately, building a common cyber platform that supports all different applications would avoids excessive investment and increases overall efficiency. Considering the social and legal aspects of DFES engages more stakeholders, coordinating the technical development and legal approval can increase the efficiency of project management, which thereby helps maximize the social benefits delivered from engineering side. Overall, by understanding and handling the research themes and their relationships, the resulting synergy effects will give rise to the effect of "whole is greater than the sum of the parts".

III. THEME 1: ENERGY STORAGE INTEGRATION

In energy system digitalization, energy storage plays a key role in improving system flexibility, economy and security. This section presents five energy storage technologies that see great potentials in DFES. A summary of each energy storage technology is given in Table 1, including their names, pros, cons, applications, and related literature.

A. CHEMICAL ENERGY STORAGE

Chemical energy storage is a promising long-term storage solution for excessive renewable energy since the energy density of the chemical bond is unrivaled. Chemical energy storage typically includes power-to-gas (P2G) and power-to-liquid (P2L). P2G technology refers to converting renewable electric energy into storable and usable gas, such as methane (i.e. synthetic natural gas) [14], whereas P2L technology stores electricity in the form of methanol. Methane and methanol synthesized from CO2 and hydrogen can be produced on a large scale without significant difference in production costs. The stored gas/liquid could be combusted in gas turbines for immediate electricity supply or transported to the desired locations for future gas/liquid-to-power conversion [15].

The potential benefits of P2G/P2L technology penetrate different phases of renewable energy systems [16]. At the generation side, P2G/P2L can improve the flexibility in energy shifting to tackle electrical power variations and enhance energy decarbonization. The transmission side benefits include participating in ancillary services, facilitating RES integration, and co-managing electrical and gas networks. The distribution network is facilitated by deferring infrastructure upgrade, reinforcing voltage regulation, and enabling synergy with other networks such as gas and heat.

Despite the above benefits, the P2G/P2L technology is rather costly and requires major advances in economics and efficiency to attract worthwhile investments. The development of modular components to obtain different sized P2G systems can be a systematic approach for cost reduction and efficiency enhancement [17].

B. HYDROGEN STORAGE

Hydrogen as an energy storage medium has drawn great attention from academic and industrial sectors over the past decade, mainly motivated by the unused surplus renewable energy from energy systems. The existing electrolysis technologies could deliver hydrogen at 25 bar with an electrical efficiency of 70% [14]. Future research would target at >75% electrical efficiency of electrolysis. When the supply of renewable energy falls below demand, the stored gas will be burned to generate electricity [18].

Compared to conventional deficient battery storage, hydrogen storage shows several advantages, such as high energy density, high energy efficiency, large capacity (typically more than 100GWh), low operation/maintenance costs, and light weight, which breaks the capacity bottleneck in energy storage industry and greatly expands the applicability of excessive electricity [19]. Moreover, hydrogen storage is available for remote installations. For example, for offshore deep-sea renewable energy, the stored hydrogen can be collected and transferred to the mainland via shipment without the need of long-distance transmission [20]. All the above merits demonstrate the great potential of hydrogen storage as a new type of large-scale long-term energy storage technology.

In recent years, hydrogen storage has been deployed in the forms of direct combustion and hydrogen fuel cell [21] and has become attractive energy carrier in the fields of energy system, transportation, and aerospace [22]. Though, provided that hydrogen storage technology is still at its initial research and development stage, its broad application is limited by a series of implementation issues, such as low temperature, safety, storage costs and power management. Further investigations on its potential applications are also imperatively needed.

C. SUPERCAPACITORS

Supercapacitors (SC) integrate the characteristics of traditional capacitors and electrochemical batteries, which significantly improves the capacitance and the energy density of conventional capacitors, thus enable compact designs. The most important features of SCs are the long cycling time and high cycle efficiency, but high self-discharge rate and high capital cost [23], making SCs more suitable for short-term rather than long-term energy storage applications. Some examples of industrial applications of SCs are uninterruptible power supply for critical loads, intermittency mitigation for RESs, and energy buffer for adjustable variable drives [24].

For SCs to be deployed across the entire system, research is needed to further increase energy and power densities, reduce costs and ensure high safety. Research on structural supercapacitors can promote small and lightweight energy storage, which will benefit electric vehicle industry. These composite materials can carry structure loads while storing electro-chemical energy, which could enable significant volume and mass savings of energy storage systems (ESS) if designed with sufficient structural and energy efficiency [25].

D. COMPRESSED AIR ENERGY STORAGE

Compressed air energy storage (CAES) as a thermodynamic technology is mostly connected with renewable energy sources to accommodate excess energy. During the charging period, the renewable energy is used to compress air and store it in a high-pressure vessel, and the compressed air is preheated and expanded in turbines to discharge electricity [26]. Compared with other large-scale energy storage technologies, CAES is more advantageous in its fast construction time, low investment costs, long service life, and high reliability [27].

Serving as a large-scale energy storage technology, only two commercial CAES plants have been built in the world: the 290MW Huntorf CAES plant in Germany and the 110MW McIntosh facility in US [28]. The reason of such scarcity is that its demand on suitable underground geology [29]. The CAES systems are then further developed into small scales that are more suitable for applications in distribution level [30]. A mainstream application is to integrate small-scale CAES systems into combined cooling, heating, and power (CCHP) system to improve energy conversion efficiency [31].

The current research efforts have been made mainly on the theoretical enhancement of CAES and CCHP, such as improving energy and energy efficiencies, optimization in design and operation. To integrate into DFES calls for raising the practical values of these technologies, include reliable modelling of CAES for energy system studies, evaluation and validation of practical performance, and attractive policy making to encourage technology implementation.

E. VIRTUAL ENERGY STORAGE SYSTEM

Managing users' electricity demand can shift and smooth energy more cheaply than installing a battery. A virtual ESS (VESS) aggregates a cluster of DERs as a single high-capacity ESS with lower capital cost [26]. Such VESS is the key to energy affordability and reliability and could help to improve power quality, yet it is likely to be under-utilized and could create negative impacts on the grid. The research in VESS needs to focus on creating a framework to identify and control devices, and further building system models, market models and methodologies to allow devices to be properly incorporated, which encourages the following development:

1) Intelligent residential energy management techniques, using stochastic programming to address supply uncertainties so as to optimally schedule a single building's energy resources and manage residential communities.
2) Decomposed Virtual Power Plant (VPP) energy management technology, to aggregate geographically distributed energy resources to participate in grid-level markets. A generic energy management framework is needed to decompose the decision-making of the VPP. Uncertainties stem from RESs, market price and load demand also need to be carefully handled to realize practical deployment of VPP [32].
3) A new Micro-Virtual Power Plant (Micro-VPP) concept that aggregates DERs to sell energy to multiple end users, rather than to the grid-level market. Developing optimal bidding strategies can support Micro-VPP decisions in transactive grids.
4) Batteries to enhance renewable energy uptake at the distribution network while supporting economic benefit of end users and enhancing the supply quality and resilience of the distribution network services.

IV. THEME 2: TRANSPORTATION ELECTRIFICATION

Considering the research in EVs ties with battery storage and the uptake of EVs will link electricity to mobility [33], the knowledge, theories, and tools are still in silos. Therefore, DFES calls for a new generation of simulation and analysis tools that can address various aspects in transport electrification.

A. TRANSPORT BEHAVIOR

The transport behaviors of EVs are similar to traditional fuel-based vehicles in their multi-faceted transportation needs and the compliance of traffic rules and regulations. However, there are unique concerns on the convenience of EVs in terms of availability of charging facilities and the endurance of batteries, which could greatly reduce travel efficiency and impair user experience [34].

The transport system is required to consider the characteristics of EVs and ensure sufficient efficiency in terms of mobility and planning. It is essential to improve the charging infrastructure to ensure the convenience of charging services and promote the connection of charging facilities from various suppliers. It is expected to achieve an equilibrium between the transport and charging behavior of EVs, which should represent a situation where EVs on road can attain enough energy to reach their target locations with minimum amount of time.

B. ELECTRICITY SYSTEM BEHAVIOR

The future deployment of EV has co-effect on the operation of transport and electricity systems. Significant EV adoption will boost the load demand, and the randomness of EV charging/discharging behavior will bring uncertainty to the electricity systems, which calls for new system simulation tools that can model the likely electricity demand from charging EVs across the network at a high fidelity of time with new simulation approaches that extend existing frameworks [34].

The energy storage allows users to have flexibility in charging behavior, which makes EV a flexible and controllable energy resources, especially for a fleet of EVs. The vehicle to grid (V2G) concept has recently made charging/discharging control possible [35]. This means that the EVs can be regarded as mobile energy storage facilities to benefit the grid. Smart vehicle charging strategies can help reduce the peak load to alleviate the need of network augmentation, reduce generator start-ups for lower generation costs, and participate in frequency/voltage regulation and spinning reserve to enhance power transmission reliability [36]. Reasonably coordinating EV battery control and variational RES generation allows electricity systems to accommodate more intermittent energy, which further promotes grid decarbonization.

C. MARKET BEHAVIOR

The commercial development of EV also brings about enormous economic values. Optimistically, future wide use of EV means a huge increase in sales, which not only promotes the revolution of the entire automobile market, but also drives the further development of various related industries (e.g. solar highway, batteries, and automated driving). However, so far, the transportation electrification is not smooth due to insufficient facilities, high price and uncertain quality [37].

Promoting the commercial development of EV market requires the efforts from all the government, EV manufacturers and power utilities. Firstly, the government actively promotes the construction of efficient charging networks, improves EV related facilities, and accelerates the planning and establishing of EV charging grids. Consumers are also stimulated by financial subsidies and tax rebate. Secondly, manufacturers can use trade-in and provide after-sales services (e.g. free battery replacement) to stimulate consumption. Thirdly, power utilities can expand the power grid infrastructure in response to the increased electricity load from the integration of EV, and in the meantime, develop new power transmission and distribution technologies, such as distributed generation, energy management, demand response, energy storage, to ensure sustainable and economical operation of power systems.

D. TRANSPORT INFRASTRUCTURE FUNDING

At present, EV is still an emerging industry, and its convenience of use has been greatly constrained by the insufficient EV-related facilities. Petrol taxes have served as the major funding for transport infrastructure for many years [38]. However, in DFES, significant EV share would have huge implications on petrol taxes. Therefore, new financial supports from fiscal and taxation policies are needed for electrified transportation. Replacing petrol tax with congestion pricing [39] is also envisaged to fund the transport infrastructure.

Transition towards electrified transport system requires the government to give full play of regulatory policies, make full use of existing resources, and efficiently use financial funds for transport infrastructure investment. Moreover, due to the huge amount of required capital, the traditional way of relying on government investment has been limited by its long recycling period, low rate of return, and difficulty in attracting social investment. Establishing a distributed and efficient financial model and broadening the financial income are essential to improve the profitability in EV industry.

E. CHARGING INFRASTRUCTURE LOCATION AND OPERATION

The reasonable charging facility planning and operation can provide efficient charging services for EV [40], [41]. This could be implemented through three stages – charging facilities plan, charging path optimization, and charge/discharge control.

The planning of charging facilities should reflect the goal of rapid charging, generalization of charging, smart charging and high-efficient power conversion. In order to optimize the charging path and the control strategies, the EV, the transportation network and the distribution network must also be managed coordinately. The following are highlighted for optimizing the charging path:

- Reasonably controlling the number of EV for each charging facility at each time period, aiming to shorten the waiting time and improve the charging efficiency of the facilities.
- A charging navigation system to satisfy users' needs while avoid EV congestion at specific charging facilities [42].
- An intelligent electricity dispatch system to optimally allocate the charging facility loads in real-time based on the power network structure, so that the time and space distribution of load can be more reasonably managed.

V. THEME 3: ROBUST PHYSICAL CONNECTION

Moving from a "few to many" to a "many to many" supply chain introduces new load types and exponentially increases the complexity of load composition. The digitalization of future energy infrastructure would lie in the following areas.

A. DATA-CENTRIC NETWORK MONITORING AND MODELLING

Accurate modelling of the physical electricity network is the primary step before other analysis. Thanks to the advancement in sensing and communication technologies, real-time monitoring of energy network becomes possible. At high and medium voltage levels, the wide deployment of phasor measurement units (PMU) and micro-PMUs is envisaged in future power networks to capture the network states in a time-synchronized manner. Such facilities enable real-time monitoring of RES and load variations, making future electricity network situation-awarded. This calls for real-time security assessment and control tools for more reliable system operation [43]. Smart meters and the advanced metering infrastructure (AMI) at the low voltage end is capable of trasmitting user consumption data to the utiliites, which provides great opportunities to comprehensively understand and model the electric load behavior in a non-intrusive way [44]. In future energy system with end users actively participating in the energy market, the appliance-level non-intrusive load monitoring and modelling provides fine-grained demand side data, which is crucial for many applications such as demand response, energy storage integration, and renewable integration.

B. ENERGY SYSTEM OPERATION AND PLANNING

In a carbon-constrained world, new challenges are created for DSO, which drives the need for enhanced methods and tools for the secure and efficient operational planning of DFES. This calls for a transition of optimization approach from the conventionally deterministic towards a more explicitly stochastic way. Moreover, in the future environment with temporally coupled characteristics of various new technologies, such as the centrally dispatched storage and the time-flexible demand, innovative multi-stage mathematical programming is needed to economically and efficiently dispatch and control DERs to achieve system balance. More complete, accurate, integrated and co-optimized models are needed to suit efficient and faithful valuation and pricing.

Long-term electricity system planning targets at finding optimal generation and transmission investment plans to replace retiring equipment, reinforce existing network, and feed on growing demand. One example is the Australian retirement plan of the aged coal-fired power plants, which creates a perfect timing and opportunity for widespread renewable integration. Such long-term planning involving equipment retirement and upgrade is a dynamic problem in nature, which is distinct from the static planning that optimizes the network constructions in a single snapshot [45]. In this situation, dynamic investment planning in multiple time scales can determine the optimal long-term roadmap. For future grids with highly coupled components and bi-directional power flow, co-planning of generation, transmission and distribution systems could provide a more integral and cost-effective view.

C. ENERGY SECURITY/RESILIENCE

The intermittent RESs and volatile demand-side activities inject more uncertainties to the grid, which requires the systems to fast react to unintended security events. Compared to conventional offline slow-react optimizations, online and real-time decision-making are beneficial to maintain reliable system operation under increasing uncertainties. Under data-centric infrastructure, data-driven intelligent techniques have been identified as powerful tools to achieve the real-time security service, given the high complexity of the system and the computational difficulties in modelling the physics behind the complex system dynamics [46]–[49].

To make this step further, the majority of worldwide electrical utilities have identified the necessity of enhancing systems' resilience on extreme weather threats driven by climate changes [50]. Deploying DERs, AMI, communication and control technologies at the distribution level aims to construct self-managed, fast-acting and potentially more controllable distribution systems, which plays a key role in providing resilience to the external disturbances. Generating, storing, and managing energy in a locally decentralized manner without the need of long-distance transmission also helps strengthen the network resilience against disasters and enables the ability of faster and more efficient emergency management. Moreover, self-healing has been identified as an important feature, which relies on preventive and/or corrective control actions to handle insecure situations [51]. Its objective lies in minimizing service disruption through the deployment of a series of data-driven technologies that support data acquisition, decision-making, interruption prevention, dynamic power flow control, and fast energy service restoration [52].

D. CONTROL/COORDINATION OF DISTRIBUTED ENERGY RESOURCES

In the transition toward an energy system that increasingly relies on DERs, such as energy sources, controllable loads, batteries and EVs, appropriate control/coordination of numerous DERs will be crucial to handle the variability, unpredictability, stability, and complexity in the system. This coordination is a decentralized and large-scale problem that must be solved in real-time, which is substantially different from conventional centralized control on a small number of units. Consensus-based distributed control methods and reinforcement learning techniques [53] could be effective approaches to achieve optimal interaction and coordination of future massive number of DERs. These methods do not rely on model prediction and can make optimal control decisions in real-time. Multi-stage scheduling and robust optimization algorithms would also be explored as mathematical basis for short-term planning and risk management. Consumer/prosumer behaviours in device control and demand response will also impact physical grid operations and necessitates the understanding of consumer/prosumer's social behaviour.

VI. THEME 4: CYBER SYSTEMS AND SECURITY

The cyber system of DFES acts as the key in grid digitalization to enable distributed control and communicate in a network penetrated by RESs and DERs. By deeply integrating cyber and physical infrastructures, a DFES will be formed up as a CPS that transforms the energy sector from a conventional high-voltage-dominated system into a low-voltage self-organizing, scalable, active customer-centered system [54]. This section envisages the secure cyber systems in DFES.

A. CYBER-PHYSICAL INFRASTRUCTURE

The CPS is a system that combines and coordinates the internet and physical energy system elements, which covers all the domains including energy generation, transmission, distribution, and utilization [55]. In DFES, the three core technical fields supporting the cyber-physical infrastructure are IoT-based system for ubiquitous computing, blockchain-based system for secure and distributed data processing, and cloud-based system for multidimensional service delivery, which collaborate to form the backbone of the cyber infrastructure and support the operation of the physical infrastructure [5].

In CPS infrastructure, the distributed devices are connected via a cross-layer framework where the communication burden faced by the networks are constantly escalating. To enable standard communication link between heterogeneous devices and systems, CPS Interconnection Protocol (CPS-IP) is widely used, which is designed for special-purpose CPS systems which requires global regulation and performance assurance for cyber-physical interactions. Distributed applications also require communication protocols in different network domains. In the home area network, Zigbee and Z-Wave are currently the main smart home network standard protocols [56]. In the neighborhood area network, wifiAware [57] is a neighboring device discovery protocol. In the wide area network applications, distributed networking protocol 3.0 (DNP3) and Modicon communication bus (ModBus) are usually used [58]. The following international standards are commonly applicable to be complied with by the communication models [55]: IEEE 802, IEC 61850, and IEC/TS 62351.

CPS has been applied to facilitate the following areas:

- Energy storage integration: cyber technologies enable energy storage systems to be flexibly managed and regulated, so that heterogeneous energy storage devices can be controlled and coordinated to fit many applications in the physical layer, such as energy management and regulation services. By fully spelling the strength of energy storage, its charging/discharging flexibility can help achieve multi-scale energy balance and support multi-energy conversion.
- Transportation electrification: CPS aims to ensure both ''real-time'' and ''high effectiveness'' in V2G. Since EVs act similarly to DERs, most protocols and standards of DERs also apply on EVs. Moreover, ISO 15118 [59] is an international standard specifically for V2G

communication interface. Based on the CPS, decentralized control strategy allows the EV users directly choose their charging schedules, which more focuses on user convenience, require less computational complexity, and more appropriate for real-time implementation. It considers randomness in charging stations and vehicle mobility with low computation and communication needs, which can effectively alleviate the burden of handling enormous data from EVs and charging stations in future EV-enriched systems.

- Robust energy-information flow: Due the coupling of energy and information flow, there are risks of propagating disturbances across energy and information spaces, especially in extreme operating events. This raises the CPS resilience threats. In this situation, intelligent dynamic routing [60] is an effective strategy for information transmission, which aims to dispatch the critical information through more reliable route, so as to provide high resilience to network failure in extreme conditions.

B. DATA SECURITY AND INTEGRITY

Provided the needs of communicating sensitive data, in real-time, often wirelessly, from a range of consumer and industrial devices, with low latency, the major vulnerability of CPS falls in its reliability and security. Deploying large number of smart devices and wireless technologies increases the risk of sensitive data being leaked or destroyed during transmission. In the meantime, with the adoption of cloud service, a large amount of data that is generated by energy enterprises and users are accummulated at the cloud end, making secure transmission of data increasingly challenging. Moreover, AMI enables a two-way flow of information between customers and utility. Failure of the protection will seriously jeopardize the privacy of enterprises and customers and affect the deployment of smart meters [61]. All the above challenges require the cyber system to be able to communicate data, often in real-time and wirelessly, from a wide range of consumer and industrial devices, with low latency and high security.

The following technologies could be contributive to enhance data security. 1) Data leak prevention (DLP) is an approach for detecting potential data breaches or ex-filtration and preventing destruction of sensitive data while in use [62]. 2) Secure Multi-Party Computation (SMC) is an emerging data mining technique which is to promote the collaboration between multiple entities in a decentralized way that each entity is unable to obtain any input information from other entities except the final results [63]. Such decentralization of SMC could further evolve into a collaborative computing architecture that protects privacy between a group of distrustful participants and allows utility companies to make operational decisions without revealing meter data. 3) Homomorphic encryption is a new form of encryption which calculates the ciphertext without decrypting it, and thus realizes plaintext calculation [64]. It ensures that sensitive data is operated securely without revealing data information, which fundamentally solves the confidentiality issues when delegating data to third parties. When homomorphic encryption and SMC are incorporated, the cyber system can allow utilities to read and operate meter data without decryption, which promotes the development into a secure wide-area demand response system.

Besides data security, ensuring data integrity is also an essential objective in cyber system development. The methods to defend against data integrity attacks can be divided into protection-based and detection-based schemes. The former tries to alleviate false data injection through identifying and protecting critical meters, which is usually costly and unreliable for large-scale systems [65]. By contrast, the poster exploits anomaly detection techniques to identify maliciously modified measurements. Its data-driven mechanism allows better scalability and well suits future digitalized infrastructure [66].

From the legal perspective, some regions, such as US and Europe, have put into place a series of standards and regulations to protect energy sector from cyber threats. The approaches adopted by US and Europe are in differences but complementary. US tends to issue strict and detailed standards on cybersecurity, such as NISTIR 7628, IEEE C37.240, and IEC 62351 [67]. By contrast, Europe has adopted a more flexible and exhausitve approach generalizing a wide range of cybersecurity issues. For example, an important document is Regulation No 2019/881 [68], which provides the basis of a European framework for the certification of cybersecurity.

C. DATA STORAGE AND PROCESSING

Big data plays an important role in cyber system operation. In the future, the organization of energy resources will transform from a centralized to a distributed structure where the data collected from the monitoring systems can be massive and complicated. Most of the traditional centralized methods for data storage and processing will not suit such big data context and research on distributed data management is necessary.

The data management system is expected to store huge volumes of data in both the cloud and the distributed devices themselves. The distributed storage systems can store data reliably over long periods of time using a distributed collection of storage nodes, which offers the opportunity to process huge amounts of data from an array of internet-connected DERs across the energy value chain. The distributed file storage over the Internet supports not only the storage of distributed data at large data centers but also peer-to-peer data communication and processing [69]. One example is the distributed file system [70] that allows multiple users on multiple devices to share files and resources, and permits individual users to get a local copy of the stored data. These new distributed data storage nodes may require data analytics in both the cloud and the devices to allow real-time distributed decision making. This is impossible with traditional computing, but needs cutting-edge AI technologies such as deep learning and reinforcement learning [71].

VII. THEME 5: SOCIO-POLITICAL-ECONOMIC FRAMEWORK

The social and economic dimensions of energy policy run more deeply than political cycles, and many of the challenges are global. The prospect energy transition requires new concepts and models for analysing the performance of electricity distribution and use, in view of economic and social impacts, to inform consumers, communities, non-government organizations, agencies, governments and industry. Open-source, transparent, easily validated modelling tools will be the key outputs. The expected research involves the followings

A. WHOLESALE MARKET DESIGN

Existing liberalized market mechanisms for power supply are designed on marginal cost theory, which is based on two assumptions: positive marginal costs and the dispatchability of power. However, the intermittent RESs have zero marginal cost and are non-dispatchable in nature [72]. When vast renewable generation is incorporated into the market, both assumptions will be violated, resulting in low and even negative electricity prices. This situation would discourage the investors from entering the market, which can slow down the renewable energy transition. All these concerns foresee a redesign of the market clearing mechanism to reflect the full renewable cost structure, including the high levelized cost of electricity and the near zero marginal cost of production. The new market clearing mechanism should also accurately accommodate both renewable energy and fossil fuel generators. The former emphasizes the environmental value of generation, and the poster contributes to energy system security and reliability.

B. RETAIL TARIFF DESIGNS

Mainly three categories of tariff-based financial policies have been recently implemented over the world. First, European and Oceania countries have established feed-in tariff that credits a fixed price for renewable production regardless of the market price [73], [74]. Second, in US, production tax credit is provided as tariff to support the expansion of wind energy market [75]. Its mechanism is to pay a fixed amount on top of the market price. Third, in US solar energy industry, investment tax credit is available to offer direct subsidy for initial investment [76]. All these tariff designs have strengthened the value proposition of wind and solar power.

On top of those, new retail tariff designs may be required to incentivize new products and services and encourage consumer participation in demand response. New retail tariff designs can focus on how to define the prices within community microgrids and how to distinguish the prices for peer-to-peer supply and locally-generated supply.

C. PRIVACY OF ELECTRICITY DATA

The future digitalized energy systems are envisaged to be operated in an IoT environment. Privacy of electricity data from multitudes of connected energy devices need to be paid close attention. While more electricity data is required for new and more benefits, the leakage of private information could be harmful: degradation of consumer's experience, loss of confidence on products and systems, cyber attacks, economic losses, emotional damage, etc [77]. The grid digitalization has changed the people's views on privacy and the related issues of trust and identity. To ensure consumer choice and protection, a privacy-aware policy framework needs to be developed for new products and services, which aims to balance the benefits and risks perceived by consumers.

D. DSO MARKET MANAGEMENT

Future energy systems require deep fusion of physical system operations and market activities. The distribution system supports the real-time and decentralized control of DERs to ensure continuous and efficient energy supply. Consumers and suppliers are also engaged in decentralized markets that strive towards improved economy, reliability and sustainability of the energy systems. Such coordination is accomplished by energy transactions among parties to pay for their consumed or produced energy [78]. With the development of peer-to-peer transactions, the role of a DSO is to manage the interoperability among entities and DER owners. DSO is typically in charge of schedule, monitor and control the devices in the portfolio, and the remote controller is the key enabler of market operations [79]. Noting that future decentralized market will be impacted by the considerable unforeseen uncertainties from forecasting, generation, demand-side activities, and cyber-physical interactions, developing robust market management strategy for DSO to optimize the benefits of all parties is also pressingly needed for future energy systems.

VIII. THEME 6: LEGAL-REGULATORY FRAMEWORK

Industry reform processes generally progress more slowly than technology and the marketplace require. The deployment of digital technologies in the energy system can be hindered by the outdated local regulation and law in different countries, especially when there is a bias towards capital investments in system infrastructure at the expense of potentially cost-effective alternatives. For instance, in Australia, the energy regulatory and legal environment has become increasingly complex: the Australian Energy Regulator monitors 58 energy retailers and, compared to 2005, regulates >4 times as many energy networks, monitors >4 times as many market participants, and enforces >3 times as many rules and laws. Australia's National Electricity Rules, made under National Electricity Law (NEL), have the force of law and any changes to the NEL must be agreed by all jurisdictions through Council of Australian Governments (COAG). Rule change requests reviews can take up to 2 years before decisions are made and then subject to the legislative process. Finkel's 2017 Blueprint proposed 50 rule changes, of which 49 have been accepted by COAG for review [80].

The review of laws and regulations takes place not only in Australia, but also globally. To innovate the legal-regulatory framework, the legal experts in electricity law and regulation requires to work close with the policy framework development research under Theme 5. This legal-regulatory research must be interdisciplinary: there is no escaping the complex laws of physics that must be understood when designing the rules of law and regulation for the energy market.

IX. POTENTIAL RESEARCH OPPORTUNITIES

The integration of new elements in energy systems, such as energy storage and EVs, are only effective when they are economically feasible, socially beneficial, and comply with regulation. In this sense, interdisciplinary research can help accelerate the energy transition. This section presents potential research topics that involve the interplay of multiple disciplines, and then suggests interdisciplinary research practices.

The potential interdisciplinary research topics are as follows:

- Multi-energy system co-simulation and co-optimization: The development of advanced energy storage and transportation electrification technologies facilitate the ‘‘Internet of Energy’’ concept which aims to incorporate the power, transportation, gas, and thermal systems in a single platform [81]. This vision requires interdisciplinary research across multiple sectors, each of which follows its own policies and regulations, and with different social behaviors and needs. Investigating such complexity first calls for a unified platform with co-simulation and co-optimization ability on all networks. The overarching communication and control protocols/standards are also imperatively needed to enable such ‘‘Internet of Energy’’.
- Autonomous electric vehicles: Autonomous vehicles are the next-generation vehicles that use driverless technologies for transport, which will dramatically change the characteristics of EV integration [82]. One example is that EVs can self-travel and control their charging and discharging behavior to meet various power grid needs. From the economic perspective, the autonomous electric vehicles would result in a totally different business model and can improve the efficiency for the EV aggregator to participate in the competitive power market. How to standardize and regulate the autonomous control of vehicles and the behavior of vehicle owners also needs further investigation.
- 5G communication network: 5G extends and outperforms the current 4G wireless communication technology in terms of higher data rate, wider connections, higher reliability, lower latency, and lower terminal energy consumption [83]. Despite the advantages, applying 5G networks in DFES is subject to communication security and privacy issues. For these reasons, CPS would need new cybersecurity standards and regulations in the 5G context.

In interdisciplinary research, collaboration and knowledge sharing among researchers would be essential. Despite the diversity in background, the common research goal would be put at the center, ensuring all decisions throughout the lifecycle of the research are fit for purpose. Following such logic, a research platform that can engage stakeholders across industry, government, research institutes, and community, would maximize the uptake of research in interdisciplinary areas.

X. CONCLUSION

This paper proposes an interdisciplinary template with six themes to shape the DFES. The six research themes are closely inter-linked and the DFES template is designed such that the ‘‘whole is greater than the sum of the parts’’ to drive the outcomes and impacts of DFES.

Theme 1 focuses on energy storage integration. Various energy storage technologies have been highlighted as potential future-proof solutions to balance supply and demand, smooth the intermittency of renewable energy, use excess renewable energy and connect primary and secondary energy systems.

Theme 2 refers to transportation electrification. The interplay of electricity and mobility introduced by EVs have been investigated, calling for advanced simulation and analysis tools for the joint planning of electricity and transport sectors.

Theme 3 addresses robust physical connection. The challenges involved in infrastructure transformation to suit the energy transition have been explored. To tackle these challenges, future research would be targeted on the data, operation, security/resilience, and control perspectives from both systematic and device levels.

Theme 4 refers to cyber systems and security. Future research on cybersecurity and distributed data storage and processing is expected to realize real-time distributed decision making. The technologies in Theme 3 and 4 can be combined to end up with an efficient CPS for future energy system.

Themes 5 and 6 are interdisciplinary themes to consider the social, political, economic, and legal factors that inevitably promote and/or constrain the technological innovation for future energy systems. The integral impact of these factors manifests the needs of a reasonable social-political-economic framework and a supportive legal-regulatory framework.

Potential interdisciplinary research topics are also provided. These topics focus on multi-energy system, autonomous electric vehicle, and 5G communication network, which are emerging technologies that have the potential to lead future energy system revolution but requires precise interdisciplinary analysis from economic, social, and legal aspects.

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