Beyond Smart Grid—A Cyber–Physical–Social System in Energy Future

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Smart grids (SGs) are electric networks that use innovative and intelligent monitoring, control, communication, and self-healing technologies to deliver better connections and operations for generators and distributors, flexible choices for prosumers, and reliability and security of electricity supply. SGs are a complex cyber–physical system by their very nature, and this has impacted the way energy is generated, transported and used. In our 2016 paper [1], we examined the SG concept in the context of cyber–physical systems (CPSs), and outlined the challenges ahead alongside with fast development of advanced technologies such as Internet of Things, cloud computing, big data and complex networks.

In line with the global movement toward a sustainable renewable energy future to address climate change, we now firmly believe that the very concept of SG is too narrow to reflect what will be needed in the 21st century. The fundamental issue is that the SG concept is deeply rooted in traditional "grid"-based thinking. The whole energy chain can be depicted as in Fig. 1, which consists of basically three phases, namely, primary energy, secondary energy, and end-use energy. The objective of SGs is mainly limited to the secondary energy phase, without sufficiently considering the increasing randomness and intermittency of the primary energy and active prosumer participation in the end use of energy. Furthermore, the impact of general physical and environmental conditions is not considered, let alone the influence of market gaming behaviors that may adversely affect the reliability costs of electricity delivered to consumers.

Traditional power system analysis is based on the assumptions that the primary energy source and the end-use energy usage are invariant and fully controllable [2]. We believe that these boundary conditions are no longer appropriate for dealing with future profiles of the whole energy supply chain, as ever increasing injection ratio of renewable energy and versatile user behaviors, influenced by wide participation of socioeconomic elements, and constrained by various resources, market competition, regulation, environment, and social welfare, will make the boundary conditions difficult to hold. In fact, as shown in Fig. 1, SG's scope is only limited to the green-color-shadowed area mainly concerning the secondary energy phase and some aspects of the primary energy and end-use energy.

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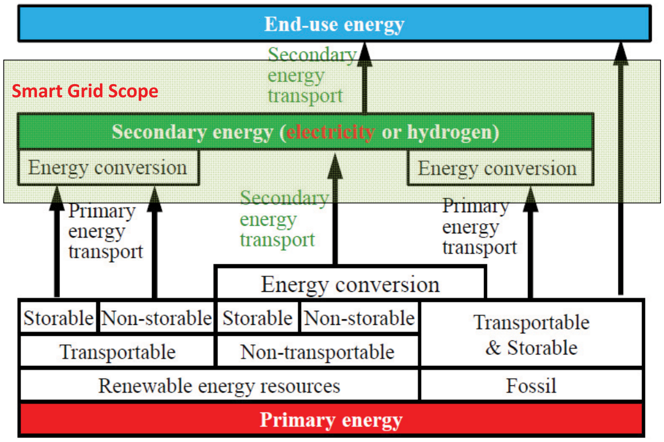

Fig. 1. *Three energy phases and their relations.*

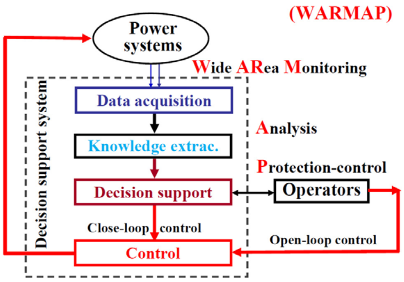

Fig. 3. *System architecture of WARMAP.*

We argue that energy in the form of electricity is still by far the most convenient medium for managing traditional or renewable energy in terms of its transport, storage, and usage. On one hand, electric energy plays a central role in the whole energy supply chain since changing the energy form from electric to nonelectric may not be as effective as using electricity directly, as study has shown that in developed countries, 1% increase of electrification would contribute 3.7% drop of the energy intensity [3]. An outlook from a report by the National Development and Reform Commission of the Chinese Government, shown in Fig. 2 about the landscape of energy end use in China in 2050 [4] (traditional or renewable), further confirms our view. While other nonelectric forms of power are on the increase, electric power will continue to be the dominant form of energy supply. On the other hand, any changes in primary energy and end-use energy significantly affect electric power reliability. In order to ensure the energy safety and security, both primary energy (up-stream) and end-user energy (down-stream) should be taken into consideration.

There has been substantial progress in addressing the limitation of SGs [namely, cyber–physical system in electric power (CPSP)]. Energy systems have evolved through the years from the traditional power systems to SG, and further to CPSs in energy where primary energy and end-use energy phases are taken into consideration. We believe a more holistic (system-of-systems) approach must be taken to deal with future energy system.

Our view is informed by the many years of research and development in China's Power Industry by the first author, Yusheng Xue, and his team in China's State Grid Electric Power Research Institute (SGEPRI), especially the work on the Wide ARea, Monitoring, Analysis Protection-control (WARMAP), which has been designed to detect potential faults and disastrous scenarios and provide prognostic measures to avoid system-wide blackouts in China for many years. WARMAP is enabled by an integrated control structure as shown in Fig. 3.

WARMAP has been serving over 80% provincial and above power grids across China as shown in Fig. 4, making vital contributions to China's energy safety and security.

System-wide blackouts around the world are caused by a variety of factors, including malfunctions of grid components (generators, transmission lines, load buses, communication facilities, etc.), the increasingly stringent constraints of emissions regulations, market volatility [5]. Diagnosis and prognosis for preventing system-wide blackouts requires information and smart technologies at a level higher than the current SG can offer. The WARMAP system has already taken factors beyond the SG environment

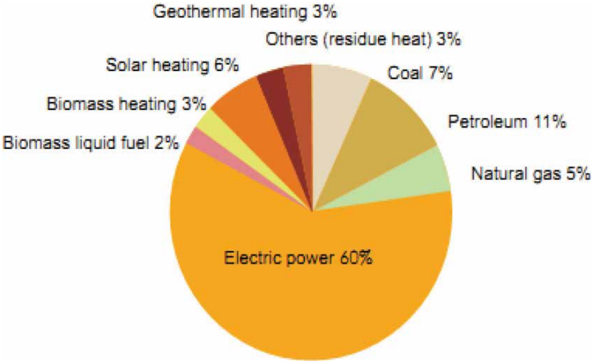

Fig. 2. *Share of end-use energy in 2050 in China.*

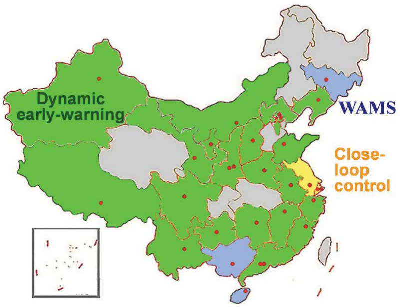

Fig. 4. *WARMAP serving more than 80% of China (green colored).*

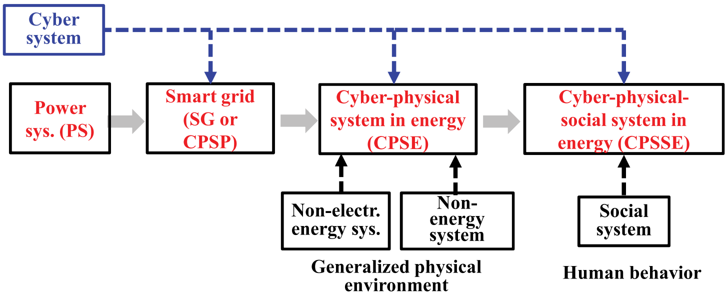

Fig. 5. ***Evolution of energy systems.***

into consideration [6], and serves to illustrate the promise of the holistic (systems of systems) approaches to the SG problems, but we think it has not gone far enough.

Another example is the Zhixin Carbon Index (ZXCI), the first carbon market index in China, which was launched on the Shanghai Environment and Energy Exchange on April 30, 2014. This is an authoritative reference designed by SGEPRI for investment regulation [7].

Further consideration should be given to coordination of various generalized environmental factors [8] and economic, social factors, and human behaviors [9], as well as a hybrid research framework across various disciplines concerned and different time and space scales. This will enable collaborative mining of large data with hidden causal relationships in the complex cross-social, technological, economical, and environmental dimensions.

We advocate for a new concept of "cyber–physical–social system in energy' in which the energy (primary energy, secondary energy, and end-user energy) can be considered in a broader framework in which grid-based thinking (generation–transmission–distribution–usage) is a core but not the whole; and there are other essential factors to be considered, such as strong volatility and intermittent renewable energy sources, transition among different primary energy sources, influence of electric power and carbon markets and their regulation of end-use energy (e.g., electric vehicles), and gaming behaviors of various kinds of participants.

In [1], we elaborated on the key roles of the enabling technologies of Internet of Things, big data, cloud computing, and network science in the SG developments. For cyber–physical–social system in energy, additional enabling technologies will include economics, environmental science, social science, psychology, cognitive science, and political science. These will enrich the cyber–physical–social systems in energy thinking. We see it as a part of the journey from PS to SG, CPSE and eventually CPSSE, as shown in Fig. 5. The driving force induced by interaction between them may be much more powerful than the internal driving forces of information systems, energy systems, and human societies. All these will be critical for a bright cyber–physical–social system in energy future. ■

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