



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0383

ELECTRICAL ENERGY MATRIX CHANGES AND ITS IMPACTS ON ENERGETIC SECURITY

Renata V. C. S. G. Francisco

Dept. of Mechanical Engineering, Federal University of Itajuba, MG, 37500-903
renata.vitorf@gmail.com

Diana S. Siqueira

Dept. of Mechanical Engineering, Federal University of Itajuba, MG, 37500-903
dyana.sylver@gmail.com

Genésio J. Menon

Dept. of Mechanical Engineering, Federal University of Itajuba, MG, 37500-903
genesio@unifei.edu.br

Rogério J. Silva

Dept. of Mechanical Engineering, Federal University of Itajuba, MG, 37500-903
rogeriojs@unifei.edu.br

Abstract. *The use of thermal power plant has shown to be important to guarantee the energy supply when there is an unfavorable hydrological period, verified by the excessive use of thermal power plant on past three years. Before the current period of water scarcity, in 2000-20001 the energy crisis had earlier revealed the vulnerability of a massive use of renewable sources only in the electrical energy matrix. However, the 10-year Energy Plan 2024 shows thermal energy power will decrease Brazilian electrical energy matrix while solar and wind power will increase. Brazil already has a strong participation of hydropower plants, and these are facing serious interruptions on operation due water shortage, caused many reasons, such as changes in the amount of rainfall and increase in electrical energy consumption. Hence, the purpose of this paper is to discuss if the alternative sources expansion in the Brazilian electrical energy matrix will guarantee energy supply for the country, even with long hydrological periods unfavorable.*

Keywords: *electrical energy matrix, thermal power plants, energetic planning, energy security*

1. INTRODUCTION

In recent years, the world electricity consumption has been stagnant due to the lowest global economic growth; but, in 2016, it showed signs of recovery with a 2.2% increase in energy generation compared to 2015 (World Energy Council, 2016). Growth in the generation was led by China, which accounts for, approximately, 60% of electricity consumption in Asia (World Energy Council, 2016).

Considering the total electricity generated globally in 2016, 24% was produced by renewable sources, showing a growth of 14.1% over 2015 (not including hydroelectric plants) (British Petroleum, 2017). The increase was mainly driven by wind and solar production, with the Chinese market being the largest generator. Some factors, such as advances in technology, improved efficiency in electric power generation, and greater control of greenhouse gas emissions, have boosted the technologies uses around the world.

Most of the world's electricity is generated from fossil fuel, being coal the most important energy source for electric power generation (British Petroleum, 2017). Usually, thermoelectric plants are used as baseload power because of the ability to provide safety to the energy system, especially coal and thermonuclear.

Natural gas is emerging as an alternative to the use of coal, due to the price of fuel, reduced operating costs, and low greenhouse gas emissions. However, price volatility, as well as the risk of importation dependency, make gas not very attractive to many countries (World Energy Council, 2016). However, new natural gas discovery and the growth in liquefied natural gas supplies shows a new horizon for the enlargement of natural gas use.

In Brazil, the electrical energy matrix is dominated by renewable sources, in especial of hydraulic generation, which has changed over the last ten years. The reduction of hydropower participation in baseload power has reduced, mainly,

because of the decrease in rainfall rate that has decreased the storage energy in reservoirs. The lack of hydropower has been compensated by thermal power generation, which has grown over the last three years, in opposition to the worldwide trend. The participation of wind power has also increased, so the electrical energy demand can be attended, especially in Northeast.

Nevertheless, according to with the 10-Year Energy Plan 2024, the participation of thermal power plants will decrease in 0.5%, in opposition to solar and wind power will increase to 14.9% of the total of the electrical energy matrix (EPE, 2015). Hence, the purpose of this paper is to discuss if the alternative sources expansion in the Brazilian electrical energy matrix will guarantee energy supply for the country, even with long hydrological periods unfavorable.

2. WORLD ENERGY OUTLOOK

Thermal power generation is responsible for majority power production, in which the fuel most used in the last 44 years is coal (International Energy Agency, 2017a). However, natural gas and renewable sources have increased its participation in the world electrical energy matrix, and it is expected that they will still growth until 2050 (IchorCoal, 2017).

Mineral coal is responsible for 41% of world power generation (World Energy Council, 2016); yet, its use to produce electrical energy has fallen 6.1% in OCDE countries while worldwide it has increased in 0.4% (International Energy Agency, 2017b). India, China, and North America will have the larger rise in coal demand until 2050; until there, in 2015, the power production in China was greater than twice the United States production (World Energy Council, 2016). Meanwhile, in Europe is expected to reduce the dependency on coal, rising the use of renewable sources.

An important factor related to the reduction of coal consume is the use of natural gas, which has rise annually since 2009 and is expected to have an annual increment of 1.6% in global demand until 2022 (International Energy Agency, 2017c). The global natural gas demand has increased 2.7% in 2016 in comparison to 2015 (International Energy Agency, 2017d) and power generation has the higher use among the sectors that consume the fuel (British Petroleum, 2017). Also, this is the second source most used in power generation, responsible for 22% of world production (World Energy Council, 2016).

The unconventional gas production, such as shale gas and gas hydrates, responded for 10% of total gas production in 2014, which led to an increase in competition in regional markets and it contributed to a surplus of gas and low costs (World Energy Council, 2016). In 2040, it is projected that natural gas, wind power, solar power and nuclear power will have a rise in the participation of world electrical energy matrix (Exxon Mobil, 2017).

There are nuclear power plants in 31 countries, representing 11% of the power generation in the world (World Energy Council, 2016). Since 2011, the participation of nuclear power plants in the world electrical energy matrix has a low rate of rising; still, it is predicted that its participation will grow between 1.9% and 56% until 2030 (International Atomic Energy Agency, 2017).

3. GENERATING CAPACITY IN BRAZIL

In Brazil, the Brazilian National Interconnected System (*Sistema Interligado Nacional, SIN*) is responsible for the public service of power generation and transmission, with exception of the state of Roraima. The SIN has the objective to assure the electrical energy demand with the minimal operational cost so that hydropower plants are preferable to operate because of its low operational cost.

The system operation allows the power exchange among the regions using the electrical grid to enhance the reliability of the operation (Taesa, 2017). There are four subsystems in Brazil, even though there are five regions in Brazil, and each subsystem has its own particularity.

The Southeast/Mid West (SE/CO) subsystem is the system with larger generating capacity, which corresponds to 55.8% of the total SIN (ONS, 2017a) and larger electrical energy demand, so it imports electricity from the other systems. The North (N) subsystem exports energy for, at least, 9 months, because of its low electricity demand and high power production in the rainy period.

The South (S) subsystem is a higher variability of energy storage, due to its hydrology; the exchange of energy varies greatly during the year. The Northeast (NE) has the second larger generating capacity, which is 17.8% (ONS, 2017a) and is a subsystem is designed to import energy (Deus, 2008). However, this has changed through the last years due to the unfavorable hydrological period and the growth of wind power generation. This way, the direction of the exchange varies depending on the wind generation.

The Brazilian electrical energy matrix has never been so diversified as in the last years. In 2006, the hydropower was 84.1% of generating capacity, the thermal power was 13.5% and wind power was 2.1% (ONS, 2017a). On the other hand, in August 2017, the hydropower was 68.9% of generating capacity, while the thermal power and wind power had a percentual increase, so they represented 22.4% and 7.3%, respectively (ONS, 2017a). The growth of thermal power was driven by the increment of new plants using natural gas, as it is shown in Fig. 1.

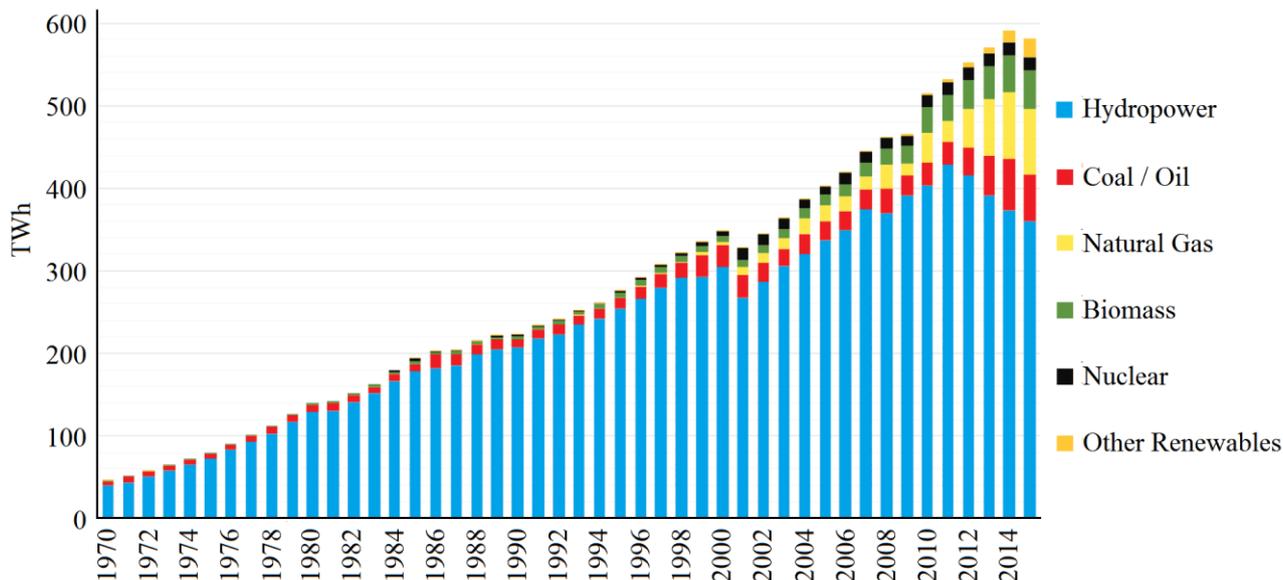


Figure 1. Electrical energy matrix evolution between 1970 and 2015
Source: Modified from Instituto Acende Brasil (2017).

The water scarcity caused by drought events associated with high temperatures, the reduction in stored energy in reservoirs and the increase of electrical energy consumption are the main factors that caused the energy crisis in 2000-2001 and 2014-2015. During the 2000-2001 crisis, Brazil had water and energy rationing and blackouts as well, which led to an increase in the diversification of the electrical energy matrix.

The Alternative Energy Sources Incentive Program (*Programa de Incentivo às Fontes Alternativas de Energia Elétrica, PROINFA*) was created in 2002 with the objective to increase the diversity in electrical energy matrix, through project implementations of wind power, biomass power, and small hydropower. The generating capacity had an increase of 372% from 2000 to 2010 for energy sources other than hydropower, with an annual increase superior to hydropower (MME-SPE/N3E, 2017).

3.1 Stored Energy

The reduction of the number of reservoirs constructed over the last years in Brazil are directly related with the reducing of hydropower generation in electrical energy matrix. Although this is a renewable source, the large reservoirs have many environmental restrictions, such as the inundation of landscapes, forests and the removal of traditional communities of their territory. Consequently, the new projects of hydroelectric power plants have opted by small reservoirs or run-of-river hydropower.

Hydroelectric power plants can be divided in storage hydropower or run-of-river hydropower. In the first case, a dam is constructed to build a reservoir that has the role to regulate the flow rate of the river, in which the regulation can be monthly, annually or biannually. On the other hand, the run-of-river hydropower doesn't have a reservoir, so there is no energy storage.

The stored energy in the reservoirs is calculated considering the water volume and the plant productivity (COENERGY, 2017), which refers to the turbine, the installed capacity, the size of the dam and the dam type (Amaral, 2011). The storage is calculated for each region (or subsystem), and it is expressed in percentage of the total capacity or MWmed. The National System Operator (*Operador Nacional do Sistema, ONS*) monitors and provides the stored energy data for each region.

The North region has the higher rainfall rate in Brazil (Quadro, *et al.*, 1996), so the reservoirs are capable to recover after a drought event quickly than the other regions. However, as it is shown in Fig. 2, the stored energy variability in the region are becoming higher year to year, in which the maximum peak in 2016 was lower to the 2015 peak and so on. The South region has a regular rainfall rate, which is the opposite of the other Brazilian regions (Quadro, *et al.*, 1996). Figure 2 shows that the South did be not affected by the drought in 2000-2001; besides, the region does not have a usual behavior in the energy storage in the last years.

The Southeast and Mid West region are the transitions between the hot weather in the North and the cool weather in the South (Quadro, *et al.*, 1996). The stored energy has decreased in the region and it does not have recovered in the last years before another reduction on the water level, as shown in Fig. 2. In the last three years, the regions had a decline in, approximately, 30% of the maximum peaks. The Southeast region alone concentrates 70% of the total Brazilian reservoirs (Amato, 2016); as a result, this reduction affects directly the SIN operation.

Among the Brazilian regions, the most vulnerable one is the Northeast, where it has a history of low rainfall rate and drought events. The stored energy has decreased drastically over the last three years, showing percentage values below the ones during the 2000-20001 energy crisis, as it is shown in Fig. 2. The last maximum peak occurred in February 2012, with 85% of the total stored energy; after that, the reservoirs were not able to fully recover, showing maximums peaks of 49% in May 2013, 43% in April 2014, 27% in April 2015 and 33% in March 2016. To compensate the lack of hydropower generation, the thermal and wind are supplying the system (ONS, 2017b).

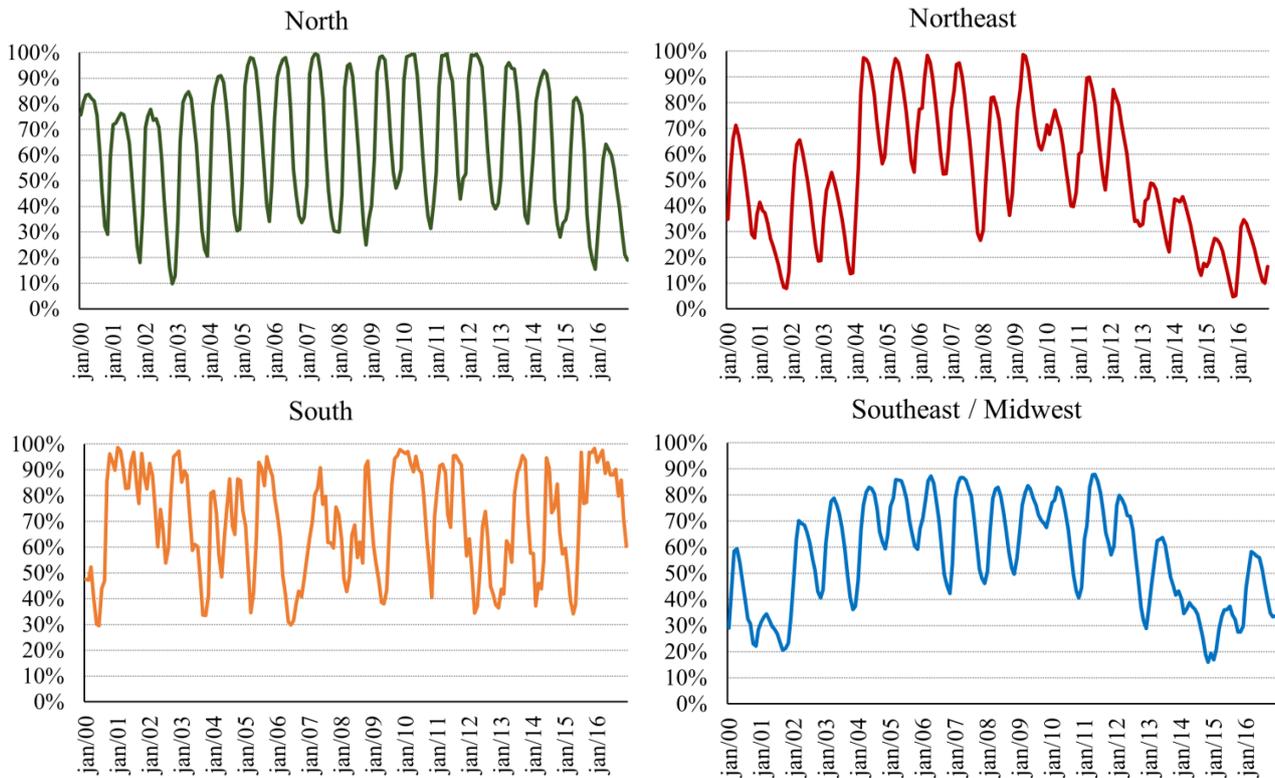


Figure 1: Stored energy by subsystem
 Source: Modify from (ONS, 2017b)

4. ELECTRICAL ENERGY MATRIX IN OTHER COUNTRIES

There is a world tendency to replace the fossil fuel power plants for renewable sources as a result of a series of factors, such as the lower greenhouse gases emissions, the lower cost of the fuel (or zero cost), etc. Therefore, around the world, there are many examples of countries that are changing or had already changed its electrical energy matrix to a more diversified one, such as Germany, Spain, and the UK. However, it is important to note that even though the fossil fuel participation has decreased in the three countries cited, it was not totally removed from the electrical energy matrix, as it is shown below.

4.1 Germany

Several investments in renewable sources were made in Germany during 2002 and 2010, in which biomass had an increase of 470%, offshore wind power had an increase of 220% and solar power an increase of almost 6,000%. However, after the nuclear accident at Fukushima Daiichi, the German government decided to close all nuclear stations until 2022, claiming that the nuclear generation is too risky. To compensate the lack of energy produced by nuclear plants, Germany increased the participation of wind power and solar, arguing that they have low cost.

The current generating capacity has 42.3 GW of solar power plants and 53.5 GW of wind power plant (onshore and offshore), which represents 20.8% and 26.4% respectively. The other sources have the following participation: 3.5% of biomass, 2.8% of hydropower, 5.3% of nuclear power, 10.3% of brown coal, 14% of hard coal, 2.1% of mineral oil and, 14.7% of natural gas (Fraunhofer, 2017).

After the changes in the electrical energy matrix, the country went from energy importer and exporter in 2011 to an exporter in 2017. According to Fraunhofer, (2017), it has registered a generation of 38.3 GW from a total of 67.4 GW generated in 13/09 at 11h; however, there are days that wind power is lower to 0.5 GW. On the other hand, there are days that solar power generating hits 24.2 GW while wind power is only 4.2 GW, in 04/09 at 12h, as it is shown in Fig. 3.

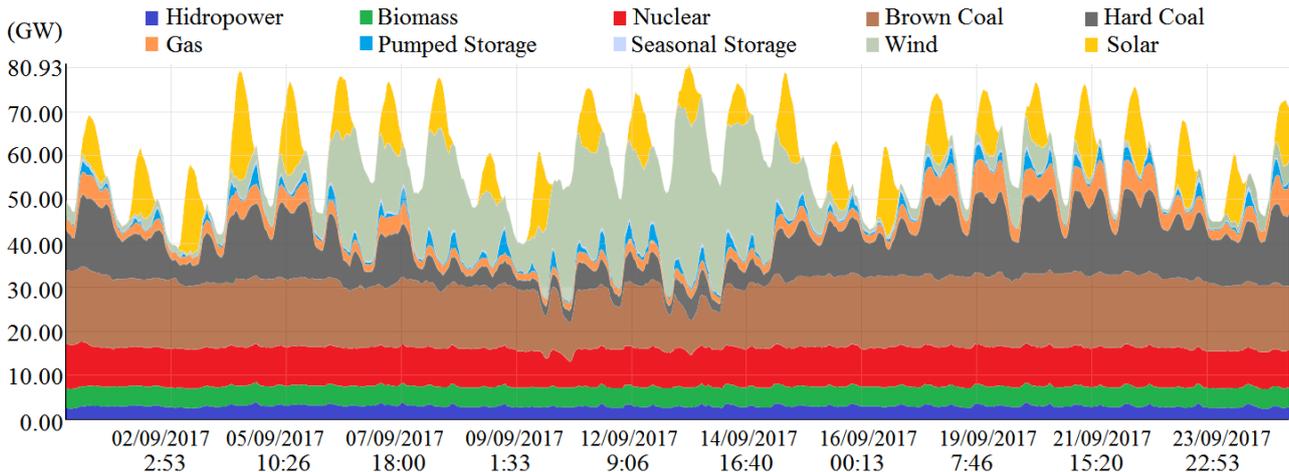


Figure 2. Power generation in Germany through 31/08/2017 to 25/09/2017
Source: Modified from Fraunhofer (2017)

The high participation of renewable sources shows that the generation is intermittent; therefore, it is necessary the use of thermal power plant, which is stable sources on the baseload system. It is used hard coal and natural gas power plants and, in minor scale hydropower and pump storage. With that said, the country is still dependent on thermal power plants using fossil fuel (mainly coal and natural gas) to assure the energy security. These thermal power plants operate when there is a reduction of wind and solar power, in which the hard coal power plants are the ones with larger thermal load variations.

In 18/09 at 18h, it was registered a total generation of 66 GW, in which the hard coal power plants of 18.1 GW and a natural gas power plants of 7.1 GW; meanwhile the solar power and wind power generated 0.1 GW and 4.7 GW, respectively. On the other hand, in 09/09 at 12h, it was produced a total of 77.4 GW, in which 11.12 GW was from solar power and 30.4 GW was from wind power; on the opposite, the production from hard coal and natural gas was 4.4 GW and 2.1 GW. This variability of production from these different sources reinforces the affirmation that the thermal power plants are necessary to complement the system.

Another important point related to the thermal power generation is that the hard coal is mainly from importation, of which 86% is imported from Russia, United States, Canada, Australia, Colombia and South Africa. The power generation and heat production are the major consumers, responsible for 67% of the demand (Statistisches Bundesamt – Destatis, 2017)

4.2 Spain

Spain showed an expressive growth in last decade of the participation of renewable sources in its electrical energy matrix. In 2007, the renewable sources, such as hydropower, wind power, solar power, were 21.3% in generating matrix; in contrast, in 2016 the participation increased to 40.8% of the matrix (Red Eléctrica de España, 2017a).

The generating capacity in 2016 (105,279 GW) had the following participation by source: 19.3% of hydro; 7.2% of nuclear; 9.5% of coal; 2.4% of natural gas; 25.3% of natural gas with combined cycle; 21.9% wind power; 6.6% solar (photovoltaic and thermal); 0.7% of other renewables; 6.3% cogeneration; and, 0.7% waste (Red Eléctrica de España, 2017b).

The electrical generation in 2016 (262,161 GW), in which the source with higher generation was 21.4% of the total generation, following by wind power with 18.2%, hydropower with 14.9%, coal power with 14.3% and natural gas combined cycle with 11.2% (Red Eléctrica de España, 2017b).

Although the electrical growth had an expressive of renewable sources, the thermal power plants (nuclear, coal and combined cycle) still have a prevalence. Besides, the combined cycle plants represent the larger generating capacity, and this source is used to supply the energy demand when the renewable sources are not generating. The generating of the natural gas combined cycle and wind power are used to complement the generation, as shown in Fig. 4. In 21/09 at 1h20min, it was registered the total accumulated power generation of 30,213 MW, in which 1,033 MW is from wind power while 7,735 MW is from natural gas with the combined cycle.

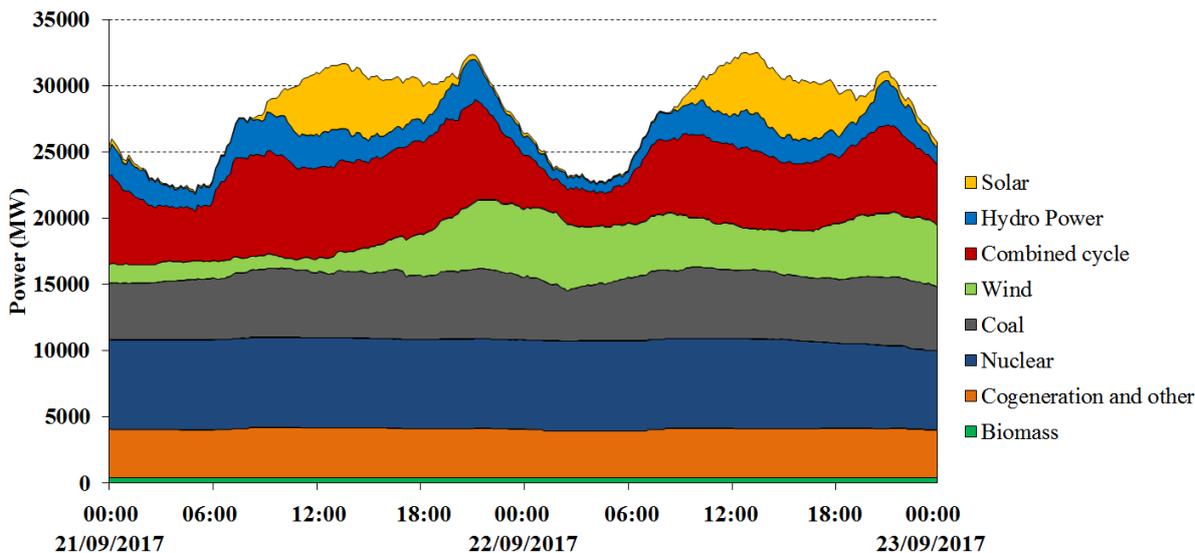


Figure 4. Power generation in Spain through 21/09/2017 to 23/09/2017
 Source: Modified from Red Eléctrica de España (2017c)

4.3 United Kingdom

UK had a generating capacity in 2016 of 78.3 GW, in which 40.5% refers to natural gas with combined cycle, 21.4% to conventional steam station, 12.1% nuclear station, 1.8% gas turbine and oil engines, 2.0% hydropower, 3.5% pumped storage, 8.9% wind power, 2.6% solar power and 7.0% from other renewable sources (United Kingdom Energy Statistics, 2017).

Despite the large predominance of fossil fuel in the electrical energy matrix, these sources had a substantial reduction in the participation during 2012 and 2016, especially conventional steam station that in 2012 accounted for 34.5% of the total installed. Nevertheless, the sources that had a major expansion in the participation during this period was wind and solar power, with the growth of 180% and 680%, respectively (United Kingdom Energy Statistics, 2017).

The total generated in 2016 was 763.5 TWh, in which the natural gas plants represented 39% of the generation, followed by the nuclear power plants, with 23.5%. The natural gas power plants have a high variability of generation, used to supply the energy demand when the renewable sources are not generating.

In Fig. 5 is shown the generation variability by source for two days. In 21/09 at 21h35 min, it was registered a total generation of 28.4 GWh, in which the natural gas with combined cycle represented 15.1 GW while wind and solar power were 1.6 GW. In 22/09 at 11h05 min, it was registered a total generation of 34.4 GW, in which the natural gas with combined cycle was 14.2 GW, while wind and solar power were 4.0 GW and 5,720 GW, respectively.

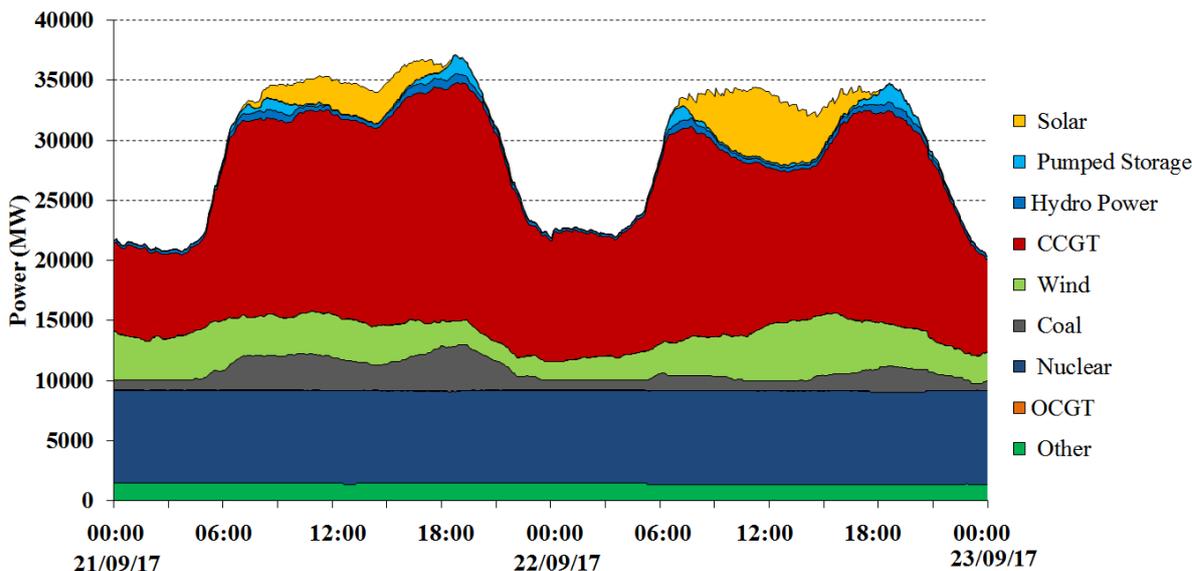


Figure 5. Power generation in UK through 21/09/2017 to 23/09/2017.
 Source: Modified from BM Reports (2017)

5. POWER GENERATION IN BRAZIL

Historically in Brazil, the renewable sources are the most used in power generation, in which 73.4% of the total generated in 2016 was hydropower, followed by thermal power plants, with 17.9% (ONS, 2017c). The participation of hydropower generation has decreased over the last ten years. The last maximum peak happened in March 2012, when the total hydro generation of the SIN was 42.4 TWh. After that, the thermal power generation has increased continually, hitting its maximum generation in October 2015, when it was produced 12.6 TWh; currently, in August 2017 the thermal generation reached 12.7 TWh, indicating that a new record of generation has broken (ONS, 2017c)

Moreover, in 2016 rainfall rate was higher in comparison with 2015 resulting in an apparent recovery in the reservoir water level. Because of that, the natural power generation decreased 28.9% in 2016, the coal generation decreased 9.8% and, the petroleum products decreased 52.8% (EPE, 2017). The hydropower generation increased 5.9%, which did not allow the reservoirs to fully recover; in addition, in 2017 the low rainfall rate resulted in a considerable decrease in stored energy.

The thermal power plants operation in Brazil is intermittent and is determined by, basically, two situations: when hydropower generation is not enough to supply electrical energy demand they start to operate and to attend structural deficits of the system. The operation of the thermal power plants is determinate by the water level in hydroelectric reservoirs, the rain forecast, the thermal power plants fuel and operational cost. The evaluation of the operational cost uses these parameters, in which is determined each plant that will start to operate.

To understand the particularities in Brazilian generation is necessary to observe the subsystems behavior individually. In the North subsystem, the majority of hydropower plants are run-of-river in such a way that the power generation has a wide range. Fig. 6 (a) shows the power generation between 2000 and 2017, in which is notable that the range of maximum and minimum is escalating annually. Because of that, during the minimum hydropower generation the region import electrical energy from Southeast region (ONS, 2017d).

The South subsystem has a wide range of hydropower generation, as it is shown in Fig. 6 (b). Contrarily to the North, in the South, the historical participation of thermal generation has declined after reach a maximum peak in April 2015. The thermal power plants in this region have a capacity factor lower than the other region mainly due to the low overall efficiency of the plants, since most of the plants are, at least, 30 years old (ANEEL, 2011). Presently, there are three projects of coal power plants and one natural gas power plant in the region (ANEEL, 2017). Wind power in the region is quite low, in which the generating capacity is almost five times smaller than the Northeast; however, the region has a great wind generation potential (Xavier, 2017).

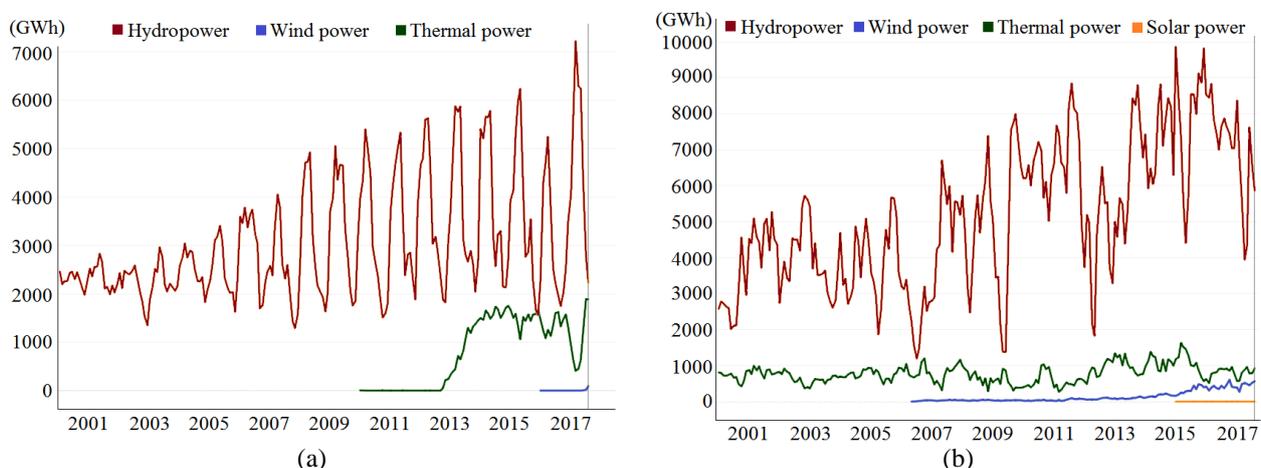


Figure 6. Electricity generation by sources between 2000 and 2017 for (a) North subsystem; (b) South subsystem
Source: Modify from ONS (2017c)

The Southeast/Mid West subsystem and the Northeast subsystem are in a more critical situation than the other regions in respect to hydropower generation. In August 2017, the Southeast subsystem received 179 GWh from Northeast; in August 2014, Southeast receive 17 GWh (ONS, 2017d). In 2014, the Northeast region thermal power production was higher than hydropower in almost 800 GWh; meanwhile, in 2017, the wind power generation was 3652 GWh, overcoming hydropower (1208 GWh) and thermal power (2787 GWh), as it is shown in Fig. 7 (a).

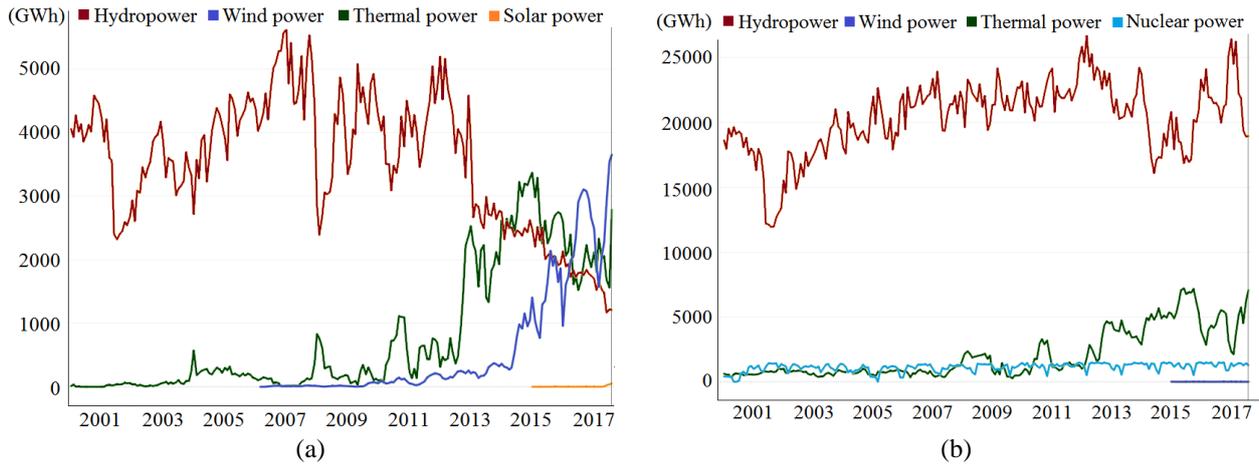


Figure 7. Electricity generation by sources between 2000 and 2017 for (a) Northeast subsystem; (b) Southeast/Mid west subsystem
 Source: Modify from ONS (2017)

Southeast region has the singularity to be the only region with nuclear power generation in Brazil, which although is smaller than the production from other sources, it is responsible for 50% of electrical energy demand of the state of Rio de Janeiro (Alana, 2017). Figure 7 (b) shows that the thermal generation in August 2017 was almost the same as the maximum peak of generation of October 2015; on the other hand, the hydropower generation production was as low as the production during the water crisis in 2015.

6. DISCUSSION

Using hydropower generation always was the priority in Brazil due to its abundance of hydraulic potential and low cost of operation, which has led the country to overuse this source. As a consequence, the country became highly dependent on favorable hydrological condition to attend the electrical demand, using it as a baseload power source while thermal power and other renewable were used to complement the system.

Notwithstanding, the dependency in only one source of power generation has been proven to not be able to assure security to the electrical energy matrix, especially because it is an unstable generation source. Environmental restrictions with respect to reservoir construction and its water level variability have restricted the hydroelectric plant operation and, in addition, it affects negatively the investment in new projects. Furthermore, climate changes have reduced the capacity to recover of the reservoirs, resulting in restrictions in the hydropower plants operation, a condition that has a few possibilities to change in a near future because the forecast is pointing to a reduction in rainfall rate and increase in temperature (Alisson 2013).

In opposition to the unfavorable hydrological conditions in the three years, wind power generation has grown due to the high investments in this source, which led to an expressive increase of it in the electrical energy matrix. Based on this, according to with EPE (2015), the wind power generation will be 24 GW, responding for 11.6% of the generation capacity.

Regardless the optimism about the wind power generation, it is important to point that its generation is as unstable as hydropower generation, in which the maximum generation happens during the dry season when the hydraulic generation has its lowest generation. For that reason, the growth of the generating capacity will continue to rely on favorable climatic conditions; besides, because the maximum generation during the year of these sources does not coincide, it is necessary to use the third source to complement the system and assure that the electrical demand will be attended.

The thermal power generating is the source used to complement the system during periods of high demand and low renewable sources generation. Still, thanks to the low hydropower generation, the thermal generation is been used as baseload power, just as it happened in during the dry season of 2015. Hence, because the thermopower plants are currently not prepared to be used for long periods whether in a technical or a contractual sense, resulting in a rise in electrical energy costs.

The Instituto Brasileiro de Petróleo, Gás e Biocombustíveis (2017) suggests that the thermal power generation should operate as baseload power and the hydropower and wind power should be used to complement the system during the entire year, changing the operational mode of the system. It is also suggested that investments in natural gas should rise in Brazil.

Presently, less than half of total thermal power plants operating uses natural gas, and it is the second most representative fuel used for power generation, accounting for 8.6% of generating capacity in 2016 (MME-SPE/N3E, 2017). Technically, the natural gas power plants reach its maximum power generating in short time; furthermore, the combustion of natural gas emits low greenhouse gases in comparison with coal and combustible oil. Another characteristic

of natural gas power plants is that because of combined cycle technologies, it can reach an overall efficiency around 50% to 60% (Ray, 2015).

Natural gas used in Brazil can be from national production or imported from Bolivia and Argentina. There are three regasification terminals, one in Southeast region (Baía de Guanabara-RJ) and two in Northeast region (Pecém-CE and TRBA-BA) which can receive up to 41 Mm³/d of liquified natural gas. Until 2018, it is expected the construction of two terminals in South region that can receive 19.5 Mm³/d and another one in Northeast with a capacity of 14 Mm³/d (Instituto Acende Brasil, 2016). With respect to the logistics of fuel supply, the country had an expansion of gas pipeline, mainly in the coastal region (ABEGÁS, 2017). Therefore, it permits the construction of new power plants near to large consumers, reducing the losses in the transmission line.

On the opposite of the last three years operation results, the 10-year Energy Plan 2024 says that the participation of thermal power plants in the electrical energy matrix will reduce gradually for the next ten years. It is expected that the gap left by this source will be fulfilled by other renewable sources, such as wind and solar power, just as it already happens in Spain, Germany, and the UK. The reduction of the greenhouse gases emissions and the investment in sources with low operation cost have driven the changes in Brazilian power generation.

7. CONCLUSION

The Brazilian option to increase the renewable sources participation in electrical energy matrix demonstrate a concern to adopt clean technologies, which has a small emission of greenhouse gases. Besides, the low operational cost of these sources is another motivation to invest in them, as a way to reduce power costs. However, considering the energy security, a large participation of renewable sources is not suitable due to their generation instability. Thus, the system operation needs to be reviewed, because the model that Brazil has adopted is exhausting the reservoirs and using thermal power generation for long periods that are larger than the usual for the country.

The use of thermal power generation that uses coal and natural gas is growing in the electrical energy matrix worldwide. The natural gas, in particular, is showing a world trend in thermal generation, due to its low cost and low greenhouse gas emissions. This way, it is desirable that the small investment in unstable sources be reviewed and, the hydro-thermal baseload power be maintained; also, it necessary to amplify the generating capacity of these sources, so they can be a backup against the instability of renewable sources.

8. ACKNOWLEDGEMENTS

The authors thank FAPEMIG and CAPES, Eletronuclear for the support to this work.

9. REFERENCES

- ABEGÁS, 2017. "Gasodutos" 26 Sep 2017. <http://www.abegas.org.br/Site/?page_id=842>
- Alana Gandra, 2017. "Usinas nucleares atingem em 2016 melhor marca em ano de troca de combustível" 25 Sep 2017. <<http://agenciabrasil.etc.com.br/geral/noticia/2017-01/usinas-nucleares-atingem-melhor-marca-em-ano-de-troca-de-combustivel>>
- Allison, E., 2013. "Climate Changes in Brazil through 2100". In Agência Fapesp. 29 Aug 2017. <http://agencia.fapesp.br/climate_changes_in_brazil_through_2100/18009/>
- Amaral, B. M., 2011. "Modelos VARX para geração de cenários de vento e vazão aplicados à comercialização de energia" Rio de Janeiro, Dissertação (Mestrado em Engenharia Elétrica) – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.
- Amato, F., 2016. "Usinas do Sudeste e Centro-Oeste têm melhor janeiro desde 2012" 23 Mar 2017. <<http://g1.globo.com/economia/noticia/2016/01/usinas-do-sudeste-e-centro-oeste-tem-melhor-janeiro-desde-2012.html>>
- ANEEL – Agência Nacional de Energia Elétrica (Brasil), 2011. "Nota Técnica nº. 034/2011-SRG/ANEEL" <http://www2.aneel.gov.br/aplicacoes/audiencia/arquivo/2011/043/documento/nota_tecnica_034_2011_srg.pdf>
- ANEEL – Agência Nacional de Energia Elétrica (Brasil), 2017. "Banco de Informações da Geração". 08 Sep 2017. <http://www2.aneel.gov.br/aplicacoes/Manuais_banco_de_Informacoes/>
- BM Reports, 2017. "G.B. National Grid Status" <<http://www.gridwatch.templar.co.uk>>
- British Petroleum, 2017. "BP Statistical Review of World Energy June 2017" Pureprint, London, 66th edition.
- COENERGY, 2017. "Reservatórios" 19 Sep 2017. <<http://www.coenergy.com.br/info.rese.php>>
- Deus, M. L. D., 2008. "Séries temporais aplicadas ao Planejamento da Operação do Sistema Interligado Nacional – SIN" Rio de Janeiro, Dissertação (Mestrado em Engenharia Elétrica) – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.
- EPE – Empresa de Pesquisa Energética, 2015. "Plano Decenal de Expansão de Energia 2024." 22 Apr 2017. <<http://www.epe.gov.br/>>

- EPE – Empresa de Pesquisa Energética, 2017. “Balanço Energético Nacional 2017: Ano base 2016” Rio de Janeiro. <https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2017.pdf>
- Exxon Mobil, 2017. “2017 Outlook for Energy: A view to 2040” 19 Sep 2017. <<http://cdn.exxonmobil.com/~media/global/files/outlook-for-energy/>>
- Fraunhofer, 2017. “Electricity production in Germany” In *Energy Charts*. <<https://goo.gl/g0f4NW>>.
- IchorCoal, 2017. “Market Research” 19 Sep 2017. <<http://www.ichorcoal.com/our-business/market-research>>
- International Atomic Energy Agency, 2017. “IAEA sees Global Nuclear Power Capacity Growing Through 2030”. 11 Sep 2017. <<https://www.iaea.org/newscenter/pressreleases/>>
- International Energy Agency, 2017a. “World Energy Balances: Overview (2017 edition)” In *World Energy Statistics 2017*. 6 Sep 2017. <<http://www.iea.org/publications/>>
- International Energy Agency, 2017b. “Coal Information 2017” 5 Sep 2017. <<http://www.iea.org/publications/>>
- International Energy Agency, 2017c. “IEA sees global gas demand rising to 2022 as US drives market transformation” 11 Sep 2017. <<https://www.iea.org/newsroom/news/2017/july/>>
- International Energy Agency, 2017d. “Natural gas Information: Overview (2017 edition)” 12 Sep 2017. <<http://www.iea.org/publications/>>
- Instituto Acende Brasil, 2017. “O Setor Elétrico Brasileiro no Contexto das Mudanças Climáticas e do Acordo de Paris” São Paulo, 17th edition.
- Instituto Acende Brasil, 2016. “O Mercado de Gás Natural e a Geração Termelétrica” São Paulo, 16th edition. <http://www.acendebrasil.com.br/media/estudos/2017_WhitePaperAcendeBrasil_17_AcordodeParis.pdf>
- Instituto Brasileiro de Petróleo, Gás e Biocombustíveis, 2017. “Geração termelétrica é uma das saídas para aproveitar reservas de gás natural do pré-sal” 26 Sep 2017. <<https://www.ibp.org.br/noticias/geracao-termeletrica-e-uma-das-saidas-para-aproveitar-reservas-de-gas-natural-do-pre-sal/>>
- MME-SPE/N3E, 2017. “Capacidade Instalada de Geração Elétrica Brasil e Mundo (2016)”. In *Boletins de Energia*. 14 Aug 2017. <<http://www.mme.gov.br/documents>>.
- ONS – Operador Nacional do Sistema, 2017a. “Capacidade Instalada” In *Histórico de operação*. <http://ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/capacidade_instalada.aspx>
- ONS – Operador Nacional do Sistema, 2017b. “Energia Armazenada” In *Histórico de operação*. <http://ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/energia_armazenada.aspx>
- ONS – Operador Nacional do Sistema, 2017c. “Geração de Energia” In *Histórico de operação*. <http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx>
- ONS – Operador Nacional do Sistema, 2017d. “Intercâmbios de Energia” In *Histórico de operação*. <http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/intercambios_energia.aspx>
- Quadro, M. F. L., et al., 1996. “Climatologia de precipitação e temperatura” In *Climanálise (Boletim de Monitoramento e Análise Climática, Especial de 10 anos)* <climanalise.cptec.inpe.br>
- Ray, R., 2015. “Combined Cycle: The Preferred Option” In Power Engineering, PennWell Corporation. <<https://www.energy.siemens.com/hq/pool/hq/power-generation/power-plants/gas-fired-power-plants/Combined-Cycle-PE-article.pdf>>
- Red Eléctrica de España, 2017a. “The Spanish Electricity System 2016” Madrid.
- Red Eléctrica de España, 2017b. “Spanish Electricity System 2016 Report” In *Statistical Data*. <<http://www.ree.es/en/statistical-data-of-spanish-electrical-system/annual-report/spanish-electricity-system-2016-report#>>
- Red Eléctrica de España, 2017c. “Estructura de generación” <<https://demanda.ree.es/movil/>>
- Statistisches Bundesamt – Destatis, 2017. “Data on energy price trends” In *Prices*. <<https://www.destatis.de/EN/Publications/Specialized/Prices/Prices.html>>
- Taesá, 2017. “Sistema Interligado Nacional – SIN” 18 Sep 2017. <<http://institucional.taesa.com.br/a-taesa/nosso-negocio/sistema-interligado-nacional-sin/>>
- United Kingdom Energy Statistics, 2017. “Digest of United Kingdom energy Statistics 2017” <www.gov.uk/government/collections/digestof-uk-energy-statistics-dukes>
- Xavier, M. 2017. “Rio Grande do Sul mostra potencial na produção de energia eólica” 26 Sep 2017. <<http://correiopovo.com.br/Noticias/Economia/2017/02/611196/Rio-Grande-do-Sul-mostra-potencial-na-producao-de-energia-eolica>>
- World Energy Council, 2016. “World Energy Resources 2016” World Energy Council, London.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.