Energy Transition Technology: The Role of Power Electronics

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I. POWER ELECTRONICS IN RETROSPECTIVE

Over 100 years have passed since the invention of the mercury-arc rectifier—the first ever power electronic device—by Hewitt in 1902 [1]. This technology enabled numerous applications, such as the electrification of railways utilizing dc motors. Nevertheless, the modern era of power electronics starts with the introduction of semiconductor devices. Thyristors were first commercialized by General Electric in 1958 and remained the main power electronic device for 20 years [2], [3]. More recent history of high-frequency converters started with the invention of insulated gate bipolar transistor (IGBT) by General Electric in 1983, which resulted in the appearance of commercial products from Toshiba, Fuji Electric, and Mitsubishi Electric in 1985, 1986, and 1987, respectively. At about the same time, research on silicon carbide devices started [5], resulting in a vibrant modern market of power devices available in different voltage classes [6]. All these innovations revolutionized electric energy conversion, resulting in more compact, efficient, and reliable power converters. Considering the electric nature of modern renewable energy sources, power electronic converters have become the backbone of future power systems [7], [8], [9], [10].

The articles in this month's issue provide insight into the most important power-electronics-based technologies for energy transition.

Since the end of the 1990s, numerous attempts have been made to reduce the cost of power converters by using standardized power electronic building blocks [11], [12], [13]. Despite strong backing from U.S. Navy, the initial approach of integrating only basic components for the simpler and cheaper design of power converters did not show much impact due to high variability in application requirements. Recent research shows that power electronic building blocks have been reimagined as application-specific ready-to-use devices integrating power components and application-specific control [14], [15], [16]. For large enough markets, the new approach opens better possibilities for fast deployment of products, owing to their applications-tailored design.

Nowadays, the role of power electronics has shifted from a tool enabling emerging trends to a critical technology for the sustainable development of society. Two main trends support this transition: increased renewable energy generation capacities and electrification of end-use applications, including heating and cooling. Despite a relatively high level of maturity, this field continues active development caused by the emergence of numerous new applications along with the introduction of new wide bandgap semiconductor materials and advancements in the technology of passive electronic components.

II. BACKGROUND FOR THIS SPECIAL ISSUE

The development of humanity requires the steadfast rise of energy used by all sectors of the economy. Rapid industrial growth in the last 70 years is associated with the immense consumption of fossil fuels. As a result, greenhouse gases were produced at a much-accelerated

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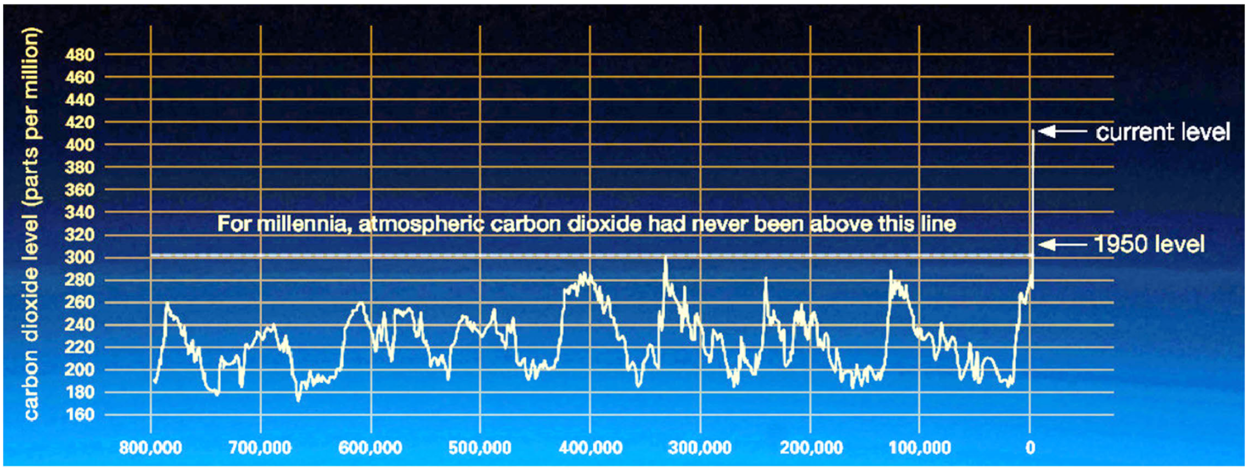

Fig. 1. ***NASA estimate and measurements of CO_2 level (NASA: https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/).***

rate, while deforestation only intensified unfavorable effects on ecology and climate. NASA estimated CO_2 levels for the last 800 000 years and found that its average level steadily rose from the 1950s, as shown in Fig. 1. The world soon realized that fast actions must be taken. First, the Kyoto Protocol of 1992 was ratified by 129 countries until now. The protocol was not just an agreement but a set of targets with legal force behind it. Recently, it has become apparent that actions taken are not enough as CO_2 levels keep rising.

Hence, Paris Agreement was signed in 2016. The agreement does not enforce any legal measures but requires 186 countries to present more aggressive national plans for emission reduction. Apart from the agreement, other national and international plans are setting targets in this area. For example, the European Union sets 2030 energy goals that require a 55% reduction in greenhouse gas emissions from 1990 levels, an increase in renewable energy consumption to 45% of the total energy, and an increase in energy efficiency by 33%.

The recent rise of nonconventional renewable energy sources, such as solar, wind, wave energy, and so on, shows the clear path toward sustainable energy generation. According to forecasts of the International Energy Agency shown in Fig. 2, the renewable electric energy generation is lagging behind the scenario of Net Zero Emissions by 2050. It anticipates the growth in share of renewables from 29% in 2021 to well over 60% in 2030. To support this trend, the annual increase in generation capacities should see a compound annual growth rate of over 12% during 2022–2030, effectively doubling the rates observed in 2019–2021. The two leading nonconventional renewables, namely, solar photovoltaic (PV) and wind, will grow much faster and primarily within electricity generation. The electrical energy share is expected to grow to over 30% from the global energy use.

The rapid growth of electricity share in the world energy mix will support the electrification of the economy. Electrification is envisioned as the main way to a 100% renewable world with zero emission, because all major nonconventional renewables enable zero-emission electricity generation.

Current trends in renewable energy generation show that technology cost reduction is the main driver that will make renewable energy domination inevitable. However, a life cycle analysis (LCA) of environmental impact shows that sustainable energy use is as essential as its generation. A good example: LCA analysis of renewable energy technologies shows that carbon footprint reduction achieved with clean energy generation is set back by pollution from coal-fired factories supplying production lines of renewable energy devices. This was a serious issue for Asian manufacturers, but in the last several years, this trend has been reversed due to the fast deployment of renewable energy plants.

Hence, the electrification of all industrial sectors is on the rise, which will push demand for electric energy much faster than for any other type. From the electrical energy production side, we have new alternatives, such as PV and wind energy, where power electronics play a critical role. But also, the role of power electronics systems is increasing rapidly in the use of electrical energy due to high flexibility and increased system efficiency.

This special issue will address topics of electric energy use after generation based on the framework in Fig. 3.

1) *New Trends in Electricity Generation:* Main factors driving cost down and enabling technologies for PV, wind, hydro and wave, and other renewable energy generation systems. In the last years, droughts have increased in frequency and severity, harming the agriculture industry and hydro energy production. This spotlights opportunities for energy production from wind and sun.

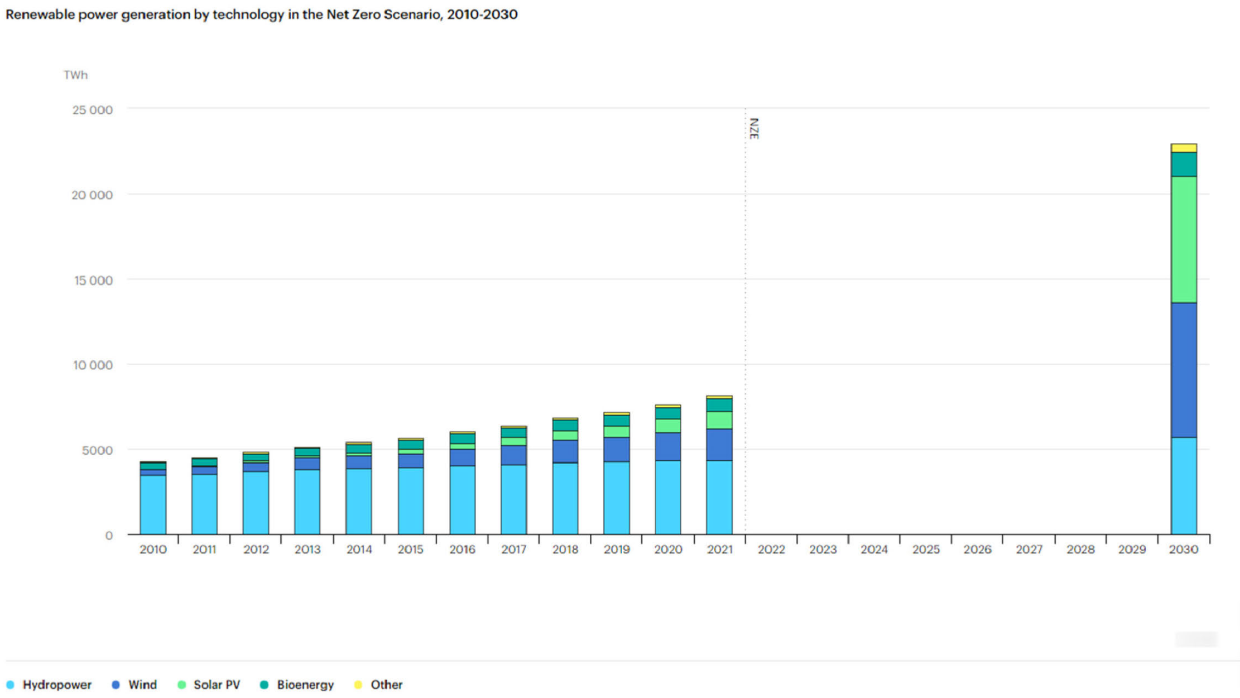

Fig. 2. ***Renewable power generation by technology in the Net Zero Scenario, 2010–2030 (IEA: https://www.iea.org/reports/renewable-electricity).***

2) *Low Carbon Industry:* Carbon footprint reduction of factories through use of more efficient converters, on-site generation, utilization of microgrid concept, and so on.
3) *Transportation:* Technologies for fast and rapid charging for hybrid electric vehicles (EVs), battery EVs, and light EVs have to be supported with efficient power electronics for low-cost charging infrastructure. Also, an efficient power train converter can ensure the best utilization of the energy stored in the battery and reduce the range anxiety of users.
4) *Buildings:* Considering their 40% share in CO_2 emission, future buildings will utilize façade or roof-integrated PV solar panels, and solar heat collects recuperative ventilation and so on. Considering high peak-hour consumption, buildings will need on-site energy storage to avoid overloading future distributed grids. The dc and hybrid dc/ac microgrids are expected to be a superior solution for integrating building energy generation and storage systems with high efficiency and overall resilience compared with that of ac microgrids.
5) Generation, storage, and use of green hydrogen as the new clean energy source.

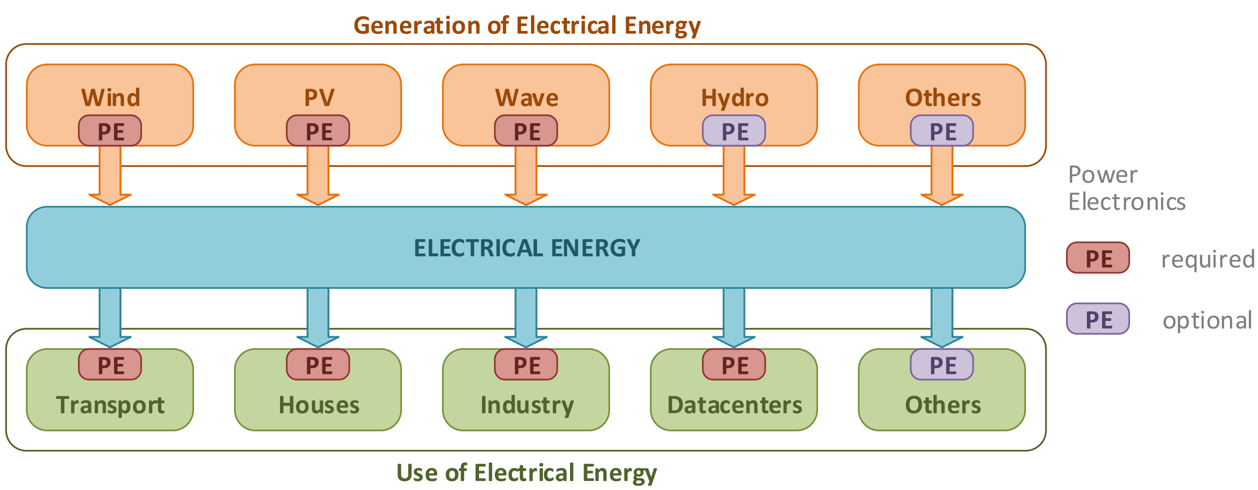

Fig. 3. ***Role of electrical energy in the future electrification of society.***

III. OVERVIEW OF THE SPECIAL ISSUE

This special issue contains five papers solicited from highly recognized experts in their respective fields. They cover the most important power electronics-based technologies for the Energy Transition. We welcome readers of PROCEEDINGS OF THE IEEE to engage in reading the papers to understand better the recent advancements and future challenges on the way to the sustainable future. These articles will find their readers across the wide pool of IEEE members but would be of particular interest to the members of Industrial Electronics, Power Electronics, Industry Applications, and Power and Energy Societies.

Power Electronics Technology for Large-Scale Renewable Energy Generation
by F. Blabjerg, Y. Yang, K. A. Kim, and J. Rodriguez
This article establishes a link to the previous special issues published in PROCEEDINGS OF THE IEEE on renewable energy generation and associated power electronic technologies. It provides the latest statistics and describes the newest developments in large-scale renewable power generation. It explains what power electronic concepts were adopted in this field and how they should be controlled. Also, the authors demonstrate how future challenges will pave the way for the ubiquitous presence of power electronic technologies from the power generation to the end consumer. Hence, it shows how technologies described in the other papers in this special issue are connected in the big picture.

The More-Electric Aircraft and Beyond
by G. Buticchi, P. Wheeler, and D. Boroyevich
Recovering from COVID-19 pandemic, the aviation industry sees considerable growth in travel demand. However, airplanes contribute a substantial part of greenhouse gas emissions. Compared with EVs, the technology of more electric aircrafts faces significant challenges in the full electrification of onboard systems and their reliability. The authors of this article present a historical retrospective of aircraft electrification and an overview of the existing frameworks of aircraft electrification. Special emphasis is given to possible power electronic solutions and associated semiconductor technologies, and to modern concepts of electrical machines and their integration with power electronics. In the end, an outlook based on the NASA Roadmap for aircraft electric propulsion is presented to draw a picture of the most recent advances and future challenges.

Charging Infrastructure and Grid Integration for Electromobility
by S. Rivera, S. M. Goetz, S. Kouro, P. W. Lehn, M. Pathmanathan, P. Bauer, and R. A. Mastromauro
The rapid uptake of EVs resulted in a significant demand for charging infrastructure. This article demonstrates possible charging approaches and architectures, discusses related standardization issues, and explains associated control algorithms. The authors have demonstrated how the advancement of battery technologies and power electronic technology resulted in new challenges and solutions for EV charging. They show how widespread charging infrastructure can influence the power distribution grids and what grid services it can provide. Finally, future challenges, such as nonisolated charging, are discussed. This article would be interesting for both power electronics engineers and power systems professionals.

Grid-Connected Energy Storage Systems: State-of-the-Art and Emerging Technologies
by G. G. Farivar, W. Manalastas, Jr., H. D. Tafti, S. Ceballos, A. Sanchez-Ruiz, E. C. Lovell, G. Konstantinou, C. D. Townsend, M. Srinivasan, and J. Pou
The authors begin with a demonstration of how rapidly increasing renewable energy generation capacities are pushing massive deployment of grid-connected energy storage systems. They explain the pros and cons of available energy storage technologies and provide their key performance indicators. Reading further, you will find in-depth descriptions of applications where energy storage systems are needed and the grid services they can provide. Understanding application requirements is the key to the selection of an appropriate energy storage technology. Based on these fundamentals, authors demonstrate different power electronic solutions, and their real-world examples to better visualize the scale and complexity of the needed power electronics converters. Control of energy storage systems and possible practical limitations are explained to complement the description of hardware technologies. In the end, they introduce emerging technologies approaching commercialization and explain the role of power electronics in their deployment.

Unlocking the Hidden Capacity of the Electrical Grid Through Smart Transformer and Smart Transmission
by M. Liserre, M. A. Perez, M. Langwasser, C. A. Rojas, and Z. Zhou
The power systems are experiencing a shift to high penetration of power electronic converters. This results in numerous challenges related to their stability and reliability, but provides a previously unseen level of power flow control. The authors emphasize the importance of faster adoption of smart transformers instead of traditional transformers at the power distribution level to enable widespread adoption of distributed energy generation. They also explain the practical technological and economic challenges that need to be sorted out first. At the power transmission level, they demonstrate the superiority of the high-voltage dc (HVdc) technology and explain what power electronic solutions can be used to implement these transmission systems. However, they also show what challenges remain in

this field and limit the widespread adoption of HVdc technology. This article demonstrates how power electronics will become the dominant technology in the future distribution and transmission grid. Power systems engineers can find here a one-stop introduction to this topic.

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