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ENERGY SECURITY: THE GEOPOLITICAL AND ECONOMIC ROLE OF INNOVATIVE ELECTRICITY TECHNOLOGIES

by

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ENERGY SECURITY: THE GEOPOLITICAL AND ECONOMIC ROLE OF INNOVATIVE ELECTRICITY TECHNOLOGIES

Abstract

Energy is a fundamental element of modern societies, therefore energy security as a reflection of the availability of affordable energy has been in the heart of political planning and academic research for many decades. The objective of the study presented in this thesis is to highlight the impact that breakthrough technologies in the electricity sector can have on energy security, under the scope of geopolitics and energy economics. The research is carried out on the axis of renewable and smart grid technologies, being critical components of a worldwide energy transformation which implies major geopolitical rearrangements in the medium to long term, as well as structural alterations in national electricity markets. An inductive qualitative grounded analysis is conducted, based on the simultaneous collection and interpretation of secondary data from heterogeneous academic sources, in order to adequately correspond to the multidimensional nature of the aforementioned research topics. This methodology produces intriguing conclusions regarding the future structure of the international system, with the emergence of new important players and others facing the challenge of internal destabilization, recession and geopolitical degradation unless they adapt their economies to the suggested energy paradigm. It also highlights the multiple benefits of the energy transition for the energy security of the developed countries, as well as the unique opportunities that it entails for countries with high energy poverty indexes in sub-Saharan Africa to upgrade their electrification status and advance with leaps and bounds towards achieving their sustainable development goals.

Keywords: energy security, technological innovation, renewable energy, distributed energy resources, distributed storage, smart grids, affordability, electrification, energy transition, energy geopolitics

Dedication

I dedicate my research to my parents, Dafni Spanou and Michail Fountoulakis, as well to my beloved Lamprini, who stood by me in this difficult yet creative journey.

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List of abbreviations

AC: Alternating current

AMI: Advanced Metering Infrastructure

AMR: Automated Meter Reading

APERC: Asia Pacific Energy Research Centre

BESS: Battery Energy Storage System

CPP: Critical Peak Pricing

CSP: Concentrated Solar Power

DC: Direct current

DER: Distributed Energy Resources

DFR: Digital Frequency Recorder

DLC: Direct Load Control

DSR: Dynamic Swing Record

EDR: Emergency Demand Response

EES: Electrical Energy Storage

e.g.: For example

et al.: And others

EVs: Electric Vehicles

FLISR: Fault Location, Isolation & Service Restoration

GDP: Gross Domestic Product

GHG: Greenhouse Gas

GPS: Global Positioning System

GW: Gigawatt

HAN: Home Area Network

HAWT: Horizontal Axis Wind Turbine

HEM: Home Energy Management

ICE: Internal Combustion Engine

IEA: International Energy Agency

ICT: Information and Communications Technology

IoT: Internet of Things

IRENA: International Renewable Energy Agency

ISA: International Solar Alliance

ITC: Investment Tax Credit

ITRE: Committee on Industry, Research and Energy

kW: Kilowatt

kWh: Kilowatt-hour

LCOE: Levelized Cost of Electricity

MCC: Millennium Challenge Corporation

MW: Megawatt

NAN: Neighborhood Area Network

NERC: North American Electric Reliability Corporation

NIST: National Institute of Standards and Technology

Ni-MH Battery: Nickel-metal Hydride Battery

OCEF: Off-Grid Clean Energy Facility

O&M: Operation & Maintenance

OAPEC: Organization of Arab Petroleum Exporting Countries

OPEC: Organization of the Petroleum Exporting Countries

PHEV: Plug-in Hybrid Electric Vehicle

PMU: Phasor Measurement Unit

P2G: Power-to-Gas

P2H: Power-to-Heat

PV: Photovoltaic

R&D: Research and Development

ROI: Return on Investment

RTP: Real-Time Pricing

SCADA: Supervisory Control and Data Acquisition

SEAR: State of Electricity Access Report

SGO: Smart Grid Optimized Buildings

SHS: Solar Home Systems

SSA: Sub-Saharan Africa

STOR: Short Term Operating Reserve

TOU: Time-of-Use Pricing

T&D: Transmission and Distribution

UN: United Nations

USD: United States Dollar

VAWT: Vertical Axis Wind Turbine

V2G: Vehicle-to-Grid

WAMS: Wide Area Management System

WAN: Wide Area Network

WEC: World Energy Council

WEF: World Economic Forum

WLAN: Wireless Local Area Network

WSN: Wireless Sensor Network

WTO: World Trade Organization

Chapter 1: Introduction

1.1. Preamble

“To truly transform our economy, protect our security, and save our planet from the ravages of climate change, we need to ultimately make clean, renewable energy the profitable kind of energy.” - Barack Obama

Energy security has been a cornerstone of national policies and strategies worldwide since the first oil crisis that took place in 1973, after the embargo proclaimed by the Organization of Arab Petroleum Exporting Countries (OAPEC). Back then, energy security totally depended on ensuring a steady oil supply at competitive prices for the standards of the time. As a result, economic growth, the geopolitical power correlations and the international system stability were largely determined by the possession and commercial exploitation of hydrocarbon deposits. Four decades ever since, the global energy landscape is undergoing a radical transformation, as its center of gravity is gradually moving from the universal use of fossil fuels - i.e., coal, oil and natural gas - to the exploitation and expansion of renewable energy sources. Concerns over climate change, ascending demand for energy due to population growth and improved living standards, as well as occasional regional natural gas supply disruptions driven by national interests and political agendas, have fueled the interest of many national governments for exploring their renewable energy potential and reinventing their economies for an upcoming clean energy race. Therefore, the present research will focus on the electricity sector.

Within the context of the ongoing energy transformation, the notion of energy security has been attributed new characteristics and dimensions, which render it a more complex and dynamic concept than it was; renewable energy deployment, energy efficiency and the reduction of greenhouse gas (GHG) emissions are some of these new dimensions. Technological innovation holds a prominent position towards achieving those targets. Among others, by improving the overall generating capacity and efficiency of solar photovoltaic (PV) and wind energy modules, advancement in technology has a major contribution in the reduction of their cost, rendering them more and more competitive to traditional methods of energy generation. The growing renewable cost-effectiveness, combined with electricity storage technologies, which are constantly evolving and gaining market share, have facilitated the electrification process of traditional fossil fuel-based sectors such as domestic heating, industry and transportation. Electrification is rightfully deemed a driver for sustainability and entails significant benefits both for energy providers and the consumers. Yet again, innovation is the key for unlocking its full potential through enabling a coupling of advanced digital systems, automation and Information and Communications technology (ICT) with conventional electric grids.

Smart grids came about as a response to the dire need of electricity systems to be upgraded, in order to successfully incorporate and accelerate the utilization of renewable technologies, as well as to optimize power delivery to end-users. It is assumed that smart grids could play an essential role in enhancing energy security, as they are able to manage fluctuations of demand and supply in real time, through demand forecasting, network remote control and fault detection. Not only that, they promote customer engagement in energy decision-making in two ways; by providing them financial incentives to redefine their consumption patterns in a mutually beneficial way and deploying additional capacity deriving from the consumers' distributed renewable generation and storage. Distributed energy resources (DERs) in the form of small-scale units of local generation - i.e., micro-grids, nano-grids etc. - have well entered the global electricity landscape, offering a wide range of benefits especially for consumers in remote areas. Hence, smart grids assisted by DERs and distributed energy storage, are acting as a balancing mechanism, adding resilience to the system and ultimately leading to more affordable electricity bills for end-users.

Redefining energy security and its critical components, under the status of a global-scale energy transformation, is expected to agitate the foundations and recalibrate the basic principles of the global geopolitical map, forged for decades by fossil fuel-based economic models and policies. Inspired by insufficient academic research for a rather contemporary issue, the aim of this research is to identify and analyze the most prominent geopolitical and economic effects of applying innovation in the electricity sector, their spillover to other sectors and their contribution to energy security. In addition, it will present global leaders and pioneers in this context and make assumptions regarding the major threats for international stability and security stemming from the energy transition. Last but not least, the present thesis intends to provide some useful points in terms of addressing the energy poverty issue in the most vulnerable region of the world. To this purpose, the potential benefits from deploying renewable-based DERs in rural and remote areas of a country in sub-Saharan Africa (SSA), specifically the Republic of Benin, will be explored as a paradigm for enhancing energy security and achieving sustainability in other countries of the region, too.

1.2. Structure of the thesis

The present thesis is divided into 5 Chapters. After the introduction and the thesis outline, presented in chapter 1, the research unfolds with the presentation of the literature review in Chapter 2, which focuses on the concept of energy security, its definitions, dimensions and fundamental elements. Afterwards, the chapter is elaborating on key features and advantages of renewable energy sources, namely solar and wind, being indispensable components of the innovative smart grid technologies which form a clear path for the short-and long-term enhancement of energy security on a national, regional and international level. Chapter 3 introduces the two research questions stemming from the academic literature, as well as the methodology to be used. Chapter 4 elaborates on the research questions and the results of the research will be accordingly presented, while Chapter 5 draws the conclusions of the thesis, including recommendations for further academic research on topic.

Chapter 2: Literature review

2.1. Introduction

This section will provide an overview of the various definitions and typologies of energy security, as well as an insight into the application of innovation in existing energy production and consumption technologies, mainly in the residential sector. With regard to renewable energy sources, this chapter will focus on solar and wind energy, as they constitute the driving force behind the smart grid revolution. Moreover, the most recent economic figures and factors affecting the cost of these technologies will be presented, as a means to assess their degree of affordability for the average citizen of the developed world, both in the present and the near future. Another aspect of this chapter will be a brief reference to global pioneers and game-changers in each market, as well as the interaction and competition among them. Last but not least, the prospect of further exploiting these technologies to enhance energy security in specific regions of the developing world will be examined as well.

2.2. The concept of energy security

2.2.1. The geopolitical dimension of energy security

Undoubtedly, energy in its various forms has dominated global economies, let alone is a critical component of our everyday lives. One of each country's energy policy priorities is to safeguard its strategic reserves and main supply routes, while simultaneously providing a stable, uninterrupted and economically viable flow of energy within its territories. These issues have further implications upon international relations and geopolitics, as many disputes and fundamental developments have emerged during the last fifty years throughout the world.

For decades, energy geopolitics has had its epicenter on how hydrocarbons - namely oil and gas - impact the way states develop, structure their economies and behave within the context of the international system. According to the IEA International Energy Outlook 2016 (as cited in O'Sullivan et al., 2017) these resources represent more than 50% of global energy consumption and they are related to approximately 70% of total investment in energy supply for the period 2000-2015, facts which prove the high degree of dependence upon oil and gas supply up to this day. Therefore, serious concerns about energy security arose with the emergence of oil crises back in 1970s, which exposed the vulnerability of western economies to oil price shocks, and were solidified during the 2000s, due to increased demand in Asia, disruptions of gas supply in Europe and pressure to de-carbonize energy systems (Cherp & Jewell, 2014).

However, as technology evolves, and the international scene and global energy economy are constantly changing, the traditional interest of geopolitics has been partially displaced, from securing access to energy resources to investing in infrastructure capacity and management system efficiency (O'Sullivan et al., 2017). This fact is inextricably linked to the development and dynamic penetration of renewable energy sources, primarily solar and wind power, into the global energy mix. The ability to generate and supply intermittent, yet infinite and environmentally acceptable energy has provided a whole new perspective in terms of defining energy security and global energy geopolitics. In 2016, renewable energies represented approximately 23% of the aggregate global electricity production and around 59% of the newly set up capacity (Hache, 2018). In addition, it is remarkable that according to the most recent data, renewable power is becoming highly competitive, approaching the range of generation costs of fossil-based electricity. With technological innovation providing continuously decreasing equipment and installation costs, as well as more efficient power-generating methods, the global weighted average cost of electricity of solar PV and onshore wind projects has reached its lowest rates in almost a decade, accounting for USD 0.10/kWh and 0.06/kWh, respectively. In fact, renewable electricity is soon expected to be more profitable than most fossil fuels, as forecasts anticipate at least a matching of cost range by 2020 (IRENA, 2018).

These developments are shaping a new reality in international politics, the so-called “geopolitics of renewable energy”. As long as renewables are gradually becoming a primary and, hopefully, a dominant source of energy, technological innovation and investment in energy infrastructure might become a field of cooperation or geopolitical rivalry, not only among states but also non-state actors, the role of which is very well recognized. For example, cross-border solar energy trade has already caused serious tensions between the European Union and China, as well as between the United States and India.

2.2.2. Energy security definitions

Being a quite multifaceted and complex notion, energy security has been given numerous definitions in academic literature, some of which are very well corresponding to contemporary data. A common and largely acceptable definition is provided by the Asia Pacific Energy Research Centre (APERC, 2007) four A’s of energy security, which refers to “*the ability of an economy to guarantee the ability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy”*. This definition encompasses the classic energy security definition of International Energy Agency as “*the uninterrupted availability of energy sources at an affordable price*” (IEA, 2014), alongside with the most recent notions of accessibility and acceptability included in the World Energy Council goals of the three A’s (WEC, 2000). Similarly, Sovacool defines energy security as “equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed, and socially acceptable energy services to end users” (Sovacool, 2012). Another definition based on the four A’s has been proclaimed by the European Commission (2010) in the context of a common European energy policy. It presents energy security as “*the uninterrupted physical availability of energy products and services on the market, at a price which is affordable for all consumers (private and industrial), while contributing to the EU’s wider social and climate goals”*.

More specifically, these definitions present three fundamental elements of energy security; the physical one, referring to guaranteed access to commercial energy for all and an uninterrupted, high-quality supply of energy services (accessibility-availability); the economic, which includes the affordability of resource acquisition and energy infrastructure development; and the environmental sustainability one, which ensures a minimum negative impact on the environment (acceptability) (APERC, 2007).

At this point, it is crucial to present a detailed breakdown of two of the four aforementioned dimensions of energy security that will be an indispensable part of this research, i.e., availability and affordability, to their main components. Availability is closely related to energy independence, meaning that a country produces and manages sufficient resources - hydrocarbons, fuels, electricity etc. - in order to meet its indigenous demand without heavily relying on imports. In addition, another aspect of availability is diversification, which includes three types. The first one is source diversification, which implies the exploitation and utilization of various energy sources and fuel types, of course emphasizing on renewable energy. Another type of diversification is the spatial one, which according to Sovacool (2011) is about "*spreading out the locations of individual facilities so that they are not disrupted by single attack, event, malfunction, or failure*". The third and most important type of diversification is the supplier diversification, according to which a country must not depend on a single provider, either if it is a specific company or a country, but it should purchase energy from multiple suppliers and transportation routes. This way, significant control over the market can be avoided and, subsequently, so does the risk of undergoing political pressure and unexpected price fluctuations or even disruptions deriving from the supply side.

That was the case in 1997, when Russia cut down the natural gas supply to Turkmenistan to force higher prices after contractual disputes. Similar circumstances led to the Russian-Ukrainian gas disputes of 2005 and 2007, as well as to the recent 2014 natural gas dispute between the two neighboring countries, which put the energy security of the European Union under serious threat. Being around 70% dependent on Gazprom's transit lines passing through Ukraine, the European member-states faced the possibility of a "cold winter" for many private households, due to the Russian threat of turning off the natural gas supply until being fully compensated for a pending Ukrainian debt of $5.3 billion (Kirby, 2014). In all the above cases, a single, dominant natural gas supplier attempted to weaponize this dependency in order to renegotiate multiannual supply contracts with multiple importers, coerce higher prices and extract more rent, without hesitating to prevent serious blackouts or even a regional energy crisis.

Another critical component of the definition of energy security is the affordability of energy services. This term is related to low energy prices in order for every consumer to be able to afford them, but also encompasses price stability and fair and equitable access to energy commodities and services. It is also closely related to transparent pricing methods and prices that incorporate full costs of energy production and consumption, such as environmental and social costs (Sovacool, 2011). However, numerous interpretations of the term affordability have been formulated over the years. More specifically, APERC (2007) interprets it as the profitability of energy investments, while Kruyt et al. (2009) and Hughes (2012) define it as low energy prices for consumers. Other versions also connect it with government accounts in terms of subsidy levels and import/export balance (Cherp, Jewell, 2014). Undoubtedly, energy price volatility and sudden price fluctuations - the so-called "price spikes" - of natural gas, oil and coal throughout the years have rendered many investments in power plants unprofitable or even unrealizable, and have triggered significant augmentations in electricity prices in many regions. According to Sovacool (2011), "*high levels of access to electricity and energy services correlate with higher levels of energy consumption and lower rates of energy poverty*", and vice versa. Furthermore, high levels of energy consumption, along with advancements in energy consuming technologies, have been an indicator of industrialization and economic development, especially in the past century (Warr & Ayres, 2010).

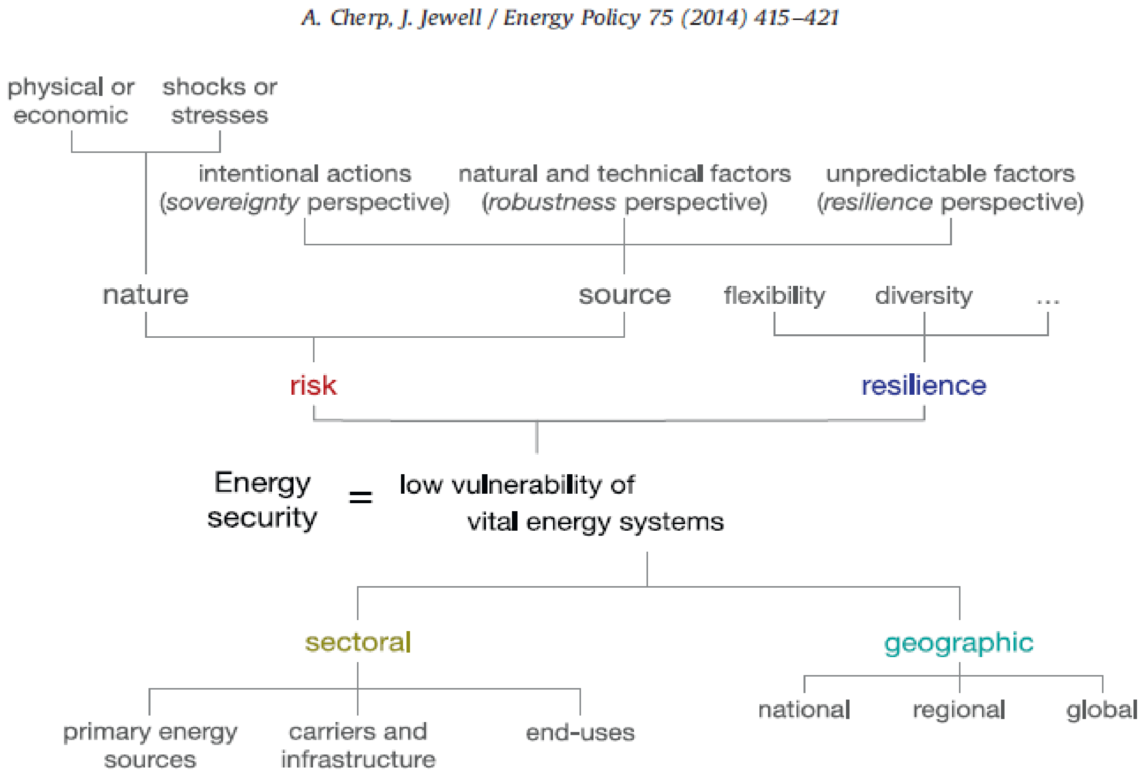

Figure 1. Analysis of the energy security definition as "low vulnerability of vital energy systems" to its main components. *Source:* Cherp & Jewell, 2014.

A quite generic, yet simultaneously flexible and essential definition has been provided by Jewell et al. (2014), which defines energy security as "*low vulnerability of vital energy systems*". According to this point of view, energy security is about safeguarding energy systems, the failure or collapse of which may disrupt the functioning and stability of a society. Such systems may be primary energy resources like natural gas, existing or future energy technologies and infrastructure, or even end-use sectors such as transportations, all being critical components of the energy supply chain and vital economy sectors. Energy systems can also be distinguished according to geographic criteria (national, sub-national, regional etc.). Vulnerability can be defined as the degree of resilience of vital energy systems when being exposed to risks. All aspects of this definition are clearly presented in Figure 1. A notably intriguing and differentiated approach on the notion of energy security has been proposed by Johansson (2013), who formulated a broad typology to describe the interconnection between energy and security (Figure 2). In particular, Johansson distinguishes energy security into two aspects, security of supply and security of demand, and presents some key figures concerning both types of security.

Furthermore, he deems an energy system not only as an object susceptible to various threats, but also as a factor which may as well generate or enhance insecurity within a society. According to this typology, security of supply refers both to the availability of energy and the energy prices, including critical infrastructure and all sectors along the energy supply chain such as extraction, transportation, transformation, refining, distribution and final use. Energy disruptions/interruptions and price augmentations due to supply and demand imbalances constitute the primary threats to a well-functioning energy system.

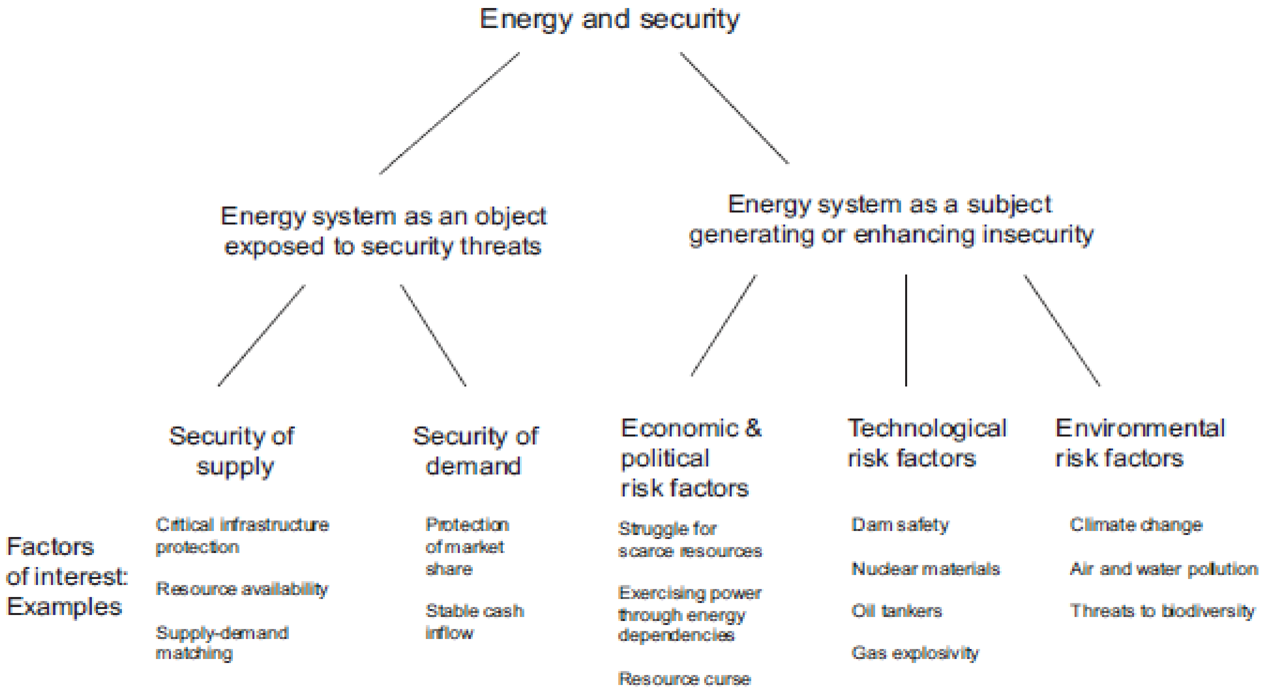

Figure 2. A breakdown of the correlation between energy and security. *Source*: Johansson, 2013.

However, for energy producing and exporting countries, security of demand should be as significant as security of supply is. Many countries, such as Saudi Arabia and Russia, depend a large part of their annual GDP on the revenues from exports of oil or natural gas. Therefore, it is a priority for them to safeguard their strategic transportation routes and a stable income from their exports, while preserving price levels as high as possible. Nevertheless, such an ambition usually is confronted with the interests of consuming countries, which strive to keep the prices at relatively low levels. Their bargaining power is directly related to the availability of alternative suppliers, supply routes or their capability of exploiting alternative energy sources.

On the other hand, energy can be a factor generating threats to security. International disputes and conflicts have risen in the name of competition for finite resources. The possibility of exploring, extracting and, eventually, taking advantage of extremely valuable energy resources has triggered multipolar tensions in the Arctic Region, as well as in the Eastern Mediterranean during the last decade. Additionally, constant technological advancements and rising deployment of technology in the energy systems have generated a new threat, i.e., critical damages to energy facilities, infrastructure and operational systems, such as power generating plants, distribution systems, oil tankers etc. Damage can be caused by technical factors, unexpected events like extreme weather conditions, or even deliberately, as a result of terrorism (Johansson, 2013).

Innovative technology, however, may be the key to addressing major energy security issues and providing short-term and long-term solutions to problematics emerging especially in the electricity sector. In the context of a large scale deployment of renewable energy in order to reduce GHG emissions and cope with the repercussions of the climate change, electricity and new technologies related with it have the potential to reshape the reality of the functioning of energy systems, attribute a new meaning to the notion of sustainable development and initiate major developments in the international scene.

2.3. Solar energy

Without a doubt, the development and deep intrusion of renewable energy technologies in the energy industry is a benchmark of the last decade, with a great potential to reconfigure the global energy map massively and irreversibly. On a theoretical basis, solar energy holds such potential, as it is capable of satisfying the global energy demand, given the appropriate technologies to fully harvest this energy (Kabir et al., 2018). Deriving from an inexhaustible source, and being an easily obtainable and safe form of energy, solar constitutes the very definition of sustainable energy. Thereby, it is closely related to energy security, being capable of providing relative energy independence to a large part of the world’s population through decentralized generation, despite the limitations the existing solar energy technologies pose.

2.3.1. Historical background

Nonetheless, the exploitation of solar energy with the use of PV panels is definitely not a recent discovery. In the first place, solar technology was deployed back in the 1970s, in the aftermath of the oil crisis, as an alternative to oil. Being unaffordable, though, and without serious political support, its expansion was prevented. A huge impetus for the re-emergence of PVs was the establishment of a feed-in tariff by the German federal parliament in 2000, to incentivize the use of renewable energy sources. This was a turning point, especially for solar energy, as its negligible market share rose and a satisfying degree of economic efficiency was achieved (Carlson et al., 2018).

2.3.2. Passive and active solar systems

According to Kabir et al. (2018), *“the whole solar energy concept is regarded as the harvesting and utilization of light and/or heat energy generated by the Sun and technologies (passive and active) involved in achieving such goals”*. This definition distinguishes the available solar technologies into two categories, the passive and active. Passive solar energy systems use sunlight solely for heating and cooling purposes (Vidadili et al., 2017). Their main characteristic is that they do not rely on external electrical devices and do not include any form of energy conversion. More specifically, they capture solar radiation through large glass areas and absorbing surfaces, based on the laws of thermodynamics that heat is transferred from warmer to cooler surfaces, and store it within an insulating thermal mass. Then, it can be distributed and released through natural radiation and convection to different areas of the building, or used to heat water during periods when there is no sun.

On the other hand, active solar systems collect solar radiation through a collecting device and convert it to heat and electric power with the use of hot water pumps or fans. Active solar systems can be further categorized into PV and solar thermal systems (Kabir et al., 2018). PVs consist of solar cells integrated into larger structures (solar panels), which generate electricity by directly converting solar radiation through a semiconducting material. Such semiconductors are the monocrystalline, polycrystalline and thin film silicon solar cells, in order of decreasing performance and price. Regarding the solar thermal technologies, they deploy high-magnification mirrors as concentrating collectors, and a receiver, such as water, that is placed on the focus point of the collector. When this receiver reaches a high temperature, the heat is being transformed into mechanical energy by powering up a steam turbine which, subsequently, generates electricity (Vidadili et al., 2017).

2.3.3. Pros and cons of solar PVs

Solar energy signatures the future of global electricity consumption, as recent statistics indicate. Only in 2016, solar PV production surpassed 74 GW, being the largest part of all additional electricity generation globally above coal, wind and natural gas (Carlson et al., 2018). Of course, solar technology also demonstrates some significant, yet not insurmountable drawbacks compared to fossil fuel or nuclear power plants. According to Kabir et al. (2018), one of the primary considerations regarding this form of energy is the relatively high initial cost of installation of a solar energy system. For example, the average installation cost for domestic use in the US in 2018 varied from USD 2.87 to USD 3.85 per watt. Assuming 5 kW per household, an average upfront investment for solar panels, inverters to convert direct current (DC) power to alternating current (AC) power, mounting hardware, wiring and installation would reach approximately USD 13,000, taken into account the 30% tax credit the Solar Investment Tax Credit (ITC) offers for the purchase and installation of solar panels. In case the purchase of a battery storage system is also included, e.g. the Tesla 14 kWh Powerwall battery costing around USD 7,000, the initial cost may significantly rise, even reaching double figures depending on the battery’s capacity. Yet, a rather high installation cost can be counterbalanced by very low operational and maintenance costs (O&M costs) compared to competing energy sources and long life cycles (approximately 20-25 years). An improvement of the inverter output efficiency and lifetime from about 15 to 20 years, while representing around 20% of the initial investment, is a determinant factor of reducing O&M costs. In addition, the absence of moving components in a solar PV system corresponds to much less physical deterioration over the years, hence very low expenses intended for cleaning and small repairs.

Another major concern about the solar energy technologies, especially when it comes to commercial use, is their return-on-investment (ROI), as usually, such projects display relatively long payback periods and small revenue streams (Kabir et al., 2018). That depends on several factors, such as incentivization methods, the availability of sunlight and air pollution levels in a specific location, as well as average electricity prices. Interestingly enough, in comparison with other domestic infrastructure investments, a PV panel installation can provide home-owners with 100% ROI and lead to an appreciation of their home value. The intermittent power generation is another drawback of renewable sources, especially solar PVs. Due to their total dependence on sunlight intensity, they are non-operational during the night and have a very limited output on cloudy and stormy days. Hence, solar may be an insufficient and unreliable energy source in regions with extreme or unsustainable climate and weather conditions, like Russia and Canada. This matter, though, can be addressed, either by connecting to the local grid or by saving the energy surplus in a storage system like a battery, which raises the overall investment cost and requires large storage space.

2.3.4. Levelized cost of solar energy

Nevertheless, solar technology is expanding more and more in the last years, primarily due to a considerable reduction of its cost (Figure 3). In fact, according to IRENA (2018), since 2010, the global weighted average levelized cost of electricity (LCOE) - which includes the generation, transmission, distribution, O&M and fuel costs - of utility-scale solar PV has decreased by 73%, reaching a price of USD 0.10/kWh in 2017 and even USD 0.05/kWh in recent auctions. In addition, the price of concentrated solar power (CSP) can also fall to USD 0.06/kWh by 2020, being directly competitive towards fossil fuel generation and setting higher standards in achieving the energy security target of affordable electricity.

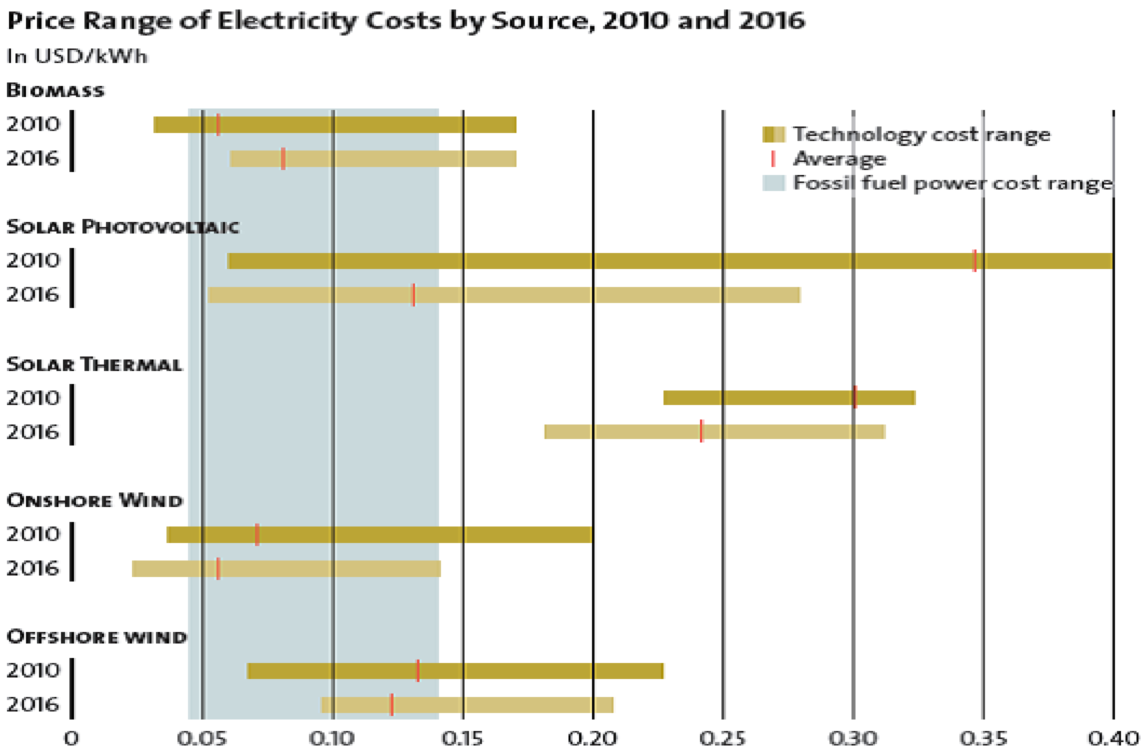

Figure 3. Price Range of Electricity Costs by Source, 2010 and 2016. *Source*: International Renewable Energy Agency (as cited in Carlson et al., 2018).

This continuous cost decline has been driven by several factors, which function as a chain. To be more specific, the ever-growing political support for renewable technologies has led to big investments in innovation, research and development (R&D), and more efficient infrastructure in terms of capacity and reduction of installed costs. Emerging technologies like rooftop solar tiles and building integrated PV (BIPV) can have a direct impact on the installation cost of solar panels. Moreover, the unlocking of economies of scale in the manufacturing industry, the optimization of capital utilization and the implementation of supportive regulatory frameworks and schemes, i.e., feed-in-tariffs, to lower capital costs have contributed to a considerably broader adoption of renewable technologies, especially solar and onshore/offshore wind on a global scale (IRENA, 2018).

2.3.5. Global leaders

Even though the development of solar technology originally took place in Europe and the US and Europe remains the most solarized continent with about 100 GW of installed capacity (Kabir et al., 2018), the first country to recognize and truly exploit its economic potential was China. For the moment being, China is a global leader in renewable energy production and a pioneer in providing energy finance, accounting for 32% of 2016 global renewable energy financing (Baker & Shen, 2017). Among other emerging economies, it has integrated the development and deployment of renewable technologies in its national strategy for a secure and decarbonized energy supply (Hübner, 2016). Just for the record, China holds over 60% of the global solar manufacturing capacity, and only in 2016 half of the new solar power plants installed were in China (Carlson et al., 2018). Through building up a powerful PV manufacturing industry, a high degree of market protection, concentrated production (Carlson et al., 2018) and acquisitions of many of its western suppliers of technology, China is attempting to become a monopoly in solar PV markets. Quite impressive is the fact that China is also a dominant player with respect to raw materials supply chain, such as rare earths, indium, cadmium, lithium and cobalt, which are critical for the construction of solar, wind and battery system technology. Holding around 57% of global reserves along with Russia, and controlling the biggest part of rare earth elements' mining, production and processing in the world (O'Sullivan et al., 2017), Chinese manufacturers are capable of providing international markets with integrated renewable energy solutions, like in the case of electric vehicles (EVs), in unbeatable prices. According to Armaroli and Balzani (2016), "*the almost 7-fold drop of the PV module price in the last decade has been primarily the consequence of the 10-fold increase of the Chinese production; this has made PV a truly game changer in the global energy market*". This severe price drop had a negative impact on many European and US producers, as it ultimately led them out of competition or even to bankruptcy. Moreover, despite the fact that the country owns over one-fourth of the global installed solar PV capacity, the Chinese government is planning to triple the country's solar capacity by 2020, from 43 GW at the end of 2015 to 150 GW (Kabir et al., 2018).

2.3.6. Solar PV deployment in the developing world

One of the most important benefits that solar technology offers with regards to energy security is the provision of electricity in regions that have restricted or no access to this commodity at all, mostly being developing countries. The United Nations (UN, 2015) has set the goal of universal access to affordable, reliable and modern energy services until 2030. Despite the fact that access to clean energy is a precondition for sustainable development, still more than one billion people lack such a privilege and hundreds of millions live with unreliable, intermittent or unaffordable power (Figure 4). The energy poverty issue is more intense in the Asian and African continent, where in particular the average household electrification rate reached 42% in 2016. In specific sub-Saharan regions, which actually hold vast quantities of energy resources, this percentage reached even less than 10%, being the lowest electrification rate globally. At the same time, enormous deviations have been observed between urban and rural households, with 71% and 22% respectively (World Bank, 2018). Even more alarming is the fact that, according to the International Energy Agency (as cited in the World Bank SEAR, 2017), while almost one billion people in the sub-Saharan region alone may gain electricity access by 2040, due to population growth, an estimated 530 million people shall continue to live without electricity.

On the other hand, the African continent displays huge potential in renewable energy generation, especially from sun and wind. In particular, micro-grids based on solar PV and wind turbines, which will be thoroughly presented in the following chapters of this research, can be a very promising medium and long-term solution for the electrification of sub-Saharan regions. This argument is based on the fact that these off-the-grid technologies can be exploited in countries where the extension of the utility grid is very challenging, due to limited or zero capital funds and poor infrastructure. Especially when it comes to rural areas, which are characterized by remoteness and sparse population density, decentralized power generation via PV panels may be the most suitable and attractive option in comparison to diesel-based generation or grid extension (Szabo et al., 2011). Combined with a storage system, solar PVs could serve either as individual domestic systems to supply single households, or as local grids to cover primary local community needs, such as healthcare centers, water pumps, schools etc. (Dimitriou et al., 2014). In some cases, however, solar and diesel-based power systems are not competitive with each other. Countries such as Kenya, Mali, Senegal etc. have already deployed PV-Diesel hybrid systems, which have the peculiarity to exploit sunlight until mid-day hours, while the diesel engines cover load demand for the rest of the day (Kansara &Parekh, as cited in Dimitriou et al., 2014). Taking advantage of the decreasing costs of solar PV technology and battery systems, as well as the favorable climatic conditions for renewable power generation, the sub-Saharan countries should attract public and private sector investments in off-grid solar systems. Yet, serious progress has to be made from national governments regarding the establishment of support schemes and tax alleviations, in order to boost the expansion of renewable technologies in the sub-Saharan market (Moner-Girona et al., 2018).

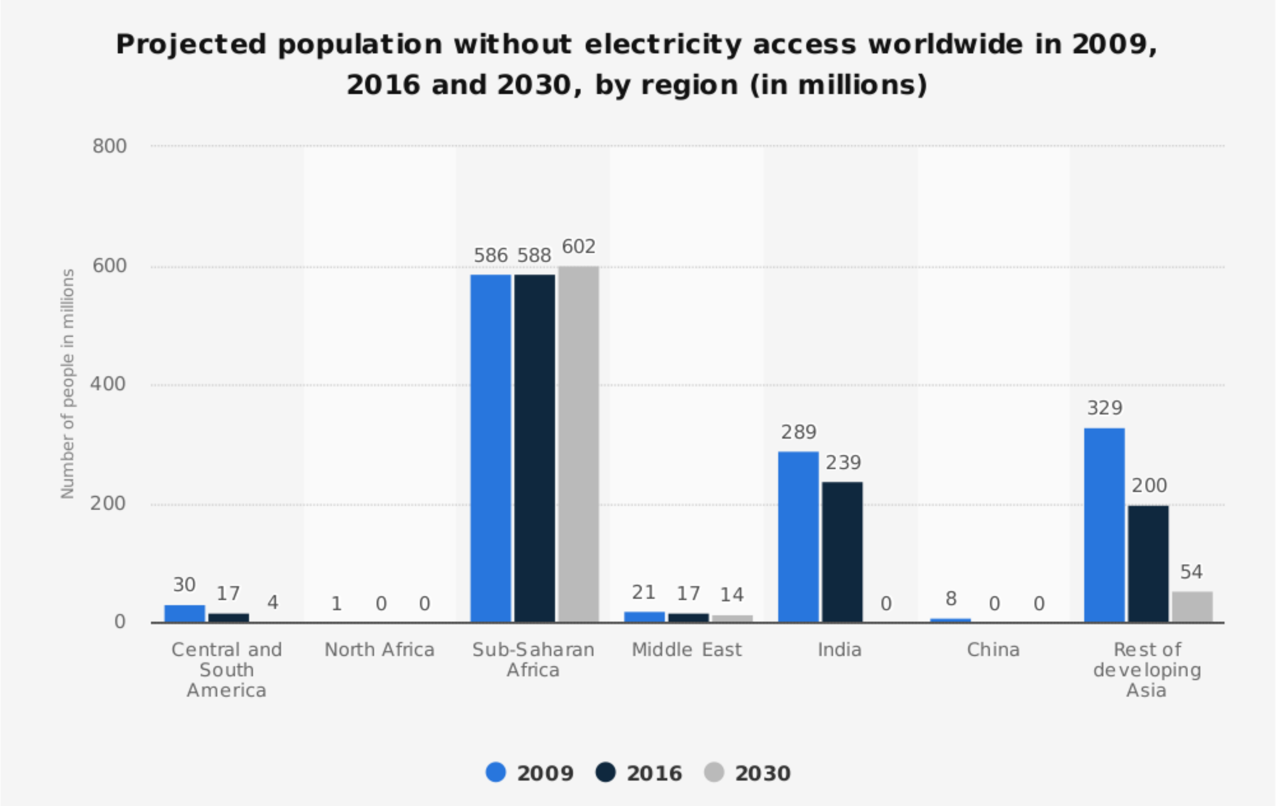

Figure 4. Projected population without electricity access worldwide in 2009, 2016 and 2030, by region (in millions). *Source:* IEA/Statista 2018.

2.4. Wind energy

Wind is a form of solar energy generated by the air movement in relation to the earth's surface, as solar radiation unevenly hits the earth's surface, and which is being modified due to the earth's rotation and irregularities in its topography. For thousands of years, mankind has been harnessing the power of the wind for a wide set of purposes and utilizations. For instance, windmills built from wood, cloth and stone were used in the past for pumping water or milling corn (Schubel & Crossley, 2012). One of the most ground-breaking, however, accomplishments of the modern era is the conversion of kinetic energy from the wind directly to electricity. Wind offers a clean, highly available and efficient source of energy which, from an economic perspective, has low operating costs, does not need any fuel transport and requires little land (Kumar et al., 2016). Wind energy technology is deemed very mature, bearing in mind that modern turbines already extract approximately 50% of the energy transmitted through the wind, with a maximum possible efficiency of 59,3% known as the Betz limit (World Energy Council, 2016; Burton et al., 2011). The most significant part of a wind energy system is the wind turbine, the blades of which capture kinetic energy from the air and transform it into other forms, either mechanical in water-delivering mechanisms (water pumps and windmills) or electricity through a generator placed in modern wind turbines (Wizelius, 2007). Historically, the first power-generating wind turbine was developed back in 1887 in Scotland. Since the replacement of classic versions of windmills with fossil fuel engines during the 19th century, exceptional progress has been made regarding the optimization of wind technology and its output efficiency.

2.4.1. Wind turbine technology

Current wind technology displays a wide variety of designs and sizes, mostly depending on the location where it will be installed, the available capital and the desired generation capacity. Utility-scale wind turbines vary in size, from 100 kW to some MW of nameplate capacity, while small turbines are in many cases characterized by a rated capacity of below 50 kW, although there is not a commonly acceptable definition (Probst et al., 2011). As claimed before, the wind turbine constitutes the very heart of every renewable wind power generation system and represents the biggest part of its installation cost. Usually, a wind turbine consists of a hub, a three-blade rotor, a tower, a nacelle, a gearbox and a generator, as shown in Figure 5. As the air flows across the blades, the difference in air pressure between the two sides of the blades exerts two forms of aerodynamic force on them, particularly lift and drag. These forces cause the rotor to spin, which in turn feeds the generator, either directly in the case of a direct drive turbine, or indirectly through a drive shaft and a gearbox, to generate electricity. Contemporary wind turbines tend to comprise of longer blades, as they can collect more wind from a broader area and have improved energy output (Kumar et al., 2016).

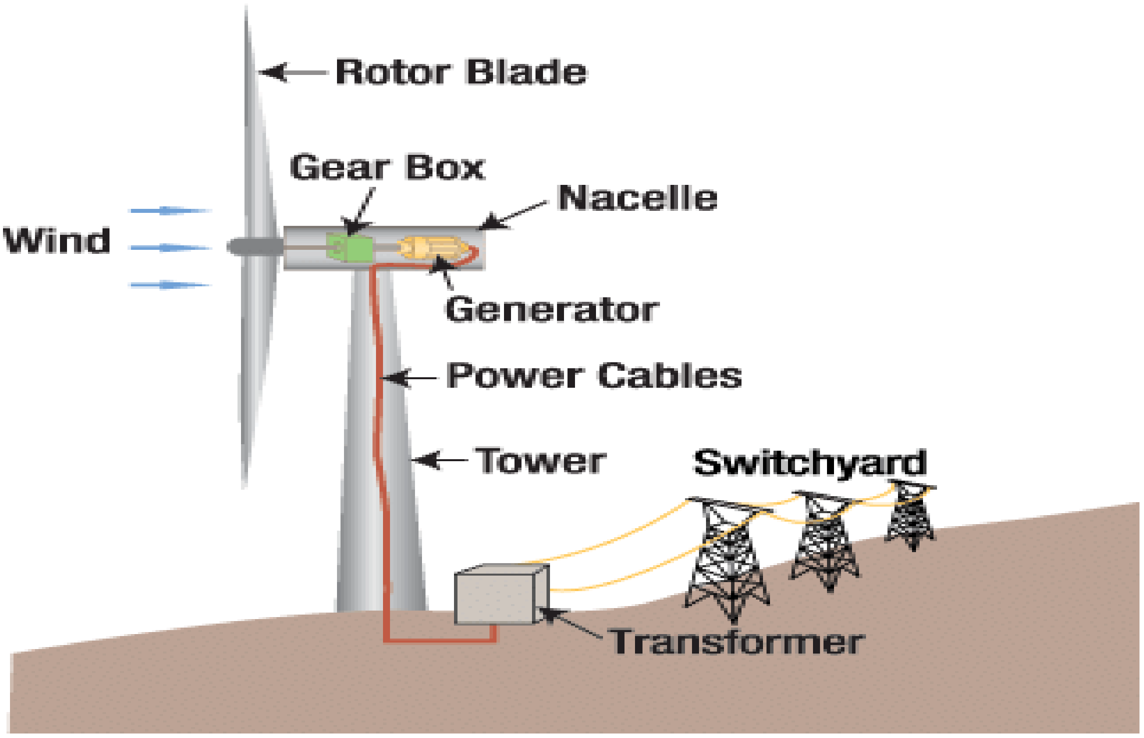

Figure 5. Parts of a wind turbine. Source: http://askmel.tripod.com/workshow2.html.

2.4.2. Wind turbine design

Another typical classification of small wind turbines is based upon the orientation of the rotational axis and the shaft (Schubel & Crossley, 2012). Particularly, they are divided into two categories, the horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) (Figure 6). The most commonly used in wind farms and individual installations are the three-bladed, stall-or-pitch regulated, horizontal-axis turbines, which operate at a near-fixed rotational speed (IRENA, 2016). That is due to higher output efficiency in comparison with VAWTs, combined with relatively low installation and O&M costs and increased rotor control through pitch and yaw control. In addition, VAWTs exhibit a number of disadvantages. Being installed close to the ground - while HAWTs are mounted horizontally parallel to the terrain - they are less exposed to wind's movement, leading to decreased efficiency. Not only that, they have a low tip speed ratio, and they require a greater size, more durable components and usually a separate power source to initiate the rotor, thereby higher initial cost than HAWTs in order to be equally productive.

Figure 6. Examples of HAWTs (left), VAWTs (middle) and Shrouded HAWTs (right). Sources: https://quintongraybealsanmarin.weebly.com/outdoor-classroom-design.html & http://www.wind-works.org/cms/index.php?id=541

Nevertheless, VAWTs, especially the Darrieus-type ones, display easier maintenance, as the generator and the gearbox are placed near the ground, improved adaptation to wind direction alterations (omnidirectional), they do not require the use of yaw mechanisms and they are capable of a minimum energy output even in case of low wind speeds. Due to their design, VAWTs could be an optimal solution for urban use, in rooftops and small-scale applications. Still, much progress has to be made in R&D in order for VAWTs to be actually competitive. A subcategory of HAWTs are the shrouding horizontal axis micro-wind turbines, which incorporate a circular duct that encloses the rotor. This additional feature functions as a diffusion augmenter, stabilizing and accelerating the amount of air passing through the blades, hence the power output of small wind turbines (Kosasih & Jafari, 2014). Despite the high extra cost of the augmenter and the wear and tear its weight causes on the turbine's tower, interest in shrouded wind turbines has exploded in the recent years, as they offer an efficient solution for urban-built environments, where wind velocity is low and high turbulence levels are met (Bukala et al., 2016).

2.4.3. Onshore and offshore wind farms

Regarding the wind energy systems' installation location, this can be either onshore or offshore. Onshore wind turbines, which currently produce the cheapest form of renewable energy, are installed on land and usually they are grouped together on large open spaces into wind power plants, known as wind farms, in order to massively provide the electrical grid with power. On the other hand, offshore turbines are located beyond the coasts, at sea or in freshwater. The growth of offshore wind farms has been accelerated during the last years, mostly due to stronger winds over the oceans and their ability to deploy larger turbines over larger areas, features which increase their rated capacity and, subsequently, the investors' interest.

In fact, 10 MW turbines are expected to be fully commercial until 2020, resulting in a great reduction of offshore wind energy levelized cost, even 35% by 2025 (WEC, 2016; IRENA, 2016). Moreover, they do not require long-distance power transmission, as generally the largest urban centers are located in coastal areas, and they lack issues of land property with local communities unlike the onshore projects (Kumar et al., 2016). However, being situated in districts of limited accessibility, as well as being subject to severe natural conditions and tidal corrosion, O&M activities in offshore wind farms typically represent an estimated 25–30% of their total lifecycle costs, almost equaling construction and installation costs (Röckmann et al., 2017). In general, the global weighted average LCOE generated from offshore projects is considerably higher than that of onshore projects, reaching a price of USD 0.14 per kWh, in comparison to USD 0.06 per kWh for onshore-generated power, in 2017 (IRENA, 2018). Therefore, offshore wind technology is principally attractive to countries with limited onshore wind resources.

2.4.4. Global installed capacity and levelized cost of wind energy

The incessant innovation achievements regarding wind turbine design and operation, such as higher hub heights, more advanced turbine towers and larger areas covered by longer blades, as well as increased competition in the long run have been some of the most significant factors driving the upward competitiveness of renewable wind technologies, in terms of cost and efficiency (IRENA, 2016). According to the World Energy Council (2016), from 2000 to 2015, cumulative installed wind capacity has grown at a compound annual growth rate of approximately 25%, reaching around 539 GW in total and nearly 19 GW offshore in 2017, being capable of covering more than 5% of the global electricity demand (Global Wind Energy Council, 2018; World Wind Energy Association, 2018) (Figure 7). Moreover, according to IRENA (2018), the global cumulative installed capacity of onshore wind energy is expected to reach 712 GW in 2020, an augmentation driven by a constant cost reduction through the development of economies of scale and innovative technologies.

The world's leading wind energy market is China, with an aggregate installed capacity of 188 GW in 2017, followed by the US, Germany, India and Spain (World Wind Energy Association, 2018). The Chinese primacy, as well as India's competitiveness, can be explained by the fact that these two countries have considerably lower average installed costs of onshore wind farms, due to cheap labor, strong manufacturing capacity and availability of low-price raw materials. Indicatively, weighted average costs for 2015 reached about USD 1,560/kW, while in China and India they accounted for USD 1,270/kW and 1,325/kW, respectively (IRENA, 2016). Similarly, for the years 2014-2015, China had the lowest LCOE with USD 0.053/kWh, followed by North America with USD 0.06/kWh, as Figure 8 indicates. On condition that capacity factors of wind technology shall be ameliorated, the global weighted average LCOE of onshore wind could even be halved by 2025, to reach USD 0.053/kWh.

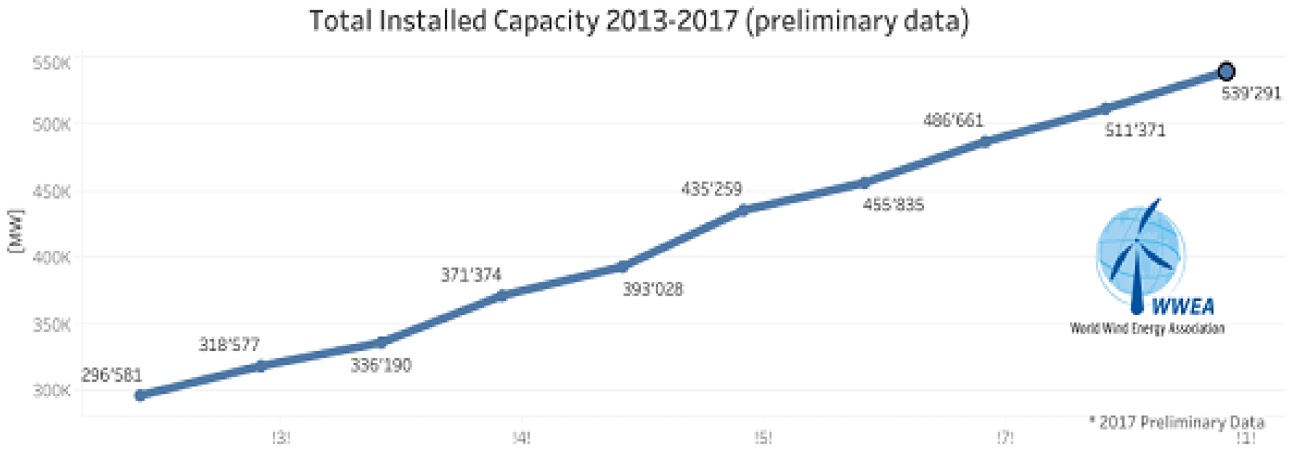

Figure 7. Total Installed Capacity 2013-2017 (preliminary data). Source: World Wind Energy Association, 2017.

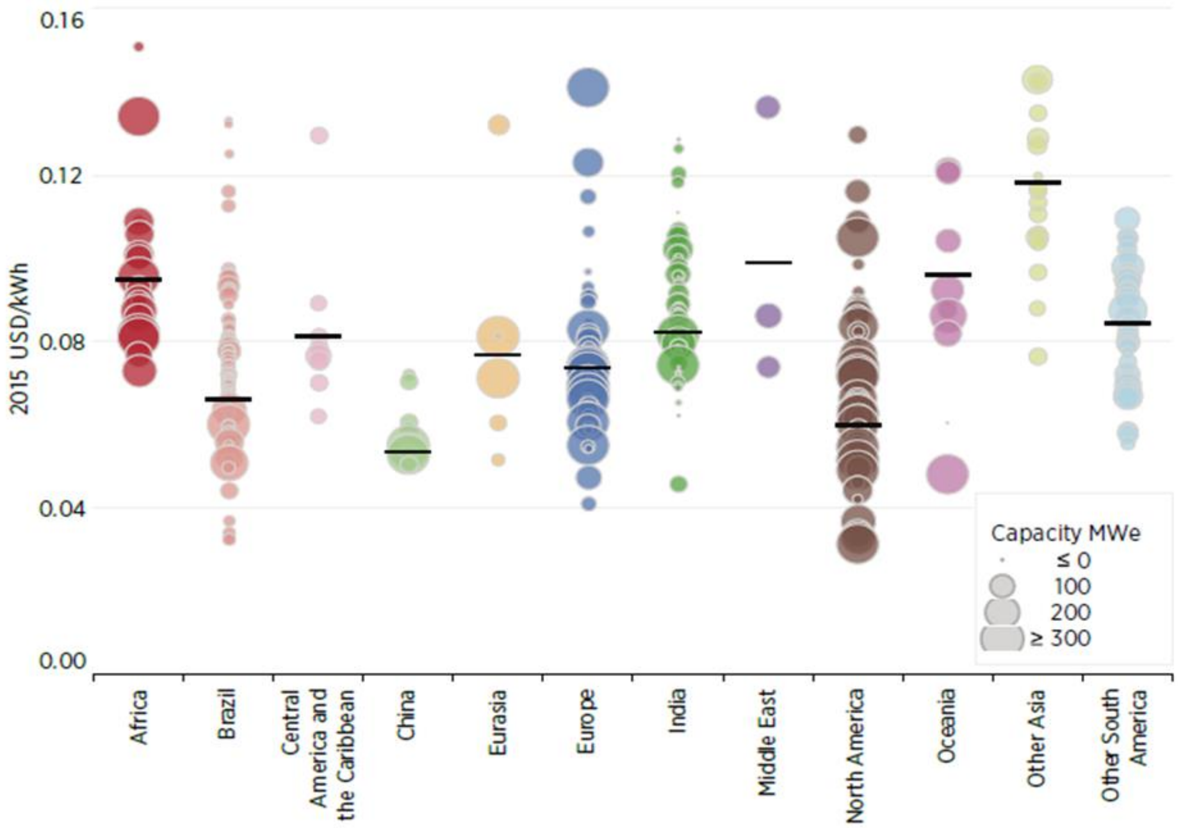

Figure 8. Levelized cost of electricity for onshore wind farms by project, and weighted averages by country and region, 2014-2015. *Source:* IRENA Renewable Cost Database (as cited in WEC, 2016).

2.4.5. Wind-based off-grid systems

The rapid expansion of the off-grid or stand-alone electricity markets has upgraded the role of small-scale wind and solar PV technology, especially when it comes to the issue of electrifying remote and rural areas of the developing world with dysfunctional or insufficient transmission and distribution (T&D) systems. In 2017, about 0.8 million households were entirely powered by small scale wind systems (World Bank, 2017), which can be easily installed on rooftops or in backyards. In order to be considered as a reliable source of power and to minimize costs, small wind turbines could as well be hybridized, either as wind-PV-hydrogen or as wind-diesel energy systems, and combined with an additional set of equipment called balance of system (Kaldellis, 2010). This may include a storage system, charge controllers, meters, safety equipment etc., which will maintain, safely transmit the electricity to the load that will use it, and store it for cases of limited or zero production (Off-Grid or Stand-Alone Renewable Energy Systems, n.d.). Unsurprisingly, along with the swift spread of solar PV and wind technology during the last years, the option of shifting to autonomous and resilient to grid failure schemes of renewable energy production for residential purposes has become a very popular and attractive option for individual households and small communities in many regions of the developed world, too (IRENA, 2015a). This fact is very closely related to a significant decrease in the average price of battery energy storage systems (BESS). Mini-grids, micro-grids and nano-grids already represent an essential part of the distributed generation, reducing the power transmission lengths and integrating alternative power sources. However, the penetration of ICT in the electricity sector has contributed to the emergence of the most radical and promising type of electrical grid, the so-called “smart grid”.

2.5. Smart grid technologies

2.5.1. Conventional grid architecture

Conventional electricity grids are interconnected power networks including generating stations, power transformers, high-voltage transmission lines, transmission substations, distribution lines, distribution substations, and various types of loads, operating in a passive way to deliver energy to consumers from substations installed far away from densely populated areas. Traditional power plants function primarily on fossil fuels or hydro turbines to produce electricity. However, as nations and cities are becoming more and more technologically advanced, the electrification of various sectors is on the process and the robustness of international markets continuously rises, cumulative global energy demand is growing exponentially year by year. Only in 2017, global primary energy demand rose by 2.2%, meaning more than twice the previous year’s growth rate and more than the 2005-2015 average of 1.7% (BP Statistical Review, 2018). Moreover, according to the Global Energy Statistical Yearbook (2018), total electricity consumption increased by 2.6% in 2017, most of it occurring in Asia.

This enormous demand growth poses several challenges to global energy security. Future projections foresee a need to triple the global electricity supply until 2050, in order to be able to satisfy demand (Amin, 2015). This fact, though, is totally contradictory to the 2015 Paris Agreement target of a transition towards a low-carbon energy sector, as evidenced by the 1.4% increase of energy-related carbon dioxide emissions in 2017 (IEA, 2018). In addition, security of energy supply is being jeopardized by power grid congestion, a case in which the transmission or distribution lines are unable to accommodate the required load during periods of high/peak demand, excessive electricity generation or during emergency load conditions, such as extreme weather conditions or system failures. The aforementioned issues have brought up the need to upgrade the existing electricity grid infrastructure, in order to achieve improved network efficiency and power delivery effectiveness, and integrate DERs based on renewable energy - mainly solar PV and wind - as a part of the realization of a sustainable energy future. The exploitation of telecommunications and Internet services is the key to reshape the grid and establish a dynamic, two-way communication system with bidirectional flow of energy and data (Colak et al., 2015). This will have beneficial effects both for the consumers and the energy security of each respective country.

2.5.2. Introduction to the smart grid concept

Smart grids were developed as a response to the urgent need of modernizing the grid. A forerunner of the smart grid was the "Intelli-Grid", presented as a complex, interactive and fully automated network/system by the US Electrical Power Research Institute in 2002 (Zhou et al., 2016). Thenceforth, the term "smart grid" was widely adopted and attached to different approaches. For instance, in Europe it was described as "*an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supply*" (Smart Grids European Technology Platform, as cited in Peng & Yan, 2011). In contrast, the United States Department of Energy (as cited in Clastres, 2011) has provided a function-oriented definition, according to which "*a smart grid must integrate the characteristics or deliver the performance described below: self-healing from power disturbance events; enabling active participation by consumers in demand response; operating resiliently against physical and cyber-attack; providing power quality for 21st century needs; accommodating all generation and storage options; enabling new products, services, and markets; optimizing assets and operating efficiently*". The IEEE Standards Committee (as cited in Tao et al., 2015) has provided a more concise definition, which refers to smart grids as "*the integration of power, communications, and information technology for an improved electric power infrastructure serving loads while providing for an ongoing evolution of end-use applications".*

While conventional electricity grids can only transmit and distribute energy, smart grids also incorporate storage, two-way real-time communication, data processing and decision-making capabilities (Tuballa & Abundo, 2016). In other words, a smart grid not only has the capability to perform all processes of a conventional grid, but also based on the convergence of electricity and data flow - enabled by advanced information and communication technology - it incorporates distributed generation from renewable sources, electricity storage systems, EVs and plug-in hybrid EVs (PHEVs), demand response through the installation of smart meters, and remote system-wide, real-time monitoring operations (Figure 9). Additionally, the development of smart technology can have a positive impact on energy conservation for the domestic end-users, especially in terms of load shifting through changing their basic daily usage habits and consumption patterns (Laicane et al., 2015). Being regarded as a next-generation conventional grid, the smart grid has the ability to transform the current grid to one that operates more cooperatively, responsively and organically (Litos Strategic Communication, 2008). Entailing significant economic, societal and environmental benefits, it has attracted the interest of most countries as a modern instrument to maximize reliability, accessibility, efficiency and economic performance of the electricity sector, along with boosting competitiveness towards hydrocarbons and combating climate change.

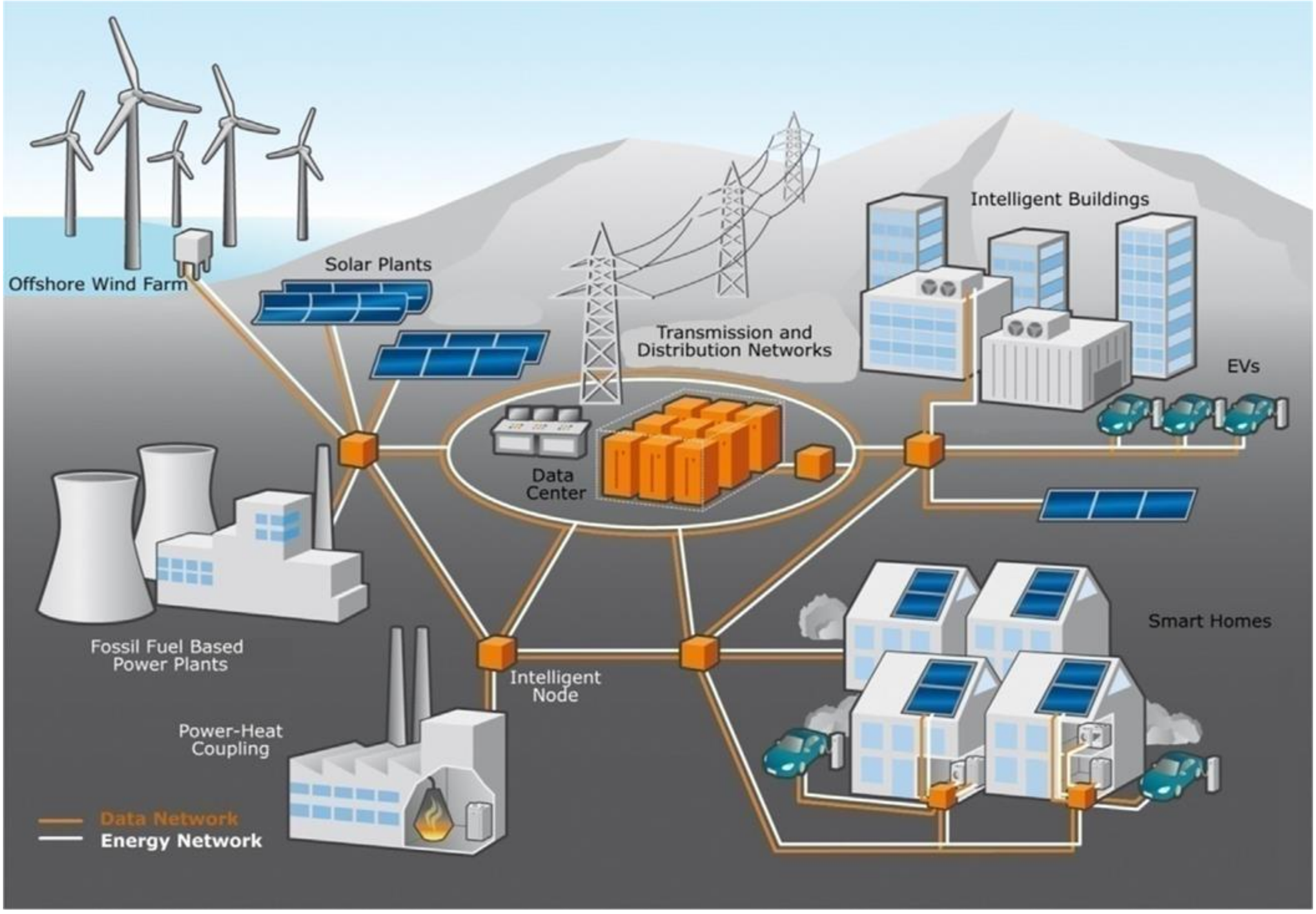

Figure 9. Graphic representation of a smart grid model. *Source:* Hossain et al, 2016.

2.5.3. Smart grid design

A smart grid - especially after the integration of non-dispatchable and intermittent distributed renewable generation - is an inherently complex, multifunctional system which integrates many stakeholders, varieties of digital computing, communication technologies and advanced software into the power system infrastructure. The National Institute of Standards and Technology (NIST, as cited in Tuballa & Abundo, 2016) has developed a conceptual model to divide a smart grid into seven domains and sub-domains, each of which includes several distinctive actors and applications. This model is presented in Figure 10. Actors may be devices - such as smart meters, renewable energy generators etc. -, computer systems/software and/or stakeholders which own and operate them. Accordingly, NIST classifies applications as tasks performed by the actors within a domain. Some applications are performed by a single actor, while others are carried out by several actors of the same domain working together.

As Figure 10 shows, though, in many cases actors from different domains interact and interoperate through predefined interfaces, as some of them encompass features and components of other domains to enable the smart grid functionality and optimize the system's performance. Interoperability is indispensable for ensuring the planning and implementation of the grid architecture. Therefore, NIST has initiated the Smart Grid Interoperability Panel (SGIP), in order to coordinate standards development for smart grids and ensure the unobstructed and harmonized operation of all system domains (Tuballa & Abundo, 2016). For instance, a distribution facility may contain actors in the customer domain, such as smart meters, and distribution management systems in the operations domain.

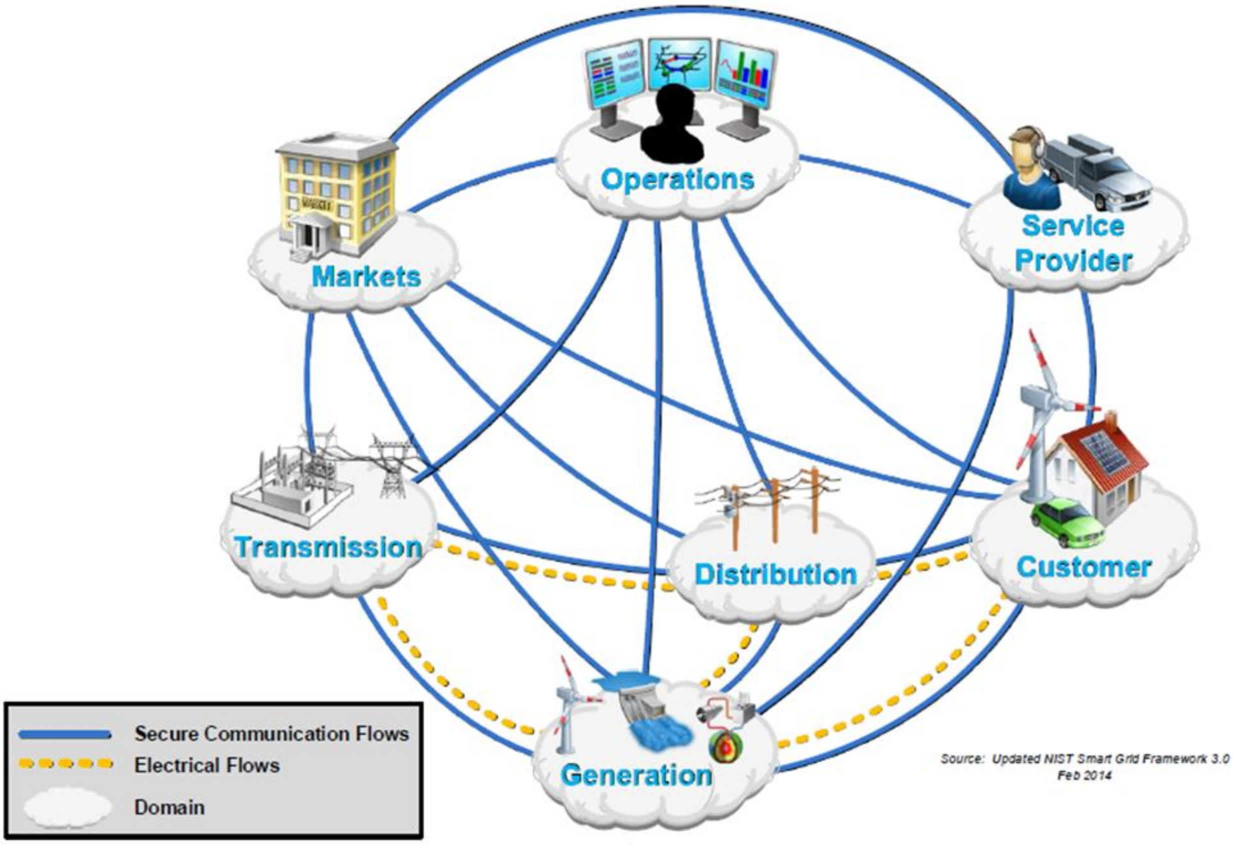

Figure 10. Interaction of domains in the NIST Smart Grid Conceptual Model. *Source:* NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0, 2014.

2.5.4. Communication systems, metering infrastructure and functions

While conventional power grids deploy a limited number of sensors for data transmission and acquisition, located in major T&D nodes, smart grids are digitalized on a big scale, basing their operation on a large number of WiFi-based wireless sensor networks (WSNs) and actuators scattered across all levels of the grid infrastructure. Advanced automation schemes such as fault location, isolation, and service restoration (FLISR), have already been deployed in distribution systems, along with supervisory control and data acquisition (SCADA) systems and advanced metering infrastructure (AMI) or automated meter reading (AMR), for real-time monitoring and control. These systems aim at addressing challenges like cost-effective grid reliability and flexibility improvement, features necessary to facilitate DER integration (Aguero et al., 2017). In particular, low voltage network observability, power quality notification, automated outage detection and detailed demand forecasting are only some of the innovations that the use of AMI and AMR entails, which upgrade the overall system security (WEF, 2017). In addition, large urban centers and regions require the installation and use of advanced equipment, such as digital frequency recorders (DFRs), phasor measurement units (PMUs), dynamic swing records (DSRs), global positioning systems (GPS) and wide area management systems (WAMS) (Hossain et al., 2016).

A smart grid can operate on three different network types depending on the bandwidth needs, specifically Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN). The most simple and widespread type is HAN, usually deployed within limited areas - homes, small offices etc. - and having a relatively low rate of data transmission (Baimel et al., 2016) (Figure 11). The broad expansion of wireless local area networks (WLANs) and the Internet of Things (IoT), which encompasses all kinds of industrial, domestic-used and wearable/portable devices that collect and transmit data within the context of a network, could as well be exploited towards achieving efficient grid operation, home energy management (HEM) and boosting customer engagement with innovative, grid edge technologies. HEM systems can access, monitor, control and optimize the performance of essential parts of the smart grid infrastructure (Zhou et al., 2016). Typical examples of data transfer devices are portable computers, mobile phones, vehicles or automated devices and machines, such as smart home appliances and applications (Bayindir et al., 2016).

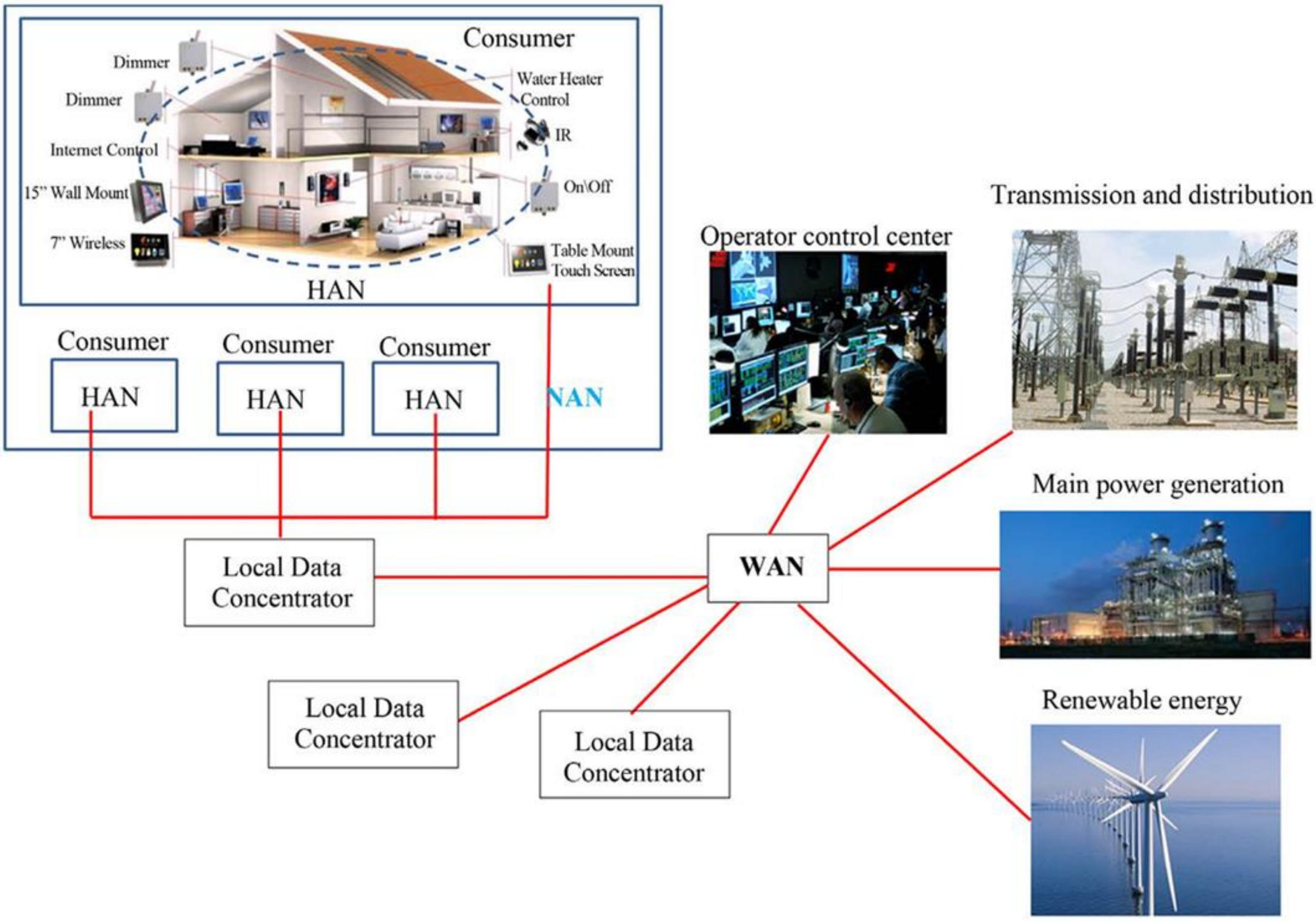

Figure 11. Example of a smart grid communication infrastructure. *Source:* Baimel et al., 2016.

Smart appliances and devices offer the benefits of automatically switching off during peak demand hours and shifting energy use to periods of abundant electricity supply. In addition, they can respond to external signals, transmitted from system operators, to serve as operating reserves, a responsive mechanism responsible for coping with unpredicted demand augmentations, losses of transmission lines and other contingencies (NERC, as cited in Denholm et al, 2010). As Nistor et al. (2015) conclude, a 20% penetration of smart appliances in British households could provide up to 54% of the maximum Short Term Operating Reserve (STOR) requirements of Great Britain's power system, depending on the time of day. Future estimates create expectations for a rapid adaptation of smart IoT-enabled devices, encouraged by the decreasing cost of sensor technology, leading to more automated, flexible and cost-effective management of the customers' electricity needs. Nevertheless, the transition to a fully digitalized, customer-centric electricity grid implies the development of innovative business models for the use of data, as well as the establishment of the necessary legal framework and interoperability standards for energy data sharing among market agents.

According to Alohali et al. (2016), "*the HAN and NAN are functional groups of the smart grid infrastructure that are interconnected in a functional hierarchy*". Several HANs deployed within an area of some hundred meters can be connected to a single NAN and provide it with energy consumption data through the smart meters. Subsequently, this data is transmitted from NANs to local data centers, where it is used for charging the consumers and analyzing their power production and demand patterns. One of the most complex, yet revolutionary functions of the smart grid, strongly correlated with the operation of HEMs and NANs is demand response. According to the European Parliament's Committee on Industry, Research and Energy (ITRE, 2017), electricity demand response is defined as "*changes in the electricity use patterns of end-users triggered by price signals or incentive payments*". This technology uses AMI, distributed generation and storage to provide price/volume signals and financial incentives, aiming at adjusting energy use and generation resources during peak demand and high-price periods. Especially, smart digital meters, as a part of AMI, are able to record power usage in real-time, provide dynamic pricing and remotely connect or disconnect power.

The demand response schemes are divided into two types, the price-based and incentive-based demand response. The first one affects the consumers' decision-making regarding their electricity usage behaviour, by providing them retail prices during fluctuating electricity demand. Specific companies use statistical artificial intelligence and behavioral game theory to collect and analyze all the rates available, predicting and indicating the best option for the consumer based on his preferences (The Carnegie Mellon's Scott Institute for Energy Innovation, 2014). These prices derive mainly from day-ahead markets, including time-of-use pricing (TOU), real-time pricing (RTP) and critical peak pricing (CPP). Incentive-based demand response has developed standardized methods - such as direct load control (DLC), emergency demand response (EDR) etc. - to offer flat rates to retail customers and provide them with voluntary incentives to induce a timely response. Consumers who participate in this process are eager to either shift loads from peak to off-peak periods, or adjust their demand patterns to periods of limited or abundant supply, especially during extremely sunny or windy days. Demand response can contribute to grid congestion alleviation and to a considerable reduction of scheduled investments in peak capacity and grid reinforcement, as well as to facilitate distributed renewable generation scheduling, resulting in more affordable customer bills. Even though demand response programmes have been primarily designed for commercial and industrial clients, examples of successful deployment in the residential sector in Sweden or California through the utilization of devices like smart refrigerators, pre-cooling air conditioners and smartphone apps pave the way for other countries, too.

2.5.5. Electric Vehicles (EVs) and energy storage technologies

One of the current and rapidly growing trends in the electricity sector, inextricably linked to the dissemination of renewable generation and smart grids, is the deployment of electricity storage technologies. Due to the intermittent and unpredictable nature of renewable energy sources, as well as fluctuations in electricity demand, storage devices are necessary for storing the renewable energy surplus generated during favourable weather conditions, in order to be available for use during peak demand hours. Hence, this technology is essential for the alleviation of grid congestion, it enhances the flexibility, reliability and cost-effectiveness of power systems, and enables a broader penetration of distributed solar and wind power into the electric grid. Currently, deployment of storage systems is relatively limited, reaching 5% of total installed electricity capacity.

While battery storage is necessary for the evolution of renewable technologies and smart grids, the opposite is not the case. Electrical energy storage (EES) technologies can be applied in a diverse range of sectors, including portable electronics, EVs and stationary systems (Nikolaidis & Poullikkas, 2017). Yet, one of the most promising functions of energy storage is the establishment of a dynamic interaction between buildings and smart grids. Residential, industrial and commercial-type buildings and construction represent a considerable percentage of global energy consumption, approximately 36% of the total final energy use (UN Environment & IEA, 2017). Smart Grid Optimized Buildings (SGOBs) can utilize embedded battery storage systems in order to respond to various notifications from the smart grid, demand response and real-time electricity pricing, totally transforming a building’s power consumption patterns. By assessing the hourly building loads, the battery storage system is able to charge during low or minimal energy activity of the building and unleash its full capacity during hours of peak demand (Georgakarakos et al., 2018). In case the discharged capacity exceeds the building’s consumption, the extra power can be redirected to the grid to compensate households through feed-in-tariffs or net metering. Deployed on a wide-scale, along with smart grid IoT infrastructure and distributed generation, this technology could perfectly perform as a supply-and-demand balancing mechanism with a beneficial impact on the affordability, reliability and efficiency of electric power.

The development of battery storage systems has accelerated the electrification process of the transportation sector. Electric mobility includes all types of street vehicles, i.e. cars, buses, and trucks, which either run on an electric battery-powered motor instead of an Internal Combustion Engine (ICE) and a tailpipe, or include both (hybrid and PHEVs). EVs have a great potential for reducing dependence on oil, as well as our carbon footprints. Not only that, they can improve the livability, workability, and sustainability of smart cities. Due to the fact that EVs and PHEVs are plugged into specially designed charging spots when parked, they can serve the electric grid as an independent, ancillary energy source, delivering power from their batteries to the grid through vehicle-to-grid (V2G) technology. V2G enables a bidirectional communication and energy flow from the vehicle to the grid and vice versa, in order to provide peak power and spinning reserves, or even renewable energy storage and backup (Yiyun et al., 2011). Being an essential part of the demand-side response, smart charging entails mutual benefits, as car owners can enjoy lower charges such as off-peak differential tariffs, and suppliers can exploit data from smart meters installed in the vehicles to adjust charging and discharging of the EV fleets to the variable supply and demand. According to ABI Research (2018), V2G could enable consumers to save up to USD 272 per year on their electricity bill, as well as bring cost-savings and additional revenues amounting to USD 2 billion to global energy suppliers in 2025. Nevertheless, V2G technology comes with a cost. Given the fact that battery life is being determined by the number of charge and discharge cycles, V2G could downgrade the life expectancy of batteries, leading to a faster depreciation of the initial investment (Mahmoudzadeh Andwari et al., 2017). Not only that, serious concerns and uncertainty remain regarding the time-consuming charging of the battery and the relatively low number of charging spots, especially in urban centers.

The abovementioned barriers can be counterbalanced by the perpetually declining EV battery costs during the last years, taking into account that they represent a large proportion of the entire vehicle’s cost, around 43%. According to a McKinsey & Company study (as cited in Carlson et al., 2018), the price of batteries has decreased by 80% since 2010, reaching USD 227 per kWh in 2017. This price is expected to drop below USD 200 by 2020 and account for around 19% of the total EV cost in 2030, resulting in even shorter break-even periods in comparison with conventional ICE cars (WEF, 2017). The most commonly used, especially in the automotive and IT industry, are lithium-ion (Li-ion) battery packs. Having a small size and being very light renders them ideal for portable devices and EVs; however, their use in large-scale applications requires vast quantities of lithium, the global reserves of which are already being depleted due to the rise in global consumption (Rade & Andersson, as cited in Nikolaidis & Poullikkas, 2017). Controlling almost half of the global lithium production (Figure 12) and by establishing multiannual trade deals with African countries for the supply of cobalt reserves, China holds a dominant position both in the production of advanced EV battery technology and in electric mobility, overcoming early movers in the respective markets such as Japan and South Korea. Only in 2018, more than one-third of the EVs sold were Chinese and future assessments forecast a 70% market share in the EV batteries industry until 2021. Like in the case of PVs, the involvement of Chinese companies in every segment of the supply and value chain of these industries, as well as economies of scale, give them the opportunity to keep prices at low levels even for a marginal product like EVs, threatening traditional car manufacturers in Europe and the US.

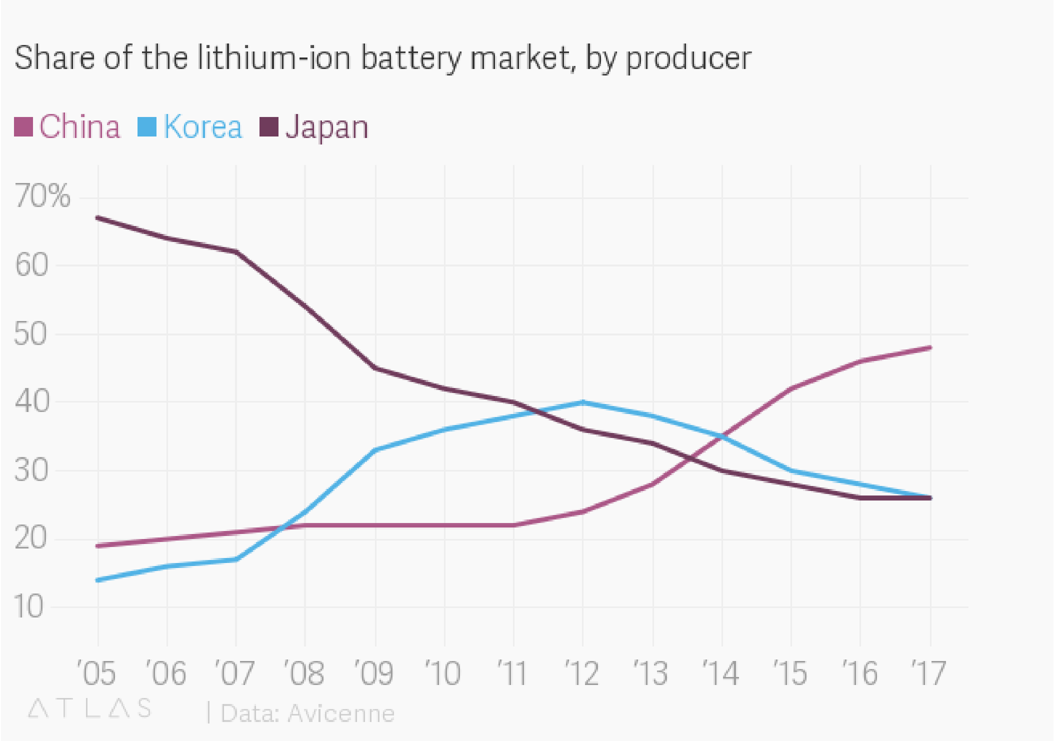

Figure 12. Share of the Li-ion battery market by producer. *Source*: https://www.theatlas.com/charts/SJoo4e3JX

Chapter 3: Methodology

3.1. Research questions

The previous analysis on the concept of energy security and the penetration of renewable and grid edge technologies - i.e., technologies advancing the transition to the next-generation electric grid - in the electricity sector highlights the paramount importance that access to clean and affordable energy has for the prosperity and functioning of modern societies. Accordingly, it raises the following research questions, which will be answered in Chapter 4 of the present research:

RQ1: What are the geopolitical implications of applying renewable and smart grid technologies in the electricity sector?

RQ2: In which ways could these technologies be applied in order to enhance energy security in SSA?

At this point, the research will focus on the changes, opportunities and possible threats the transforming energy sector is about to bring in the field of international politics, under the prism of the conflictual nature of international relations. Moreover, the potential of renewable and grid edge technologies will be assessed, in terms of their impact on the sustainable development goals of SSA.

3.2. Methodology

In order to elaborate on and answer the aforementioned research questions, an inductive qualitative grounded analysis has been conducted, mainly based on the simultaneous collection and interpretation of secondary data from other researchers and institutions. This method was selected due to the abundance of available bibliography relative with energy security, energy geopolitics and innovative electricity technologies, yet publications are more limited when it comes to the direct or indirect impact of such technologies on global politics and energy security. This leaves room for future estimations and hypotheses, as well as the formation of a new theoretical paradigm. As the dissertation topic refers to contemporary technologies rapidly changing, research has focused on publications made in the past ten years. Data is acquired from research papers, journal articles, annual reports, government publications and digital books. These sources were found through Google and Google Scholar, as well as in academic databases such as ScienceDirect, IEEE Xplore, Researchgate, Books.google, Academia, Taylor&Francis Online and Wiley Online Library.

Chapter 4: Results

4.1. Introduction

The results of the present research will be presented in two sections, each covering the respective research question. The first section deals with the tremendous impact that continuous technological advancements and innovation may have on the geopolitical power correlations, international trade, security and national electricity markets. The second part of this chapter will suggest viable solutions for a broader electrification of SSA. Specifically, Benin will be examined as a case study for the applicability of the proposed energy systems and their role as a driver for socio-economic development and energy security.

4.2. Geopolitical implications within a changing energy landscape

Undoubtedly, innovative technologies introduced in the energy sector - especially in electricity - during the last decade, have created a new dynamics in the field of international relations, as well as within the framework of global economics. They have also triggered a fundamental shift from a traditional security approach, based on the control of geographical spheres of influence, fossil fuel resources and military supremacy, to the race for controlling critical material supply chains and the flow of commodities, capital and information (Goldthau et al., 2018).

4.2.1. Ongoing and expected systemic changes

4.2.1.1. Renewable-based electrification

Technological innovation is contributing to the formation of more complex energy systems, by rendering more energy resources available to a much wider number of actors, in a local, national and transnational level. In a world dominated by oil and natural gas, with traditional powers like Russia and the oil-producing member-states of the Organization of the Petroleum Exporting Countries (OPEC), revolutionary techniques such as hydraulic fracturing or “fracking” and horizontal drilling in the US have brought forth unconventional energy resources with the power to limit or even terminate established global energy dependencies. The availability of shale oil and shale gas not only has unlocked the potential of the US for energy independence during the past five years, but also has rendered it the primary natural gas producer, threatening the energy-driven regional strategic influence of Russia. Just like in the case of shale gas, renewable and cutting-edge technologies relying on ICT and rapidly-evolving storage systems pave the way for further electrification of economy sectors, such as transportation and residential heating, which may imply alterations in the structure of national energy sectors. Electricity already accounts for 19% of total final energy consumption, being the fastest growing segment of final energy demand. While mitigating climate change becomes an increasingly important aspect of national strategies, the adoption of sustainable energy sources in the electricity sector shall continue to accelerate in the upcoming years, also given the fact that wind and solar technologies have almost reached grid parity. Figure 13 illustrates the energy transition trends with a view to 2100.

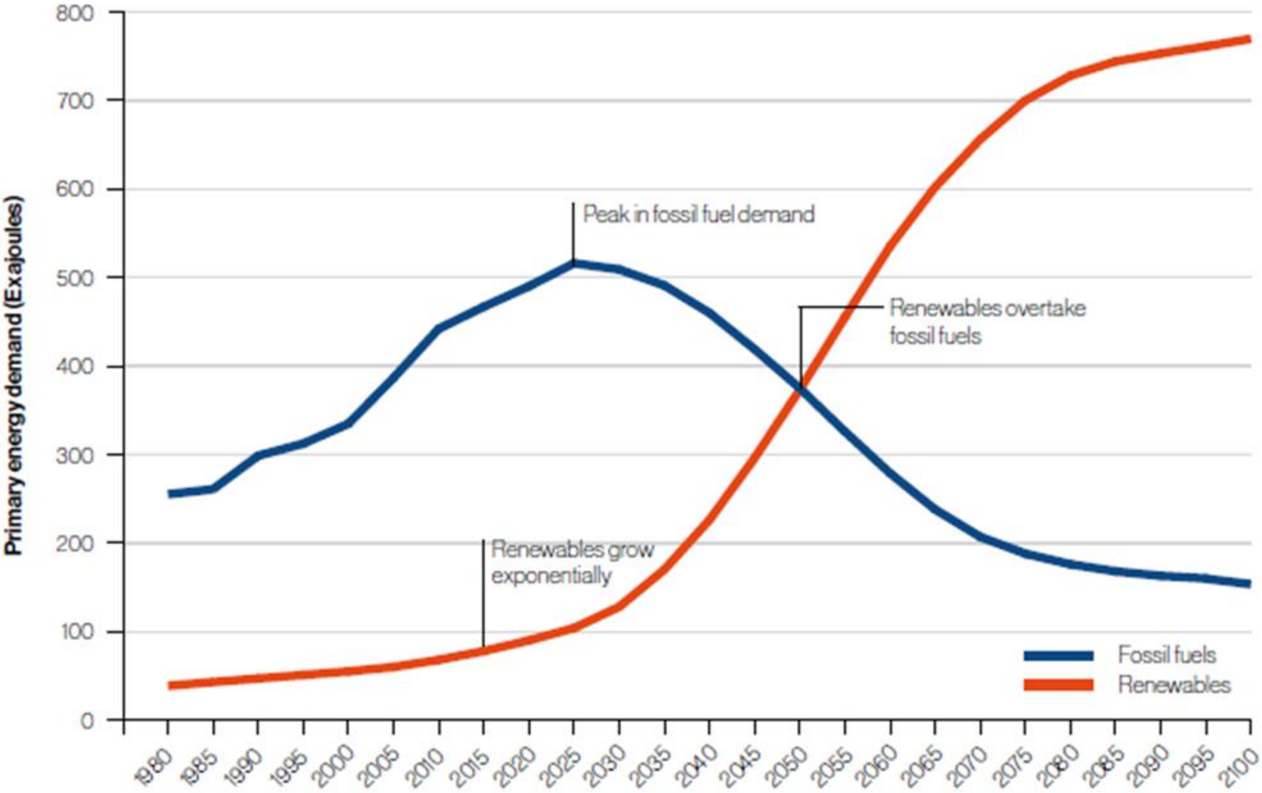

Figure 13. Energy transition trends. *Source:* Shell Sky Scenario 2018 (as cited in Global Commission on the Geopolitics of Energy Transformation, 2019).

4.2.1.2. Shifting away from traditional geopolitics

It is a fact that, unlike hydrocarbon resources which are highly concentrated and finite, renewable generation is available in abundance in much more countries, on condition that they have developed the necessary T&D infrastructure. The progressive integration of solar, wind and smart grid technologies in national energy systems, within the context of wider electrification, is expected to mitigate the oil and gas-related conflicts and undermine the strategic importance of traditional geostrategic assets, such as transit routes, maritime chokepoints and marine trade routes for the global oil supply. Global energy markets are more likely to become more regional, composed of electricity pools, grid communities and interconnectivity projects, and it will be harder for a single country to develop hegemonic plans. In addition, international strategic alliances are shifting away from fossil fuel-based collaboration, to coalitions focused on renewable energy and advanced technology development, such as the International Solar Alliance and the Global Geothermal Alliance. On the contrary, global energy demand will continue to rise, due to population growth and the increasing prosperity in rapidly-growing emerging economies. According to the BP Energy Outlook (2018), a one-third augmentation of global demand is expected within the upcoming 25 years, raising concerns regarding the sufficiency of renewable energy production. Unless energy efficiency and climate policy goals are achieved in the short-to-medium term, hydrocarbons will not cease to have an indispensable role in satisfying ascending demand, especially in large-consuming countries like China and the US.

4.2.1.3. New interdependencies and the clean energy race

In the new status-quo that is shaping up, it should be added that the accumulation of profits is shifting from the possession and trade of primary energy sources, to low-carbon technologies and methods converting these sources to end-use energy and services. For the last forty years, energy resources have been the driving force of world economy, playing an essential role in ensuring national and global security and stability. Access to considerable hydrocarbon resources has been exploited by several countries, which built and relied their economic and foreign policies on harvesting large oil and natural gas rents from their exports and exerting political and diplomatic influence whenever it served their respective national interests. However, by adding grid edge technologies into the current geopolitical equation, global energy interdependencies are being recalibrated, with heavily import-dependent states being less exposed to perilous fuel price volatility and currency fluctuations, and claiming a strong position in the clean energy race. These countries will be presented as follows:

China

Despite overcoming the US as the biggest importer of oil from the Middle East and being intensively dependent on oil and coal imports in general, China is a pioneer in the energy transformation competition. It holds a leading position in crystalline silicon PV modules, wind turbine components, EV and storage technology manufacturing, as well as in innovation and integration of renewable sources, being the world largest investor in clean energy technologies and energy efficiency with around USD 126,6 billion only in 2017 (Huang, 2018). These sectors, along with the country’s beneficial position regarding critical material supply chains and industrial clusters, are not only capable of reducing environmental damage and carbon footprint, but also of counterbalancing China’s massive energy trade deficit. While Russia, the Middle East and the US are the leading powers in the hydrocarbon sector, China has all the makings of becoming the future renewable energy monopolist (Carlson et al.,2018). In addition, China represents the “Global Energy Interconnection” initiative, a USD 50 trillion worldwide electricity grid based on wind and solar energy, estimated to be operational until 2050. This “supergrid”, which is a part of the broader “Belt and Road Initiative”, will connect the North Pole with regions in the equator, and could enhance China’s geopolitical prestige and energy security in its periphery. Another important parameter of China’s decarbonization process is the positive impact the partial displacement of coal from clean technologies can have on the dangerously high levels of air pollution in most urban centers. Improving air and water quality is a prerequisite for social security and stability, especially in a very densely populated country like China.

USA

Although its energy-related benchmark during the last five years has been the shale revolution, which has brought natural gas prices up to 80% down and nearly doubled its oil production, and despite its withdrawal from the 2015 Paris Agreement, the US is also very well-positioned in advanced electricity technologies.

Along with China, the US has positioned itself at the forefront of the renewable energy race, consuming the equivalent of 143 million tonnes of oil in renewable energy in 2016 and having the second largest installed solar PV and wind energy capacity. According to MacDonald et al. (2016), the US electricity sector carbon footprint could be reduced up to 80% in comparison to 1990 levels, without increasing the LCOE. Moreover, US companies hold a strong position in technology sectors such as machinery, artificial intelligence, wind turbines and EVs, all of which are critical components of smart grid systems. In an effort to counterbalance and contain the increasing power of China, the US administration has given priority to the "Free and Open Indo-Pacific" strategic initiative, planning to engage in deeper economic activity in the Indo-Pacific region in the form of bilateral economic cooperation with Japan, India, Australia and Mongolia. In this context, the US has committed to investments worth US$113.5 million in energy infrastructure development and digital interconnectivity projects, envisioning to promote sustainability and energy security in the region (Palit & Sano, 2018). In addition, in the 2016 "Three Amigos Summit" in Ottawa the US, Canada and Mexico leaders jointly pledged to generate 50% of their combined electricity production from non-carbon emitting sources by 2025 (Meadowcroft et al., 2018).

India

It is a fact that around 80% of the growth in global energy demand comes from fast-growing developing economies, with half of it stemming from India and China. Just like in the case of China, India has benefited from a remarkable resource endowment and very low installed costs - due to low labour and raw material costs and their access to low-cost local manufacturing hubs - to build up a great dynamics in the solar PV and onshore wind markets. Investing in its renewable energy potential is of vital essence for India, given the limited availability of oil and gas reserves and its high dependence on fossil fuel imports. This fact was reflected in the formation of the International Solar Alliance (ISA), an intergovernmental treaty-based organization of solar resource-rich nations initiated by India in 2015, with the ambition to replace OPEC as a key global energy supplier in the future. The country has also made significant progress in eradicating the issue of energy poverty through national electrification projects based on off-grid renewable energy mini-grids and it is expected to surpass China as the world's largest energy growth market by mid-2020s (BP Energy Outlook, 2019).

Germany

While not enjoying the most favourable conditions for renewable energy generation, Germany has managed to establish itself as one of the global leaders in clean energy. Committing to drastically reduce the country's GHG emissions and transform its energy sector, the German government in 2010 adopted the so-called "*Energiewende*", a planned effort to reconfigure its energy system towards renewable energy, demand management and energy efficiency. To this context, it has set a long-term goal to generate 80% of its electricity from renewable sources by 2050 and encourages mutually beneficial collaboration among German and Chinese wind and solar firms. Germany has the third largest share of total installed wind capacity and, among European countries, it leads the way with around 31.000 renewable energy patents (Global Commission on the Geopolitics of Energy Transformation, 2019). Not only that, it displays a notably high degree of decentralized renewable generation and customer engagement, as private individuals owned 31.5% of installed renewable energy capacity in 2016. Nonetheless, Germany has a long way to go regarding the decarbonization process of its heating and transport sectors, with German car manufacturers insisting on developing diesel-based combustion engines instead of EVs and PHEVs.

4.2.1.4. Decentralisation of national energy systems

As the case of Germany indicates, a major transformation is taking place in the core structure of national energy systems. The spread of technological innovation has the potential to reshape the traditional model of centralized, state-owned power plants which has dominated the western world for decades. Specifically, the higher the penetration of renewable and smart grid technologies is, the more decentralized the energy system will become. This transition is based on the principle of "enabling power generation closer to where it is being consumed". This fact implies that, as the battery systems' cost and the LCOE of solar PV and wind energy continue to decrease, and smart distribution systems become more integrated and widespread, passive electricity consumers will be able to become "prosumers", i.e. consumers and producers simultaneously within an interconnected, bidirectional energy flow grid. The ability to generate electricity domestically, in offices etc. would imply the potential of a peculiar societal rejuvenation. More specifically, it would result in a much larger number of generation facilities and owners, empowering private individuals and regional authorities vis-à-vis central governments and private interests, through granting them the choice of preferable electricity sources and a considerable share of economic benefits (Scholten, 2018). Decentralized renewable generation will certainly have a positive impact on infrastructure costs, enabling the adjournment of O&M expenses during periods of overcharging, as well as on the overall grid capacity and efficiency through IoT technology and smart demand-side management.

4.2.1.5. The effect of distributed storage on negative pricing

The contribution of the decentralization process to energy security can be further comprehended if we examine another key aspect of it, the distributed storage capability. Electricity storage could be a valuable asset in the hands of policymakers and stakeholders when it comes to addressing the issue of negative pricing in liberalized energy markets. Whereas liberalized market mechanisms require positive marginal costs - i.e. marginal production costs that are lower than the market clearing price, generating incremental revenues for power plants to cover their fixed costs - and dispatchability of power, these two preconditions are not compatible with wind and solar technologies, which are highly intermittent and have nearly zero marginal costs (Blazquez et al., 2018). Given that prices in power markets are determined by supply and demand and the fact that renewable energy is being given priority in the dispatch order, negative pricing occurs during certain hours of the day when oversupply of electricity entering the grid from renewable sources surpasses demand, creating an imbalance described as the "load duck curve" (WEF, 2017).

In cases of big-scale renewable technology deployment, the difference between their relatively high LCOE and their negligible marginal cost creates a divergence between the true cost of the system and electricity prices in wholesale markets, which fall to zero levels or, even worse, below zero. Negative prices are, in fact, market signals indicating that producers should temporarily shut down some power plants. However, as many power production facilities are not designed to immediately ramp up and down, it is often less detrimental for them to keep the plants operating and distribute energy for free or even pay consumers to use the excess power, merely losing a part of their expected profit (Starn, 2018). This phenomenon, which is very common in Europe and the US, could be mitigated through a broad deployment of distributed storage systems, such as Li-ion batteries, compressed air energy storage (CAES), pumped heat electrical energy storage (PHEES), flywheels and vehicle batteries through V2G technology. Distributed storage offers resilience, as power surpluses during sunny/windy days or low-demand hours shall be stored and utilized during peak-demand or emergency cases, flattening out the peaks and valleys of supply and reducing price volatility. (Renewable Energy Association, 2016). Not only that, grid operators could exploit grid-connected distributed storage capacity to create virtual power plants, with domestically-generated excess power being fed into the grid and redirected to other homes that lack a storage system. In Germany, more than 100.000 grid-connected battery storage systems have been installed in households so far and, according to recent projections, global demand for energy storage will increase from 400 MWh in 2015 to nearly 50 GWh in 2025 (Rathi, 2018; WEF, 2017).

4.2.1.6. Sector coupling

Until now, national policies have been focusing on individual sectors, i.e., heating and cooling of buildings, transportation and industry, as well as on their respective fuel mixes. Yet, the energy transition is about to bring forth and, to some extent, will be based on another essential change in the existing power markets, the sector coupling. This concept encompasses the "*co-production, combined use, conversion and substitution of different energy supply and demand forms – electricity, heat and fuels*", describing the interconnection and integration of the abovementioned end-use market segments with the variable renewable energy producing sector (IRENA, IEA and REN21, 2018)(Figure 14). Transportation and residential heating are operating mostly on fossil fuels, however as solar PV and wind power reach grid parity and technologies such as EVs, V2G, smart charging and heat pumps are more and more being adopted, the indirect electrification of these sectors would enhance the grid's operational efficiency and flexibility. Sector coupling creates new links between energy carriers and transport infrastructure, with technologies such as Power-to-Gas (P2G) enabling excess electricity to be used for producing hydrogen through water electrolysis and synthetic methane via methanation. These fuels can be stored on a large scale for long periods or even replace fossil fuels in many end-use applications, and hydrogen may as well be mixed with natural gas in order to partially decarbonize the gas grids and fully utilize the value of existing gas assets. In the same way, a part of generated renewable power could be utilized to heat large amounts of water for heating houses, indirectly electrifying the heating sector through Power-to-Heat (P2H) technology. Market coupling is necessary for achieving the energy transition objectives, i.e., competitiveness, sustainability and security of supply, in a cost-competitive and publicly acceptable way (Olczak & Piebalgs, 2018).

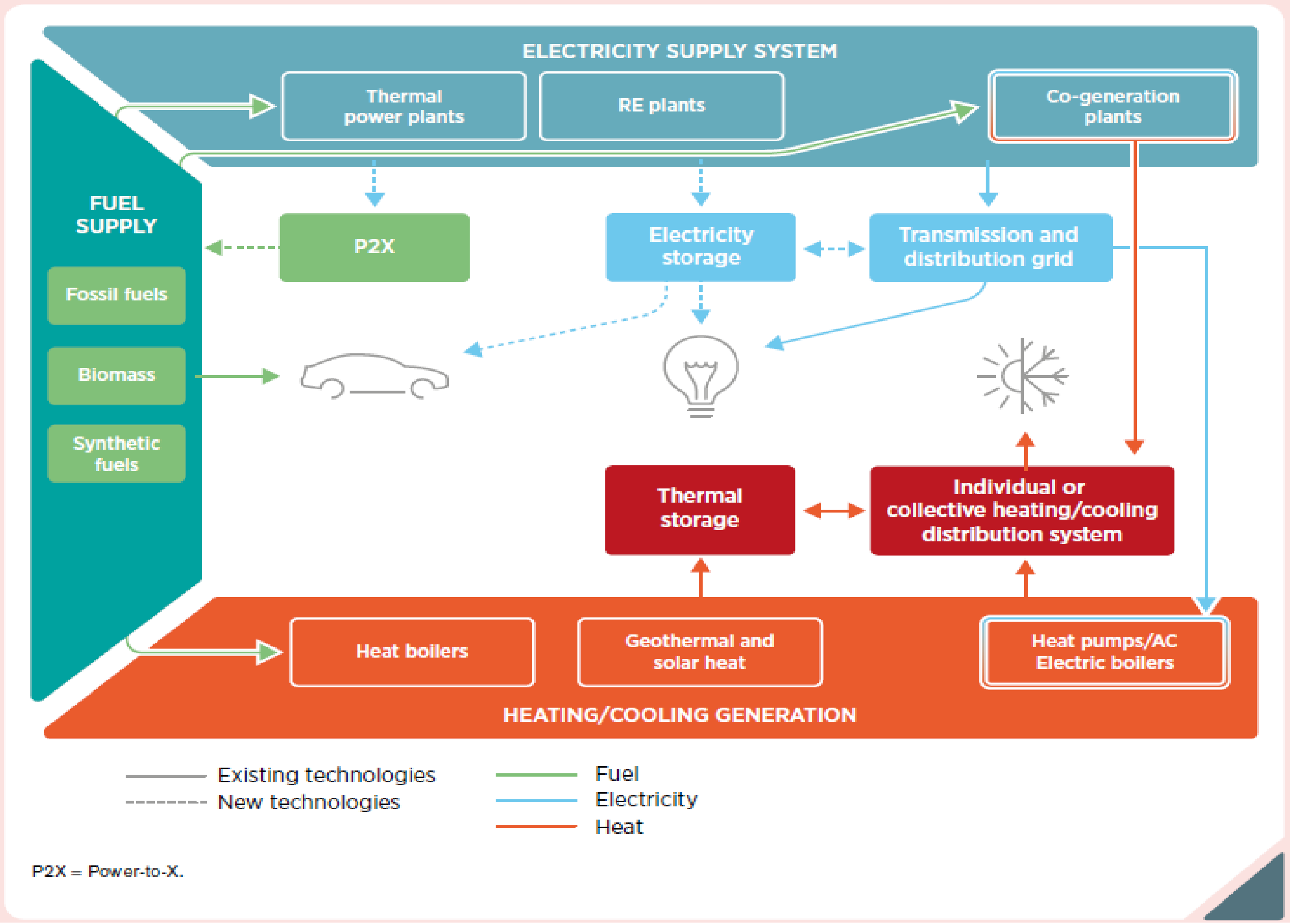

Figure 14. Graphic representation of sector coupling. *Source*: IRENA, IEA and REN21, 2018.

4.2.2. Potential threats to international system stability

4.2.2.1. Geopolitical race for control over critical materials

A common assumption with respect to the consequences of the ongoing energy transition is the intense competition over materials critical for renewable energy hardware. Rare earth metals are widely used in the construction of wind turbines and solar panels. For instance, neodymium, praseodymium, terbium and dysprosium are necessary for manufacturing permanent magnets for direct-drive wind turbines, even though the majority of turbines operate on a gearbox (De Ridder, as cited in Overland, 2019). Moreover, light metals like lithium, cobalt, nickel, indium, aluminium and copper are significant for manufacturing Li-ion and nickel-metal hydride (Ni-MH) battery technology, electric turbines and distribution infrastructures. Although rare earth elements theoretically are relatively geologically abundant, they are usually found in dilute quantities, which renders their extraction, processing and commercial exploitation very capital intensive. Not only that, like other markets, rare earth and mineral markets are cyclical, as it usually demands time for suppliers to respond to demand rises. This leads to price spikes, overinvestments in mining projects by the involved companies and a subsequent price collapse which closes the cycle.

As previously stated, China holds an uncontested dominant position in these respective markets by producing 85% of global supply, hence it is expected that it will attempt to gain geopolitical leverage over countries lacking such resources, either unilaterally or in the form of cartelization along with other significant players like Russia, Australia and the Democratic Republic of Congo. Besides, China has already resorted to methods of exerting political pressure in the past. Specifically in 2008, the Chinese government restricted the supply of rare earths to foreign importers, jeopardizing international security through uncertainty and soaring prices. Thereinafter, a territorial dispute and a subsequent diplomatic crisis which occurred in 2010 between China and Japan led the second to impose an embargo for two months, as a means of diplomatic coercion and power projection towards its adjacent country (Wilson, 2017). This unprecedented incident not only led to the intervention of the World Trade Organization (WTO) in China's rare earth export policy in 2014, but also triggered technological innovation in the US, Japan and Europe, weakening China's grip on the market (Gholz, as cited in Overland, 2019). With current data, the most possible scenario is that critical materials will remain a significant source of revenues for exporting countries and a valuable asset of global energy security. Moreover, leading exporters will most likely one-sidedly attempt to use them as a foreign policy instrument. However, the formation of a cartel to control critical material markets will be much more difficult than in the case of oil. First of all, considerable efforts to lower dependence on such materials have been made, such as the development of cobalt-free batteries and a big-scale replacement of supermagnets in EV and wind turbine motors by advanced silicon-made control software and power electronics. In addition, unlike fossil fuels, most critical materials for renewable technologies can be recycled, re-used and stockpiled, facts which reduce their degree of scarcity (Lovins, 2017). As long as technological methods evolve and investments in geological exploration will continue to be made, additional supply sources for rare earth elements may emerge in different countries, mitigating the current Chinese supremacy.

4.2.2.2. Vulnerability of fossil fuel exporting countries

A gradual transition to solar and wind-based smart electricity grids will probably entail significant challenges for major oil and gas producers, in the medium-to-long term. At this point, it should be highlighted that energy transformation would not automatically imply a holistic replacement of oil and gas with alternative energy forms; besides 22% of global electricity production derives from natural gas. Moreover, the transportation sector is still dominated by oil, with individual mobility accounting for about one-third of total oil demand and electric mobility still being at a quite premature stage, slowly gaining market share. Yet, there is the other side of the coin. Traditional fossil fuel-rich countries, the international status and political influence of which has been defined by their exporting capability, are more and more likely to face key challenges both in their internal and external policy, unless they manage to adapt to the new circumstances. While fossil fuel demand is projected to peak in the mid-2020s, major oil producers such as Russia, Saudi Arabia, Nigeria and Venezuela are already witnessing serious fiscal deficits due to the downward trend of oil prices and, consequently, of their net oil export revenues. In the US, despite the country's prominent position in the clean energy competition, the oil price drop has brought about a rise in unemployment in specific oil-producing states, like

Texas and Alaska. The restriction of oil and gas demand driven by the necessity to keep global warming well below 2°C and the reduction of expected fossil fuel rents, through which rentier states have propelled their economic development and financed other economy sectors, will devaluate these energy resources and lead them to become stranded assets. This fact could have a crucial destabilizing effect on these countries, not only by undermining their economic growth, but also by triggering social backlash and political upheaval in the short-term. They will also be prone to experiencing a decline in their global reach and geostrategic influence, which countries like Russia and Venezuela have exerted in multiple cases within their periphery in the form of "stick and carrot".

The degree of readiness of fossil fuel-producing countries to redefine their national strategies, prioritize political and economic reforms and diversify their economies will highlight their exposure or resilience to the challenges posed by the ongoing energy transition. This is clearly illustrated in Figure 15, which includes countries in which fossil fuel rents account for more than 5% of their GDP. Some countries, particularly the Gulf States such as Saudi Arabia, Qatar, Kuwait and the United Arab Emirates, as well as Malaysia, Norway, Colombia, Bahrain and Indonesia, have already exhibited considerable efforts to diversify their economies and reposition themselves in the new global energy status quo, mainly due to sufficient state resources.

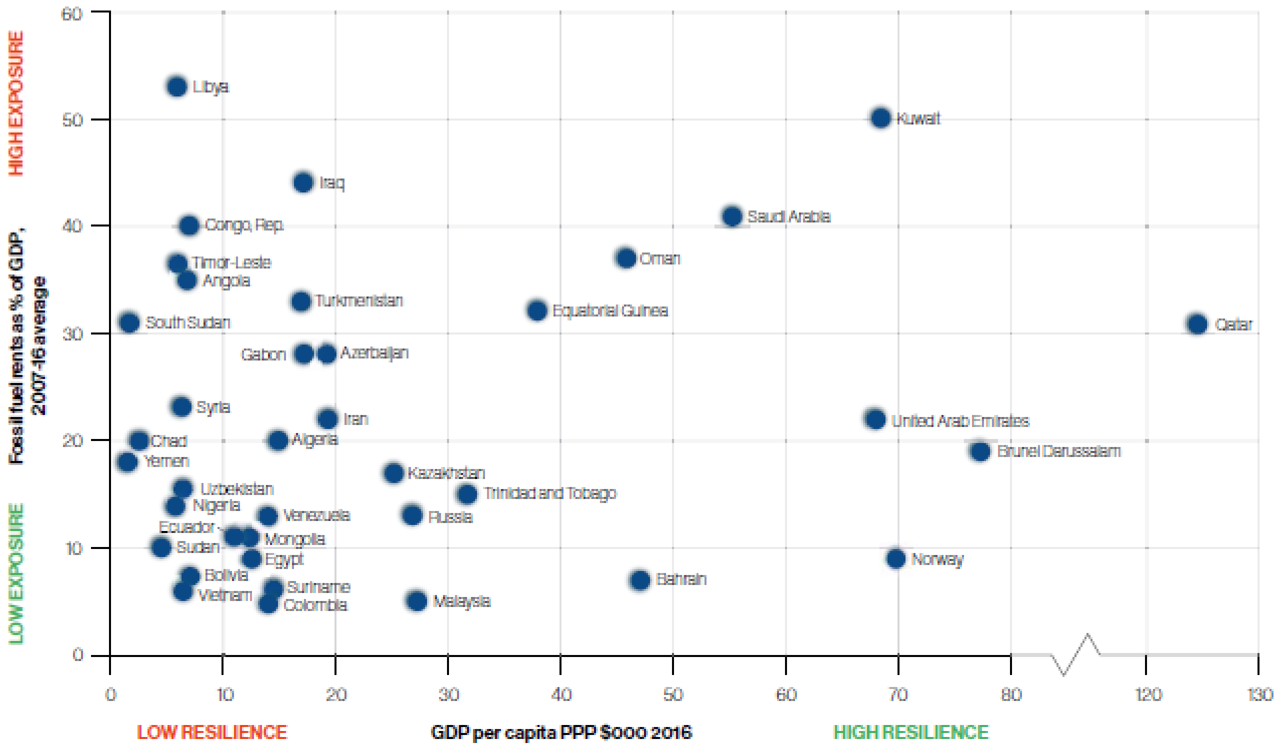

Figure 15. The relative degree of readiness of fossil fuel-producing countries for adopting to the energy transition. *Source*: IMF World economic outlook database April 2018, World Bank (as cited in Global Commission on the Geopolitics of Energy Transformation, 2019).

On the other hand, there are partly resilient and vulnerable countries like Russia, Nigeria, Iran, Algeria and Azerbaijan, which remain highly dependent on fossil fuel exports and are struggling to reconsider their long standing policies. However, the most exposed are Iraq and the African oil-rich countries, such as Libya, Angola, the Republic of Congo and South Sudan, some of which are deemed failed states and others already suffer from dysfunctional public sectors, racial/civil conflicts and stagnant economies (The Oxford Institute for Energy Studies, 2019). Regardless the unique characteristics and the potential of each of these countries, the energy transformation will affect the balance of power in the international system, the relationships among states, as well as between central governments, private sectors and individuals.

4.2.2.3. Critical grid infrastructure and cyber-terrorism

Energy infrastructures have become a lifeline for the daily function and welfare of modern economies and developed societies. The electricity grid infrastructure is a segment of the critical energy infrastructure, comprised of all the power-generating plants and facilities, grid-connected micro-grids, as well as the T&D lines delivering power to end-use customers. These components of the electric power system are all vulnerable to failure due to natural, operational or manmade events, with cascading effects on other critical infrastructure, such as the healthcare and industrial one (Campbell, 2018; Goldthau et al., 2018). Therefore, the unimpeded, reliable and perpetual operation of electricity grids is considered a vital part of the energy security, both on a national and a regional level. Yet, the application of grid edge technologies, new business models and practices in the electricity sector is not only leading to a broader electrification of national economies, but also transforming the established grid architecture, creating new uncertainties and potential threats.

Smart grids are operating within a complex framework of interconnected ICT devices and digital functionalities, controlled by SCADA systems and embedded into the physical power system. The high degree of digitalization and system integrity is driving technological and social changes which are progressively unlocking grid balancing and optimization, distributed renewable energy deployment, a more active household, community and industry engagement in energy decision-making processes, efficiency and demand management, and new energy services (Meadowcroft et al., 2018). Nevertheless, in the absence of an international legal framework, it has introduced cyber-attack issues, which are directed towards critical energy delivery functions and can be perilous both for the national security and social prosperity of the developed countries. Cyber-attacks can be conducted by individual hackers, criminal organizations, terrorists, or even by another country's security services, aiming at causing power supply sabotages, extensive damage to internal markets or acquiring essential financial, military or industrial information. The most vulnerable digital targets of power grids are the control centers and applications, the IoT-enabled devices and AMI/AMR systems, while the physical are the T&D systems. A typical example of cyber assault has been the case of a cyber-attack in the information systems of three energy distribution companies in Ukraine in 2015. As a result of this attack, which is the first confirmed attempt to take down a power grid, thirty substations in Western Ukraine were switched off, leaving about 230.000 people without electricity for a period of between 1 and 6 hours (Zetter, as cited in Overland, 2019). In addition, malware infections of IoT devices, usually causing a denial-of-service or launching other cyber-attacks, has been an increasing phenomenon (Campbell, 2018).

The cyber-threat could be more prominent in the case of transnational interconnections via renewable-based supergrids, which will be an inherent component of the energy transformation. As many countries are engaged and interdependent within a multinational grid, a potential cyber-intrusion in the ICT systems one of those countries would affect the others too. In the worst case scenario, a well-designed cyber-attack could disrupt cooperation and solidarity among the interconnected countries, by creating distrust or even tensions between them, especially in case a single country is facing severe power outages. On the other hand, there is a more dispassionate scientific approach in academic literature, according to which the digitalization of the electricity sector is not a new case; on the contrary, electric grids have been digitally controlled for decades, hence traditional grids were as well exposed to cyber-crime (Overland, 2019). In addition to that, distributed renewable generation and storage based on off-grid and near off-grid installations and micro-grids - being able to operate independently of the grid - might enhance the grid resilience to cyber-attacks, by providing backup power in emergency situations. Besides, grid operators and the incumbent companies are already applying counter-measures and designing contingency plans in order to cope with weather-related power outages or terrorist attacks in critical infrastructure and, much more, to enhance cyber-security of smart grid systems.

4.3. Boosting energy security in SSA

4.3.1. Introduction

Although African economies and energy demand are growing at a fast pace, SSA remains the most energy-impoverished region in the world, having very low household electrification rates even compared to other developing regions. Accounting for around 13% of the global population, its primary energy demand reaches only 4% of the aggregate. Not only that, roughly one-third of SSA inhabitants have access to electricity, which in most cases is unaffordable, insufficient and unreliable due to the lack of the appropriate grid infrastructure. This element is directly impeding the region’s economic development. Yet, SSA is rich in natural resources and has ample potential regarding distributed solar PV and wind generation. This chapter will suggest attainable technical solutions for unlocking the region’s renewable energy potential and enhancing its energy security. For this purpose, Benin will be examined as a focus case for the applicability of renewable and micro-grid technologies in rural and remote areas, which will pave the way to a more cost-effective, secure and environmentally sustainable electricity supply in sub-Saharan countries.

4.3.2. Key figures and challenges

According to the World Bank 2016 stats[1], access to electricity in central and southern Africa averages 42.8%, ranging from 7.59% of total population in Burundi and 8.83% in Chad, to 59.3% in Nigeria, 79.3% in Ghana and 91.4% in Gabon. Besides Burundi and Chad, other countries where the problem is more intense are South Sudan (8.95%), Malawi (11%), the Central African Republic (13.99%), the Democratic Republic of Congo

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[1] World Bank Sustainable Energy for All database (2016). Access to electricity (% of population). Retrieved from https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2016&locations=ZG&start=2000&view=chart

(17.15%), and Burkina Faso (19.16%). Energy poverty is exacerbated in rural areas of the SSA, where the traditional grid cannot easily be extended, hence around 75% of the population lack access to electricity. Instead, rural dwellers still depend mostly on the use of traditional biomass - i.e., charcoal, wood, agricultural residues etc. - and small diesel-fired thermal power stations for heating and cooking purposes, a fact which entails considerable environmental and public health risks (IRENA, 2015b). In particular, exposure to polluted air has increased lung infection outbreaks and incomplete combustion of carbon from coal used for cooking has also a tremendous impact on global warming and climate change (Legros et al., as cited in Dioha, 2017). The majority of rural residents also lack the ability to satisfy basic needs, such as the ability to light, warm or cool their homes, being exposed to extreme weather conditions depending on the season.

Most SSA countries are also facing several issues, deep-rooted in their national energy sectors, economies and societies. Due to the inadequacy of many of the traditionally built power grids and delivery systems, electricity generation reaches only 40% of the installed capacity in the region. The non-upgraded and poorly maintained T&D networks are responsible for frequent power outages and huge power losses during delivery. Apart from the insufficient technology diffusion and unreliable electricity supply, SSA countries exhibit highly corrupted energy sectors and administrations, social inequality and very low per capita incomes (Dioha, 2017). One of the major challenges for the region, however, is to establish a comprehensive legal framework to regulate the energy industries and implement renewable energy production.

It is expected that urban dwellers will outnumber rural residents for the first time in Africa by 2050 (Saghir & Santoro, 2018). Given the fact that the GDP of many SSA countries is concentrated, or even reliant, on the productivity of urban centers, and the expected 6-fold growth of those countries' national economies in a thirty-year horizon, demand for electricity in the region will indubitably multiply (Murenzi & Ustun, 2015). This fact alone threatens their energy security, in the sense that the number of people without access to energy services is growing faster than the number of people newly connected to the electricity grid. However, advanced technologies and recent reductions in the LCOE of solar PV and wind energy are creating new opportunities for SSA countries to address their energy challenges, by ensuring universal access to modern energy services in a more effective and affordable way, without increasing greenhouse gas emissions and environmental pollution.

4.3.3. Rural electrification of Benin through decentralized energy systems

Being located in the Gulf of Guinea in West Africa, Benin is facing most of the aforementioned challenges and impediments on its way to achieving energy security. Benin demonstrates a nearly moderate electrification status, with electricity access being available to 41.4% of its total population and to 18% of rural dwellers. Therefore, this part will focus on the energy security of rural and remote areas of Benin. Domestic consumption is dominated by firewood, charcoal and other forms of non-sustainable biomass, at a rate that exceeds 80% when it comes to rural and low-income populations. At the same time, almost all the petroleum products and around 76% of electricity are imported from Nigeria, Ghana and Côte d'Ivoire, with the country being frequently subject to power shortages due to curtailed supply from its neighboring states (The University of Abomey-Calavi Foundation, 2018). SBEE, the Beninese electrical power company, has very limited financial resources, let alone its growing financial losses, and the country in general lacks the appropriate institutional capacity and technical expertise. Another important downside of the Beninese energy sector is the average residential electricity price, estimated at USD 0.16/kWh[2], which is very high in relation to the average solar PV cost of USD 0.10/kWh.

Benin has a considerable, yet untapped renewable energy potential, especially regarding solar generation. A very promising solution for untapping this potential are the off-grid micro-grids, based on renewable sources, which offer various benefits. Micro-grids are divided into two categories, decentralized and stand-alone systems. Decentralized micro-grids are small-scale, self-sufficient power systems, composed of a cluster of loads and production sources interconnected with energy management, control and protection devices and associated software (Murenzi & Ustun, 2015). They also have the ability to operate both in grid-connected and islanding mode (Fauteux & Belmokhtar, 2018). Hence, they can either supply electricity to single households or deliver power to localized groups of customers and several communal structures - i.e., health centers and schools - within small villages. Micro-grids are suitable for cases in which grid expansion is either unaffordable or technically unfeasible, due to lack of know-how and remoteness of rural communities, like in the case of Benin. Instead, energy is produced in the place where it is consumed, requiring any costs for T&D. They can be very cost-efficient over their lifetime, relatively easy to deploy and install, and they have low maintenance costs compared to diesel engines (Dimitriou et al., 2014). As Figure 16 illustrates, solar PV potential is considerably higher in the central and northern parts of the country, which include several rural communities suitable for the installation of solar-based micro-grids, reaching an annual generation capacity of 1.6MW per unit.

On the other hand, stand-alone systems share the characteristics of decentralized micro-grids, yet they are not grid compatible. The most common example is solar home systems (SHS), i.e., stand-alone solar energy systems comprising of a solar panel, a battery, an inverter and a charge controller. SHS could be the key for electrifying Benin's remote dwellings, as they are able to meet a household's basic electricity needs, powering low-consuming appliances such as lighting systems, refrigerators, radios and small TVs. Their biggest advantage is their modular configuration, which means that they can be expanded in accordance with growing demand. Moreover, alternative payment methods applied in other developing countries, have increased the affordability of SHS for low-income populations. Instead of purchasing them in advance, Beninese customers may opt for pay-as-you-go SHS. Such systems are based on solar lanterns, which are small, portable lighting fixtures, usually consisted of a LED lamp, a rechargeable battery and a separate small solar panel[3]. Solar lanterns are twice as efficient as the quite harmful kerosene lamps are and they prevent a significant amount

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[2] United for efficiency. (n.d.). Retrieved from https://united4efficiency.org/country-assessments/benin/

[3] Electrical4U. (2018). Solar lantern. Retrieved from https://www.electrical4u.com/solar-lantern/

of carbon emissions. Moreover, they provide about eight hours of emission-free lighting each day and enough power for mobile phone charging, reducing a household's weekly energy expenses by up to 50%. In this way, customers are exempt from the up-front costs for installing solar panels and engage to very low hourly, daily, weekly or monthly payments via their mobile phones. Not only that, once SHS are fully paid-off, they automatically switch to client ownership status. A broad deployment of SHS will replace diesel engines and contribute to improved air quality, reliability of supply and living standards of local populations. It is also expected to facilitate private sector participation in the development of new commercial supply chains for solar power technologies.

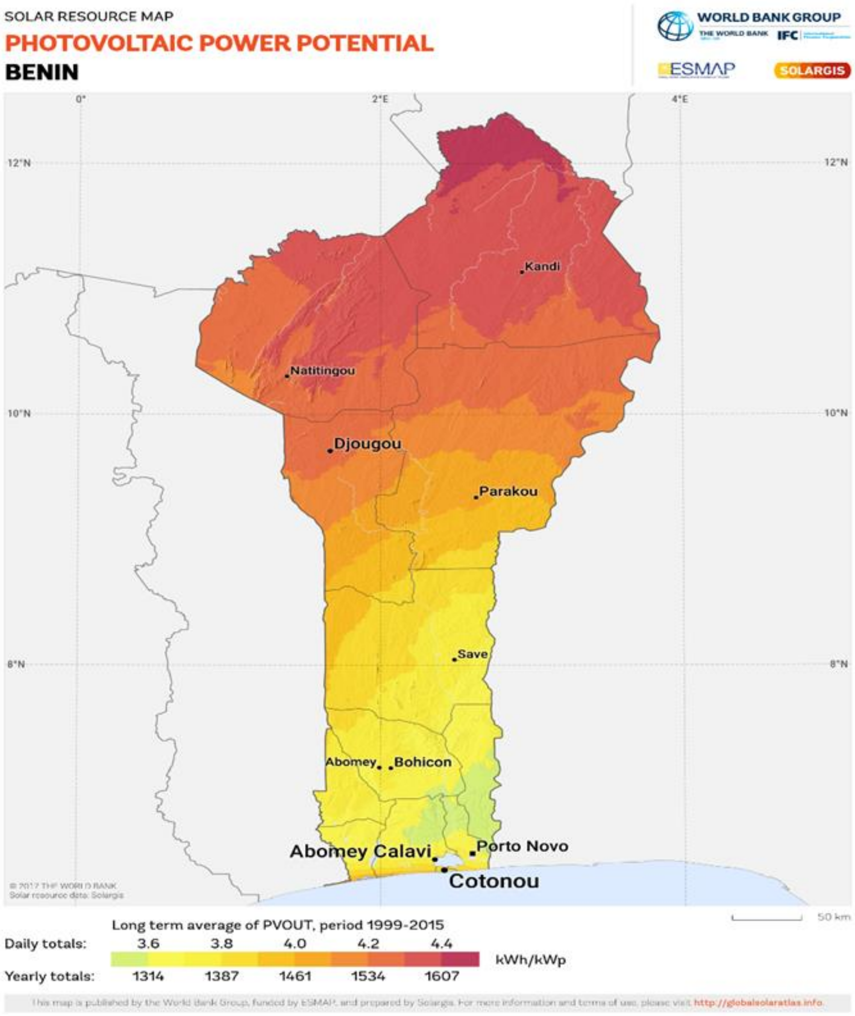

Figure 16. Solar PV power potential in Benin. *Source*: https://globalsolaratlas.info/downloads/benin

Solar-powered drip irrigation systems have also started gaining momentum in Beninese remote locations. These systems are composed of solar PV arrays which power a water pump, delivering low-pressure water - and usually fertilizers - directly to plants and crops through a water reservoir. Solar-powered pumps offer a cost-effective, durable and long-term solution, operating without the need of battery systems and enabling the expansion and higher productivity of valuable crops in dry regions where they would be hardly sustained solely by rainfalls. As an initiative by the International Crops Research Institute of the Semi-Arid Tropics, several pilot solar-powered drip irrigation systems have been installed for years in high-priority North-eastern villages in Benin, such as Kalalé, Dunkassa and Bessassi, with very encouraging results regarding food security, local incomes and environmental sustainability.

However, a key issue is the funding projects and initiatives that will uphold and accelerate the deployment of off-grid solutions in poor and remote regions of Benin. The Off-Grid Clean Energy Facility (OCEF), is a USD 32 million challenge fund, aiming at financing sustainable and reliable off-grid micro-grid and efficiency projects for households and essential public facilities in Benin over a five-year period (2017-2022). OCEF is part of the Off-Grid Electricity Access project financed by the Millennium Challenge Corporation (MCC) of the United States of America and implemented by the Millennium Challenge Account Benin-II[4]. In addition, the Power out of Poverty Partnership is a public-private initiative led by the Netherlands Development Organisation, in partnership with MTN Benin Telecommunication enterprise, the Government of Benin, local solar power companies and a local micro-finance institution. This partnership aims at distributing modern solar power products to the off-grid populations of Benin, such as pico-solar systems, solar lanterns and lamps for indoor and outdoor lighting purposes. Regarding large-scale generation projects, the Economic Community of West African States (ECOWAS) is planning to construct two solar power plants north Benin, specifically in Kandi and Djougou, with a capacity of 5.9MW and 5MW, respectively (Bazyomo et al., 2016). In the context of EU’s Africa Renewable Energy Initiative, the European Commission has announced the construction of a 25MW solar plant in Benin, among other projects that include rural electrification and grid upgrades. These projects are capable of upscaling the electrification rate of rural Benin, providing its populations with more affordable and sustainable forms of energy, bringing in technical expertise and encouraging the private sector development. Not only that, they will provide the necessary ground for the upcoming urbanization of the country, by upgrading and expanding urban electricity grids and facilities, and enhancing its overall electricity production capacity.

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[4] Millennium Challenge Corporation. (2018). New Opportunities in Benin: A Call for Proposals. Retrieved from https://www.mcc.gov/blog/entry/blog-022718-benin-call-for-proposals

Chapter 5: Conclusions

The principal issue considered in the previous chapters is the contribution of pioneering technologies already in place in the field of electricity, to international energy security. For this purpose, a heterogeneous set of energy security definitions derived from various academic sources was initially quoted, with emphasis given to the concepts of affordability and accessibility of energy, as a theoretical framework for analyzing essential geopolitical and economic effects from applying advanced technologies both in the developed and the developing world. This chapter will summarize the key points and conclusions drawn from the literature review and the results of this research, along with suggestions regarding further research on the related topic.

5.1. Summarizing the impact of advanced electricity technologies on energy security

For about two decades now, the concept of energy security has been under a redefinition process, to include new parameters and criteria. Simultaneously, the global energy map is being transformed to a great extent, in order to deal with newly emerging issues, such as the worldwide rise in energy demand, energy poverty and environmental preservation. It is a non-debatable fact that innovation in technology plays a key role in this transition, boosting a shift from fossil fuel sources to renewable energy through a serious decline in solar PV and wind technology cost and a continuous development of more affordable and efficient energy storage systems. A bottom-up retrofit of conventional electric grids via the deployment of ICT, digital software and IoT-enabled equipment especially in the domestic sector, supported by decentralized power production models and a broader adoption of EVs in transportations, has introduced the prospect of smart grids as a means of achieving wider renewable-driven electrification of national economies. This comes with significant benefits for their energy security:

- ✓ alignment of energy supply and demand through demand forecasting, demand-response mechanisms and automated fault detection and reconfiguration
- ✓ reduction of the final electricity cost for domestic consumers through improved efficiency and lower O&M expenses for T&D infrastructure
- ✓ promotion of sector coupling, i.e., interconnection of the electricity, heating and mobility sectors with renewable energy production
- ✓ integration of non-dispatchable and intermittent DERs, distributed storage and EVs as independent, supplementary energy sources for grid congestion alleviation
- ✓ provision of clean and sustainable energy
- ✓ protection of large-scale producers from negative pricing through grid-connected distributed storage capacity
- ✓ consumer-empowerment through more active involvement in decision-making processes and bidirectional flows of energy and data within decentralized power grids (“prosumer” principle)
- ✓ enhanced overall grid resilience through the co-existence of all the abovementioned elements

Moreover, as shown by the results of this research, specific technologies and power generation systems are capable of addressing the intense energy poverty in the sub-Saharan countries, with rural and remote areas being the starting point for their sustainable electrification. A focus study on the case of Benin, as a typical sub-Saharan country, indicates that decentralized and stand-alone systems based on solar PV production could offer direct, environmentally acceptable and cost-efficient solutions for rural households, communities and agricultural irrigation. Provided the necessary financial support and funding schemes from supranational entities, combined with large-scale generation projects in urban centers, it is assumed that SSA countries will have the opportunity to make great strides towards the UN goal of universal access to affordable, reliable and modern energy services until 2030.

Nevertheless, the energy transition is expected to bring about structural changes in national economies and societies, along with rearranging geopolitical power correlations and international energy affairs in the short-to-medium term. To begin with, renewable energy resources tend to be geographically more evenly distributed than fossil fuels, thus the economic and security advantages of access to sustainable energy will be available to a much bigger number of countries. As a result, traditional geopolitical competition and conflicts among great powers over transportation chokepoints and valuable territorially determined assets will gradually fade. Instead, energy markets will acquire a more regional character, based on dispersed electricity pools and transnational interconnectivity projects, leading to more cooperative and mutually beneficial energy relations among countries. This assumption is also reflected on the meaningful shift of international alliances, from fossil fuel-based collaboration to strategic partnerships centered on renewable energy and advanced technology development. At this point, it should be pointed out that the target of achieving 100% renewable electricity with current technological means is not yet feasible in most countries, therefore fossil fuels will continue to be necessary for addressing the ascending global energy demand for many years to come.

As renewable energy sources are abundant but diffuse, the accumulation of profits is shifting from the possession and trade of primary energy sources, to technologies for collecting, storing and converting these sources to end-use energy and services. This fact will clearly have an impact on global energy interdependencies. Specifically, fossil fuel import-dependent states will have the chance to increase their energy independence and reduce their vulnerability to fuel price volatility and currency fluctuations by investing in renewable capacity and grid edge technologies. In addition, a new form of international competition has risen, based on innovative technology patents and intellectual property rights, namely the clean energy race. In this context, specific countries such as China, the US, India and Germany have the economic capacity, the means of production and the required level of technological development to lead the energy transition and dominate the global solar PV and wind energy markets. Especially China will in all probability attempt to gain advantage from its primacy in the field of critical materials for renewable energy hardware, and use it as a foreign policy instrument. However, unlike the international system that was built upon fossil fuels, the new energy era will hardly yield opportunities for monopolies and absolute control over markets and import-dependent countries.

At the same time, the energy transformation fueled by technological innovation and renewable energy will generate prominent challenges for oil-producing countries, especially those which rely a large part of their national revenues on oil exports. An upcoming decline in oil demand will significantly reduce oil rents extracted for decades, as well as the political leverage exploited multiple times in several geographical spheres at the expense of import-dependent states. Each of the countries that meet these characteristics has exhibited a different degree of readiness to reconsider its national energy strategy and diversify its economy, in order to adapt to the energy transition; the most vulnerable to experience destabilizing effects are Iraq, the African oil-rich countries, such as Libya, Angola, the Republic of Congo and South Sudan, and to a less extent Russia, Venezuela, Nigeria, Algeria and Azerbaijan. Another challenge for energy security is the increased vulnerability of smart grids to cyber-attacks, due to their high degree of digitalization and system integrity, though mitigated by the application of counter-measures and the deployment of off-grid DERs and distributed storage in emergency situations. Cyber-crime will possibly be more difficult to be addressed in the case of multinational renewable-based supergrids, due to the number of involved countries and their functional complexity.

5.2. Recommendations for further research

This study was an attempt to bridge the gap between advanced technology and international politics, within the context of energy security. Nevertheless, with the latter being a multifaceted concept, and given the fact that the technologies under consideration are constantly improving and obtaining new features, it is harder for researchers to conduct a thorough and up-to-date investigation on all the implications of this topic. Future research could, for instance, focus on:

- ✓ microeconomic aspects of applying innovative technologies in the electricity sector, through examining potential economic models in specified countries or regions of the world
- ✓ redefining energy security indexes and indicators, in order to include new parameters and to be more flexible towards practical data ambiguities
- ✓ smart grid optimization and wide-scale implementation, through analyzing power flows, grid resilience and robustness, renewable energy resources integration, digital system protection and enhanced automation methods

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