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How Decarbonization, Digitalization and Decentralization are changing key power infrastructures

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ABSTRACT

This paper addresses the impact over key power infrastructures of the three main drivers for change of these times: Decarbonization, Digitalization and Decentralization. The three phenomena, according to prominent observers, are affecting all fields of our lives but, in the literature, it is difficult to find an analysis of their impact on electrical power systems. The framework proposed in this paper, based on the main power systems evolution models proposed by CIGRE, uses data from open databases and tries to find out general guidelines for power systems development at a worldwide level. Taking as reference the European and COP21 environmental objectives and beyond, the technological evolution of some key enabling technologies is explored. What emerges is that HV bulk transport links, storage technologies and the so-called digital revolution are taking a leading role in different parts of the world for the development of a deep decarbonization of the electricity sector, of new energy business models at distribution level and of new power distribution architectures.

1. Introduction

Recent analyses from several experts consider the three "D"s, namely Decarbonization, Decentralization and Digitalization as the main drivers for change in these times and in the years to come. These three phenomena appear disruptive in every field, posing a big challenge to stakeholders. The electrical power systems, in particular, are being affected with strongly different management, coordination, resource mix and market models as follows:

a) international and national policies encourage *decarbonization* through low carbon energy generation while supporting the use of renewable energy sources (RES) and efficiency improvement in power generation, transport and use;
b) increased customer participation and increased demand requires *decentralization* of energy supply generating new needs especially at distribution level;
c) urban development and *digitalization* produce new ways to exchange goods and services by new business models based on the paradigm of 'digital business' by peer-to-peer and transparent transactions.

Together with the latter challenges, some other side-changes are also relevant for power systems:

– considering the aging of infrastructures, there is a widespread need for investment in end-of-life grid renewal;
– considering all the new energy resources connected to the grid, there is a need to handle grid congestion (with market-oriented policies);
– market design and regulatory mechanisms are evolving to support the transformation towards equity, access to electricity and lower costs;
– environmental compliance and sustainability are needed for new and existing infrastructures.

It is expected that two main power systems development models will appear clearly in the years between 2020 and 2040 [1]:

– BULK: large networks for bulk transmission capable of interconnecting load regions and large centralized RES, including offshore, as well as to provide more interconnections between different countries and different energy markets;
– MICRO: clusters of small, largely self-contained distribution networks that comprise decentralized generation, storage and active customer participation operated in a smart way.

New architectures, in particular, are indeed coming up, such as microgrids, implementing the second model [2], while the first seems to be arising from all projects already started by major TSOs around the world. Power systems of the future will thus comprise a mixture of the

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Nomenclature

AC	Alternating Current
BI	Building Integrated
CCUS	Carbon Capture, Utilization and Storage
DC	Direct Current
DOE	Department of Energy
EU	European Union
EV	Electrical Vehicle
EVSE	Electric Vehicle Supply Equipment
FiT	Feed'in Tariff
GDP	Gross Domestic Product
GHG	Green House Gas
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
ICT	Information and Communication Technology
IEC	International Electrotechnical Committee
IEEE	Institute of Electrical and Electronic Engineers
INDC	Intended Nationally Determined Commitments
ITU	International Telecommunication Union
LCOE	Levelized Cost of Energy
LV	Low Voltage
MCS	Mid Century Strategy
MGI	Mckinsey Global Institute
MV	Medium Voltage
RES	Renewable Energy Source
SGCC	State Grid Corporation of China
TSO	Transmission System Operator
TYNDP	Ten years TSO Network development
UHVDC	Ultra High Voltage Direct Current
UNEP	United Nations Environment Programme
US	United States of America

above two models since additional bulk interconnections and active distribution networks are needed in order to reach decarbonization by the ambitious environmental, economic and security-reliability targets imposed at national and International level by COP21 and the EU strategy for 2020–2030 and 2050.

The desired large penetration of RES, that is so crucial in attaining decarbonization, calls for flexibility:

– in transferring electricity from generation centers to load centers (mainly in center Europe or south-east China);
– in transforming electricity in other types of energy and maybe vice versa;
– in time shifting of electricity consumption using new customer-oriented platforms.

For these reasons – in this study, mostly focused on electricity - energy storage, transmission systems capacity increase and digitalization are considered as well as their development stage, in the most influential areas of the world, namely EU, China and USA.

Recent papers analyze the impact of the three "D"s on the energy sector, but mostly accounting for the building sector in different areas of the world [3]. In [4], technologies for energy sources and energy mix are dealt. In the latter study, a baseline and two 60% reduction scenarios of combustion-related emissions by 2050 from 1990 levels are considered for the North American context. Projected demands for energy services and availability of technology options for carbon mitigation are also considered. As the results show, three main changes need to occur simultaneously in order to achieve ambitious decarbonization targets: electrification of end-use sectors, decarbonization of electricity generation, and efficiency improvements. However, there are other disruptive changes like 'digitalization' and 'decentralization' *to be taken into account*, which the cited study does not address.

The latter two aspects will indeed produce new peer-to-peer energy business models that will probably let emerge the MICRO model, while it is not yet clear how storage and power technologies and installations will evolve and will be affected by the climate changes.

This study tries to investigate about how these big phenomena are affecting and will affect power infrastructures in the US, Europe and China where, based on peculiar features of the relevant political systems, geomorphology and economic growth, different development models for power systems can be envisaged. In this way, some indication for future developments of power systems is given according to available data and some technical considerations.

The main contribution of the paper resides in drawing a picture of how power systems are evolving worldwide. The study can be used by technology providers and manufacturers in order to anticipate trends and develop new markets and, at the same time, provides to researchers an overview about the most relevant research trend in power system in different areas of the world.

The remainder of the paper is organized as it follows. Section 2 points out the current trends of China, EU and the US in the fields of Decarbonization, Digitalization and Decentralization. Section 3 discusses the main evolution models of power systems in different parts of the world. Section 4 explores the impacts on electrical power systems, discussing the main aspects of the power system sector in which the impact of the 3Ds is leading to significant transformation, and in particular: the changes in transmission and distribution systems, the new applications of electrical energy storage systems, the rise of the microgrid model and the impacts on electrical transportation with a special focus on urban contexts, the new business models due to digitalization and the potentiality of Demand Response (DR). Section 5 summarizes the key enabling technologies and the regulatory framework for China, EU and the US. Finally, Section 6 contains the conclusion of the work.

2. Decarbonization, Digitalization and Decentralization

2.1. Decarbonization: COP21 objectives and their fulfillment

The term "Decarbonization" indicates the declining average carbon intensity of primary energy over time thanks to the exploitation of new and clean energy sources. Decarbonization targets in most parts of the world have been set recently at a worldwide level for the first time at COP21 in Paris in 2015. COP22 in Marrakech in 2016, called "the COP of the action", opening the way to the practical implementation of the Paris COP21 agreement [5].

COP21 was recognizing that climate changes were related to human-caused Green House Gases (GHG) emissions and set actions to keep a global temperature rise well below 2 °C this century and to drive efforts to limit the temperature increase even further to 1.5 °C above pre-industrial levels.

Out of the 17 sustainable development goals set at COP21, a few were directly related to the decarbonization issue. In particular:

- *Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all.* While the main focus is in providing access to electricity to the widest number of people in the world there is also a concern about increasing substantially the share of renewable energy in the energy mix across the world.
- *Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation.* Considering electrical power infrastructure development, this goal is translated into the following: