UNIVERSIDADE DE SÃO PAULO - USP

ESCOLA POLITÉCNICA

CAROLINA SILVA MARQUES

Wind Integration into Power Systems Operation

São Paulo

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Dissertation submitted to The Engineering School of the University of São Paulo for obtaining the title of Specialist in Renewable Energy, Distributed Power and Energy Efficiency.

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RESUMO

O rápido crescimento da fonte eólica nas matrizes de geração ao redor do globo suscita a necessidade de integrá-la corretamente ao sistema elétrico. Os desafios dessa integração relacionam-se à intrínseca variabilidade e incerteza do recurso eólico. O presente estudo descreve este cenário e reúne as alternativas para mitigar tais atributos a fim de preservar a estabilidade da rede. Adicionalmente, enfatiza a contribuição de procedimentos de resposta do sistema para uma operação segura e econômica. Por fim, confirma que a integração adequada da fonte eólica ao sistema elétrico prova-se suficiente para patrocinar índices de penetração dessa tecnologia de até 44% - em termos de energia gerada - sem atingir um limite, e que essa fração tende a aumentar ao longo dos próximos anos.

ABSTRACT

The rapid growth of wind energy in electric matrixes around the globe leads to the necessity of properly integrating this source into the power system. Challenges of the integration relate with the intrinsic variability and uncertainty of the wind resource. Current study describes this scenario and compiles the alternatives to mitigate such attributes in order to preserve grid stability. Furthermore, it emphasizes the contribution of responsive system procedures to a secure and cost effective operation. Finally, it confirms that the appropriate integration of wind into the power system proved enough to support penetration levels of this technology as high as 44% - in terms of power output - without reaching its maximum, and that these figures are likely to increase over the following years.

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LIST OF ACRONYMS

AC – Alternating Current

ANEEL – National Energy Agency

CSP – Concentrated Solar Power

DFIG – Double-fed Induction Generator

EIA – U.S. Energy Information Administration

ERA – European Centre for Medium-Range Weather Forecasts Re-Analysis

GHG – Greenhous Gases

GWEC – Global Wind Energy Council

HVAC – High Voltage Alternating Current

HVDC – High Voltage Direct Current

IEA – International Energy Agency

MV – Medium Voltage

NREL – National Renewable Energy Laboratory

ONS – National System Operator

POI – Point of Interconnection

RE – Renewable Energy

REN21 - Renewable Energy Policy Network for the 21st Century

R&D – Research and Development

SGCC – State Grid Corporation of China

UHVDC – Ultra-high Voltage Direct Current

USA – United States of America

V – Volt

VRE – Variable Renewable Energy

W – Watt

WPP – Wind Power Plant

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INTRODUCTION

The support for clean energy technologies evolves with the increasing concerns associated with fossil fuels. Economic, environmental and security reservations drive the market towards alternative sources of energy, which are continually increasing their penetration levels around the globe. (COCHRAN et al., 2012).

According to REN21 (2018) and GWEC (2017), renewable energy sources accounted for 70% of net additions to global power capacity in 2017. Such fraction corresponds to the largest annual increase ever experimented, with an estimated 178 gigawatts. Wind energy contributions stand out providing nearly 30% of this volume due to its consistent grow along the last few years.

Between 2002 and 2017, wind capacity increased by 508 gigawatts globally, figuring only behind fossil fuels additions (GWEC, 2017; REN21, 2018). Major drivers for this expansion are the decreasing costs of energy, the regulatory and policy incentives and the pursuit of lower GHG emissions levels. As the share of wind grows, the necessity of properly integrating these units into the grid becomes imperative (COCHRAN et al., 2012).

Main challenges for wind integration into the grid rely on the intermittent and stochastic characters of the wind resource, which lead to uncertainty and variability. Due to the consequent net load oscillations, the system is required to constantly balance generation-load discrepancies in order to remain stable. Such necessity is attended through responsive system operations. (JAIN and WIJAYATUNGA, 2016).

The suitability of these procedures in countries’ system operation depends upon their implementation costs and timescales, as well as on technical and physical constraints. The assertiveness of the method carried out plays a critical role by directly affecting operation costs and grid permeability to variable generation sources. (JAIN and WIJAYATUNGA, 2016).

Subsequently, the adequate integration of wind into developing power systems is essential to support the continuity of its global expansion towards the generation bases. (IEA, 2017a).

MOTIVATION AND OBJECTIVES

The global electric matrix experiments profound changes driven by the search for alternative sources of energy. This process is marked by the consequent introduction of wind into the generation strategy. A comprehensive analysis of this phenomenon provides relevant information for planning and structuring power system operations. (COCHRAN, BIRD, *et al.*, 2012; REN21, 2018; JAIN and WIJAYATUNGA, 2016).

Hence, the motivation of this work is acknowledging the evolution of power sources in countries' electric matrix with specific emphasis on wind energy, addressing the outcomes of this advancement as well as the requisites to support it. Based on such understandings, it aims to identify global tendencies for power generation and indicate the major challenges experienced to enable the evolution of this structure towards a renewable configuration. Thereby, the following sections are designed to unveil the requirements of wind integration into the power systems and to determine if an upper limit for wind penetration levels apply in order to secure a successful operation.

Conducted discussions include quantitative and qualitative analysis, which validate the assumptions with tangible arguments exposed throughout the text. They not only provide the best practices for wind integration into the system but also demonstrate, through a case study, previous experiences in this process, serving as an important reference to shape future decisions.

In line with the aforementioned topics, the major objective of this research is supporting the establishment of wind as a reliable source of power by discussing the barriers for its advancement and delivering substantial background to assist on power system operation.

Else, following reflections intend to prove viable operating a power system with high shares of wind capacity without compromising neither basic aspects of power quality nor generation reliability.

METHODOLOGY

The evolution of wind energy is addressed through a comprehensive quantitative analysis that includes global and national indicators of this source, reflecting its installed capacities and penetration levels over recent years. The interconnected grids, networks throughout which this technology spreads, are characterized in order to allow a better understanding of the system structure.

Thereafter, the impacts of incorporating wind energy into the power system are acknowledged by extensive literature review, which disclosures technical and economic aspects of the integration process and presents appropriate alternatives to support it. Among them, responsive system operations particularly stand out.

Abovementioned operations are thoroughly discussed in terms of suitability, viability and implementation costs reported by the accessed references. Further alternatives to mitigate the impacts of wind expansion into the generating matrix are also outlined, complementing the essential values of power system planning and structuring.

Finally, the Denmark case study is presented in order to demonstrate the viability of employing wind as a major source of power without compromising neither the costs of energy nor the system reliability. A historical analysis of the wind trends in this country is also conducted with the purpose to identify potential factors that contributed to the outstanding advancement of this source within the national generation system.

Based on the findings, the existence of upper limits of wind penetration into a power system is discussed encompassing both technical and economical aspects.

Nonetheless, the role of system integration in the establishment of wind as a major source of power in the near future is attested.

ORGANIZATION OF THE WORK

The first chapter is dedicated to describe the evolution of power systems over the last few years by examining installed capacities and penetration levels of alternative sources of energy into global generating pool. Specific emphasis is given on wind trends.

Chapter two introduces the concept of interconnected power systems, and establishes the reasons why countries operate through this structure rather than with isolated generating units.

The impacts of integrating wind into the power system and the alternative processes to mitigate them are expressed in chapters three and four, respectively, while chapter five assesses the relative costs of such interventions.

Chapter six brings Denmark case study, which demonstrates the viability of operating power systems with high wind penetration levels.

Lastly, conclusions of this work are articulated in the closing section, stating wind power limitations and prospections.

1. WIND ENERGY PENETRATION INTO THE ELECTRIC MATRIX

Global figures of installed electricity capacity declared by the U.S. Energy Information Administration (EIA) allow a detailed analysis of this indicator along the years. Compiled data, presented in Table 1, unveil the additions in generating capacities by source over a 15-year period, between 2002 and 2016.

Table 1 – Global Added Electricity Capacity by Source, 2002 - 2016

Type	Δ2002-2016 [GW]	Δ2002-2016 [%]
Fossil Fuels	1576.1	56.1%
Wind	436.9	15.5%
Hydroelectric	380.9	13.5%
Solar	295.2	10.5%
Biomass and Waste	77.5	2.8%
Hydro Pumped Storage	46.9	1.7%
Geothermal	4.1	0.1%
Tide and Wave	1.3	0.0%
Nuclear	-7.0	-0.3%
All	**2811.8**	**100.0%**

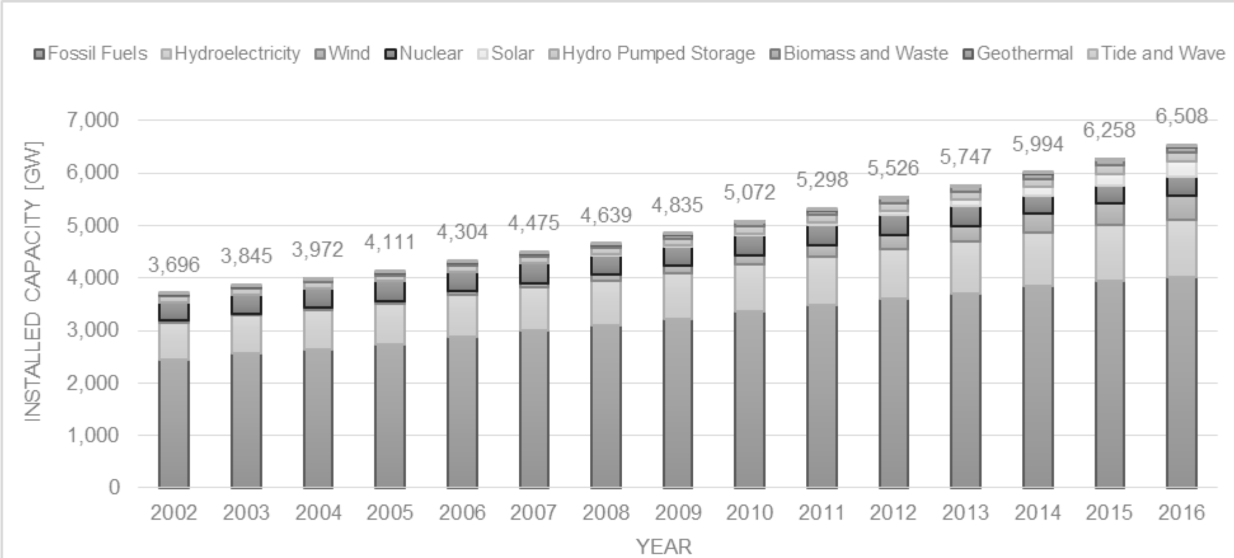
Source: EIA (2016c).

Total installed electricity capacity increased approximately 2.8 TW within this period, an equivalent growth of 176%.

Fossil fuels based plants were responsible for 56.1% of the additions, leading the indicator. Regardless of the 40% gap between fossil and wind contributions, wind assisted in a substantial 15.5% increase in capacity, followed by hydro and solar, with 13.5 and 10.5% respectively. These sources accounted together for 95.6% of the additions.

Annual records of this period reveal that the highest jump in installed capacity occurred in 2015, when additions reached approximately 263.8 GW, as illustrated in Figure 1. In the same year, fossil fuels contributed with 37.3% of the new installed capacity, wind with 24.9%, and solar and hydro with 18.4 and 12.2%, in this order.

Figure 1 – Net Global Cumulative Installed Electricity Capacity



Source: EIA (2016c).

Despite fossil fuels massive additions, renewables clearly play an important role in power generation. Its increasing volumes contribute to meeting the load in continuous growth, not only ensuring power supply but also diversifying the matrix and, thus, maintaining system reliability.

Renewable energy (RE) sources in 2017 provided 178 GW of net added capacity around the globe. According to the REN21 (2018), solar PV leaded the classification being responsible for more than 55% of the additions, followed by wind, with expressive 29.1%, hydro, with 10.6%, and bio-power, with 14.5%. Mentioned values are expressed in Table 2.

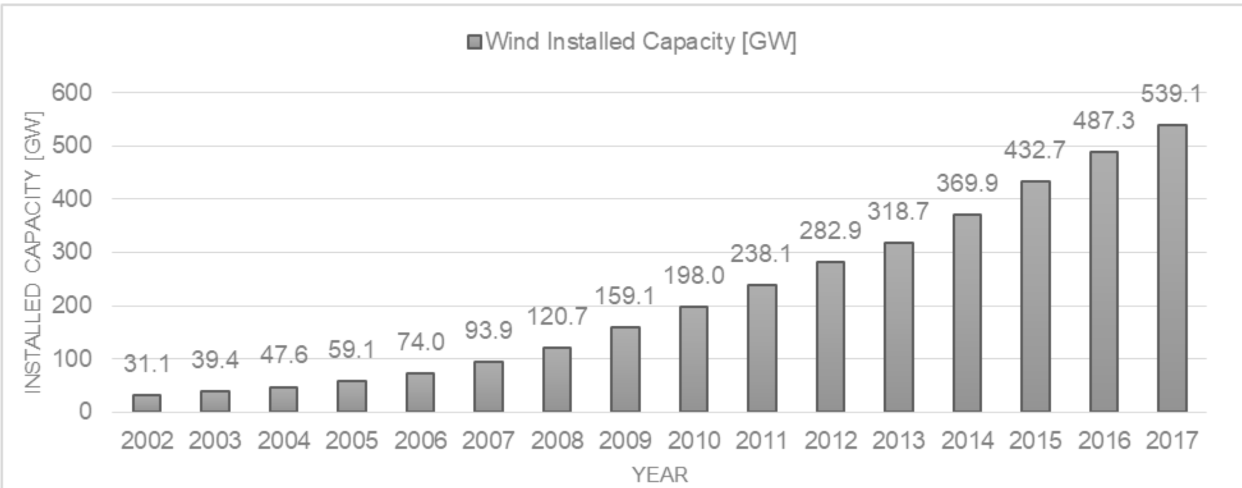
Table 2 – Global Added Renewable Electricity Capacity by Source, 2017

Source	2017 Additions [GW]	[%] of Total
Solar PV	99.0	55.4%
Wind	52.0	29.1%
Hydroelectricity	19.0	10.6%
Bio-power	8.0	14.5%
Geothermal	0.7	0.4%
Concentrating Solar Thermal	0.1	0.1%
Ocean	0.0	0.0%
All	**178.8**	**100.0%**

Source: Adapted from REN21 (2018).

Results point to the consistent wind expansion over the past few years. The Global Wind Energy Council (GWEC) latest indicators report an addition of 508GW in total installed wind capacity between 2002 and 2017, as revealed by Figure 2, below (GWEC, 2017).

Figure 2 - Global Cumulative Wind Electricity Capacity



Source: Adapted from GWEC (2017).

From January to December 2017, China was responsible alone for 37.9% of the global installed wind capacity. United States (USA), Germany, United Kingdom and India also contributed with significant shares. Table 3, below, presents the 10 countries with the greatest installed wind capacities in 2017, as well as their additions within this year (GWEC, 2017).

Table 3 – Added Wind Electricity Capacity by Country, 2017

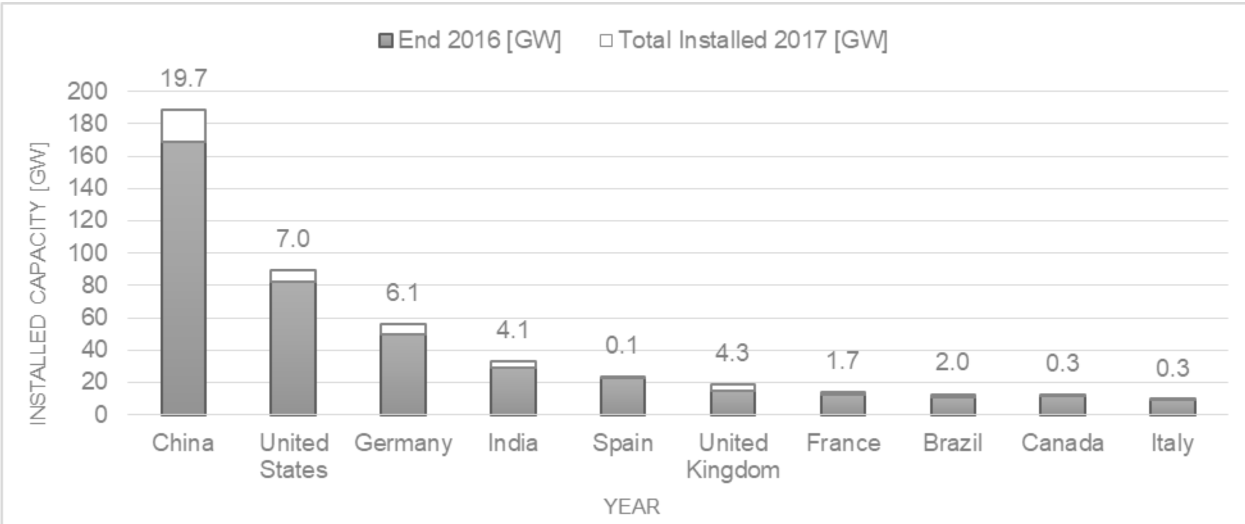
Country	End 2016 [GW]	Installed 2017 [GW]	End 2017* [GW]	[%] of Total Additions 2017
China	168.7	19.7	188.4	37.9%
United States	82.1	7.0	89.1	13.5%
Germany	50.0	6.1	56.1	12.7%
India	28.7	4.1	32.8	8.0%
Spain	23.1	0.1	23.2	0.2%
United Kingdom	14.6	4.3	18.9	8.2%
France	12.1	1.7	13.8	3.3%
Brazil	10.7	2.0	12.8	3.9%
Canada	11.9	0.3	12.2	0.7%
Italy	9.2	0.3	9.5	0.5%

Source: REN21 (2018); WIND EUROPE (2018); GWEC (2017).

*Note: *Net installed wind capacity.*

Presented data confirm that China additions exceed USA contributions by 20%, which correspond to significant 12.7 GW. Figure 3, in sequence, displays aforementioned amounts over the cumulative installed wind capacity by country.

Figure 3 - Added and Cumulative Wind Electricity Capacity by Country, 2017



Source: REN21 (2018); WIND EUROPE (2018); GWEC (2017).

Cited countries were also the ones with the largest installed wind capacities in 2016, what indicates the consistent growth of this technology in their electric matrix.

Also in 2016, their wind penetration levels in terms of installed capacity reached up to 24.0% in Germany and 21.8% in Spain (EIA, 2016b), as stated in Table 4.

Table 4 – Wind Penetration Levels by Country, 2016 (Installed Capacity)

Country	Wind [GW]	Total [GW]	Wind [%]
Germany	50.0	208.5	24.0%
Spain	23.1	105.9	21.8%
United Kingdom	14.6	97.1	15.0%
China	168.7	1653.2	10.2%
France	12.1	130.8	9.2%
Canada	11.9	143.5	8.3%
Italy	9.2	114.2	8.1%
India	28.7	367.8	7.8%
Brazil	10.7	150.8	7.1%
United States	82.1	1206.9	6.8%

Source: EIA (2016b); GWEC (2017).

However, it is important to notice that, regardless of presenting greater cumulative wind capacities, those are not necessarily the countries with highest wind penetration levels into the power system.

Concerning installed capacities, wind penetration exceeded 36% in Denmark, in 2016. Ireland and Uruguay follow the ranking with an approximate share of 27 and 26%, respectively. The 10 countries with highest wind penetration levels in terms of installed capacity in 2016 are shown in Table 5.

Table 5 – Highest Wind Penetration Levels, 2016 (Installed Capacity)

Country	Total Capacity 2016 [GW]	Wind Capacity 2016 [GW]	Penetration Level 2016
Denmark	14.34	5.23	36.5%
Ireland	9.95	2.70	27.1%
Portugal	20.56	5.31	25.8%
Uruguay	4.81	1.21	25.2%
Germany	208.50	50.02	24.0%
Spain	105.91	23.08	21.8%
Sweden	40.29	6.49	16.1%
Cape Verde	0.16	0.03	15.7%
United Kingdom	97.06	14.60	15.0%
Poland	38.11	5.81	15.0%

Source: EIA (2016d); GWEC (2017).

Note: [1]Falkland Islands are also known as Malvinas. [2]Two decimal cases were exceptionally used in this table to better represent small amounts of power capacity. [3]Wind capacities were extracted from GWEC registries.

Antarctica electric matrix is fully dependent on wind power due to geographic constraints. Numbers of this country, thus, were not considered in this comparison.

Analogously, wind penetration levels in terms of power production over the total electricity generation achieved substantial percentages the same year. Wind power output corresponded to impressive 42.8% of total electricity generation in Denmark, stating the reliability of this country on such technology. Lithuania and Luxemburg also presented massive wind contributions to meet the electricity demand, which summed 36.4 and 30.2%, respectively. Mentioned values are presented in Table 8, in sequence.

Table 6 – Highest Wind Penetration Levels, 2016 (Power Output)

Country	Total Generation 2016 [TWh]	Wind Generation 2016 [TWh]	Penetration Level 2016
Denmark	29.84	12.78	42.8%
Lithuania	3.13	1.14	36.4%
Luxembourg	0.33	0.10	30.2%
Uruguay	13.13	2.99	22.8%
Portugal	56.90	12.34	21.7%
Ireland	28.53	6.15	21.6%
Spain	258.59	47.71	18.5%
Cape Verde	0.40	0.07	17.5%
Nicaragua	4.45	0.73	16.4%
Germany	612.79	78.22	12.8%

Source: EIA (2016d).

Note: [1]Two decimal cases were exceptionally used in this table to better represent small amounts of power capacity.

According to the GWEC, these indicators keep rising. In 2017, wind penetration levels in Denmark (in terms of generation) summed impressive 44%. Likewise, Uruguay achieved 30%, Portugal and Ireland achieved 24%, and Germany achieved 16.1% of wind output over their total generation (GWEC, 2017).

Presented data explicitly report the development and consolidation of wind as a reliable source of energy in several countries around the globe. The complexity of this process increases with the network extension, whereby the Brazilian power system characterizes a singular and delicate scenario for the expansion of this technology.

According to the National Grid Operator ONS (ONS), Brazilian interconnected system transmission lines added up to 134.765 km in 2016 and are expected to totalize 154.748 km by the end of 2019 (ONS, 2018).

The National Energy Agency (ANEEL) states that, currently, 7144 interconnected units provide the electricity drained by the country’s network, as detailed in Table 7. Hydroelectric, thermoelectric and wind power plants account, respectively, for the higher installed capacities in commercial operation. Nonetheless, thermoelectric, solar and hydro present the greater number of active units, thanks to the distributed power concept. (ANEEL, 2018).

Table 7 – Installed Electricity Capacity in Commercial Operation in 2018, Brazil

Type	**Units**	**Capacity [GW]**	**[%]**
Hydroelectric	1338	102.9	64.0%
Thermoelectric	2999	41.1	25.5%
Wind	546	13.4	8.4%
Nuclear	2	2.0	1.2%
Solar	2258	1.4	0.9%
Tide and Wave	1	0.0	0.0%
Total	**7144**	**160.8**	**100.0%**

Source: ANEEL (2018).

Considering the evolution of these sources in Brazilian electric matrix, the added amount of hydro and wind capacities stand out, as pointed in Table 8.

Table 8 – Evolution of Installed Electricity Capacity by Source [GW], Brazil

Type	**2013**	**2014**	**2015**	**2016**	**Δ2013-2016 [%]**
Hydroelectric	86.0	89.2	91.7	96.9	48.0%
Wind	3.5	6.0	8.7	10.7	32.0%
Biomass and Waste	11.6	12.3	13.3	14.2	11.4%
Fossil Fuels	25.1	25.4	26.2	26.9	8.2%
Solar	0.0	0.0	0.0	0.1	0.3%
Nuclear	1.9	1.9	1.9	1.9	0.0%
Tide and Wave	0.0	0.0	0.0	0.0	0.0%
Total	**128**	**135**	**142**	**151**	**100.0%**

Source: EIA (2016a).

The large increment of hydroelectric power within the assessed period relates to the construction of Belo Monte plant, on course since 2011 and with conclusion expected by 2019. Its installed capacity accounts for approximately 11.2 GW, and its commercial operation started on April 2016. (ANEEL, 2018; NORTE ENERGIA, 2018a; 2018b).

Wind proved to be the second source to increase installed capacity within considered period, granting 32% of the additions. Quoted amount is almost three times that added by biomass and waste, consecutive on the list. Additionally, solar presented 0.3% of the additions, whereas nuclear and tide capacities remained constant. (ANEEL, 2018).

Future granted wind capacity is also substantial, as introduced in Table 9. It accounts for 25.3% of planned installations, figuring behind thermoelectric only, despite overcoming the source in number of units (ANEEL, 2018).

Table 9 – Granted Electricity Capacity, Brazil

Type	**Units**	**Granted Capacity [GW]**	**Granted Capacity [%]**
Thermoelectric	144	7.9	40.2%
Wind	215	4.9	25.3%
Hydroelectric	164	3.2	16.3%
Solar	80	2.2	11.3%
Nuclear	1	1.4	6.9%
Total	**604**	**19.6**	100.0%

Source: ANEEL (2018).

Presented data evidences that granted capacity prevenient from renewable sources exceeds fossil fuels' in 19.6%, accounting for 59.8% of future additions (ANEEL, 2018). Main reasons for this scenario are the pursuit of renewable alternatives for meeting the electrical demand - encouraged by the reduction in costs of energy -, the maturation of available RE technologies, and the broad availability of exploitable natural resources. (COCHRAN et al., 2012).

Wind demonstrably plays an important role in the switching process, contributing with substantial amounts of installed capacity globally. Its consistent advancement is likely to remain strong in the Brazilian market over the next years. (ANEEL, 2018; REN21, 2018; WIND EUROPE, 2018; GWEC, 2017).

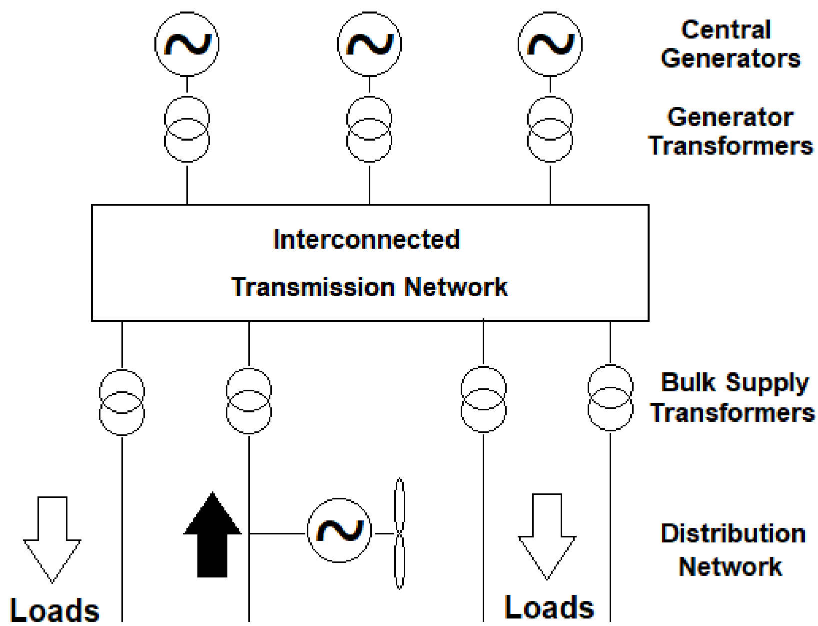
Grid integrity, however, relies on the controlled integration of this expanding variable renewable energy (VRE) source into the national interconnected power systems (COCHRAN et al., 2012).

2. WIND ENERGY AND THE ELECTRIC POWER SYSTEM

2.1. National Interconnected Power Grids

National power grids consist of interconnected power systems acting in a coordinated manner in order to meet the load and provide the ancillary services (i.e. voltage and frequency control) necessary for its correct operation. These comprise generation, transmission and distribution systems. The Figure 2 above is a diagrammatic representation of a large utility power system. (KIRBY, 2007).

Figure 4 – Large Utility Power System



Source: Adapted from BURTON, JENKINS, et al. (2011).

Since wind is a diffuse source of energy, wind farms often spread over wide geographical areas. Hence, public electricity networks are responsible for gathering their power output and delivering it to the customers. (NIKOLAKAKIS and CHATOPADHYAY, 2015).

The main purposes of grid interconnection are increasing reliability, sharing the load, regulating voltage and frequency, decreasing the necessity for power reserve capacity and conducting an economical operation (IEA, 2016e; IEC, 2016; JAIN and WIJAYATUNGA, 2016). Aforementioned topics are addressed in sequence according to the considerations of JAIN and WIJAYATUNGA (2016).

I. Increasing Reliability

Interconnected systems allow electrical power exchange among regions, assuring the state of uninterrupted power supply. The exchange serves as an alternative to meet the load in case one of the generators responsible for delivering power is unavailable or underperforming. Usual causes of these events are components malfunction, non-scheduled maintenance and unavailability of natural powering sources, e.g. wind.

II. Load Sharing

Unlike isolated systems, which must independently handle the load and its fluctuations, interconnected systems share the load by every generating unit on its network, reducing the chances of system overload and preserving its integrity.

III. Regulating Voltage and Frequency

Load variation leads isolated systems to significant voltage and frequency fluctuations, not only subjecting them to structural damage but also compromising the quality of the energy delivered. Interconnected systems, in turn, present a much higher operating inertia, acting like an infinite bus, which softens voltage and frequency oscillations and provides reliable ancillary systems.

IV. Decreasing Power Reserve Capacity

The need for individual power reserve capacity reduces drastically once generating units are interconnected and can act as a backup of the other in case of emergency.

V. Economical Operation

Interconnected systems allow the operator to meet the demand through the most cost effective generating unit at the time, despite geographic constraints. Thus, among other factors, the operation is structured according to the cost of energy, what leads to an economical operation.

Examples of countries operating through large-scale interconnected systems are China, India, and Brazil. The establishment of their grid is described in sequence based on IEC (2016) considerations.

Since the 1950s, the Chinese national grid has evolved from hundreds of isolated networks to approximately 30 provincial grids, and finally to only six large-scale regional systems in the mainland; namely: the North and Central, the East, the Northeast, the Northwest, the Tibet and the South grids.

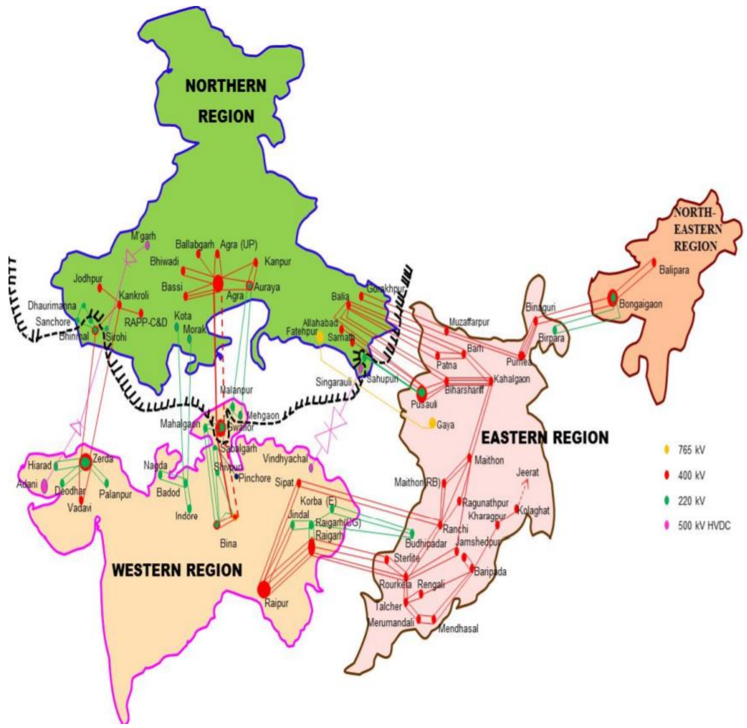
Figure 5 – Grid Interconnection in China

Source: WEI, LI and GAO (2016).

Yet, the State Grid Corporation of China (SGCC) proposed on its five-year development plan advancing towards an operation through just two large synchronous grids by 2020. Specifically the West grid, integrating a broad range of power bases given Western China's rich resource endowment, and the East grid, integrating major load centers.

Analogously, Indian network development started in 1947, with the formation of state-level grids. Between the seventies and the nineties, five regional-level grids were formed by intersecting state-level lines. The continuation of the process over the following years, hence, originated a national synchronous grid, as illustrated in Figure 6.

Figure 6 – Inter-regional interconnections in India

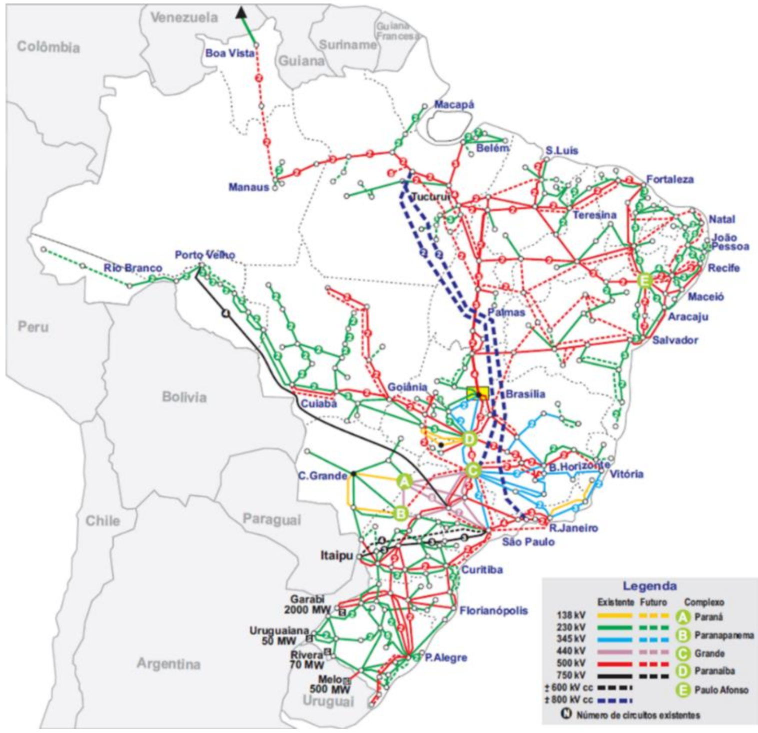


Source: NAYAK, SOONEE and SINGH (2012).

The layout and interconnection of the Indian power grid reflect the uneven distribution of energy resources and load centers around the country, similarly to the observed in China. Energy resources are mainly located in the North, Northeast and East of the country, while load centers are concentrate in the North, South and West. As a result, large amounts of power flow from East to West and from North to South in order to meet the demand.

In contrast to the given examples, cross-regional interconnections in Brazil did not start until the development of large-scale hydropower units around the country, in the 1980s. Then, four regional 500 kV backbone grids were formed, namely North, Northeast, Southeast and South. At the end of the 1990s, 765 kV, 500 kV and 345 kV links interconnected regional grids, forming the unified national synchronous system. Figure 7, in sequence, comprises an illustration of current system structures.

Figure 7 - Brazilian National Interconnected System, 2017-



Source: Adapted from ONS (2017).

As the image shows, two ±600 kV high voltage direct current (HVDC) lines were added, transmitting the power generated by the Itaipu hydropower plant, and a ±800 kV ultra-high voltage direct current (UHVDC) line is under construction to drain the power generated by Belo Monte hydropower plant.

Therefore, periodic improvements in system connections apply with the intention of enabling the power drainage. Additionally, maintenance interventions and network monitoring are essential to preserve networks structural integrity. That said, the greater the system dimensions and the generation-load distances, the more complex the electrical interconnection.

2.2. Transmission and Distribution Systems

Wind power plants operate as large central generating sets, feeding electrical power into the transmission system. Ensuing paragraphs bring the aspects of this configuration in line with BURTON, JENKINS, et al. (2011).

The power generation voltage is rather low (typically around 20kV) in order to reduce insulation requirements of the machine windings. Therefore, generator transformers elevate the voltage level to that of the transmission.

Transmission systems operate at voltage levels from 220 to 400 kV in Europe, and up to 765 kV in larger countries, such as Brazil, China and USA. It is so in order to prevent series losses along the circuit, which are proportional to the square of the current. The higher the voltage, the lower the current to travel the circuit and, consequently, the lower the power losses along the conductor, as per relation below.

$$\Delta P = R_l * i^2 \quad (1)$$

Where

$\Delta P = Power\ dissipated\ in\ conductor\ [Watts]$

$R_l = Conductor\ resitency\ [\Omega]$

$i = Electrical\ current\ in\ conductor\ [A]$

Because of their strategic importance, transmission networks comprise multiple circuits in parallel so that if an electrical fault occurs and one circuit is isolated, the grid continues to function satisfactorily. This characteristic results in a low utilization of the circuits during normal operation, and typical electrical losses lower than 2%.

In contrast, distribution networks normally operate as radial systems with a single path between bulk transformers and load centers. Distribution voltage varies according countries' regulations, but generally do not exceed 150 kV. This structure results in minimal redundancy, higher circuits utilization, and typical electrical losses of around 6%.

Besides, frequency levels in alternating current (AC) systems are defined by immediate generation-load balance. Their magnitude drops in case the instantaneous load exceeds the generation and rises in case the contrary is true. Frequency oscillation rates, in turn, depend on the inertia of spinning machines connected to the system.

Conventional generators (e.g. fossil and hydro) provide inertia to the system by adjusting their output in face of grid necessities. This response guarantees load attendance while preserves network stability and prevents interconnected circuits overload.

Large interconnected systems have strict power flow restrictions in order to prevent voltage and frequency fluctuations within the lines. However, the higher the penetration of variable sources into the generation structure, the harder to preserve ancillary services. (BURTON et al., 2011).

2.3. Wind Farm Power Collection Systems

Large wind farms operate connected to three-phase AC networks. These provide reference values for stability control of the generation system and feed the auxiliaries with power in case the turbine is not operative.

The voltage levels of turbine main circuits are lower than 1000V, despite the massive equipment dimensions. This limit relates to three main reasons:

i) the high costs of safety requirements to operate at higher voltages;
ii) the wider choice for switchgears and flexible cables at low voltages, and
iii) the higher production volumes of low voltage generators.

Therewith, a transformer located either in the nacelle, in the tower base, or immediately adjacent to it, is required to elevate the voltage to that of the collection system.

The wind farm collection system drains turbines' electrical output and joints the utility distribution network in the point of interconnection (POI), delimiting the ownership boundary. This system operates in medium voltage (MV) levels, following the practice of the local distribution utility, so that cables and switchgears are readily available.

Larger wind farms may include a transformer to increase the voltage for onward transportation (e.g. 33/132 kV transformers). The difference between the equipment costs and corresponding expenditures per electrical losses determines whether this solution is worthwhile.

Structurally, collection systems consist of simple radial circuits with limited switchgear for isolation and switching. Duplicate circuits, either in the collection structure or between the unit and the utility network, did not prove to be cost-effective based on operating experience and reliability calculations. In the event of a circuit failure, wind energy output is constrained, which regardless of the lost revenues do not prevent the load to be attended through available generators.

Thus, power collection circuits are primarily dimensioned to support current ratings and reduce electrical losses. Its physical structure comprise either an underground or an overhead MV network. Advantages of underground cables are visual amenity and safety, as large cranes operate within the wind farm area while erecting the turbines. Despite, overhead MV lines are eventually used in order to reduce costs.

Last of all, the infrastructure assessed in the preceding subparagraphs is demonstrably essential to enable the electric power drainage from generating units to major load centers. Technical constraints in aforementioned systems may result in inefficient operation, as well as on barriers for the development of variable renewable sources.

3. WIND INTEGRATION INTO POWER SYSTEM OPERATION

Integrating an electrical source into the power system implies the significant elimination of technical, physical and legal impediments for its connection to the grid. With this purpose, responsive system operations, robust infrastructures and regulatory frameworks apply in order to guarantee adequate ancillary services. (IEA, 2017a).

Major impacts of expressive wind penetration into the grid relate to the complexity of operating a system with extensive net load variability. The deployments of this characteristic are exposed in sequence as per the findings of JAIN and WIJAYATUNGA (2016), except mentioned otherwise.

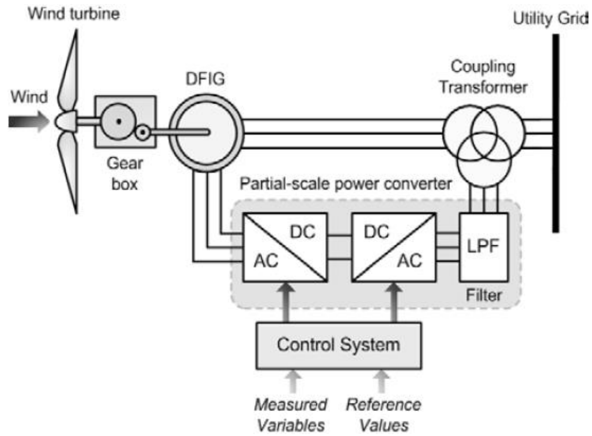
3.1. Inertial Response

Inertia is the ability of an interconnected unit to manage generation-load disparities, preserving system stability and assisting in voltage and frequency regulation. Conventional energy sources - such as thermal and hydro – rely on synchronous generation, which increases system inertial response, thus, allowing grid parameters to remain within the ranges stipulated by the grid code.

In contrast, wind technology relies on asynchronous generation and does not provide natural inertial response. Therefore, greater system flexibility is essential to support ancillary services in networks with large wind penetration. Flexibility mitigates the effects of net load variation over different time intervals, and allows the accommodation of greater VRE shares into the power system.

Nonetheless, a few wind units are able to provide synthetic inertia. This property results from the transference of mechanical inertia from the rotor to the electrical side, and is available in Type 3 double-fed induction generator (DFIG) and Type 4 full-power converter-based turbines. The block diagram for a Type 3 generator is displayed below.

Figure 8 - Block Diagram for Type 3 Doubly Fed Induction Generator



Source: AFIFI, WANG, *et al.* (2013).

Abovementioned generator types can either consume or produce reactive power to support grid functions. Else, they provide valuable power control, low-voltage ride through and high-pass filters which, among other features, increase grid reliability.

Even so, in the event that the wind unit fails to provide inertial response, synchronous generators must stay online to preserve grid stability, what may lead to uneconomical wind energy curtailments.

3.2. Wind Variability and Net Load Concept

Wind speed variability derives from Earth's rotation about its tilted axis and translation about the Sun. Combined they lead to day-and-night and seasonal fluctuations. Such behavior also arises from local surface conditions – e.g. roughness and temperature - and from diverse natural phenomena – e.g. El Niño and La Niña.

Wind power output varies with the cube of the wind speed, as stated in below:

$$P = \frac{1}{2}\, C_p \rho\, A\, v^3 \quad (2)$$

Where:

$P = Wind\ power\ output\ [W]$, $C_p = Power\ coefficient\ [-]$, $\rho = Specific\ mass\ [kg/m^3]$,

$A = Rotor\ swept\ area\ [A]$ and $v = Wind\ speed\ [m/s]$.

As a result, wind speed variability occasions sharp wind power fluctuations, consistent with the following relation:

$$\Delta P_{Out}\ [\%] = \frac{P_{Out_2}}{P_{Out_1}} = \frac{\frac{1}{2} C_{p_2}\, \rho\, A\, {v_2}^3}{\frac{1}{2} C_{p_1} \rho\, A\, {v_1}^3} = \frac{C_{p_2} {v_2}^3}{C_{p_1} {v_1}^3} = \frac{C_{p_2}}{C_{p_1}} \left(\frac{v_2}{v_1}\right)^3 = \frac{C_{p_2}}{C_{p_1}} \left(\frac{(v_1 + \Delta v)}{v_1}\right)^3 \quad (3)$$

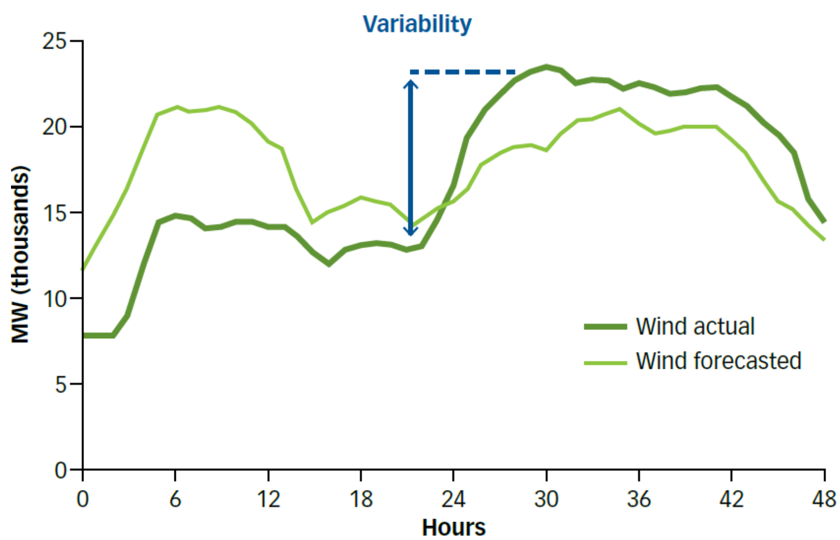
Where:

$P = Wind\ power\ output\ [W], \quad C_p = Power\ coefficient\ [-], \quad \rho = Specific\ mass\ [kg/m^3],$

$A = Rotor\ swept\ area\ [A] \quad and \quad v_2 = v_1 + \Delta v\ [m/s].$

The proportionality factor highlights that the influence of wind speed fluctuations over the power output essentially relies on the turbine power coefficient (C_p) and on the instantaneous wind speed at the time of the event (v_1). Figure 9, in sequence, illustrates the wind power variability over a two-day period.

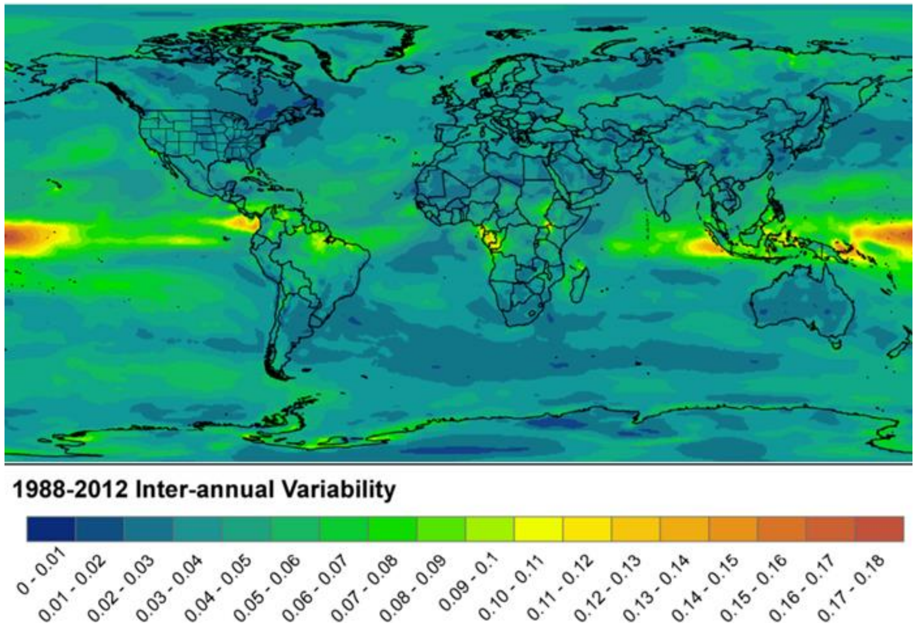
Figure 9 – Variability of Wind Output over a Two-day Period



Source: ELA, DIAKOV, *et al.* (2013)

The gap observed in the figure demonstrates that significant power oscillations may occur in a short interval, and associate with high wind variability. Deep power oscillations are likely to occur in sites with wide speed ranges, typically located at low latitudes, as Figure 10 shows.

Figure 10 – Inter-annual Wind Speed Variability at 80m a.s.l

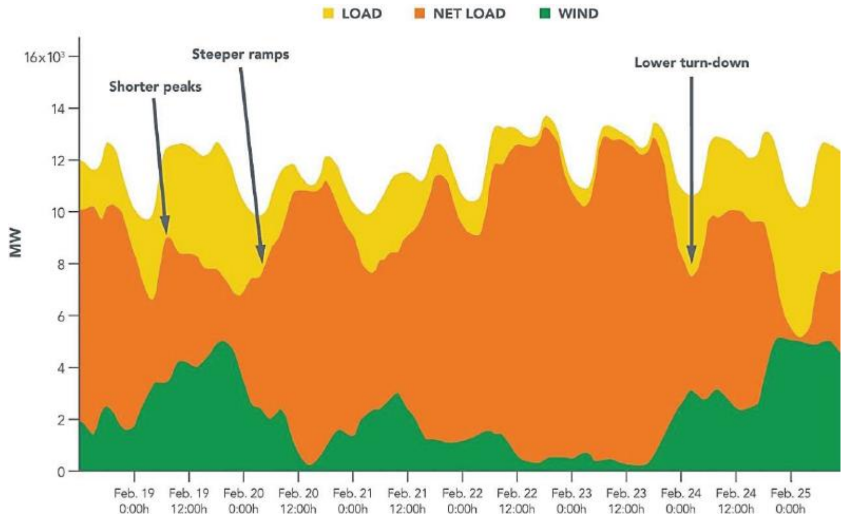


Source: ELA, DIAKOV, *et al.* (2013).
Note: Global map of inter-annual for the period 1988-2012 based on the ERA-Interim data set for a height of 80 m above ground. Values are given as a fraction of the mean speed.

The image attests inter-annual wind speed variability of global reanalysis data (ERA) between 1988 and 2018. Results point oscillations of up to 18% over mean wind speeds within the period, specially concentrated in the intertropical zone. Main reason for this scenario is the unequal incidence of solar radiation on Earth. Greater radiation levels between the tropics raise surface temperatures and trigger natural convection, thereby, affecting the wind regime. (ELA et al., 2013).

Wind power variability is commonly addressed through the net load concept. This approach considers wind production as systems' negative load and, hence, subtracts it from the actual demand to obtain the resultant load. Accordingly, this indicator assumes higher uncertainty and variability, as outlined in Figure 11 (COCHRAN et al., 2012).

Figure 11 – Net Load Variation over a Week

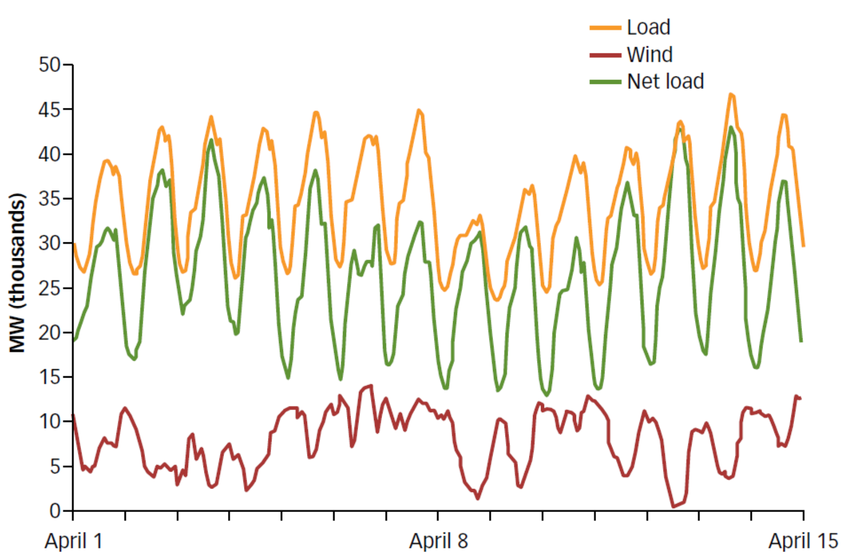


Source: COCHRAN, BIRD, *et al.* (2012).

Plotted curves attest the increase in ramping rates - demanding load-following units' response - and the extension of its ranges - revealing higher differences between minimum and maximum loads on a daily basis.

These effects are also present in Figure 12, which illustrates net load oscillations in a system with high VRE penetration levels. The intermittent character of these sources directly relate to the behavior expressed.

Figure 12 – Net Load with Increased Use of VRE over a Two-week Period



Source: DENHOLM, ELA, *et al.* (2010).

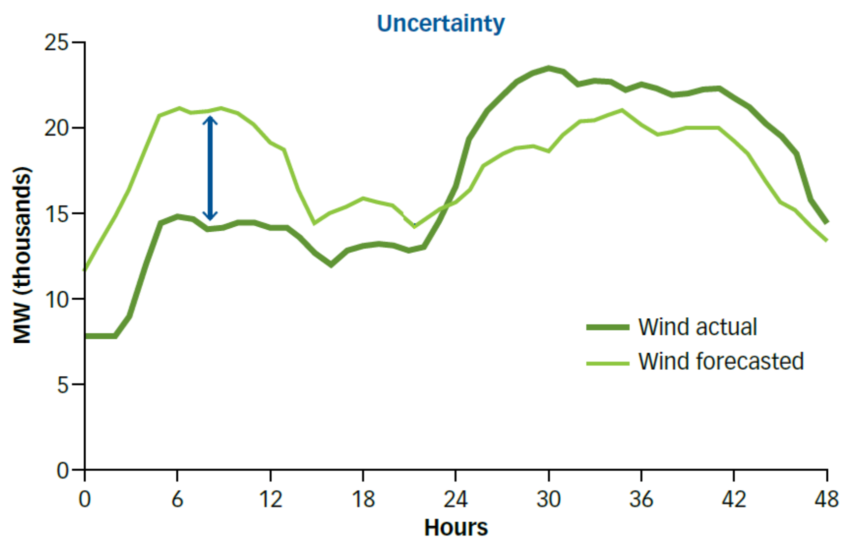
Figure 12 ratifies that load and generation cycles not necessarily coincide, so that peak demands may occur at times when the wind output is minimum. Resulting discrepancy produces sharp deviations in the net load.

Due to the wind speed variability, it is also unlikely to identify a clear pattern in wind output fluctuations. In contrast to the aggregated load, the wind output undergoes unpredicted and wide intra-day oscillations, which constantly challenge the system operator.

3.3. Wind Uncertainty and Day-Ahead Unit Commitment Process

The wind uncertainty arises from the random pattern followed by wind speed fluctuations. Such characteristic prevents accurate medium-term forecasts, despite the variety of methods dedicated to this purpose. As a result, a discrepancy between actual and expected productions take place, as shown in Figure 13. (ELA et al., 2013).

Figure 13 – Uncertainty of Wind Output over a Two-day Period



Source: ELA, DIAKOV, *et al.* (2013).

Estimation uncertainties increase with the anticipation to the period of interest. Therewith, day-ahead forecasts are less accurate than 15-minute-ahead forecasts, which, in turn, do not allow long to determine the operation strategy.

On the other hand, accuracy increases with the installed capacity and its dispersion around distinct geographic regions. These factors reduce forecast exposure to punctual deviations, such as equipment failures and modelling misconceptions, and increase its assertiveness. Yet, wind generation still reports the higher uncertainty levels among RE sources.

The unit commitment process alternatively manage the unpredictability of both wind production and real demand. This process implies assigning, with 24h anticipation, committed generators responsible for reacting in case of system imbalance. Thereby, if the actual output of a wind unit is, within an hour, lower than the predicted in the day-ahead forecast, the committed generators compensate the shortfall during this period.

In case maximum production levels of the committed generators are not sufficient to provide the demand, then spinning reserves, quick start units, and short-term purchases compensate the remaining deficit. The use of such solutions, however, negatively affects the operation costs.

Large fractions of wind in the generating pool increase net load variability and, thus, may require the addoption of expensive solutions to compensate its intrinsic instability.

3.4. Priority Dispatch

System operators usually work with hourly production schedules, defined one day in advance. It consists in a cost-effective combination of generating units assigned to meet projected load and reserve requirements. Such planning adheres to generator and transmission constraints, and invariably complies with the national grid code. Acknowledged process is, so called, economic dispatch.

In most grids, wind energy has the lowest marginal cost and, hence, the highest priority in dispatch. This fact culminates with the displacement of conventional generation sources, which reach lower minimum operating levels and suffer shutdowns more frequently.

In parallel, wind units are also subject to curtailment in case their production exceeds the difference between the load and minimum production levels of dispatched generators. Such restriction, though, does not apply in case redispatch and ancillary services are enough to manage the real time imbalance.

3.5. Transmission Requirements

Once wind energy is site-constrained and areas with good resource availability are usually far from load centers, network reinforcement, upgrade and extension are commonly required. Those interventions enable a successful power drainage and support the energy exchange between regions that compose the interconnected system.

Even so, long distance transmission is subject to high series losses and voltage fluctuations at the interconnection point. In order to mitigate these effects, power flow studies are desirable to attest transmission constraints, as well as to determine whether reactive power compensation in the lines apply.

Unlike, in case the transmission infrastructure is obsolete or inappropriate and the power flow is not assessed, the system flexibility is affected, placing an obstacle to the insertion of wind into the grid.

4. ALTERNATIVES TO PRESERVE GRID STABILITY

JAIN and WIJAYATUNGA (2016) state that the best practices to preserve power grid stability in face of the wind penetration into the electric matrix comprise:

i) Reducing Forecast Lead Time and Dispatch Interval
ii) Active Power Control
iii) Flexible Generation
iv) Flexible Demand
v) Grid Codes
vi) Comprehensive Planning Process

Abovementioned procedures enhance grid flexibility through responsive systems operations, and are addressed in the following sections in line with JAIN and WIJAYATUNGA (2016), unless confirmed otherwise.

4.1. Reducing Forecast Lead Time and Dispatch Interval

HOLTTINEN, TOUHY, *et al.* (2013) defends that reducing dispatch intervals unlocks the flexibility available in dispatched generators. As such, they respond to system changes and leave expensive regulating reserves to manage instantaneous disparities. Consequently, the system supports a larger amount of variability and uncertainty and operates in an economical manner.

Both the forecast lead-time and the dispatch interval are defined by the system operator in accordance with the likely amount of curtailment, the forecasting accuracy and the flexibility of generation units. Altering their time frames do not imply costly interventions but investments in operation planning and structuring. Thereby, this solution is widely explored in emerging wind markets.

In the US, for instance, several independent system operators adopted 15-minute scheduling and dispatch intervals. Such practice proved effective to accommodate higher fractions of wind in the generation bases, once it allows production schedules to rely on more accurate generation and load forecasts.

4.2. Active Power Control

As previously described in sections 3.3 and 3.4 of this document, in the event that the wind output exceeds the difference between the actual load and minimum production of dispatched generators, the turbine control enforces active power curtailment. This action complies with the system operator guidelines, supported by the grid code. Thereafter, wind becomes a dispatchable source.

Relevant considerations for the wind-integrated dispatch are:

(i) WPP must be adequately compensated for the constrained production and the additional investments in active power control;
(ii) WPP controls should not adversely impact the stability of the grid; and
(iii) WPP controls should not increase the loading of wind turbines, so as not to affect their lifetime. (ELA et al., 2014).

The criteria above intend to ensure basic conditions for wind units operation, so that the strategy is not applied to its detriment but to preserve system stability. Albeit, enabling active power curtailment implies the under-utilization of generation capacity, what leads to an increase in energy costs. Therefore, such intervention is only conducted in case other alternatives are not available.

4.3. Flexible Generation

Flexible generation corresponds to the ability of a power system to vary its output in order to meet the erratic demand. This feature strongly relies on generators response time due to the short events' timescales, which need to be matched in order to minimize generation-load discrepancies. The shorter the reaction time a unit provides, the more effective it is in rendering generation flexibility.

Accordingly, an optimum generation pool includes fast-ramping generators, able to be dispatched within minutes and to rapidly change production levels. Examples are gas peaking plants and hydropower turbines. In contrast to steam turbines – with typically lower ramping rates – these technologies are appropriate to balance the load and support ancillary services.

Apart from them, reserve generators also present desirable high ramp rates and low minimum operating capacity. They comprise storage technologies such as pumped-hydro, compressed air, flywheels and utility-size batteries, which alternatively provide energy and power to the system. Their utilization, however, precedes high operation costs.

Likewise, active power control, detailed in section 4.2, manages the electrical output through energy curtailments, increasing generation flexibility. Regardless, its application is not cost-effective and strictly occurs in specific cases.

4.4. Flexible Demand

Demand flexibility concept is analogous to the abovementioned strategy, however, implemented from the load perspective. It employs either load-balancing or load-shifting in order to compensate generation-load disparities in an effective manner. Its implementation, in turn, not necessarily implies adverse economic effects.

The load-balancing practice conceives that customers with flexibility to postpone their operations or reduce their power consumption for a given period characterize dispatchable loads. Thereupon, corresponding demands are allocated according system capacities.

In parallel, the load-shifting alternative apportions the load of large electricity customers according to time-of-day tariffs. Therewith, customers are encouraged to shift bulk loads from times of peak demand – and, hence, high tariffs - to times of off-peak demand and high energy production – hence, low tariffs – in order to benefit from lower electricity costs.

Addressed options both comprise responsive operations implemented at low costs and minor changes to adapt the demand necessities to generation constraints. Such characteristic promotes its implementation as an effective alternative to preserve system stability.

4.5. Grid Codes

National grid codes are compilations of operating procedures and guidelines adhered by every utility connected to the grid. Such directives aim for proper, secure and economic operations and concern, among others, acceptable frequency and voltage levels, appropriate fault ride through response and power quality criteria.

It is the operator responsibility to ensure the fulfillment of code standards in order to preserve system integrity and reliability. Although, the more restrictive the code, the lower its applicability. This relation comprises both technical constraints and implementation costs. In line with that, operating procedures are constantly revised to accommodate grid changes and the development of new technologies.

The conception of a proper grid code safeguards power system conditions and allows interconnected units a reliable and economic operation (IEA, 2017). The code complience not only preserves power quality but also increases system flexibility, favouring wind penetration into the grid.

4.6. Comprehensive Planning Process

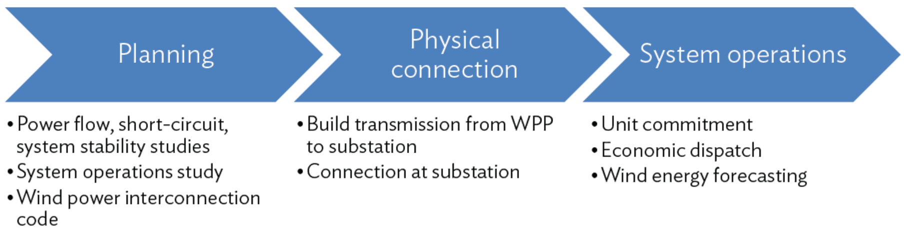
Institutionalizing a comprehensive planning process for power system development allows the anticipation of structural and operational constraints. In these terms, once prospected wind capacities are included in system assessments, an accurate perception of wind integration impacts is achieved. System assessments include power flow, short-circuit, dynamic stability and system operation studies, which provide relevant inputs for operation planning. Therewith, a long-term strategy can be developed in order address identified limitations.

Sensible planning characterizes an inexpensive solution for supporting the integration of multiple power sources into the grid. It also assists in a reliable operation by promoting favorable network conditions, in compliance with the grid code. Regardless, grid integration usually occurs on an ad hoc basis in most emerging wind markets.

5. WIND INTEGRATION COSTS

According to JAIN and WIJAYATUNGA (2016) wind integration comprises a collection of activities that split in three main stages: planning, physical connection and system operations, as illustrated in Figure 14.

Figure 14 – High-Level Activities of Grid Integration



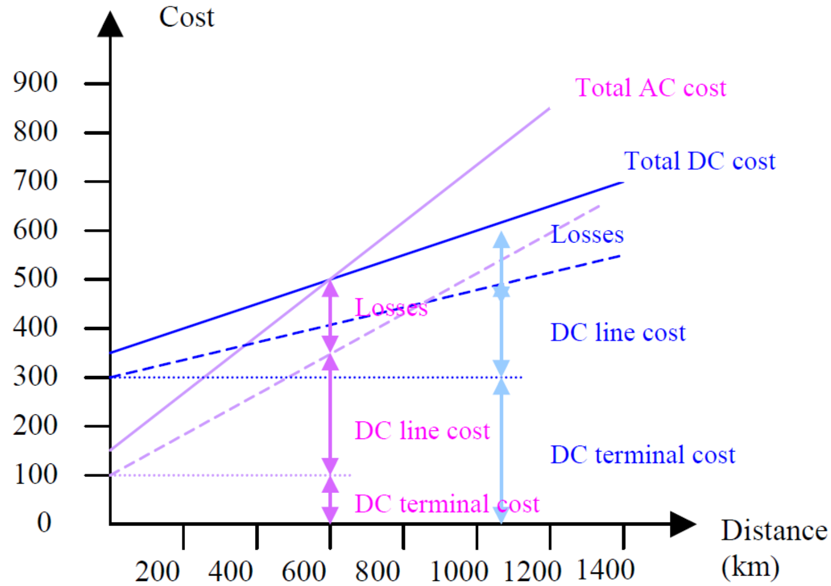
Source: JAIN and WIJAYATUNGA (2016)
Note: WPP – Wind Power Plant;

The suitability of referred interventions rely on grid specific aspects, for instance, power generation sources, existing network infrastructure, characteristic demand behavior, and others. Thereby, integration costs vary accordingly and are addressed in this chapter from a relative perspective.

Planning activities generally involve system impact studies, operation assessments and grid code implementation (JAIN & WIJAYATUNGA, 2016). As Figure 16 points, these interventions correspond to minimum relative costs and, therefore, characterize an economic manner to support the insertion of varied power sources into the grid (ELA et al., 2013).

Whereas, exploiting areas with high-quality wind resource, generally far from load centers, may demand investments in transmission infrastructure. According to IEA (2017) this amount corresponds to a small fraction of the costs intended for additional generation in order to provide an equivalent electrical output at a nearby but low-quality resource area. Thereby, physical connection corresponds to the reinforcement, upgrade and extension of the existent network. Corresponding investments vary with the line technology, the network extension, geographical and environmental constraints, economic aspects and other factors. Figure 15, in sequence, illustrates the costs of HVAC and HVDC transmission structures.

Figure 15 – HVAC versus HVDC Transmission Costs



Source: LARRUSKAIN, ZAMORA, *et al.* (2014).

The intersection point between HVAC and HVDC dashed curves indicates the approximate distance from which direct current technology becomes a cost-effective alternative for power drainage. This scenario highlights the significant impact of the line technology and extension on overall transmission costs. (LARRUSKAIN et al., 2014).

Else, NREL studies relate investments in transmission with the penetration levels of RE into the grid. According to the laboratory, the higher the RE shares, the longer the network length and, thus, the higher corresponding transmission costs. Table 10, below, presents the results of their investigation. (MILLIGAN et al., 2012).

Table 10 – New Transmission Investments According to the RE Penetration

Scenarios	New lines [10^6 MW.km]	Interties [MW]	Investments [billion $/y]
30% RE	7	6500	1.8
60% RE	28	10500	4.2
90% RE	60	85000	8.3

Source: MILLIGAN, ELA, *et al.* (2012).
Note: Investments include the costs for new transmission lines and system interconnection.

Main assumptions for grid components rely on costs from on the U.S. market and are exposed in Table 11.

Table 11 – Costs of New Transmission Lines and Interconnections

Transmission and Interconnection	Range [$]	Notes
Long distance transmission lines [$/MWkm]	746 - 3318	High-voltage infrastructure, 500 kV to 765 kV. Include a 25% contingency factor that covers the cost of redundancies in the transmission lines.
Substation costs [$/MW]	10,700 - 24,000	Applied to the endpoints of each new transmission lines.
Intertie (AC-DC-AC) costs [$/MW]	230,000	Apply when grid expansion spans 2 of the 3 U.S. interconnections.
Base grid interconnection costs [$/MW]	110,000	Applied to new generation and utility-scale storage technologies: natural gas, biopower, wind, CSP, and utility-scale PV installations.
	220,000	Applied to new generation and utility-scale storage technologies: coal, hydropower, geothermal, CAES, and PSH.
	100,000 - 1,000,000	Applied to new remotely located wind and CSP technologies to account for the distance to the existing transmission system or load centers.
Low voltage transmission lines [$/MW-km]	1491 - 6636	-

Source: MILLIGAN, ELA, *et al.* (2012).
Note: Costs extracted from on the U.S. transmission market, in dollars.

Investigation findings support that the rate with which new transmission lines are required increase with the penetration levels of RE into the system, as Table 12 states.

Table 12 – Network Extension According to the RE Penetration

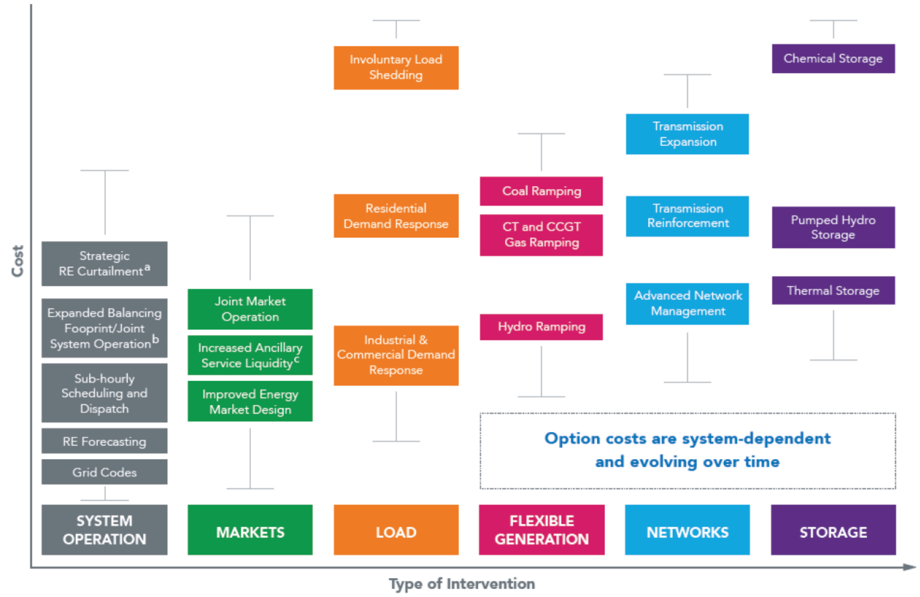
Scenarios	New lines [10^6 MW.km/%]
30% < RE < 60%	0.70
60% < RE < 90%	1.07

Source: Autor.

Moreover, reference values in Table 11 expose the great interconnection costs of remote wind units, and quantify the contribution of line length to overall transmission expenses. Extending network lines, however, reduce congestion and increase reliability.

Alongside with first stages activities, responsive systems operations play an important role in wind integration into the grid, and may characterize an obstacle if not properly managed. These practices' implementation costs vary over a wide range, as Figure 16 assigns. (JAIN & WIJAYATUNGA, 2016).

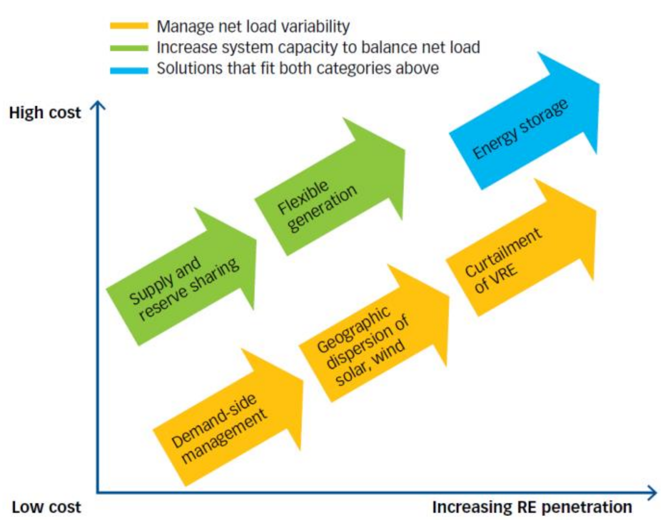
Figure 16 – Alternatives to Increase Flexibility According to Implementation Costs



Source: JAIN and WIJAYATUNGA (2016).

Aiming for a cost-effective solution, the system operator conducts low-cost interventions whenever possible, for instance, sub-hourly scheduling and dispatch, grid code standards and demand response. However, a low system flexibility may enforce the use of expensive storage and spinning reserves, increasing, thereafter, the operation costs. VRE penetration into the grid, likewise, affects the overhead, as exposed in Figure 17 . (JAIN & WIJAYATUNGA, 2016).

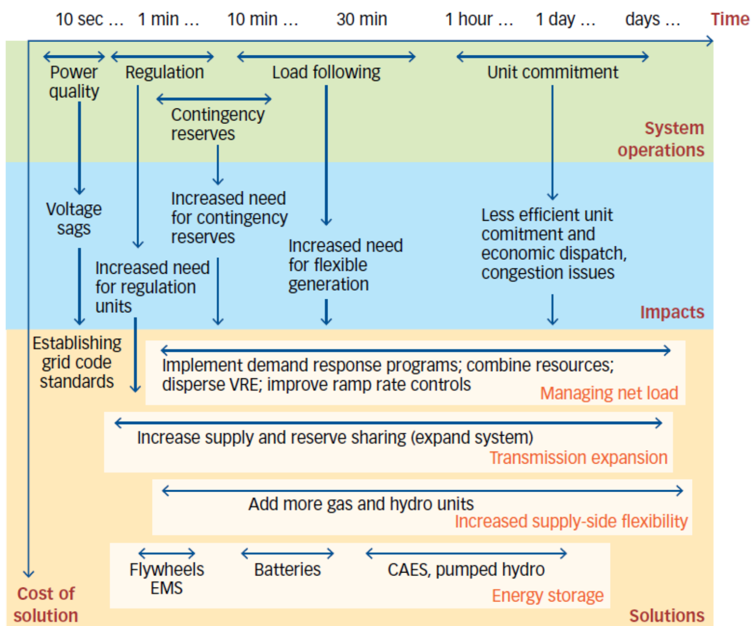
Figure 17 – Alternatives to Manage Variability According to RE Penetration Levels



Source: Adapted from DENHOLM, ELA, *et al.* (2010).
Note: This figure is indicative, individual cases may differ.

Despite being an expensive solution to manage system fluctuations, energy storage provides a reliable response in case of extreme variability levels, typical of configurations with large VRE shares. Else, in line with the alleged in subsection 3.3, geographic dispersion of wind units arise as an affordable alternative to manage load variability (NIKOLAKAKIS & CHATOPADHYAY, 2015). Concerning operation timescales, Figure 18, in sequence, provides a more detailed overview.

Figure 18 – Alternatives to Manage Variability According to Operation Timescales



Source: NIKOLAKAKIS and CHATOPADHYAY (2015).
Note: CAES = compressed air energy storage; EMS = electromagnetic storage.

The green, blue and orange areas above address the operation timeframes, impacts and costs, respectively. The scheme reveals that the instantaneous power quality relies on grid standards, while system regulation is accomplished through energy storage and transmission expansion. Furthermore, it confirms that supply-side flexibility increases with the addition of gas and hydro units to the system, which, in turn, consists of an expensive alternative to manage system variability. (NIKOLAKAKIS & CHATOPADHYAY, 2015).

Last of all, a deficient integration of wind into the grid leads to ineffective system operations, which deploy onerous responsive measures in the attempt to preserve grid stability. Power quality is, thus, negatively affected, and system reliability levels tend to drop. Whilst, energy costs experiment an inevitable hike and the advancement of VRE technologies - such as wind - is hampered. (COCHRAN, BIRD, *et al.*, 2012; IEA, 2017; NIKOLAKAKIS and CHATOPADHYAY, 2015).

6. CASE STUDY: AN OVERVIEW OF WIND ENERGY INTEGRATION TO DENMARK'S POWER SYSTEM

Global wind penetration levels, in terms of electrical power output, reached its highest stages in 2017 by accounting for 44.0% of total generation Denmark. Thus, the following case study aims to describe the developments in Danish energy matrix over the years that contributed for this scenario. Subsequent considerations are supported by IRENA (2013), unless stated otherwise.

6.1. Denmark

The commercialization of wind energy technology in Denmark, only started after the oil crises of the 1970s. Until then, the country had an exceptionally high dependency on imported oil, which corresponded to more than 90% of its energy supply. The adverse economic scenario due to the 1973 and 1979 oil crises, thereby, triggered the power shift process experimented over the following years.

According to the Danish Energy Agency, a proactive energy police through four energy plans promoted the complete restructuring of country's electric matrix. The first of them was put in place in 1976, and intended to reduce Danish dependence on imported oil by seeking energy savings and switching to coal and nuclear generations. As renewables played a marginal role in power supply, energy taxes were used to support R&D on such technologies. Thereby, an antinuclear movement (OOA) soon started in the country grounded on two alternative energy plans: "Sketch for an energy plan in Denmark", from 1976 and "Energy for the future: alternative energy plan", from 1983. By 1985, thus, the Danish parliament excludes nuclear power from its future energy planning and wind emerges as a key alternative to supply such share of electricity generation. (IRENA, 2013; DEA, 2017).

Subsequently, the Second Energy Plan, from 1981, helped establish a strong home market for renewable energy by introducing subsides for the construction and operation of wind turbines. Whereas, taxes imposed on oil and coal helped increase the competitiveness of such technologies. Additionally, an agreement between Ministry of Energy and the utilities set ambitious targets for the wind power installations, supporting the local industry's growth. The Danish government initially provided capital grants of up to 30% of the installation costs, progressively reduced with the improvement of turbines reliability and cost-effectiveness. (IRENA, 2013). The subsidy was repealed in 1988, and community-owned wind energy was supported by three main principles:

i) The right to connect to the electrical grid;
ii) A legal obligation for electrical utilities to purchase wind energy; and
iii) A guaranteed fair price. (CHRISTIANSON, 2005).

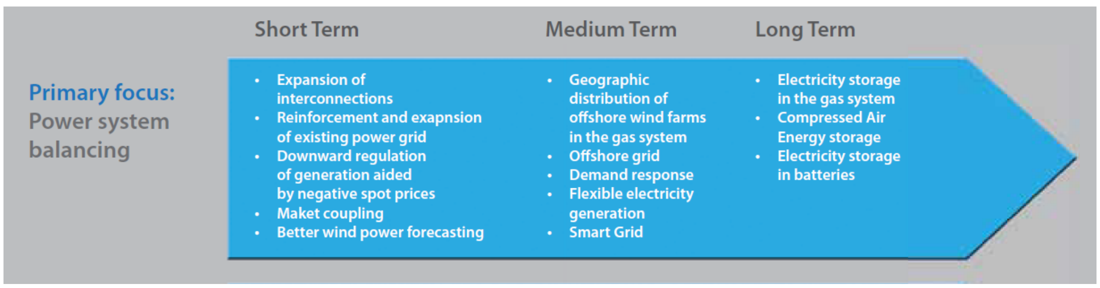
After 1990, the third Energy Plan took place along with specific targets, which included reducing CO2 emissions and supplying 10% the electricity demand wind turbines by 2005. In 1992, the "fair price" for wind power was set at 85% of the retail electricity rate, and regulations provided guaranteed interconnection and power purchase of wind-based electricity. Thereupon, in 1993, this practice was replaced by a fixed feed-in tariff set at 85% of the utility's production and distribution costs. Yet, wind projects received a refund from the Danish carbon tax and a partial refund on the energy tax, doubling their payment for the first five years of operation (BOLINGER, 2001). As a consequence, 10% of Danish electricity consumption would be supplied by wind energy by 2005.

The fourth and last plan, from 1996, envisaged that renewable energy would provide 12-14% of total energy consumption in 2005, and 35% by 2030. To this regard, the Danish Energy Agency was in charge of implementing the policies required for such development. Within this period, an important mark was achieved when Denmark became a net exporter of energy.

In the following years, rising oil prices and environmental concerns influenced new policy guidelines. The Danish government, in its energy policy statement of 2008, committed to address climate change reducing energy consumption and increasing the use of renewables. According to RATHMANN, et al. (2009) the support scheme for these technologies relied on price premiums and tenders for offshore wind power. The financing instruments were conceived and managed by the Danish Energy Agency, and subsidies costs were passed on to consumers as an equal Public Service Obligation tariff on their total electricity consumption.

Finally, current pursued goals descend from a broad energy agreement stated by the Danish parliament in 2012. It ambitiously projected that wind energy should supply 50% of country's electricity consumption by 2020. The connection to the grid consists of a major challenge for meeting this goal. According to Denmark's Energy and Climate Outlook 2017 wind power already accounted for 42% of electricity generation in 2016, and is expected to cover 48% in 2020 (DEA, 2017, IEA, 2017b). The Transmission System Operator (Energinet.dk), despite supporting the developments, expects to supply 50% of the demand with wind power by 2025, exceeding given terms. Figure 19, below, outlines its measures to address such target.

Figure 19 – Danish Operator Development Plan



Source: Adapted from IRENA (2013).

The chart places interventions on the physical network – i.e. expanding interconnections and lines –, strategic market regulation and accurate wind power forecasting as short-term alternatives for power system balancing. Except for the first, cited activities do not imply high implementation costs. Prospectively, it assigns geographic distribution of wind farms, flexible generation and smart grids as medium term interventions with the same purpose. Expensive storage technologies are only considered in the long-term range. This agenda results from the sensible planning of future operations aiming for cost-effective solutions to allow a reliable operation based on large wind shares.

A large share of wind energy increases, the necessity of strong power interconnectors to support the power exchange with neighboring countries becomes more evident. They allow the intermittent wind power production to be sold cost-efficiently, whilst minimizing the need for national capacity reserves and maintaining a high security of electricity supply. (DEA, 2017).

Overall, presented trends reveal that the expressive penetration of wind into Denmark's generation bases arise from comprehensive government incentives in the early development stages of this technology. The continuity of this process, however, was enabled by the outcomes of R&D studies that along with a comprehensive planning process transformed the wind source in a cost-effective manner to meet the electrical demand.

7. CONCLUSIONS

The consistent increase in wind capacities around the globe challenges system operations to accommodate intermittent power sources into the grid. Such achievement depends on overcoming wind variability and uncertainty, what becomes more complex and onerous as penetration levels rise. (COCHRAN et al., 2012).

Wind penetration, in terms of electrical power output, reached remarkable stages in 2017, accounting for 44.0% in Denmark and 30% in Uruguay. These figures prove possible the broad insertion of wind into the generation bases without adversely affecting power quality, system stability or supply reliability. (GWEC, 2017).

In order to accomplish such results, grid specific practices are adopted to support wind integration of into the grid. They comprise a sensible planning process, physical network connections and responsive system operations. Their corresponding costs and timescales, after all, define operation effectiveness. A faulty integrating process, thus, may hamper the advancement of wind towards energy markets. (DENHOLM et al., 2010; JAIN & WIJAYATUNGA, 2016; NIKOLAKAKIS & CHATOPADHYAY, 2015).

Furthermore, Denmark's case study revealed that strong government incentives in the early development stages of wind technology are essential to support this source introduction into the power matrix. The continuity of this process, however, relies on R&D outcomes that, along with the planning process, enable a cost-effective operation. (DEA, 2017; IEA, 2017b; IRENA, 2013).

In conclusion, current investigation findings establish that the consolidation of wind as a reliable source of power is conditioned by its proper integration into the power system, as well as by grid specific constraints and wind resource availability. High penetration levels of this technology are feasible as long as specific measures are conducted to balance the load and provide acceptable ancillary services.

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APPENDIX

GLOBAL INSTALLED WIND POWER CAPACITY (MW) – REGIONAL DISTRIBUTION

Countries	**End 2016**	**New 2017**	**Total 2017**
AFRICA & MIDDLE EAST			
South Africa	810	-	810
Egypt	787	-	787
Morocco	324	-	324
Ethiopia	245	-	245
Tunisia	119	-	119
Jordan	159	-	159
Other1	3,911	618	4,528
Total	168,732	19,660	188,392
ASIA			
PR China	28,700	4,148	32,848
India	3,230	177	3,400
Japan	1,031	106	1,136
South Korea	590	199	789
Pakistan	682	10	692
Taiwan	609	24	633
Thailand	427	-	427
Philippines	159	38	197
Vietnam	50	50	100
Mongolia	70	-	70
Other2	204,281	24,412	228,684
Total	50,019	6,581	56,132
EUROPE			
Germany	23,075	96	23,170
Spain	14,602	4,270	18,872
UK	12,065	1,694	13,759
France	9,227	252	9,479
Italy	6,091	766	6,857
Turkey	6,494	197	6,691
Sweden	5,807	41	5,848
Poland	5,230	342	5,476
Denmark	5,316	-	5,316
Portugal	4,328	81	4,341
Netherlands	2,701	426	3,127
Ireland	3,024	5	3,029
Romania	2,378	467	2,843
Belgium	2,632	196	2,828

Countries	End 2016	New 2017	Total 2017
Austria	1,539	535	2,071
Finland	5,294	455	5,745
Rest of EU	153,731	15,638	168,729
EU-284	7,612	1,166	8,777
Rest of Europe3	161,342	16,803	177,506
Total Europe	10,741	2,022	12,763
LATIN AMERICA & CARIBBEAN			
Brazil	1,424	116	1,540
Chile	1,210	295	1,505
Uruguay	319	59	378
Costa Rica	270	-	270
Panama	243	-	243
Peru	204	24	228
Argentina	180	45	225
Honduras	135	-	135
Dominican Republic	200	18	218
Caribbean5	386	-	386
Others6	15,312	2,578	17,891
Total	82,060	7,017	89,077
NORTH AMERICA			
USA	11,898	341	12,239
Canada	3,527	478	4,005
Mexico	97,485	7,836	105,321
Total	4,312	245	4,557
PACIFIC REGION			
Australia	623	-	623
New Zealand	13	-	13
Pacifi c Islands	4,948	244,9	5,193
Total	487,279	52,492	539,123

Source: (GWEC, 2017).

1 Algeria, Cape Verde, Iran, Israel, Kenya, Libya, Mozambique, Nigeria

2 Azerbaijan, Bangladesh, Sri Lanka

3 Belarus, Faroe Islands, FYROM, Iceland, Liechtenstein, Norway, Russia, Switzerland, Serbia, Turkey, Ukraine

4 Austria, Belgium, Bulgaria, Cyprus, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, UK

5 Caribbean: Aruba, Bonaire, Curacao, Cuba, Dominica, Guadalupe, Jamaica, Martinica, Granada, St. Kitts and Nevis

6 Bolivia, Colombia, Ecuador, Guatemala, Nicaragua, Venezuela Note: The stats includes a decommissioning of 648.8MW